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Research Article

A Stat-of-the-Art Review of Fiber Reinforced Concrete: Evaluating Mechanical Performance

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***Abstract* –** Fiber-reinforced concrete (FRC) incorporates fibers to enhance its properties, making it an intriguing subject for researchers to explore in different applications. Many studies have reviewed the role of fibers in concrete mixes to evaluate how they influence various concrete characteristics. However, these reviews often have limitations, such as focusing on a single type of fiber or concrete or analyzing only a limited set of concrete properties. Some reviews have specifically targeted recycled fibers, neglecting the effects of freshly manufactured industrial fibers on concrete performance. To address these gaps and limitations, this study aims to create a comprehensive database that includes diverse fiber types, properties, ratios, concrete mixtures, and aggregate particles. The literature provides insights into the impact of fibers on different forms of concrete. The present study examines how fibers affect different properties of concrete, drawing from previous sources that discuss its durability, workability, and mechanical performance.

Keywords – Fiber Reinforced Concrete, Mechanical Properties, Single Fibers, Hybrid Fibers, Recycled Fibers.

I. INTRODUCTION

Fiber-reinforced concrete (FRC) is a form of concrete that incorporates fibers to enhance its mechanical properties. Researchers are actively investigating FRC to gain insights into its behavior under diverse conditions. In accordance with AC1-116R, Cement & Concrete Terminology, FRC is defined as concrete that contains fibers distributed randomly throughout its matrix [1]. The practice of adding fibers to concrete can be traced back to ancient Rome (300 BC–476 AD), where it was used to improve the structural capacity of concrete to bear heavy loads [2]. The addition of fibers to concrete continued into the 19th century when Portland cement concrete became widespread, and efforts to further strengthen the material using fibers gained traction [3]. In 1874, Bernard from California filed the first patent for fiber-reinforced concrete, which involved adding waste iron to the concrete mix [3, 4]. Later, Alfsen's 1918 French patent introduced a method to enhance the tensile strength of concrete by mixing fibers, such as iron or wood, uniformly into the concrete [3, 4]. These fibers were roughened and their ends twisted to improve their bond with the concrete matrix.

Yoo and Banthia discovered that deformed steel fibers, such as hooked-end and twisted fibers, significantly improve the mechanical properties of ultra-high-performance fiber-reinforced concrete

(UHPFRC). They found a 32% increase in tensile strength, a 205% increase in strain capacity, and a 167% rise in flexural strength when compared to straight steel fibers cut short. Their review on the impact resistance of conventional fiber-reinforced concrete (FRC) [5] showed that deformed steel fibers, particularly hooked-end fibers, greatly enhance both the impact resistance and energy absorption capacity of plain concrete. Behbahani et al. [6] confirmed that steel fiber-reinforced concrete (SFRC) exhibited significant improvements in flexural strength and toughness compared to traditional reinforced concrete. Liew and Akbar [7] investigated the performance of recycled steel fiber-reinforced concrete under flexural loading and found that it performed comparably to concrete with fresh fibers. Nonetheless, further research is required to fully understand the influence of recycled steel fibers on various cement-based systems' compressive strength and fiber-matrix interaction.

The above-mentioned studies on fiber-reinforced concrete exhibit certain limitations, such as focusing solely on specific types of fibers or concrete mixtures. Some research only explored recycled fibers and did not address the impact of fresh industrial fibers. To bridge these gaps, this review aims to compile a comprehensive database encompassing various fiber types, properties, ratios, concrete mixes, and aggregate particles. This study will investigate the effect of fibers on 15 different concrete properties, including compressive strength, tensile strength, flexural strength, toughness, ultrasonic pulse velocity, slump, air content, and electrical resistance, based on an analysis of 148 research studies.

i. Fiber Properties And Literature Analysis

Fibers are long, thin particles incorporated into conventional cement paste, mortar, or concrete mixtures. Some fibers, like glass or polypropylene, are flexible, while others, such as steel, are more rigid [8]. Adding fibers as a supplementary component to the concrete mixture is one approach to enhancing specific engineering properties. Fibers are generally categorized into three main types: metallic, polymeric, and natural [9, 10, 11]. Fibers may be derived from natural materials like asbestos, sisal, and cellulose or synthetic materials like glass, steel, carbon, and polymers [10, 12]. Steel fibers (metallic) are the most widely used in both structural and nonstructural applications [13]. Following steel, polypropylene (PP), glass, and other fibers are also used, but they are less common in structural concrete applications [13-14]. Factors such as cost, production processes, reinforcement capabilities, and resistance to environmental conditions make steel fibers highly favorable.

Researchers have incorporated fibers into various concrete mixes, including those designed to improve normal concrete [15, 16, 17, 18, 19, 20, 21] and enhance high-performance concrete [22, 23], high-strength concrete [24, 25, 26, 27], self-compacting concrete [28–29, 30, 31], self-consolidating concrete [32, 33, 34, 35, 36–37], and lightweight concrete [38, 39, 40, 41, 42, 43]. Some studies focused on the use of fibers with recycled aggregates [44–45] to evaluate their effects on concrete properties. The data and classification of these studies are shown in Table 1. Table 2 provides a breakdown of the literature by concrete properties.

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ii. Compressive Strength

Compressive strength is a key property of concrete [46]. Several studies have investigated the effects of fibers on the compressive strength of various concrete mixtures [47, 48], as illustrated in Figures 1 through 3. According to [47], incorporating 1% by volume of glass, steel, or polypropylene fibers into normal strength concrete (NSC) increased compressive strength by 9.6%, 5.0%, and 6.9%, respectively. This demonstrates that reinforcing the binder matrix with fibers increases compressive strength and thus improves the stiffness of composite materials. Due to its higher stiffness and elasticity modulus compared to glass and polypropylene fibers, steel fiber particularly enhances compressive strength. Experimental studies with steel and polypropylene fibers [32] showed that compressive strength can increase by up to 90%, 18%, and 95% for PPFI, PPFII, and SF, respectively.

Steel fiber (SF) is one of the most commonly used fibers in concrete. Its performance depends on several factors, such as type, shape, length, cross-sectional strength, fiber content, bonding capacity, matrix durability, mix design, and mixing methods [38]. Consequently, extensive research is focused on evaluating these variables. A study [33] identified two types of steel fibers, one with straight threads and another with a hooked-end shape, and noted that fibers have a minimal impact on compressive strength. Hooked-end fibers produced compressive strengths of 33.80, 36.44, 40.92, and 40.20 MPa, while straight fibers achieved values of 38.45, 40.19, and 42.83 MPa. Fiber dosages were 40, 75, and 110 kg/m³. Haddadou et al. [41] also examined two types of steel fibers and found that the compressive strength of self-compacting concrete (SCC) was reduced when steel fibers with hooked ends and marble powder were added at 60 kg/m³.

Efforts have been made to investigate fiber hybridization's effects on compressive strength. One study [6] evaluated how hybridizing steel fibers in normal strength concrete impacted its mechanical properties and found that fiber hybridization had no significant influence on peak compressive strength. Similarly, research on mono steel fibers [38] revealed that different fiber lengths had little effect on compressive strength. Increasing fiber volume fractions from 1.0% to 1.5% reduced compressive strength, but strength began to rise beyond that point. In hybrid fiber-reinforced concrete studies, Rashiddadash et al. [37] used pumice and metakaolin, reporting that mechanical properties were higher in concrete with more steel fibers compared to concrete with a lower percentage. Hybrid fiber-reinforced concrete containing 0.75% steel and 0.7% polypropylene fibers exhibited superior mechanical properties. Additionally, the incorporation of metakaolin, particularly a 15% replacement of cement, increased compressive strength.

Liu et al. [39] investigated the effects of silica fume, steel fiber, and polypropylene fiber on lightweight self-compacting concrete (SCLAC). Depending on fiber content, compressive strength values ranged from 23.2 MPa to 26.6 MPa after three days, from 36.2 MPa to 42 MPa after seven days, from 52.8 MPa to 61.7 MPa after 28 days, and from 66.8 MPa to 80.6 MPa after 90 days. The best-performing SCLAC mix, containing silica fume and hybrid fibers (0.5SF and 0.5PPF), demonstrated compressive strengths of 42 MPa at seven days, 61.7 MPa at.

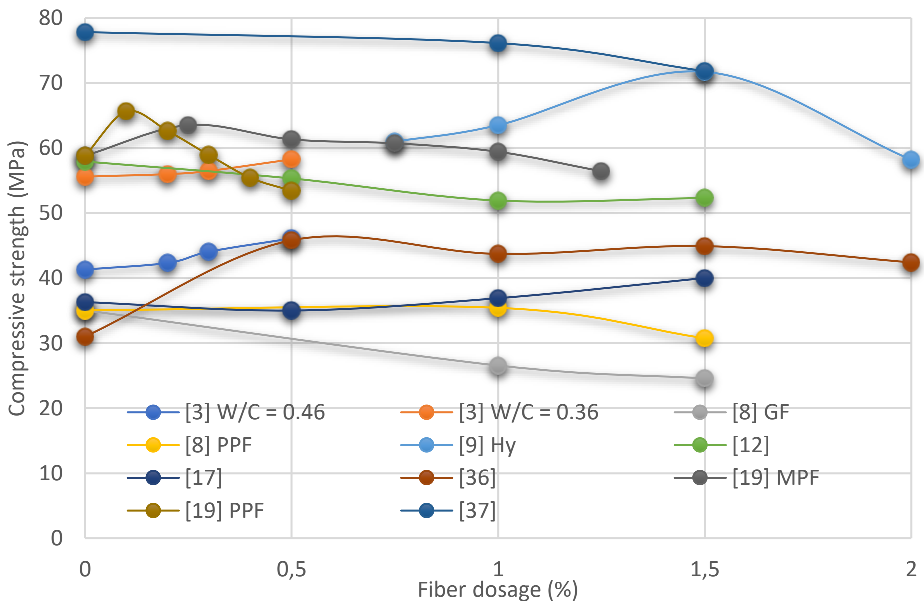

Figure 1: Compressive strength among the fiber content from the mentioned literature.

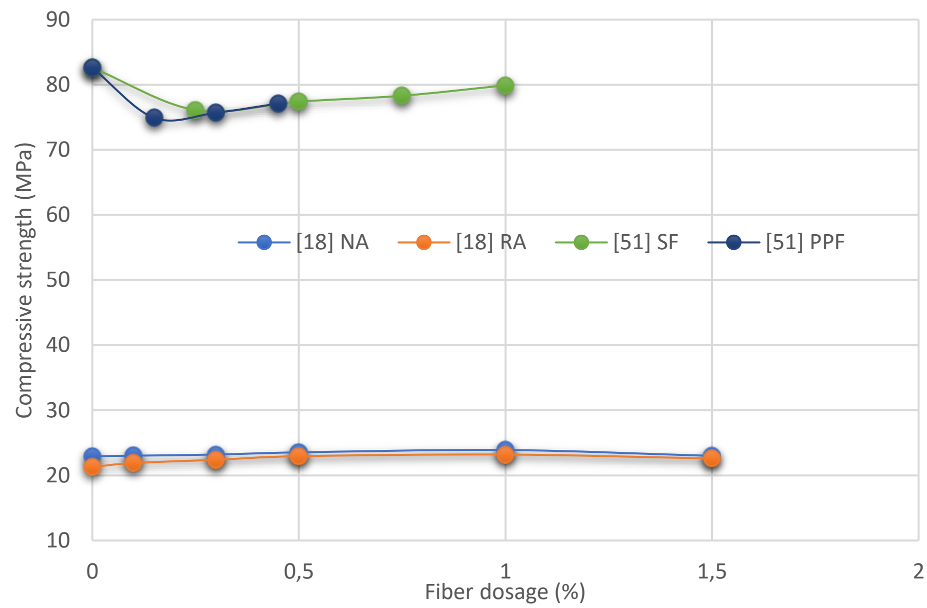

Figure 2: Compressive strength among the fiber content from the mentioned literature.

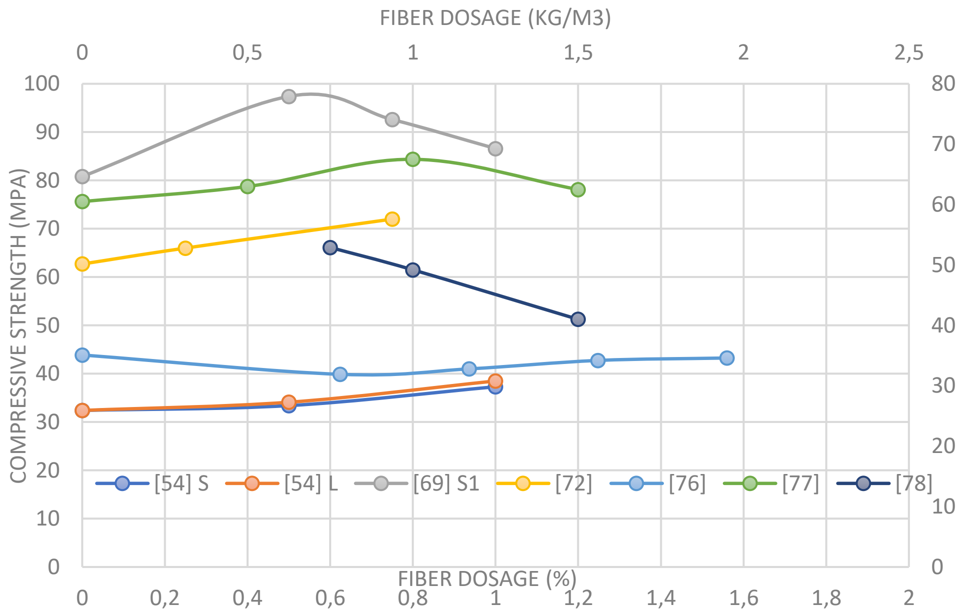

Figure 3: Compressive strength among the fiber content from the mentioned literature.

II. TENSILE STRENGTH

The mortar matrix functions as a series of struts, while the coarse particles are surrounded by unexpected threads, forming a web-like structure that resembles a space truss. Fibers embedded within the mortar matrix transfer the tensile forces generated in the system, while the concrete matrix helps distribute and pass these internal tensile stresses to the fibers integrated within the concrete [36]. These microcracks are held together by numerous fibers, preventing their further growth. By transferring the tensile load to the fibers, concrete's splitting tensile strength can be significantly enhanced, which also prevents the formation of macrocracks [36, 34]. Several studies in the literature have explored the impact of fibers on the tensile characteristics of concrete [48-49, 31, 47]. Additionally, Figures 4 through 6 display how different fiber dosages affect the tensile strength of concrete based on selected studies.

Various types of fibers have been incorporated into concrete to examine the tensile strength and behavior of fiber-reinforced concrete (FRC) under tensile loads. Steel fibers were a popular choice among many researchers, with Chen and Liu [49], among others, supporting their use. Topcu and Canbaz [37] found that concrete specimens containing steel fibers exhibited a significant increase in splitting-tensile strength. The growth observed was around 50% or 10%. When fibers, particularly steel fibers, are added to concrete, it becomes less brittle and gains ductility. Ductile materials generally possess higher tensile strength compared to brittle ones. In another case, Marcalikova et al. [33] reported that concrete reinforced with straight fibers demonstrated higher tensile strength, though not as significant as that of concrete with hooked fibers. Fiber-reinforced concrete containing straight fibers (at a dosage of 110 kg/m³) showed a splitting tensile strength approximately 17% greater than normal concrete transverse to the pouring direction, increasing from 2.64 to 3.08 MPa. As the fiber content increased from 50 kg/m³ to 75 kg/m³, the bending tensile strength improved from 3.90 to 4.98 MPa, representing a 28% increase. Similarly, the tensile strength continued to rise as splitting occurred with added fibers [40]. When comparing the peak tensile strength of composites with steel fiber dosages of (15, 30, 45, and 60 kg/m³) to normal concrete, increases of 18.6%, 23.3%, 14.0%, and 21.0% were observed, respectively, highlighting multiple advantages. As shown in [46], when steel fibers (SFs) increased to 2.0%, the split tensile strength initially increased before it declined, as depicted in Figure 5. Steel fiber-reinforced concrete demonstrated better performance in terms of crack control. Rather than completely stopping cracks, fibers help to arrest their propagation.

Additionally, the use of steel fibers (SF) with recycled aggregates (RA) has been examined by Carneiro et al. and Koushkbaghi et al. observed that the splitting tensile strength decreased as the amount of recycled aggregate material increased. For mixtures with 100% RCA replacement, the reduction in strength was 22.2% and 14.7%, respectively, for non-fibrous and fibrous specimens compared to concrete with natural aggregates. When 50% RCA was used to replace natural aggregate, the strength of non-fibrous and fibrous concrete dropped by 9.6% and 6.6%, respectively. However, other tests conducted by Carneiro et al. [47] showed that the addition of steel fibers enhanced the tensile behavior of the specimens. In fact, using recycled material instead of natural aggregate improved the tensile strength of the reference mixture.

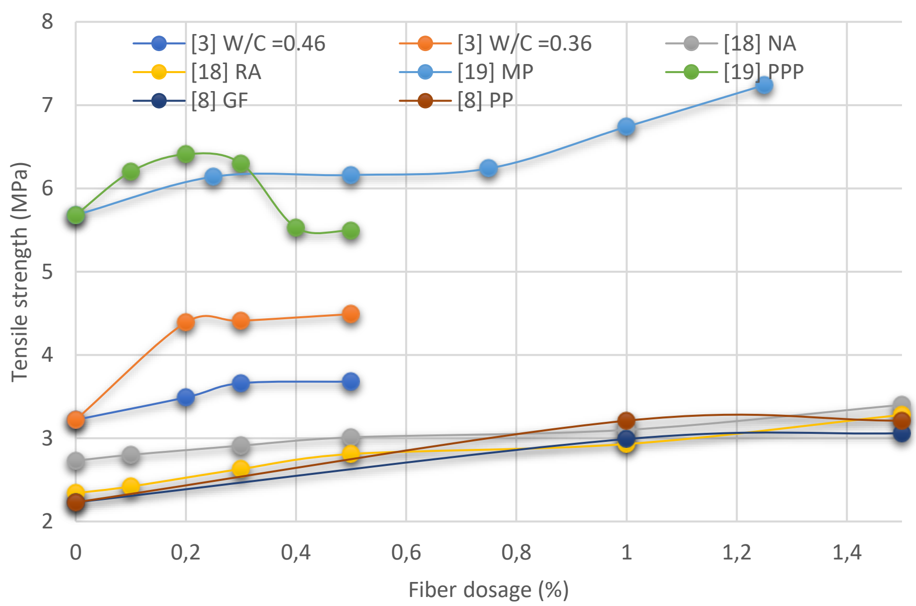

Figure 4: Tensile strength among the fiber content from the mentioned literature.

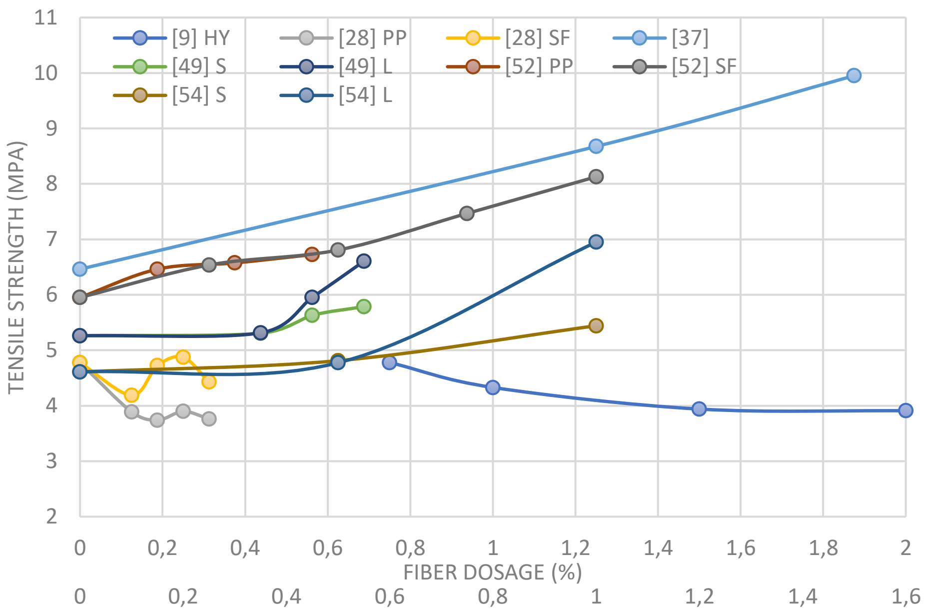

Figure 5: Tensile strength among the fiber content from the mentioned literature.

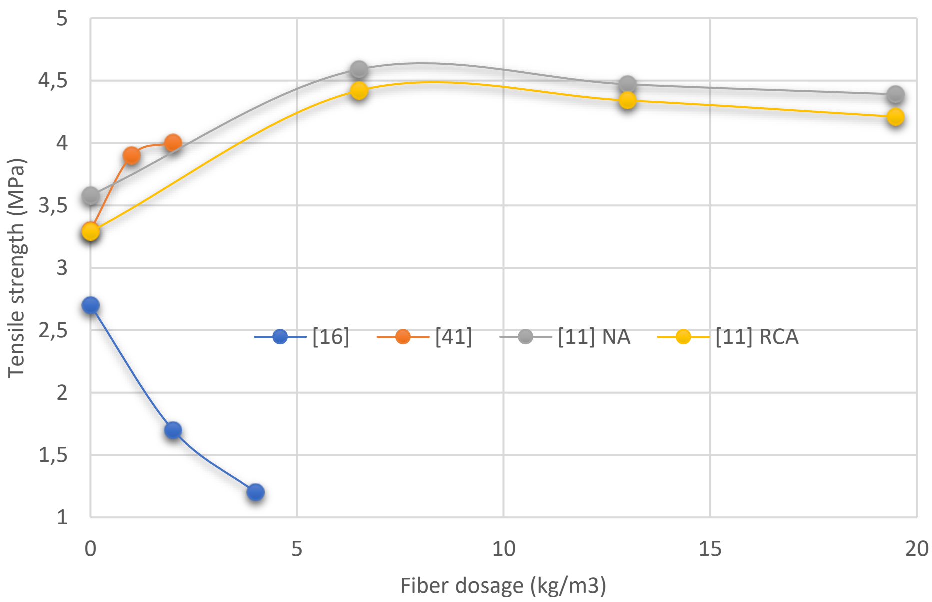

Figure 6: Tensile strength among the fiber content from the mentioned literature.

III. FLEXURAL STRENGTH

Flexural strength is a critical mechanical property of concrete, especially in a wide range of structural applications. Numerous studies [48, 44-45] have examined how various fibers influence the flexural performance of different concrete types. The findings from these studies, shown in Figure 7 and Figure 8, highlight the impact of fiber dosage on concrete's flexural strength. The inclusion of fibers improves flexural strength, with each fiber type providing a unique mechanism for resisting internal tensile stresses and preventing cracking [49]. According to Wongprachum et al. [51], fibers can also reduce the rate of flexural strength loss due to sulfate exposure when incorporated into mortar mixtures.

Choi et al. [48] conducted experimental research to assess how fiber reinforcement influences the properties of lightweight concrete, composed of fine and coarse aggregates. They compared the effects of three fiber types—steel, vinylon, and polyethylene—on flexural strength. The results showed that fibers improved the flexural strength of normal gravel concrete by 13–77%, whereas lightweight aggregate concrete (LA concrete) exhibited a strength increase ranging from 4-234%. Specifically, with 0.8% steel fibers, the flexural strength of LA concrete increased by 120%. However, further increases in steel fiber content beyond 0.8% did not result in significant strength gains. The addition of fibers also enhanced the flexural strength of normal aggregate (NA) concrete, though the improvement was only about 60%, making it less effective compared to LA concrete. When 0.8–1.0% of steel, vinylon, and polyethylene fibers were incorporated, the flexural strength of LA concrete rose by 127%, 108%, and 122%, respectively, while NA concrete showed increases of 42%, 63%, and 23%. For fiber additions up to 1.5%, LA concrete saw increases of 107%, 234%, and 194%, and NA concrete showed corresponding improvements of 64%, 77%, and 62%. These findings indicate that vinylon fibers were the most effective in enhancing the flexural strength of LA concrete.

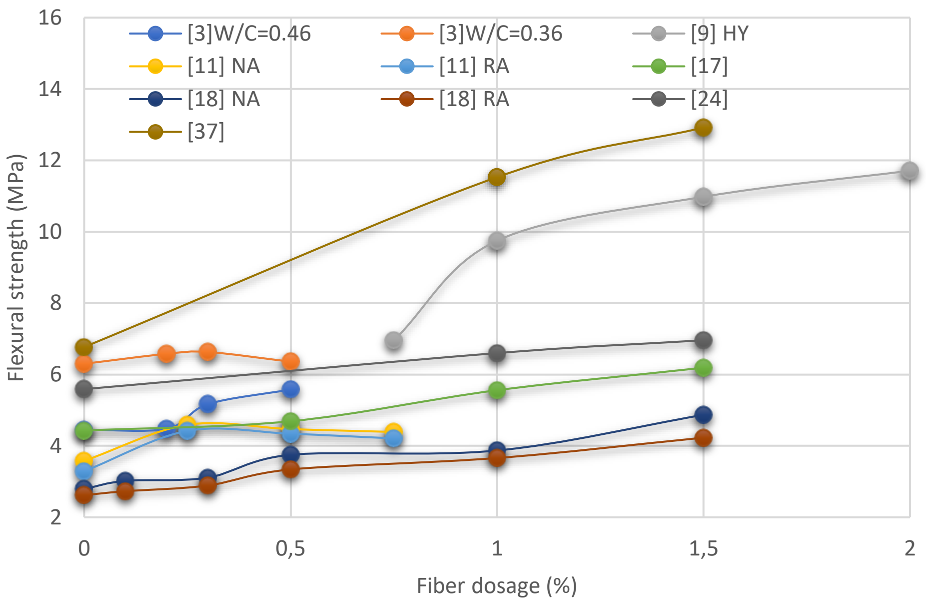

Figure 7: Flexural strength among the fiber content from the mentioned literature.

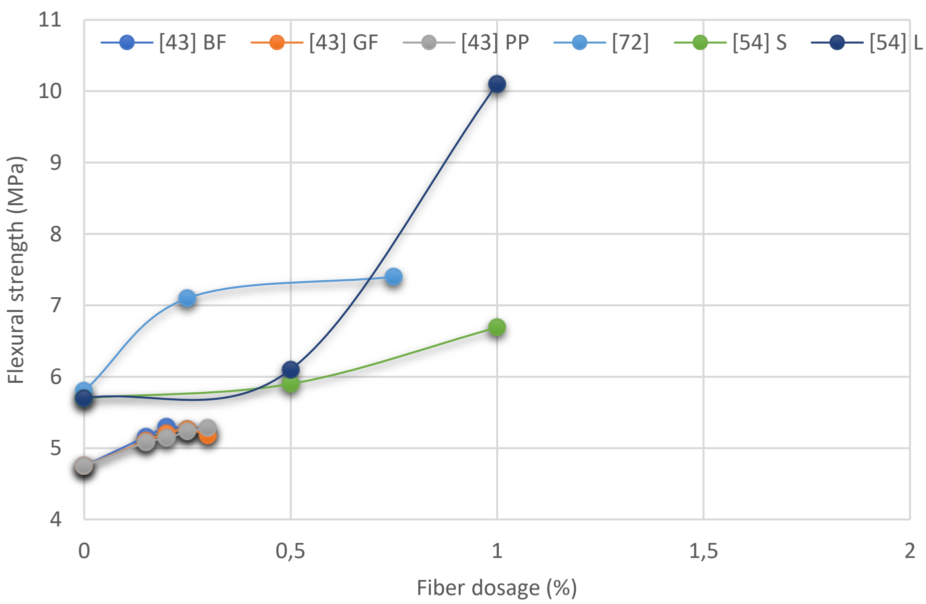

Figure 8: Flexural strength among the fiber content from the mentioned literature.

IV. CONCLUSION

The following are the main findings of the present study:

• The compressive strength of concrete improves modestly when fibers are incorporated into the binder matrix. This strength enhancement is primarily due to the stiffening effect observed in composite materials. Typically, the optimal increase in compressive strength is achieved by raising the fiber content to around 1%, with steel fibers being the most widely used and efficient choice for this purpose.

• Incorporating fibers into concrete creates a structure resembling a space truss, where the fibers handle tensile loads, while the remaining concrete components resist compressive forces. This results in a significant improvement in the material's tensile strength.

• According to the reviewed literature, increasing the fiber content up to 1.5% generally leads to an increase in concrete's flexural strength. Flexural strength gains observed in most studies range from 50% to 70%, with some showing even higher improvements.

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