# STATE-OF-THE-ART REVIEW ON FIBER VOLUME FRACTION EFFECTS ON MECHANICAL PROPERTIES OF FIBER REINFORCED CONCRETE

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## ABSTRACT:

Study represents a state-of-the-art review on the effects of fiber volume fraction to the mechanical properties of fiber reinforced concrete. Comparative research on peer-reviewed articles was used to analyse impact of fiber volume fraction. Review focuses on two most used types of fibers – steel and synthetic fibers, while connecting their volume fraction to compressive, tensile and flexural strength of concrete. For that, comparative methodology was used on most recent experimental studies. Different fibers with variable fiber type and aspect ratio were compared ensuring diversity of fibers studies. Small gains on compressive strength were recorded, while increased dosage led to decrease of compressive strength. Tensile and flexural strengths showed much higher increase – up to 218% in tensile and up to 67% in flexural strength. But variety of factors and uneven distribution of fibers often led to fluctuating performance of fiber reinforced concrete.

## KEYWORDS:

Fiber reinforced concrete, fibers, volume fraction, mechanical properties, compressive strength, tensile strength, flexural strength

# 1 INTRODUCTION

In 1874, patent number 157903 titled “Improvement in artificial stone” was applied by Achille Berard at U.S. Patent office. Berard proposed the addition of waste iron to concrete, marking the beginnings of Fiber Reinforced Concrete (FRC). But modern understanding of FRC begin to develop in 1950’s and 1960’s, when researchers like Romualdi, Batson and Mendel began experimenting with straight steel fibers [1].

Fiber reinforced concrete industry has been on rise in the last few decades, and in many civil engineering field FRC has seen numerous applications which include: industrial floors and warehouses, tunnel linings and airport runaways. Industrial floors up to 100.000 $m^2$ are regularly constructed using Steel Fiber Reinforced Concrete (SFRC). Main objectives of including fibers to concrete are: improving the rheology in a fresh state, improving the tensile or flexural strength, improving the impact strength and toughness, controlling cracking and the mode of failure and improving durability [2].

# 2 MATERIALS AND METHODS

## 2.1 METHODOLOGY

This research paper uses comparative research methods for analysing and comparing plain concrete and fiber reinforced concrete. Key sources used are academic journals, where priority was given to research papers as recent as possible ensuring state-of-the-art review. In cases where it was hard to obtain newer literature, older research may have been used. This study considers research if they fulfil three conditions:

1. experimental tests measured compressive or tensile or flexural strength after 28 days
2. steel or synthetic fibers were used for testing
3. fiber dosage was specified preferably in volume fraction, or $kg/m^3$

## 2.2 TYPES OF FIBERS

[3] proposes distinction of four main types of fibers: steel, synthetic, glass and natural fibers. Material type is probably the most important factor that impacts mechanical characteristics of FRC. Steel is one of the most used materials in construction, which properties are well known and widely researched, and very often used for making concrete fibers.

Main types of synthetic fibers include: polypropylene fibers (PP), polyester (PET), carbon, aramid, polyethylene (PE) and Kevlar. Together with steel fibers, synthetic fibers are most used in FRC [4]. They offer high mechanical strength, exceptional corrosion and abrasion resistance, but have poor recyclability. Synthetic fibers tensile strength can reach 1000 MPa, which place their tensile strength just little below steel fibers tensile strength. Most of them have lower elastic modulus, but higher ultimate strain than steel fibers. Some, like aramid and carbon fibers which have superb properties are very expensive to produce.

According to [5], two glass materials are most common for glass fibers: silica and basalt glass. Glass fibers have high tensile strength. In fact, when compared to steel fibers, glass fibers have much higher tensile strength reaching up to 4800 MPa, compared to standard steel fibers which ranges somewhere in 1300 MPa. They have lower elastic modulus and same ultimate strain as steel fibers.

Natural fibers are much less used than other types of fibers, and there are practical reasons for that. Unique about natural fibers is limitation to local availability. For example, most of European countries do not grow coconut or banana locally, so it is not expected to see broad usage of these fibers in European continent. Of course, it is possible to use any kind of natural fibers, but these kinds of fibers would primarily be used in locations of their growth. Other reason for their rare use is much lower mechanical properties than other types of fibers. Most of natural fibers are plant based like: jute, hemp, coconut (coir), wheat straw, sisal, bamboo or banana fibers. But natural fibers can be also animal based like wool and silk.

## 3 FACTORS IMPACTING MECHANICAL PROPERTIES

Number of factors are impacting mechanical properties of FRC such as: fiber material, volume fraction [6], fiber orientation [7] and aspect ratio.

[7] investigated effects of fiber distribution and orientation using a translucent fluid model. They concluded that flexural strength depends on the fiber distribution and orientation. When the fibers were oriented in the direction of tensile stresses flexural strength was improved. Opposite to that, poor workability led to poor orientation of fibers which resulted in lower flexural strength.

[8] analysed precast tunnel linings segment which was used for Barcelona metro. They took samples from lining segment, grouped in three zones. After gathering samples, they evaluated them for BCN test, after which they crushed specimens while gathering steel fibers remaining with magnet. Dosage for this lining segment was 60 kg/m$^3$, and when specimens were analysed, global average was 60,4 kg/m$^3$, with standard deviation of 12,1 kg/m$^3$.

However, some parts of segments, had lower dosage, with one specimen having only 28,5 kg/m$^3$. This observation is very important as number of fibers bridging the diametrical splitting crack directly impacts tensile strength [9], which in case of poor distribution can negatively impact mechanical properties of FRC.

[10] states that fibers diameter and length have influence on ease of mixing concrete as well as workability of FCR, but they are dealt as one parameter - aspect ratio.

Fiber dosage ($V_f$) has a significant impact on properties of FRC [6]. It is maybe the single most researched factor in FRC. Regardless, there is a lot of discussion what optimal dosage of fibers is for utilizing the potential of FRC.

[11] argues that 3% is optimal dosage for steel fibers, while he states that it’s 1 % for glass fibers. [12] showed that most optimal dosage is 2% for steel fibers, but in their research

2% was highest dosage tested. [13] argues that 0,5% is optimal dosage for jute fibers for compressive strength, while 0,75% is optimal dosage for flexural tensile strength.

[14] experimented with four dosages 1 – 4% with steel fibers. In their research specimens with 3% fibers showed better mechanical properties than 4 % dosage. But even so, some researchers still propose 4 – 5% as optimal range. [15] experimented with dosages 2 – 5% and found that increase in dosage results in increase in compressive and flexural tensile strength. They concluded that optimal dosage for maximal strength was 5%.

## 4 COMPRESSIVE STRENGTH

Compressive strength is the main indicator of concrete performance. Tests for compressive strength are mostly done on 100 x 100 mm and 150 x 150 mm cubes. As previously mentioned, this paper considers research on compressive strength results after 28 days only.

[16] experimented with different lengths of steel fibers. All specimens had dosages of 1,5%, and three lengths of fibers were classified as micro, normal and macro. Best results were achieved with macro fibers where increase of 27,17% was observed compared to plain concrete. Normal length steel fibers led to 16,45% increase in compressive strength, while micro fibers achieved only 2,81% increase.

On the other hand, [17] tested steel microfibers with three dosages and achieved much better results. When fibers dosage was 0,5% volume fraction 29,4% was observed. At 1% volume fraction 22,7% increase was observed, while at 1,5% volume fraction 14.1% increase in compressive strength was achieved.

Much bigger volume fractions (2%, 4%, and 6%) were tested by [18]. They showed that increase in volume fraction led to decrease of compressive strength of concrete. However, even without baseline values for plain concrete, in case of polypropylene fibers increase from 2% volume fraction to 4% lead to 8,7% decrease in compressive strength. Further increase to 6% of volume fraction led to 4,3% decrease in compressive strength compared to 4% volume fraction.

On the other hand, increase of volume fraction from 2% to 4% volume fraction lead in 46,9% increase in tensile strength and 36,1 increase in flexural strength. When volume fraction was increased to 6% results showed 12% increase in tensile strength and 21,15% increase in flexural strength compared to 4% volume fraction samples.

Table **Error! No text of specified style in document.** Impact of volume fraction on compressive strength of concrete

| Researcher | Dosage ($V_f$) | Impact | Type of fibers |
|---|---|---|---|
| Abd Elmoaty et al. | 4% | -8,7%[1] | Polypropylene |
| Abd Elmoaty et al. | 6% | 4,3%[2] | Polypropylene |
| Malek et al. | 0,5% | 46,5% | Green polypropylene |
| Malek et al. | 0,5% | 43,4% | White polypropylene |
| Malek et al. | 1% | 69,7% | Green polypropylene |
| Malek et al. | 1% | 62,6% | White polypropylene |
| Jayaram et al. | 0,5% | 6,15% | Polypropylene |
| Jayaram et al. | 1% | 10,8% | Polypropylene |
| Jayaram et al. | 1,5% | 3,38% | Polypropylene |
| Jayaram et al. | 2% | -1,2% | Polypropylene |
| Mengjun et al. | 0,5 % | 7,4 % | Polypropylene |
| Mengjun et al. | 1 % | 6,32 % | Polypropylene |
| Mengjun et al. | 1,5 % | 9,21 % | Polypropylene |
| Mengjun et al. | 2 % | 6,68 % | Polypropylene |
| Jasim et al. | 0,5% | 29,4 % | Micro steel |
| Jasim et al. | 1% | 22,7 % | Micro steel |
| Jasim et al. | 1,5% | 14,1 % | Micro steel |
| Nguyen et al. | 1,5% | 27,17 % | Macro steel |
| Nguyen et al. | 1,5% | 16,45 % | Normal steel |
| Nguyen et al. | 1,5% | 2,81 % | Micro steel |
| Rizutti and Bencardino | 1% | 4,35 | Steel fibers |
| Rizutti and Bencardino | 1,6% | 2,25 | Steel fibers |
| Rizutti and Bencardino | 3% | 1,35 | Steel fibers |
| Rizutti and Bencardino | 5% | -7,5 | Steel fibers |
| Sucharda et al. | 0,5% (40 kg/m$^3$) | 2,2 % | Steel fibers |
| Sucharda et al. | 0,75% (60 kg/m$^3$) | 4,6 % | Steel fibers |
| Sucharda et al. | 1,0% (75 kg/m$^3$) | 14,6 % | Steel fibers |
| Sucharda et al. | 1,15% (90 kg/m$^3$) | 9,4 % | Steel fibers |
| Sucharda et al. | 1,4% (110 kg/m$^3$) | 6,2 % | Steel fibers |
| Marcalikova et al. | 0,5% (40 kg/m$^3$) | 7,7 % | Macro hooked steel |
| Marcalikova et al. | 0,5% (40 kg/m$^3$) | 13,8 % | Macro straight steel |
| Marcalikova et al. | 1,0% (75 kg/m$^3$) | 21,1 % | Macro hooked steel |
| Marcalikova et al. | 1,0% (75 kg/m$^3$) | 18,9 % | Macro straight steel |
| Marcalikova et al. | 1,4% (110 kg/m$^3$) | 18,9 % | Macro hooked steel |
| Marcalikova et al. | 1,4% (110 kg/m$^3$) | 26,7 % | Macro straight steel |
| Mengjun et al. | 0,5 % | 5,78 % | Steel fibers |
| Mengjun et al. | 1 % | 9,39 % | Steel fibers |
| Mengjun et al. | 1,5 % | 7,76 % | Steel fibers |
| Mengjun et al. | 2 % | 5,42 % | Steel fibers |

[1] Compared to 2% volume fraction sample

[2] Compared to 4% volume fraction sample

Similar findings were shown in the study [19] where wide range of fiber dosages were tested and some of the fibers lead to decrease of concrete compressive strength. At the dosage of 5% decrease of 7,5% in compressive strength was obtained compared to plain concrete. Optimal dosage was 1%, where 4,35% increase was obtained. Negative impact of dosage increase was observed further, with dosages of 1,6% and 3% recording 2,25% and 1,35% increase when compared to plain concrete, but decrease when compared to optimal dosage.

[20] experimented with hooked and straight steel fibers. In their study increase in compressive strength ranged from 7,7% to 26,7%. They tested three dosages (40, 75 and 110 kg/m$^3$ – 0,5, 1,0 and 1,4% volume fraction). Smallest impact had hooked steel fibers dosage at 0,5% volume fraction – 7,7%. Biggest impact had straight steel fibers at dosage of 1,4%. In this case, changing dosage from 1% to 1,4% caused less impact on compressive strength when hooked fibers are used, but in case of usage of straight fibers, increase of dosage leads to increase in compressive strength.

Most significant increase was obtained by [21]. They tested white and green polypropylene fibers which led to much higher increase in compressive strength in compare to steel fibers. At dosages of 0,5% green polypropylene fibers showed 46,5% increase, while same dosage of white polypropylene fibers led to 43,4% increase. Marginal advantage for green polypropylene was observed also at 1% dosages where 69,7% increase in compressive strength was observed, higher than any increase of steel or polypropylene fibers. At the same dosage, white polypropylene led to 62,6 increase in compressive strength.

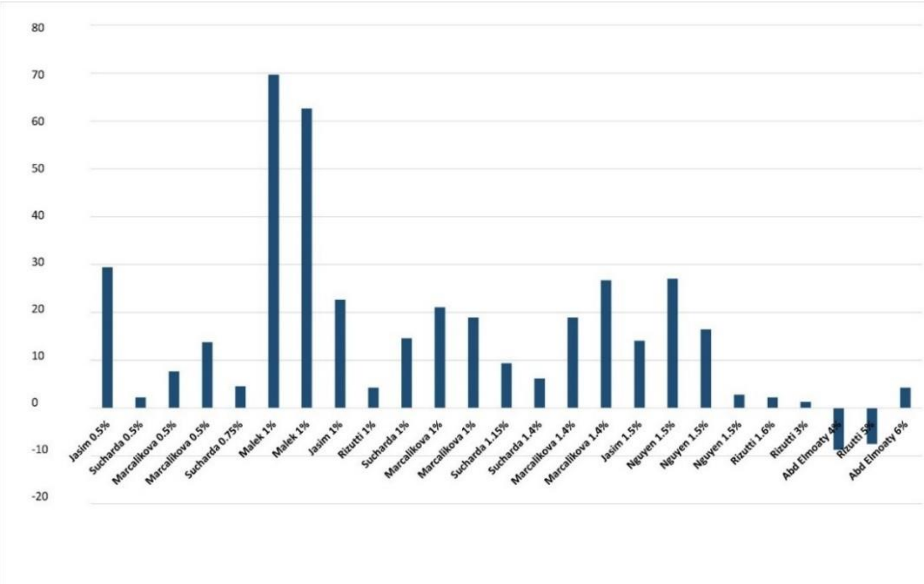


Figure 1. Concrete compressive strength increase obtained by different studies

## 5 TENSILE STRENGTH

As said earlier, SFRC shows highest tensile strengths compared to other FRC. The main reason for this is high tensile strength of steel fibers, as it regularly go over 1000 Mpa.

[17] experimented with steel fibers in dosage of 0,5%, 1% and 1,5%. After 28 days maximum increase in tensile strength was observed in dosage of 1,5%. Compared to plain concrete 83,7% increase was observed.

[20] experimented with hooked and straight steel fibers. In their study, increase in tensile strength ranged from 3% to 24,4%. They tested three dosages (40, 75 and 110 kg/m$^3$). Smallest impact had hooked steel fibers dosages at 40 kg/m$^3$ – 3%. Biggest impact had hooked steel fibers at dosage of 110 kg/m$^3$.

Table **Error! No text of specified style in document.** Impact of volume fraction on tensile strength of concrete

| Researcher | Dosage ($V_f$) | Impact | Type of fibers |
|---|---|---|---|
| Li et al. | 0,5 | 15,2 % | polypropylene |
| Li et al. | 1 | 29,8 % | Polypropylene |
| Li et al. | 1,5 | 17,3 % | polypropylene |
| Jayaram et al. | 0,5% | 6,9 % | Polypropylene |
| Jayaram et al. | 1% | 27,6 % | Polypropylene |
| Jayaram et al. | 1,5% | 20,7 % | Polypropylene |
| Jayaram et al. | 2% | 17,2 % | Polypropylene |
| Mengjun et al. | 0,5 % | 5,71 % | Polypropylene |
| Mengjun et al. | 1 % | 35,4 % | Polypropylene |
| Mengjun et al. | 1,5 % | 26,4 % | Polypropylene |
| Mengjun et al. | 2 % | 16,1 % | Polypropylene |
| Jasim et al. | 0,5 % | 32,7 % | Micro steel |
| Jasim et al. | 1 % | 65,9 % | Micro steel |
| Jasim et al. | 1,5 % | 83,7 % | Micro steel |
| Nguyen et al. | 1,5% | 201 % | Macro fibers steel |
| Nguyen et al. | 1,5% | 218 % | Normal steel |
| Nguyen et al. | 1,5% | 125 % | Micro steel |
| Marcalikova et al. | 0,5% (40 kg/m$^3$) | 3 % | Macro hooked steel |
| Marcalikova et al. | 0,5% (40 kg/m$^3$) | 15,4 % | Macro straight steel |
| Marcalikova et al. | 1,0% (75 kg/m$^3$) | 15,4 % | Macro hooked steel |
| Marcalikova et al. | 1,0% (75 kg/m$^3$) | 7,26 % | Macro straight steel |
| Marcalikova et al. | 1,4% (110 kg/m$^3$) | 24,4 % | Macro hooked steel |
| Marcalikova et al. | 1,4% (110 kg/m$^3$) | 10,7 % | Macro straight steel |
| Sucharda et al. | 0,5% (40 kg/m$^3$) | 39,8 % | Meso straight steel |
| Sucharda et al. | 0,75% (60 kg/m$^3$) | 54,5 % | Meso straight steel |
| Sucharda et al. | 1,0% (75 kg/m$^3$) | 67,6 % | Meso straight steel |
| Sucharda et al. | 1,15% (110 kg/m$^3$) | 78,6 % | Meso straight steel |
| Sucharda et al. | 1,4% (110 kg/m$^3$) | 96,7 % | Meso straight steel |
| Mengjun et al. | 0,5 % | 6,4 % | Steel fibers |
| Mengjun et al. | 1 % | 25,4 % | Steel fibers |
| Mengjun et al. | 1,5 % | 37,1 % | Steel fibers |
| Mengjun et al. | 2 % | 52,5 % | Steel fibers |

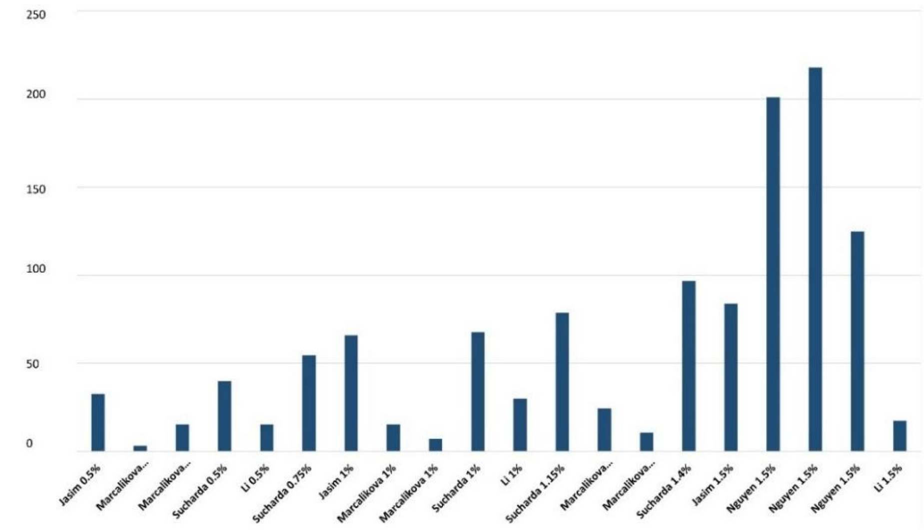


Figure 2. Concrete tensile strength increase obtained by different studies

## 6 FLEXURAL STRENGTH

Improving flexural strength is one of the main goals for including fibers in concrete [2]. Generally, specimens showed improvement of 5 to 45% in flexural strength compared to plain concrete, with exceptions of two specimens. In test by Archana et al. [22] one series of specimens underperformed and led to decrease of flexural strength by 0,7%. On the other hand, [23] achieved 67% improvement in flexural strength.

In other specimen series, [23] investigated effects of straight-end and hooked-end steel fibers in dosages ranging from 1 to 2%. Mentioned achievement of 67% increase was obtained with straight end steel fibers at dosage of 2%. Other significant improvements include hooked-end steel fibers with 1,5% dosage where 36,6% increase was obtained and straight end steel fibers at 1,5 where 26,6% increase was achieved. All highest values were obtained with dosages 1,5% and 2% volume fraction.

[17] experimented with micro steel fibers up to dosages of 1,5%. Dosages of 1% and 1,5% of volume fraction showed as optimal, as their recorded improvement was 24,5% and 27,9% respectively. Lowest improvement was achieved with 0,5% volume fraction at only 8%.

When polypropylene fibers were tested, lower dosages were preferred. [22] reported optimal dosage at 0,8% volume fraction with increase of flexural strength of 30,1%. Both 0,4% and 0,6% dosages showed notable increase of 12,3% and 19,2%, while negative impact was observed at 1% dosage. This increase in dosage led to 0.7% decrease in flexural strength compared to plain concrete.

Table **Error! No text of specified style in document.**. Impact of volume fraction on flexural strength of concrete

| Researcher | Dosage ($V_f$) | Impact | Type of fibers |
|---|---|---|---|
| Archana et al. | 0,4 % | 12,3 % | polypropylene |
| Archana et al. | 0,6 % | 19,2 % | polypropylene |
| Archana et al. | 0,8 % | 30,1 % | polypropylene |
| Archana et al. | 1 % | -0,7 % | polypropylene |
| Li et al. | 0,5 % | 27,9 % | polypropylene |
| Li et al. | 1 % | 44,5 % | Polypropylene |
| Li et al. | 1,5 % | 33,6 % | polypropylene |
| Jayaram et al. | 0,5% | 0,93 % | Polypropylene |
| Jayaram et al. | 1% | 3,52 % | Polypropylene |
| Jayaram et al. | 1,5 % | -3,1 % | Polypropylene |
| Jayaram et al. | 2 % | -6,5 % | Polypropylene |
| Mengjun et al. | 0,5 % | 6 % | Polypropylene |
| Mengjun et al. | 1 % | 22,9 % | Polypropylene |
| Mengjun et al. | 1,5 % | 16,8 % | Polypropylene |
| Mengjun et al. | 2 % | 10,6 % | Polypropylene |
| Karzad et al. | 1 % | 16 % | Straight end steel |
| Karzad et al. | 1,5 % | 26,6 % | Straight end steel |
| Karzad et al. | 2 % | 67 % | Straight end steel |
| Karzad et al. | 1 % | 5,3 % | Hooked-end steel |
| Karzad et al. | 1,5 % | 36,6 % | Hooked-end steel |
| Karzad et al. | 2 % | 27,9 % | Hooked-end steel |
| Jasim et al. | 0,5% | 8 % | Micro steel |
| Jasim et al. | 1% | 24,5 % | Micro steel |
| Jasim et al. | 1,5% | 27,9 % | Micro steel |
| Mengjun et al. | 0,5 % | 15,4 % | Steel fibers |
| Mengjun et al. | 1 % | 23,1 % | Steel fibers |
| Mengjun et al. | 1,5 % | 26,8 % | Steel fibers |
| Mengjun et al. | 2 % | 32,4 % | Steel fibers |

The study [24] showed similar optimal dosage ranges. Overall best performance was obtained at dosage of 1%, where increase of 44,5% was observed. Further increase in dosage to 1,5% led to slightly lower, but still good increase 33,6%. But, even lowest increase in flexural strength at 0,5% dosage was notable at 27,9% increase.

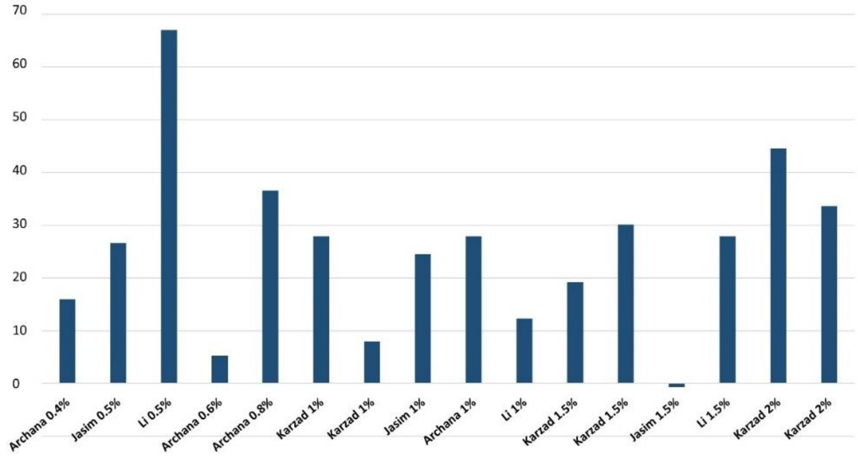


Figure **Error! No text of specified style in document.**3. Concrete flexural strength increase obtained by different studies

## 7 DISCUSSION

Addition of steel and polypropylene fibers to concrete have role in enhancing mechanical properties of concrete. Findings of this review suggest that fiber reinforced concrete have some improvements in compressive strength of concrete, while tensile strength and flexural strength improvements are more significant than compressive strength improvements.

There is clear differences between polypropylene and steel fibers at low dosages. When comparing compressive strength of polypropylene fiber reinforced concrete both [21] and [25] achieved best results at 1% dosage. In the case of [26] best result was achieved at 1,5%, and only exception is [18] with 6% dosage.

Much clearer results were achieved in tensile strength. All of studies on polypropylene fibers [24], [25], [26] showed biggest increase in dosage of 1%. Almost the same thing was observed when flexural strength was measured. Again in [24], [25], [26] biggest increase was achieved at dosage of 1%. In this case only exception was [22] where dosage of 0,8% resulted in increase of 30,1%, but when dosage was increased to 1% sudden drop of strength was noted, to the point where results were lower then plain concrete flexural strength.

Generally, in case of polypropylene fibers increase in compressive, tensile and flexural strength was observed when dosage was increased until one point, which seems to be optimal dosage for polypropylene fibers. After reaching the plateau, any further increase of dosages resulted in decrease of compressive [25], [26], tensile [24], [25], [26] and flexural strength [22], [24], [25], [26].

In case of steel fibers, especially in compressive strength, similar can be observed. Four of the studies [19], [17], [26], [27] had optimal dosage of 1% where plateau of increase was reached, and further increase of dosage led to decrease in compressive strength. Only exception to this is [20] where biggest increase was obtained at dosage of 1,4%.

Same cannot be concluded for tensile strength in case of steel fibers. All of the studies [17], [20], [27], and [26] reported biggest increase in tensile strength at the biggest dosage they tested. In case of [27] and [20] this was 1,4%, in case of [17] dosage was 1,5% and in case of [26] dosage was 2%. As they did not test steel fibers for higher dosages, there is possibility that plateau for tensile strength improvement is higher than reported dosages. And, as much higher improvements were observed in tensile strength than compressive strength, this would be great starting point for further research.

When flexural strength was measured, [17], [26], and [23] in one series of tests reported highest increase of flexural strength at the highest dosages tested. When hooked-end steel fibers were tested up to 2% by [23] optimal dosage was measured at 1,5% as only exception in the steel fiber studies. This may suggest that shape of the fibers have impact on the optimal dosage, which in case of steel fibers can go from 1,5% to over 2%, as that was highest dosage tested in reported studies.

## 8 CONCLUSION

Across all studies analysed distinction can be made between the steel and polypropylene fibers. They had different percentages of the increase, and different optimal dosages, but in all studies adding of fibers to the concrete had positive impact on the mechanical properties at some point.

Optimal dosage for improving compressive strength of concrete for both steel and polypropylene fibers was in range 1 to 1,5%. With only one exception all of the optimal dosages showed results in this range.

Average compressive strength improvements were around 15%. While this is improvement in compressive strength, there is high possibility of compressive strength underperforming. Furthermore, in some specimen effect was negative, and this improvement may not reliably translate to real world applications.

Tensile strength improvements with polypropylene fibers were highest with dosages 1,0% - 1,5%. These gains were more pronounced than compressive strength and generally showed consistent improvements, though overall performance still showed some fluctuation.

Optimal dosage for steel fibers in regards to tensile strength seem to begin at 1,5%. But upper limit can be higher than 2%. Average tensile strength improvements were around 60%, while highest improvements recorded was 218%. This represents significant improvement compared to plain concrete tensile strength. Further studies on optimal dosage of fibers for improving tensile strength of concrete should include dosages higher than 2%.

Average flexural strength increase was around 30%, while highest improvements recorded was 67%. For achieving maximum flexural strength dosages of 0,8% to 1,0% are recommended in case of polypropylene fibers. As for the steel fibers, similar to tensile strength, optimal dosages seem to begin at 1,5% but upper limit can go higher than 2%, and it should be starting point of further studies on optimal dosages.

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