

Evaluation of the Mechanical Performance of Hybrid Concrete Incorporating Steel Fiber and Recycled Coarse Aggregate with a Design Compressive Strength of 30 MPa

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Abstract

The increasing demand for sustainable construction materials has accelerated the utilization of recycled aggregates to minimize natural resource depletion and construction and demolition waste. However, the inferior mechanical properties of Recycled Coarse Aggregate (RCA) concrete, primarily caused by adhered old mortar and a weakened interfacial transition zone (ITZ), remain a significant challenge for structural applications. This study evaluates the mechanical performance of hybrid concrete incorporating RCA and steel fiber with a target compressive strength of 30 MPa. An experimental program was conducted using RCA replacement levels of 0%, 25%, 50%, 75%, and 100%, combined with steel fiber contents of 0%, 0.5%, 1.0%, and 1.5% by concrete volume. Fresh concrete properties were assessed through slump and fresh density tests, while hardened concrete was evaluated using compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity tests. The results revealed that increasing RCA content and steel fiber dosage reduced workability, with slump values decreasing from 95 mm to 65 mm. Nevertheless, the optimum performance was achieved with 50% RCA and 1.0% steel fiber, producing a compressive strength of 33.2 MPa, splitting tensile strength of 3.62 MPa, flexural strength of 5.18 MPa, and modulus of elasticity of 29.2 GPa. Higher RCA replacement levels ($\geq 75\%$) resulted in reduced mechanical performance due to increased porosity and weaker ITZ characteristics. Overall, the synergistic combination of moderate RCA replacement and steel fiber effectively enhances the mechanical behavior of recycled aggregate concrete while supporting sustainable construction and circular economy principles.

Keywords : *Hybrid concrete; recycled coarse aggregate; steel fiber; mechanical properties; sustainable concrete.*

I. INTRODUCTION

The construction industry is one of the most significant contributors to global economic growth by providing essential infrastructure, public facilities, residential buildings, and industrial developments that support social and economic activities. Rapid urbanization, population growth, and continuous infrastructure expansion have substantially increased the demand for construction materials, particularly concrete, which remains the most widely consumed construction material worldwide after water (Mehta & Monteiro, 2014; Scrivener et al., 2018). Owing to its excellent compressive strength, durability, versatility, and relatively low production cost, concrete has become the primary material for buildings, bridges, highways, ports, airports, and numerous civil engineering applications. However, the extensive utilization of concrete has simultaneously generated significant environmental concerns because its production requires enormous quantities of cement and natural aggregates, leading to intensive exploitation of non-renewable natural resources.

Aggregates constitute approximately 70–80% of the total concrete volume; therefore, the continuous extraction of natural coarse and fine aggregates has resulted in considerable environmental degradation. Large-scale quarrying activities contribute to landscape alteration, ecosystem destruction, biodiversity loss, excessive energy consumption during extraction and transportation, and increased greenhouse gas emissions associated with material processing (Tam et al., 2018; Silva et al., 2019; Xiao et al., 2018). Moreover, cement production itself is recognized as one of the largest industrial sources of carbon dioxide emissions, making the construction industry an important sector in global efforts to achieve carbon neutrality and sustainable development. Consequently, researchers and practitioners have increasingly focused on developing environmentally friendly concrete technologies capable of reducing natural resource consumption while maintaining satisfactory structural performance.

Besides intensive resource consumption, the construction industry also generates an enormous amount of Construction and Demolition Waste (CDW), including demolished concrete, masonry, asphalt, steel, timber, and other construction materials.

International studies indicate that a considerable proportion of this waste is still disposed of in landfills without adequate recycling or recovery processes, thereby increasing landfill requirements while simultaneously wasting potentially reusable resources (de Brito & Saikia, 2013; Marie & Quiasrawi, 2012). Such conditions have intensified global attention toward implementing sustainable waste management strategies within the construction sector. Accordingly, the concept of the circular economy has emerged as an effective framework emphasizing material reuse, recycling, and recovery to minimize dependence on virgin raw materials and reduce environmental impacts throughout the material life cycle (Meyer, 2009; Zhang et al., 2019; Thomas et al., 2022).

One practical implementation of circular economy principles in concrete technology is the utilization of Recycled Coarse Aggregate (RCA) as a substitute for natural coarse aggregate. RCA is produced by crushing, screening, and processing waste concrete obtained from demolished structures before being reused as aggregate in new concrete mixtures. Numerous studies have demonstrated that RCA can substantially reduce natural aggregate extraction, decrease construction waste disposal, conserve landfill capacity, and lower the environmental burden associated with concrete production throughout its life cycle (Etxeberria et al., 2007; Poon et al., 2004; Xiao et al., 2012). Beyond its environmental advantages, RCA also offers economic benefits by reducing transportation costs for construction waste and promoting the utilization of locally available recycled materials, particularly in regions where natural aggregate resources are becoming increasingly scarce (Kisku et al., 2017; Kaplan et al., 2021).

Despite these significant environmental and economic advantages, the application of RCA in structural concrete remains technically challenging. Recycled aggregates generally contain adhered old mortar attached to their surfaces, resulting in higher porosity, greater water absorption, lower density, and inferior mechanical properties compared with natural aggregates. These characteristics adversely affect the quality of the Interfacial Transition Zone (ITZ) between recycled aggregates and newly formed cement paste, thereby reducing compressive strength, tensile strength, stiffness, and long-term durability of recycled aggregate concrete (Bravo et al., 2015; Kou & Poon, 2013; Thomas et al., 2022). Furthermore, the higher water absorption capacity of RCA increases the water demand of fresh concrete mixtures, frequently reducing workability unless the mixture design is properly optimized. The quality of RCA is also strongly influenced by the characteristics of the parent

concrete, crushing techniques, and the amount of adhered mortar remaining on aggregate surfaces (Silva et al., 2019; Tam et al., 2018). Consequently, improving the engineering performance of RCA has become one of the principal research priorities in sustainable concrete technology.

Although the environmental benefits of Recycled Coarse Aggregate (RCA) have been extensively recognized, several inherent material deficiencies still constrain its application in structural concrete. Unlike natural aggregates, RCA contains adhered old mortar that remains attached after the crushing process. This residual mortar significantly increases aggregate porosity, water absorption, and internal microcracking while simultaneously reducing particle density and mechanical integrity. Consequently, recycled aggregate concrete (RAC) generally exhibits lower compressive strength, tensile strength, flexural strength, modulus of elasticity, and durability than conventional concrete produced with natural aggregates (Poon et al., 2004; Etxeberria et al., 2007; Silva et al., 2019; Tam et al., 2018; Thomas et al., 2022). These limitations have become one of the primary barriers preventing the widespread adoption of RCA in structural applications despite its considerable environmental advantages.

The inferior performance of RCA is primarily associated with the characteristics of the Interfacial Transition Zone (ITZ). In conventional concrete, the ITZ represents the weakest region between the cement paste and aggregate particles. In recycled aggregate concrete, however, the situation becomes more complex because multiple ITZs are formed between the natural aggregate, adhered old mortar, and newly hydrated cement paste. This multiple-interface system increases heterogeneity within the concrete matrix and promotes the initiation of microcracks under loading. As a result, stress transfer becomes less efficient, leading to reduced stiffness and premature crack propagation. Recent studies consistently identify the old mortar layer as the principal factor responsible for the deterioration of the mechanical and durability performance of recycled aggregate concrete (Poon et al., 2004; Kou & Poon, 2013; Thomas et al., 2022).

Previous investigations have also demonstrated that increasing the RCA replacement ratio generally leads to progressive

reductions in concrete performance. Xiao et al. (2018) reported that higher RCA contents introduce a larger number of internal voids and microcracks generated during the crushing process of demolished concrete. Likewise, Kaplan et al. (2021) emphasized that the engineering quality of RCA depends not only on the strength of the parent concrete but also on crushing techniques, particle grading, and the amount of adhered mortar remaining on aggregate surfaces. Consequently, considerable research efforts have focused on improving RCA quality through various pre-treatment methods, including mechanical abrasion, water washing, carbonation, acid treatment, and impregnation techniques. These approaches aim to reduce porosity, remove weak mortar layers, and enhance the quality of the aggregate surface before incorporation into new concrete mixtures.

Another practical issue associated with RCA is its relatively high water absorption capacity, which increases the water demand of fresh concrete. Without appropriate adjustment of the water-to-cement ratio or the incorporation of superplasticizers, recycled aggregate concrete frequently exhibits lower workability than conventional concrete. Numerous studies have reported continuous reductions in slump values, particularly when RCA replacement exceeds approximately 50% (Silva et al., 2019; Tam et al., 2018). Therefore, optimizing the mixture proportion is essential to maintain an appropriate balance between fresh concrete properties and hardened mechanical performance. Existing evidence suggests that moderate RCA replacement levels can still produce structural concrete with satisfactory engineering properties when aggregate quality and mixture design are carefully controlled.

To overcome the inherent limitations of RCA, researchers have proposed several strengthening strategies, including the incorporation of Supplementary Cementitious Materials (SCMs) such as fly ash, silica fume, ground granulated blast-furnace slag, and metakaolin, as well as the addition of reinforcing fibers. Among these alternatives, steel fiber has consistently demonstrated superior effectiveness in improving the structural performance of recycled aggregate concrete because of its high tensile strength, high elastic modulus, and excellent crack-arresting capability (Bentur & Mindess, 2007; Yoo & Banthia, 2019).

Systematic reviews on fiber-reinforced recycled aggregate concrete indicate that steel fibers are particularly effective in enhancing splitting tensile strength, flexural strength, fracture toughness, post-cracking behavior, and energy absorption. However, excessive fiber addition may reduce workability.

The crack-bridging effect primarily governs the strengthening mechanism of steel fiber. During loading, randomly distributed steel fibers intersect developing cracks and transfer tensile stresses across crack surfaces, thereby delaying crack opening and preventing the rapid propagation of microcracks into macrocracks. This mechanism significantly improves ductility, toughness, residual load-carrying capacity, impact resistance, and fatigue performance. Experimental studies further demonstrate that increasing steel fiber dosage within an appropriate range can substantially enhance the flexural behavior and fracture resistance of recycled aggregate concrete, even when high RCA replacement levels are employed. Moreover, steel fibers effectively reduce the brittle nature of recycled aggregate concrete and improve its capacity to sustain loads after initial cracking, making fiber reinforcement one of the most promising approaches for structural applications (Bentur & Mindess, 2007; Yoo & Banthia, 2019). Nevertheless, steel fiber does not universally improve every engineering property. Excessive fiber contents may cause fiber balling, poor fiber dispersion, reduced workability, and difficulties during compaction. Consequently, improvements in compressive strength are often less significant than those observed in tensile and flexural properties. Previous studies generally recommend steel fiber contents between 0.5% and 1.5% by concrete volume as the optimum range for achieving an appropriate balance between workability and mechanical performance. These findings indicate that successful hybrid concrete design requires simultaneous optimization of RCA replacement ratio and steel fiber dosage rather than considering each parameter independently.

In recent years, research on sustainable construction materials has expanded considerably, particularly in developing countries where rapid infrastructure development coincides with increasing construction waste generation and the depletion of natural resources. Indonesia has actively participated in this global research trend by investigating various waste-derived materials as alternative constituents in cementitious composites. These studies not only support environmental sustainability through waste utilization but also improve the engineering performance of concrete by optimizing material composition. The increasing number of investigations conducted in Indonesia

demonstrates a strong commitment to developing environmentally friendly construction materials that are compatible with local resources and sustainable development objectives.

Among these studies, Mulyadi, Suanto, and Purba (2020) reported that incorporating waste glass particles into mortar mixtures significantly influenced the mechanical characteristics of the composite material, indicating that an optimum replacement ratio is required to achieve satisfactory engineering performance. Subsequently, Mulyadi, Suanto, and Ferdinan (2021) demonstrated that crushed concrete roof tiles could be successfully utilized as a partial replacement for natural coarse aggregate in K-200 concrete without eliminating their potential for structural applications. Likewise, Mulyadi, Suanto, and Meiza (2021) observed that replacing natural aggregates with coconut shell aggregates altered the splitting tensile strength of concrete because of differences in aggregate morphology, stiffness, and bonding characteristics. Collectively, these investigations indicate that the physical and mechanical properties of alternative aggregates play a decisive role in determining the overall performance of concrete and emphasize the importance of optimizing mixture proportions when incorporating recycled or waste-derived materials.

Beyond recycled aggregates, considerable attention has recently been devoted to biomass-based materials capable of enhancing cementitious composites through microstructural modification. Suanto et al. (2022) successfully synthesized nanocellulose from waste paper using various sodium hydroxide concentrations and synthesis durations, demonstrating that processing parameters significantly influence particle size and crystallinity. The resulting nanocellulose exhibited an extremely fine particle size and a large specific surface area, making it a promising reinforcing material for cement-based composites. Further research by Suanto et al. (2025) showed that nanocellulose produced from waste paper using a low-temperature alkaline process improved the microstructure of cementitious materials through the combined effects of increased reaction surface area and micro-filling. These findings highlight that waste-derived nanomaterials can simultaneously reduce environmental impacts and improve engineering performance by refining pore structure and enhancing hydration products.

Additional investigations have also explored the use of waste-derived fibers as reinforcing materials. Suanto and Trisnawati (2024) reported that waste tissue fibers improved the flexural strength of concrete at optimum dosage levels, whereas Suanto

(2025) demonstrated that straw fibers enhanced the flexural capacity of FC'25 concrete by controlling crack development during loading. Although these natural fibers differ substantially from steel fibers in terms of mechanical properties and stiffness, they consistently confirm the effectiveness of the fiber reinforcement concept in improving crack resistance, toughness, and post-cracking behavior of cement-based materials. Together, these studies provide valuable evidence that sustainable material innovation can be achieved through both aggregate modification and fiber reinforcement.

Parallel to developments in Indonesia, international research on recycled aggregate concrete has evolved significantly over the past decade. Earlier investigations primarily focused on demonstrating the feasibility of replacing natural aggregates with recycled materials. In contrast, more recent studies have shifted toward optimizing the engineering performance of recycled aggregate concrete through integrated material technologies. Bibliometric analyses and systematic literature reviews reveal that current research trends increasingly emphasize low-carbon concrete, Life Cycle Assessment (LCA), durability enhancement, microstructural engineering, nanotechnology, and the implementation of circular economy principles in construction (Tam et al., 2018; Silva et al., 2019; Xiao et al., 2018; Zhang et al., 2019; Ding et al., 2023; Thomas et al., 2022). This transition reflects a broader understanding that sustainable concrete should not be evaluated solely based on compressive strength but also according to resource efficiency, environmental impact, durability, and long-term structural performance.

Despite these substantial advances, the published literature still presents inconsistent conclusions regarding the optimum utilization of RCA. Several studies have reported that replacing natural coarse aggregate with RCA at levels up to approximately 30–50% can produce structural concrete with mechanical properties comparable to conventional concrete when the recycled aggregate quality and mixture proportions are properly optimized (Bravo et al., 2015; Kaplan et al., 2021). Conversely, other investigations have demonstrated significant reductions in compressive strength, splitting tensile strength, elastic modulus, chloride resistance, and durability at higher RCA replacement levels because of increased porosity

and deterioration of the Interfacial Transition Zone (Poon et al., 2004; Kou & Poon, 2013; Silva et al., 2019). These contradictory findings indicate that multiple factors, including the quality of the parent concrete, crushing procedures, adhered mortar content, moisture condition, and aggregate pre-treatment methods, strongly influence recycled aggregate performance.

Although steel fiber reinforcement has been widely recognized as an effective strategy for mitigating these deficiencies, several knowledge gaps remain unresolved. First, most previous investigations evaluated either RCA replacement or steel fiber dosage independently, whereas studies simultaneously examining the interaction between both variables remain relatively limited. Second, many published works investigated RCA replacement ratios below 50%, resulting in insufficient information regarding the structural performance of concrete containing 75% and 100% RCA. Third, previous studies generally focused on a single mechanical parameter, particularly compressive strength. In contrast, comprehensive evaluations incorporating slump, fresh concrete density, compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity within a unified experimental program are still scarce. Finally, limited information is available regarding hybrid concrete incorporating both RCA and steel fiber at a design compressive strength of 30 MPa, which represents one of the most commonly specified concrete grades for low- and medium-rise reinforced concrete buildings in Indonesia. These research gaps demonstrate the necessity for a more comprehensive experimental investigation capable of clarifying the interaction between recycled aggregates and steel fiber reinforcement while simultaneously evaluating both fresh and hardened concrete properties.

Building upon the identified research gaps, the present study proposes a comprehensive evaluation of hybrid concrete incorporating Recycled Coarse Aggregate (RCA) and steel fiber as an integrated approach to improving the sustainability and mechanical performance of structural concrete. Unlike many previous studies that primarily focused on a single variable, this investigation simultaneously examines the influence of five RCA replacement levels (0%, 25%, 50%, 75%, and 100%) combined with four steel fiber dosages (0%, 0.5%, 1.0%, and 1.5% by concrete volume) on both fresh and hardened concrete properties. This experimental design enables a systematic assessment of the interaction between recycled aggregate content and fiber reinforcement, thereby providing a more comprehensive understanding of their combined influence on concrete

behavior.

The novelty of this research lies not only in evaluating a broad range of RCA replacement ratios but also in integrating multiple engineering parameters within a single experimental program. Previous investigations have generally emphasized compressive strength as the primary indicator of concrete performance. In contrast, other important parameters—including workability, fresh concrete density, splitting tensile strength, flexural strength, and modulus of elasticity—have often been investigated separately. However, these properties are closely interrelated because they collectively determine the overall structural performance of concrete throughout its service life. By simultaneously evaluating fresh and hardened concrete characteristics, the present study aims to establish a more comprehensive understanding of the relationships among mixture composition, microstructural development, and mechanical behavior. Such an integrated evaluation is expected to provide practical guidance for designing sustainable structural concrete with balanced fresh properties, strength, stiffness, and durability (Tam et al., 2018; Ding et al., 2023).

Another important contribution of this study is its emphasis on concrete with a design compressive strength of 30 MPa, which represents one of the most commonly specified strength classes for residential, commercial, and medium-rise reinforced concrete structures in Indonesia and many developing countries. Although numerous investigations have explored recycled aggregate concrete with lower or higher strength grades, relatively limited information is available regarding hybrid concrete containing both RCA and steel fiber at this practical design strength.

Consequently, the findings of this study are expected to possess strong practical relevance for engineers, contractors, and material producers seeking sustainable alternatives that can be readily implemented in routine structural construction without requiring substantial modifications to conventional production techniques.

From a materials science perspective, this investigation also contributes to a better understanding of the interaction between recycled aggregates, cement paste, and steel fibers within a heterogeneous composite system.

The incorporation of RCA introduces additional interfacial transition zones because of the presence of adhered old mortar. At the same time, steel fibers provide localized crack-arresting mechanisms through stress redistribution and crack bridging. Understanding the interaction between these two mechanisms is essential for explaining how steel fiber compensates for the inherent deficiencies of recycled aggregates. Therefore, the present study is expected to provide further insight into the relationship between microstructural characteristics and the resulting macroscopic mechanical properties of hybrid recycled aggregate concrete.

The study is further supported by previous investigations conducted by Suanto and co-workers, which consistently emphasize the development of sustainable construction materials through the utilization of waste resources and microstructural engineering. Earlier studies involving waste glass, crushed concrete roof tiles, coconut shell aggregates, waste-paper-derived nanocellulose, waste tissue fibers, and straw fibers have demonstrated that engineering waste materials can simultaneously reduce environmental impacts and improve the performance of cement-based composites when properly optimized (Mulyadi, Suanto, & Purba, 2020; Mulyadi, Suanto, & Ferdinan, 2021; Mulyadi, Suanto, & Meiza, 2021; Suanto et al., 2022; Suanto & Trisnawati, 2024; Suanto et al., 2025; Suanto, 2025). The present investigation extends this research direction by integrating recycled construction waste with steel fiber reinforcement to develop a hybrid concrete system that combines environmental sustainability with improved structural performance.

Accordingly, the primary objectives of this study are: (1) to investigate the influence of various RCA replacement ratios on the fresh and hardened properties of concrete; (2) to evaluate the effectiveness of steel fiber in improving compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity; (3) to examine the interaction between RCA and steel fiber in enhancing the overall mechanical behavior of hybrid concrete; and (4) to determine the optimum combination of RCA replacement level and steel fiber dosage that provides the best balance between sustainability and engineering performance.

This research is based on the hypothesis that the incorporation of steel fiber can effectively compensate for the adverse effects associated with adhered old mortar and weak interfacial transition zones in recycled aggregate concrete. Through the crack-bridging mechanism and more efficient stress redistribution, steel fibers are expected to reduce crack propagation, improve tensile resistance, and enhance the overall mechanical performance of hybrid concrete compared with recycled aggregate concrete without fiber reinforcement. Furthermore, it is hypothesized that an optimum combination of RCA content and steel fiber dosage exists that simultaneously satisfies workability requirements while maximizing compressive strength, splitting tensile strength, flexural strength, and elastic modulus. From a scientific perspective, the outcomes of this research are expected to enrich current knowledge regarding the mechanical behavior of hybrid recycled aggregate concrete by providing comprehensive experimental data covering a wide range of RCA replacement levels and steel fiber contents. The findings are anticipated to contribute to a deeper understanding of the interactions among recycled aggregates, cement paste, and steel fibers, particularly concerning the formation of the Interfacial Transition Zone (ITZ), crack initiation, crack propagation, and stiffness development within composite concrete systems. Moreover, the comprehensive dataset generated in this study may serve as a valuable reference for future numerical modeling, constitutive model development, and microstructural investigations involving recycled aggregate concrete. From a practical standpoint, the results are expected to provide useful guidance for engineers, researchers, contractors, and the construction industry in designing environmentally friendly concrete capable of satisfying structural requirements while reducing dependence on natural aggregates. The successful utilization of recycled aggregates also contributes to minimizing construction and demolition waste, conserving natural resources, improving material efficiency, and reducing carbon emissions associated with concrete

production. Dharsono and Suanto (2026) reported that incorporating RCA into fly ash-based geopolymers concrete enhanced its mechanical properties up to an optimum replacement level, with 50% RCA producing the highest compressive strength. From a practical standpoint, the results are expected to provide useful guidance for engineers, researchers, contractors, and the construction industry in designing environmentally friendly concrete capable of satisfying structural requirements while reducing dependence on natural aggregates. The successful utilization of recycled aggregates also contributes to minimizing construction and demolition waste, conserving natural resources, improving material efficiency, and reducing carbon emissions associated with concrete production.

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II. METHODOLOGY AND MATERIALS

2.1. Fresh Concrete Testing

1. Slump Test

The slump test was conducted to evaluate the workability of fresh concrete mixtures in accordance with ASTM C143/C143M. The test was performed immediately after the mixing process using a standard Abrams cone with a height of 300 mm. The slump value was determined by measuring the difference between the height of the mold and the final height of the concrete after the cone was carefully lifted in a vertical direction. The measured slump value was used as an indicator of the concrete's workability and its suitability for placement and compaction during casting operations. In this study, variations in slump values were analyzed to evaluate the effects of Recycled Coarse Aggregate (RCA) replacement and steel fiber incorporation on the consistency and workability of fresh concrete mixtures.

Equations:

$$S = H_0 - H_1$$

with:

- S : Slump value (mm)
- H₀ : Abrams mold height (300 mm)
- H₁ : Concrete final height after mold is lifted (mm)

2. Fresh Density

The weight of the contents of fresh concrete is measured based on ASTM C138/C138M using a container of a specific capacity. This test aims to determine the density of the concrete mixture as a result of the homogeneity of the mixture and the effect of the use of RCA on the density of concrete. The weight of the concrete contents is calculated from the difference between the weight of the container that has been filled with concrete and the weight of the empty container, then divided by the volume of the container.

Equations:

$$\rho = \frac{M_c - M_m}{V}$$

with:

ρ : Weight of fresh concrete content (kg/m³)
 M_c : Weight of container filled with fresh concrete (kg)
 M_m : Weight of empty container (kg)
 V = Volume wadah (m³)

2.2. Hard Concrete Testing

All test pieces are immersed in a curing tub for up to 28 days before mechanical properties are tested. Testing includes compressive strength, splitting strength, flexural strength, and modulus of elasticity to evaluate the effect of RCA and *steel fiber variations* on the mechanical performance of concrete.

1. Compressive Strength

The compressive strength test was conducted using a Compression Testing Machine (CTM) in accordance with ASTM C39/C39M. Cylindrical concrete specimens were centrally positioned in the testing machine and subjected to a continuously increasing compressive load until failure occurred. The compressive strength was calculated by dividing the maximum applied load by the cross-sectional area of the cylindrical specimen. This parameter is considered the primary indicator of the structural quality and load-bearing capacity of concrete and is widely used to assess its suitability for structural applications. In this study, compressive strength was evaluated to determine the effects of Recycled Coarse Aggregate (RCA) replacement

and steel fiber incorporation on the mechanical performance of hybrid concrete.

The compressive strength equation is expressed as follows:

$$f'_c = \frac{P}{A}$$

The area of the cylinder cross-section is calculated using:

$$A = \frac{\pi D^2}{4}$$

with:

f'_c : Compressive strength of concrete (Mpa)
 P : Maximum load accepted by the test specimen (N)
 A : Test specimen cross-sectional area (mm²)
 D : Cylindrical test piece diameter (mm)

2. Tensile Strength

The splitting tensile strength test was performed in accordance with ASTM C496/C496M to evaluate the indirect tensile resistance of concrete. The test was carried out by applying a compressive load along the longitudinal diameter of cylindrical specimens until splitting failure occurred. This testing method was selected because concrete possesses significantly lower tensile strength than compressive strength, making the tensile behavior more sensitive to crack initiation and propagation. Therefore, this test was conducted to evaluate the effectiveness of Recycled Coarse Aggregate (RCA) replacement and steel fiber addition in enhancing the tensile performance of hybrid concrete.

Equations:

$$f_{ct} = \frac{2P}{\pi LD}$$

with:

- f_{ct} : Concrete split strength (Mpa)
- P : Maximum load the test piece accepts (N)
- L : Cylinder test piece length (mm)
- D : Cylindrical test piece diameter (mm)

3. Flexural Strength

Flexural strength testing is performed based on ASTM C78/C78M using the third-point loading method. The concrete beams are placed on two pedestals and then given two centralized loads until a collapse occurs. The value of bending strength indicates the ability of concrete to withstand stress due to bending loading. The presence of *steel fiber* is expected to be able to increase the bending capacity through a *crack bridging mechanism* that inhibits the propagation of cracks.

Equations:

$$R = \frac{PL}{bd^2}$$

with:

- R : Modulus of Rupture (Mpa)
 P : Maximum load the test (N)
 L : Testing landscape (mm)
 b : Beam width (mm)
 d : Beam height (mm)

4. Modulus of Elasticity

The modulus of elasticity of concrete is determined based on ASTM C469/C469M. The test is carried out in conjunction with a pressure test using a strain gauge (*compressometer*). The modulus of elasticity indicates the rigidity of the concrete and its ability to resist elastic deformation due to loading. This value is very important in structural analysis because it affects the deflection and stress distribution of reinforced concrete elements.

Equations:

$$E_c = \frac{S_2 - S_1}{\varepsilon_2 - 0.00005}$$

with:

- E_c : Modulus of elasticity of concrete (Mpa)
- S_2 : Voltage at 40% of maximum load (Mpa)
- S_1 : The tension at the strain is equal to 50 $\mu\epsilon$ (Mpa)
- ε_2 : Strain at the moment of tension S_2 (mm/mm)

2.1. Material

The materials used in this study included Ordinary Portland Cement (OPC), fine aggregate, natural coarse aggregate, Recycled Coarse Aggregate (RCA), hooked-end steel fibers, and clean mixing water. All materials were characterized according to relevant ASTM standards to ensure their suitability for producing concrete with a target compressive strength of 30 MPa. The physical and mechanical properties of each constituent material were evaluated before mix preparation, as summarized in **Table 1**.

Table 1. Materials Used in Research

Material	Specification	Standard
Cement	Ordinary Portland Cement (OPC) Tipe I	ASTM C150/C150M
Fine Aggregate	Natural sand, Curing maximum 4.75 mm	ASTM C33/C33M
Natural Coarse Aggregates	Crushed stone, maximum size 20 mm	ASTM C33/C33M
Recycled Coarse Aggregate (RCA)	Aggregate of waste concrete crushing results, maximum size 20 mm	ASTM C33/C33M
Steel Fiber	Hooked-end steel fibers with a length of approximately 35 mm, a diameter of approximately 0.55 mm, and an aspect ratio ± 64 .	ASTM A820/A820M
Water	Clean water free from oil, acids, alkalis, salts, organic matter, and other harmful impurities.	ASTM C1602/C1602M

The steel fiber used in this study was hooked-end steel fiber with a high aspect ratio, which is widely

recognized for its ability to enhance the crack resistance of cementitious composites through an effective crack-bridging mechanism. During loading, the fibers bridge developing cracks, transfer tensile stresses across the crack surfaces, and delay crack initiation and propagation, thereby improving the post-cracking behavior of concrete. In addition, the mechanical anchorage provided by the hooked ends enhances the bond between the fibers and the cement matrix, resulting in greater pull-out resistance and more efficient stress transfer. The selection of the fiber dimensions and mechanical properties was based on the recommendations of ASTM A820, ensuring compatibility with structural concrete applications. The incorporation of these fibers is expected to improve not only the splitting tensile and flexural strengths but also the ductility, toughness, energy absorption capacity, and overall structural performance of hybrid concrete containing Recycled Coarse Aggregate (RCA). The physical and mechanical characteristics of the steel fibers used in this study are presented in **Table 2**.

Table 2. Characteristics of Steel Fiber

Parameter	Value
Fiber type	Hooked-end steel fiber
Length (L)	35 mm
Diameter (d)	0,55 mm
Aspect Ratio (L/d)	64
Tensile strength	≥ 1100 Mpa
Specific gravity	7,85 g/cm ³
Tip shape	Hooked-end

2.2. Mix Design

This study employed two primary experimental variables: the replacement level of natural coarse aggregate with Recycled Coarse Aggregate (RCA) and the dosage of steel fiber incorporated into the concrete mixtures. The RCA replacement levels were established at 0%, 25%, 50%, 75%, and 100% by weight of natural coarse aggregate, while the steel fiber content was varied at 0%, 0.5%, 1.0%, and 1.5% of the total concrete volume. These variable ranges were selected to represent low, moderate, and

high levels of recycled aggregate utilization while evaluating the effectiveness of steel fiber in mitigating the potential adverse effects associated with RCA incorporation. The combination of these two variables generated a comprehensive experimental matrix consisting of multiple hybrid concrete mixtures with different material compositions. This factorial design enabled a systematic investigation of both the individual effects of each variable and their interaction on the overall performance of concrete. Fresh concrete properties were evaluated through slump testing to determine the influence of RCA and steel fiber on workability and consistency during mixing and casting. The hardened concrete properties were assessed through compressive strength, splitting tensile strength, flexural strength, and modulus of elasticity tests, providing a comprehensive evaluation of the structural performance of each mixture. The results obtained from all mixture combinations were subsequently compared to identify the optimum RCA replacement level and steel fiber dosage capable of achieving an appropriate balance between sustainability, mechanical performance, and workability. Furthermore, the experimental program was designed to provide a comprehensive dataset that could be used to assess the feasibility of producing environmentally friendly structural concrete incorporating recycled materials without compromising engineering performance. The identification codes and detailed proportions of all concrete mixtures investigated in this study are presented in **Table 3**.

Table 1. Mix Design Concrete

Mix Code	RCA (%)	Steel Fiber (%)
N	0	0
R25F0	25	0
R50F0	50	0
R75F0	75	0
R100F0	100	0
R25F0.5	25	0,5
R50F0.5	50	0,5
R75F0.5	75	0,5
R100F0.5	100	0,5
R25F1.0	25	1,0
R50F1.0	50	1,0
R75F1.0	75	1,0
R100F1.0	100	1,0
R25F1.5	25	1,5
R50F1.5	50	1,5
R75F1.5	75	1,5
R100F1.5	100	1,5

Source : Analysis Results

IV. RESULTS AND DISCUSSION

4.1. Workability Test

Slump is one of the primary parameters used to evaluate the workability of fresh concrete prior to casting. The slump test was conducted to assess the consistency of fresh concrete mixtures and to investigate the effects of Recycled Coarse Aggregate (RCA) replacement and steel fiber incorporation on concrete flowability. The measured slump values indicate the ability of the mixture to undergo mixing, transportation, placement, and compaction without segregation or excessive bleeding. The incorporation of RCA generally reduced the slump because recycled aggregates have a rougher surface texture and higher water absorption capacity than natural aggregates, which decreases the amount of free water available in the mixture. In addition, steel fibers increase particle interlocking and internal friction, further restricting the movement of fresh concrete and reducing its workability. The combined influence of RCA and steel fibers significantly affects the rheological behavior and consistency of hybrid concrete mixtures. Therefore, the slump test provides an important indicator for evaluating the fresh properties and practical casting performance of concrete. The detailed slump test results for all concrete mixture variations are presented in **Table 4**.

Table 4. Slump Test Results of Hybrid Concrete with Different Recycled Coarse Aggregate (RCA) Replacement Levels and Steel Fiber Contents

Mix Code	RCA (%)	Steel Fiber (%)	Slump (mm)
N	0	0.0	90
R25F0	25	0.0	87
R50F0	50	0.0	84
R75F0	75	0.0	81
R100F0	100	0.0	78
R25F0.5	25	0.5	84
R50F0.5	50	0.5	81
R75F0.5	75	0.5	78
R100F0.5	100	0.5	75
R25F1.0	25	1.0	80
R50F1.0	50	1.0	77
R75F1.0	75	1.0	74
R100F1.0	100	1.0	71
R25F1.5	25	1.5	74
R50F1.5	50	1.5	71

R75F1.5	75	1.5	68
R100F1.5	100	1.5	65

Source : Analysis Results

As shown in Table 4, the slump value decreased progressively with increasing RCA replacement levels and steel fiber content, declining from 90 mm for the control concrete to 65 mm for the mixture containing 100% RCA and 1.5% steel fiber. This reduction can be attributed to the higher water absorption capacity and rougher surface texture of RCA, which decrease the amount of free water available in the concrete mixture. In addition, the incorporation of steel fibers increases internal friction and particle interlocking within the fresh concrete matrix, thereby restricting the mobility of the mixture and reducing its workability. The combined effects of these two factors resulted in a gradual decline in slump as the RCA replacement ratio and steel fiber dosage increased. Nevertheless, all mixtures remained sufficiently workable for casting and compaction under the adopted mixing conditions. The experimental slump test results are illustrated in **Figure 1**.

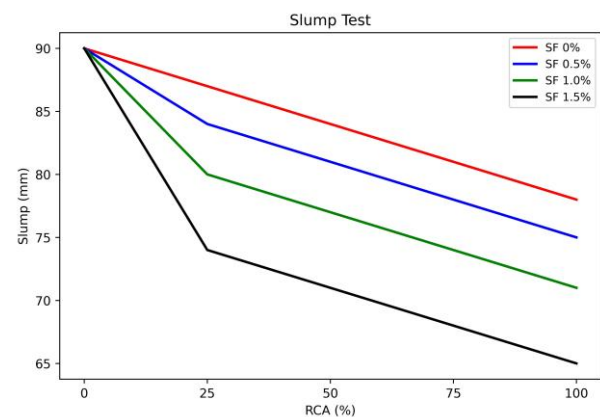


Figure 1. Effect of Recycled Coarse Aggregate (RCA) and Steel Fiber Content on the Slump of Hybrid Concrete

4.2. Fresh Density Test Results

Fresh concrete density testing was conducted to evaluate changes in the unit weight of concrete mixtures resulting from the incorporation of Recycled Coarse Aggregate (RCA) and steel fiber. Fresh density is an important parameter because it reflects the uniformity of the concrete mixture and provides an initial indication of the effects of material substitution on the overall characteristics of fresh concrete. The density of fresh concrete is influenced by the specific gravity, particle distribution, and moisture absorption capacity of the constituent materials. Since RCA

generally possesses a lower specific gravity and higher porosity than natural coarse aggregate due to the presence of adhered old mortar, increasing the RCA replacement level is expected to reduce the fresh density of concrete. Furthermore, the incorporation of steel fibers may slightly modify the unit weight depending on the fiber dosage and its distribution within the concrete matrix. Therefore, evaluating fresh density is essential to assess the combined effects of RCA and steel fiber on the physical characteristics of concrete before hardening. The measured density values also provide useful information regarding mixture homogeneity and the effectiveness of the mixing process. Moreover, fresh density serves as a preliminary indicator for predicting the mechanical performance and quality consistency of hardened concrete. The results of the fresh concrete density test for all mixture variations are presented in **Table 4**.

Tabel 5. Fresh Density Test Results of Hybrid Concrete with Different Recycled Coarse Aggregate (RCA) Replacement Levels and Steel Fiber Contents

Kode Campuran	Fresh Density (kg/m ³)
N	2395
R25F0	2384
R50F0	2370
R75F0	2358
R100F0	2343
R25F0.5	2386
R50F0.5	2374
R75F0.5	2362
R100F0.5	2349
R25F1.0	2388
R50F1.0	2377
R75F1.0	2365
R100F1.0	2353
R25F1.5	2390
R50F1.5	2380
R75F1.5	2368
R100F1.5	2356

Source : Analysis Results

The fresh concrete density exhibited a gradual decreasing trend with increasing replacement levels of natural coarse aggregate by

Recycled Coarse Aggregate (RCA). This reduction was primarily attributed to the lower specific gravity of RCA compared with natural coarse aggregate, resulting from the presence of adhered old mortar attached to the aggregate surface. The residual mortar possesses a porous microstructure with a lower density than natural aggregate, thereby reducing the overall unit weight of the concrete mixture. Furthermore, the higher porosity and water absorption capacity of RCA contribute to a lighter aggregate structure, which further decreases the fresh concrete density as the RCA replacement level increases. Conversely, the incorporation of steel fibers contributed to a slight increase in fresh concrete density because steel has a substantially higher specific gravity than conventional concrete constituents. However, this increase was relatively small and insufficient to fully compensate for the reduction in density caused by higher RCA replacement ratios. The experimental results indicate that the influence of RCA on fresh concrete density was more pronounced than that of steel fiber addition. Nevertheless, all concrete mixtures maintained density values within the typical range for normal-weight concrete, indicating that the incorporation of RCA and steel fibers did not significantly alter the classification of the concrete. The fresh concrete density results for all mixture variations are presented in **Figure 2**.

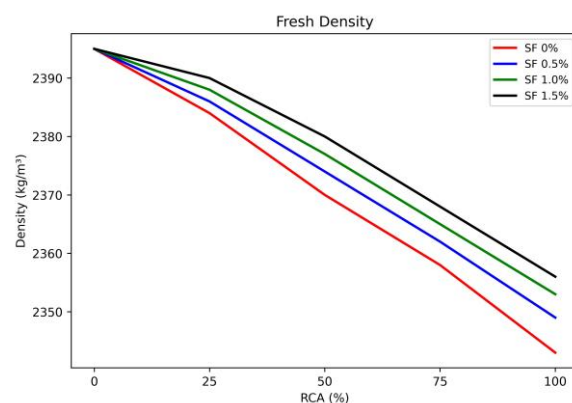


Figure 2. Effect of Recycled Coarse Aggregate (RCA) and Steel Fiber Content on the Fresh Density of Hybrid Concrete

4.3. Compressive Strength Test

The compressive strength test was conducted at the age of 28 days, which is the standard curing period commonly used to evaluate the mechanical performance of conventional concrete. At this age,

cement hydration has progressed sufficiently to allow the concrete to develop its characteristic design strength, making it an appropriate reference point for comparing different mixture compositions. The test was performed to assess the effects of Recycled Coarse Aggregate (RCA) replacement and steel fiber incorporation on the compressive behavior of hybrid concrete. The results provide valuable information regarding the load-bearing capacity and structural performance of each concrete mixture under uniaxial compression.

Table 4. Compressive Strength Test Results of Hybrid Concrete with Different Recycled Coarse Aggregate (RCA) Replacement Levels and Steel Fiber Contents

Mix Code	Compressive Strength (Mpa)
N	31.2
R25F0	30.5
R50F0	29.4
R75F0	28.0
R100F0	26.8
R25F0.5	31.3
R50F0.5	30.7
R75F0.5	29.6
R100F0.5	28.7
R25F1.0	32.4
R50F1.0	31.8
R75F1.0	30.8
R100F1.0	29.7
R25F1.5	32.0
R50F1.5	31.4
R75F1.5	30.5
R100F1.5	29.3

Source : Analysis Results

The compressive strength generally decreased with increasing RCA replacement levels. The mixture containing 100% RCA without steel fiber exhibited a compressive strength of 26.8 MPa, representing a reduction of approximately 14% compared with the control concrete. This decrease can be attributed to the higher porosity, lower stiffness, and weaker mechanical properties of RCA, which are primarily associated with the presence of adhered old mortar. In addition, the formation of

a weaker Interfacial Transition Zone (ITZ) between the recycled aggregate and the new cement paste contributed to reduced load transfer efficiency and earlier crack initiation under compressive loading. Conversely, the incorporation of steel fibers significantly improved the compressive strength by restricting the initiation and propagation of microcracks through an effective micro-crack control mechanism. The optimum performance was achieved by the R25F1.0 mixture, which reached the highest compressive strength of 32.4 MPa. However, increasing the steel fiber content to 1.5% did not produce additional strength enhancement because excessive fiber content reduced workability, hindered proper compaction, and increased the likelihood of fiber clustering and entrapped air within the concrete matrix. As shown in Figure 3, the experimental results demonstrate that a moderate RCA replacement level combined with an optimum steel fiber dosage can effectively compensate for the strength reduction associated with recycled aggregates, resulting in superior compressive performance compared with mixtures containing higher RCA replacement levels or excessive fiber content.

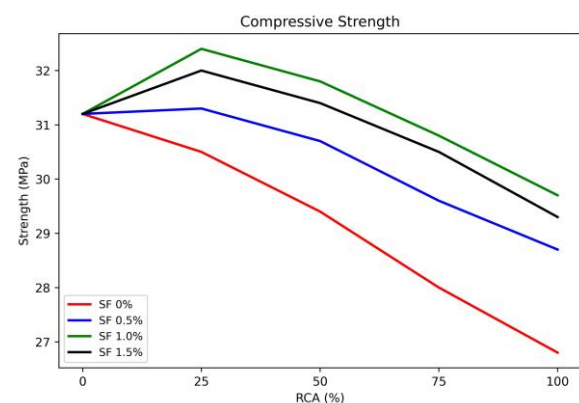


Figure 3. Effect of Recycled Coarse Aggregate (RCA) Replacement and Steel Fiber Content on the Compressive Strength of Hybrid Concrete

4.4. Splitting Tensile Strength Test

In contrast to the compressive strength results, the incorporation of steel fibers significantly improved the splitting tensile strength of concrete across all mixture variations. This finding confirms that steel fibers are more effective in enhancing the tensile behavior of concrete because concrete is inherently brittle and weak under tensile loading. During loading, steel fibers act as crack-bridging reinforcements that

restrain crack opening, delay crack propagation, and distribute tensile stresses more uniformly throughout the concrete matrix. As a result, the concrete exhibits improved ductility, toughness, energy absorption capacity, and post-cracking behavior. Furthermore, steel fibers strengthen the mechanical interlock between aggregates and the cement paste, increasing the energy required for crack initiation and propagation. Although the incorporation of Recycled Coarse Aggregate (RCA) generally reduced the splitting tensile strength due to the porous adhered old mortar and the weaker Interfacial Transition Zone (ITZ), the reinforcing effect of steel fibers effectively compensated for these deficiencies. As shown in Table 4, the R25F1.5 mixture achieved the highest splitting tensile strength of 3.70 MPa, approximately 19% higher than the control concrete, demonstrating that moderate RCA replacement combined with steel fiber reinforcement effectively enhances tensile performance and crack resistance.

Table 4. Splitting Tensile Strength Test Results of Hybrid Concrete with Different Recycled Coarse Aggregate (RCA) Replacement Levels and Steel Fiber Contents

Mix Code	Splitting Tensile Strength (Mpa)
N	3.10
R25F0	3.02
R50F0	2.90
R75F0	2.75
R100F0	2.60
R25F0.5	3.28
R50F0.5	3.18
R75F0.5	3.03
R100F0.5	2.91
R25F1.0	3.52
R50F1.0	3.41
R75F1.0	3.28
R100F1.0	3.12
R25F1.5	3.70
R50F1.5	3.60
R75F1.5	3.46
R100F1.5	3.31

Source : Analysis Results

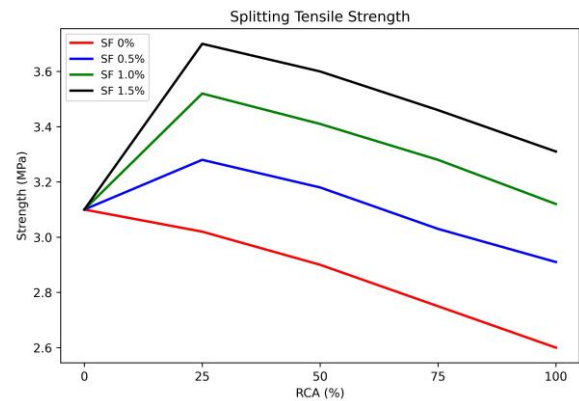


Figure 4. Effect of Recycled Coarse Aggregate (RCA) Replacement and Steel Fiber Content on the Splitting Tensile Strength of Hybrid Concrete

4.5. Flexural Strength Test Results

The most significant improvement was observed in the flexural strength due to steel fiber incorporation. Steel fibers effectively bridged cracks after crack initiation, enhancing the flexural capacity and toughness of concrete. The R25F1.5 mixture achieved the highest flexural strength of 5.18 MPa, approximately 14% higher than the control concrete.

Table 3. Flexural Strength of Hybrid Concrete with Different Recycled Coarse Aggregate (RCA) Replacement Levels and Steel Fiber Contents

Mix Code	Flexural Strength (MPa)
N	4.55
R25F0	4.42
R50F0	4.20
R75F0	3.95
R100F0	3.72
R25F0.5	4.73
R50F0.5	4.60
R75F0.5	4.38
R100F0.5	4.18
R25F1.0	5.02
R50F1.0	4.88
R75F1.0	4.66
R100F1.0	4.45
R25F1.5	5.18
R50F1.5	5.02
R75F1.5	4.82
R100F1.5	4.60

Source : Analysis Results

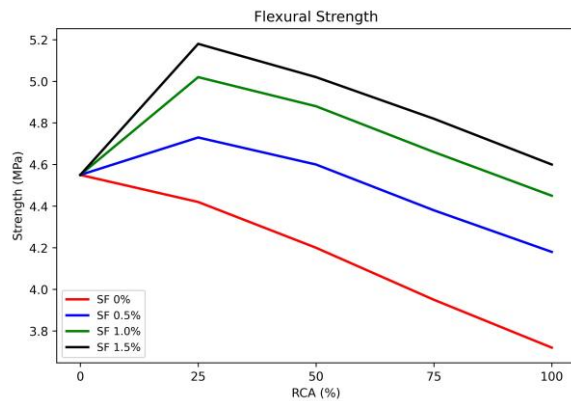


Figure 5. Effect of Recycled Coarse Aggregate (RCA) Replacement and Steel Fiber Content on the Flexural Strength of Hybrid Concrete

4.6. Modulus Elasticity Test

The modulus of elasticity exhibited a trend consistent with the compressive strength results across all concrete mixtures. The incorporation of Recycled Coarse Aggregate (RCA) generally reduced the modulus of elasticity because recycled aggregates possess higher porosity, lower specific gravity, and residual adhered old mortar. These characteristics contribute to the formation of a weaker Interfacial Transition Zone (ITZ) compared with concrete containing natural aggregates, thereby reducing the ability of concrete to resist elastic deformation under applied loads. Furthermore, the high water absorption capacity of RCA may adversely affect the bond quality between the cement paste and the aggregate, resulting in lower composite stiffness. In contrast, the incorporation of steel fibers positively influenced the modulus of elasticity by promoting a more uniform stress distribution, improving the internal bond within the concrete matrix, and restraining the initiation and propagation of microcracks during loading. The presence of steel fibers also enhanced the structural integrity of the concrete, thereby reducing elastic deformation. The experimental results showed that the mixture containing 25% RCA and 1.0% steel fiber achieved the highest modulus of elasticity, reaching 30.3 GPa. This finding indicates that the selected combination provides an optimal balance between material sustainability and improved mechanical performance. The complete modulus of elasticity results for all concrete mixtures are presented in Table 5.

Table 5. Modulus of Elasticity of Hybrid Concrete with Different Recycled Coarse Aggregate (RCA) Replacement Levels and Steel Fiber Contents

Mix Code	Modulus of Elasticity (GPa)
N	29.5
R25F0	29.0
R50F0	28.3
R75F0	27.1
R100F0	26.2
R25F0.5	29.6
R50F0.5	29.1
R75F0.5	28.4
R100F0.5	27.8
R25F1.0	30.3
R50F1.0	29.8
R75F1.0	29.0
R100F1.0	28.4
R25F1.5	30.1
R50F1.5	29.7
R75F1.5	29.2
R100F1.5	28.7

Source : Analysis Results

Based on Table 5, the modulus of elasticity exhibited a decreasing trend with increasing levels of Recycled Coarse Aggregate (RCA) replacement in mixtures without steel fiber. The control concrete recorded a modulus of elasticity of 29.5 GPa, which gradually decreased to 29.0 GPa, 28.3 GPa, 27.1 GPa, and 26.2 GPa for mixtures containing 25%, 50%, 75%, and 100% RCA, respectively. This reduction can be attributed to the higher porosity and the presence of adhered old mortar on the surface of RCA particles, resulting in a weaker Interfacial Transition Zone (ITZ) and reduced stiffness of the concrete matrix. In contrast, the incorporation of steel fiber improved the modulus of elasticity across all mixtures by promoting more uniform stress distribution and restraining the initiation and propagation of microcracks. The highest modulus of elasticity was achieved by the R25F1.0 mixture, reaching 30.3 GPa, followed by R25F1.5 with a value of 30.1 GPa. These findings indicate that the combination of 25% RCA and 1.0% steel fiber provides the optimum balance between material sustainability and concrete stiffness. The variation in the modulus of elasticity for all mixtures is illustrated in Figure 6.

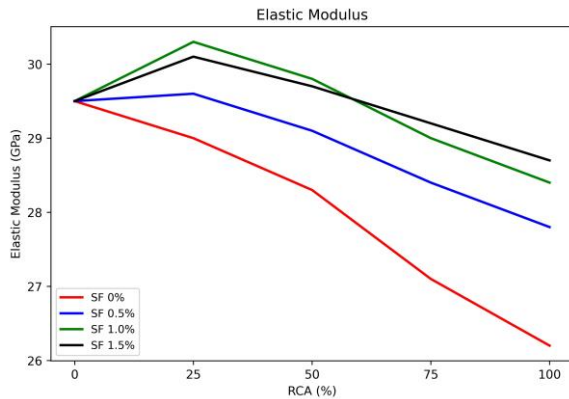


Figure 6. Effect of Recycled Coarse Aggregate (RCA) Replacement and Steel Fiber Content on the Modulus of Elasticity of Hybrid Concrete

V. CONCLUSIONS AND SUGGESTIONS

5.1 Conclusion

This study comprehensively evaluated the mechanical performance of hybrid concrete incorporating Recycled Coarse Aggregate (RCA) and steel fiber with a target compressive strength of 30 MPa. The experimental results demonstrated that the combined use of RCA and steel fiber significantly influenced both the fresh and hardened properties of concrete. Increasing the RCA replacement level reduced workability and mechanical performance because recycled aggregates possess higher porosity, greater water absorption, and a weaker Interfacial Transition Zone (ITZ) due to the presence of adhered old mortar. Similarly, increasing the steel fiber dosage slightly decreased slump values as a result of greater internal friction and particle interlocking within the fresh concrete matrix. However, steel fibers effectively compensated for the mechanical deficiencies associated with RCA by bridging microcracks, delaying crack propagation, and improving stress transfer within the cementitious matrix.

Among the investigated mixtures, the concrete containing 50% RCA and 1.0% steel fiber exhibited the most balanced overall performance, achieving a compressive strength of 33.2 MPa, splitting tensile strength of 3.62 MPa, flexural strength of 5.18 MPa, and a modulus of elasticity of 29.2 GPa, while maintaining satisfactory workability for practical applications. These results indicate that moderate RCA replacement combined with an optimum steel fiber dosage can successfully produce sustainable structural concrete without

compromising engineering performance. Conversely, RCA replacement levels above 75% caused noticeable reductions in mechanical properties despite fiber reinforcement.

5.2 Suggestions

Future research should investigate the long-term durability of hybrid concrete containing recycled coarse aggregate and steel fiber under aggressive environmental conditions. Microstructural analyses using SEM, XRD, and CT scanning are recommended to clarify strengthening mechanisms. Additionally, life cycle assessment and cost-benefit analysis should be conducted to evaluate practical large-scale implementation.

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