Steel fibre-reinforced concrete: review

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Abstract

The studies on fibre-reinforced concrete are vast, with different fibres used, cement types, binders' proportions, additives, and admixtures. Steel fibres (SFs) are the most used fibres when it comes to tensile strength. The paper gives a basic understanding of the behaviour of SFs as a reinforcing element. The SFs properties (shape, aspect ratio, and volume fraction) are highly effective in improving the steel fibre-reinforced concrete (SFRC). The addition of SFs changes the mixture and enforces new conditions for mixing it and what proportions to use. SFRC has proven a better performance in toughness as the energy absorption and ductility of the SFRC have improved; post-cracking strength has also seen improvements as the SF that have a sufficient bond with the matrix are able to bridge the cracks and transfer the stresses also the improvements of the mechanical properties of the SFRC and the flexural strength being the most sensitive to the SFs addition.

Keywords: fibre-reinforced concrete (FRC), steel fibre-reinforced concrete (SFRC), mechanical properties steel fibre, concrete, bond strength, aspect ratio, SF shape, volume fraction, workability
Kulcsszavak: szálerősítésű beton (FRC), acélszálerősítésű beton (SFRC), acélszálak mechanikai tulajdonságai, beton, tapadási szilárdság, méretarány, SF alakja, térfogat százalék, bedolgozhatóság

1. Introduction

The usage of fibres as reinforcement existed prior to the rebar reinforcement. The Mesopotamia civilisation was one of the oldest in the world. About 5,500 years ago used fibres (straw) were used to reinforce the building material (adobe clay) [1] in order to improve its properties. Concrete, one of our current building materials, is a brittle material with low tensile strength and a low strain capacity. A material with good tensile properties is added to the concrete to overcome these properties in concrete. Fibres used in cement-based composites are thin, short, and primarily made of steel, glass, and polymer or derived from natural materials. The fibre reinforcement may be used in the form of three-dimensionally randomly distributed, where the fibre distribution in different orientations significantly affects the reinforcement efficiency. Steel has proven to be a good material for tensile reinforcement in concrete. The common use of steel is in reinforcing bars, where the steel reinforcing bars are placed in the tensile zone of the concrete.

Fibres alone are not enough to improve the overall capacity of the concrete; SFs cannot work as a replacement for the primary reinforcement in most cases. Still, they improve some properties in concrete and create a material that behaves differently. The amount of fibre added to the concrete recipe is measured as a volume fraction. As the SFs volume fraction increases, the SFs are closer. This can cause "balling", but when the volume is controlled, and the SFs are correctly mixed, it will help manage the cracks by bridging them and transferring the stresses.

The usage of SFs started in the early 20th century. Within the mid of century, the science community started to study the possibility of the usage of fibres to improve concrete properties. Nowadays, there are codes that deal with the usage of SFRC, such as (NZS 3101 (2006), DafStb, Fib Model code, CECS 38:93, and RILEM TC 162-TDF). While the codes are not covering a wide range of applications, there is a driving force to improve our understanding of fibres as a reinforcing element. The addition of SFs in concrete increases its flexural toughness, energy absorption capacity, ductile behaviour prior to the ultimate failure, reduced cracking, and improved durability. This paper tries to cover a basic understanding and consideration to keep in mind when dealing with SFRC.

2. Steel fibres

A considerable number of fibres can be used to improve the concrete properties. With different fibres, we get different properties. A combination of fibres can also be used to get improvements from the added fibres' properties. The most used material of fibres is steel, as the steel holds desirable properties in tensile strength. The paper aims to narrow the fibres to steel and discuss the effect of the addition of SFs in concrete. It is necessary to mention some parameters of the types of SFs and the effect of each fibre type before the generalisation of the SFs as a part of concrete.

The bond between the steel fibre and the concrete regulates how well the materials are working together and the stresses transferred between the steel fibre and the matrix surrounding it. The most common failure for SFs is a pull-out failure [3], where the loss of bond between the SFs and the matrix happens. The bond strength (the highest value for the bond stresses) depends on physiochemical adhesion and friction at the interface, and mechanical anchorage [4], the mechanical anchorage, which is responsible for a significant part of the strength reached, is much better for deformed shapes than undeformed. It is worth mentioning that the use of straight fibres is very low, and the most used one is the hooked-end [5], as the cost of creating these deformations controls the price of the fibre.

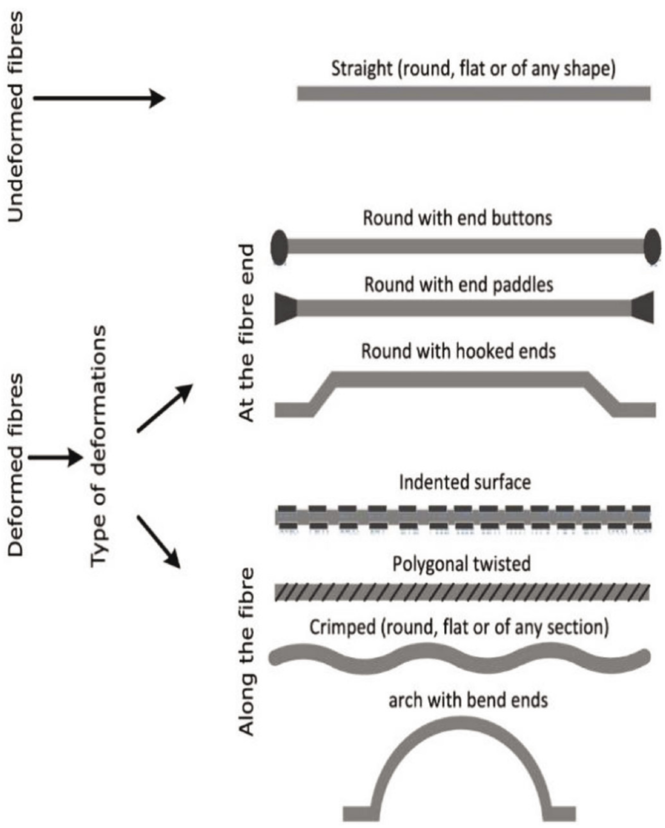

Fig. 1 Steel fibres' most common shapes [2]
1. ábra Az acélszálak leggyakoribb alakjai [2]

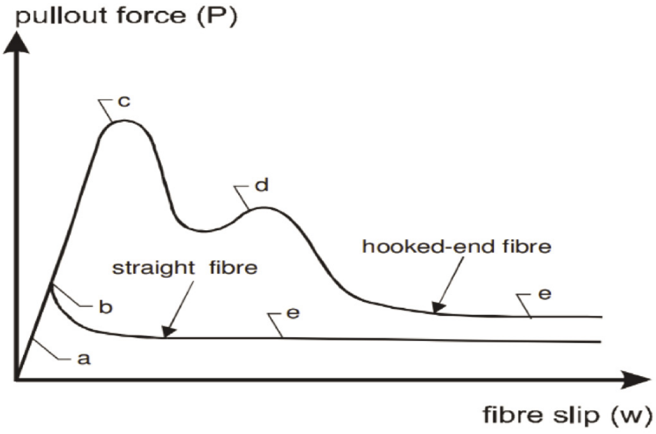

Fig. 2 Pull-out behaviour of straight and hooked-end fibres [6]
2. ábra Egyenes és kampós végű szálak kihúzási viselkedése [6]

Shapes are essential in defining the extent the fibres affect the overall properties. It has been noticed that the mechanical properties vary significantly with the same fibre's volume and different geometries [7]–[9]. The fibre's diameter (equivalent diameter for non-circular) and length influence how well the mixture can be mixed, its workability and much more, but both are dealt with as one parameter (aspect ratio), the ratio of length to diameter (l/d). The amount of fibre used in the volume (volume fraction) highly affects the properties. These three parameters can provide a guideline on what SFs to choose.

A study was done on the stress-strain curves under compression for SFRC to study the volume fraction and aspect ratio. It was found that the slope of the descending part of the stress-strain curve decreases if the fibre fraction is increased with a constant aspect ratio, and the same if the aspect ratio is increased and kept the volume fraction constant [10]. Also, it was noted that the slump decreases with the increase of either the volume fraction or the aspect ratio [11]. In another way, the area under the stress-strain curve increases with respect to both volume fraction and aspect ratio. It's worth mentioning the reinforcing index, which is a parameter used to combine both the volume fraction and the aspect ratio into one standard parameter. The reinforcing index depends on the weight fraction (representing volume) and the aspect ratio [10].

Shape

The bond is an interface between the matrix surrounding the fibre (the interfacial transition zone) and the fibre itself. Similar to the bonds between the plain bars or the deformed bars and the matrix, the bond between the fibres and the matrix is made of physicochemical adhesion and friction that will be affected by the surface properties of the fibre and a mechanical interlock affected by the shape.

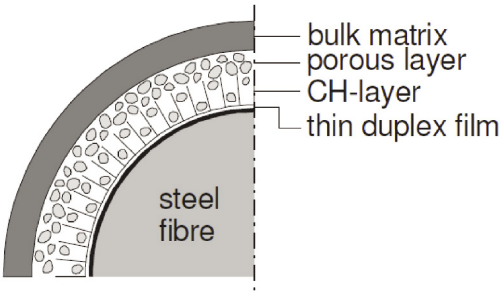

Fig. 3 Transverse cross-section of the interfacial transition zone ITZ [6]
3. ábra Az ITZ határfelületi átmeneti zóna keresztmetszete [6]

Adhesion and friction are the types of bonds controlling the bond strength for straight fibres (undeformed), assuming no bending or pre-deformation has happened. Where the efficiency of the bond depends on the continuity of the interfacial transition zone, on the other hand, the mechanical anchorage, which is a significant influencer of the bond strength, is mainly affected by the shape (deformations). The studies show that the deformed shapes behave better than straight ones [7]–[9], [11].

Volume fraction

The volume to be used in the concrete mixture affects the cost and degree of fibres modification on the concrete. Volume fraction affects mixing, placing, and the hardened concrete performance. Volume fractions used can be grouped into three categories:

- Less than 1%: Where the primary purpose is to help with the plastic shrinkage.
- Between (1-2)%: Where the cost to effect is reasonable and can help in the improvement of concrete mechanical properties.
- More than 2%: the main advantage here will be the impact and blast resistance [12].

The higher the volume, the worse the workability of the concrete and the better the flexural performance [11]. The increase in the volume fraction of fibres will increase the peak load, deflection, and toughness of concrete [9] volume fraction and aspect ratio on the flexural and acoustic emission (AE). Higher than 2% can be used, but usually, due to cost, it is limited to specialised applications.

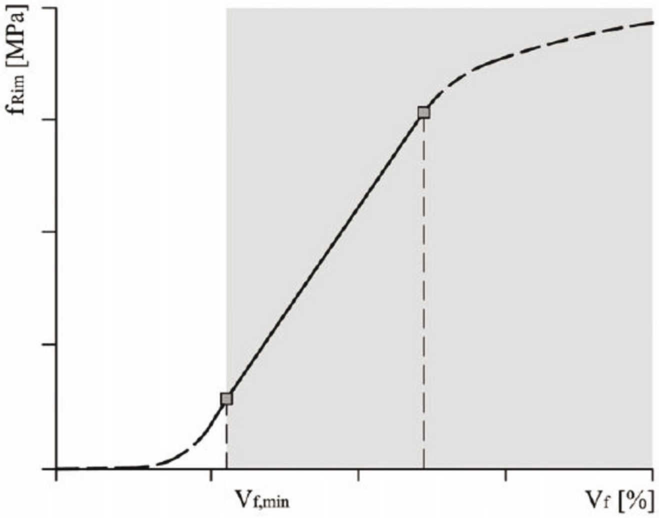

Fig. 4 The influence of fibre content on post-cracking steel fibre-reinforced concrete residual strength 2018 [13]
4. ábra A száltartalom hatása a repedés utáni acélszál-erősítésű beton maradószilárdságára, 2018 [13]

The maximum crack distance and the number of cracks have increased with the increasing fibre volume fraction. Deformed (hooked and twisted in the study) fibres showed more cracks than where undeformed (straight) fibres were used at a volume fraction between 1-2% [7].

Aspect ratio

Also called slenderness ratio (*l/d* ranges between 20-100), this parameter is also a measure of fibre stiffness and will affect mixing and placing. Fibres with relatively small equivalent diameters have low flexural stiffness, which helps to fit into the space they occupy in the concrete mixture. On the other hand, fibres with relatively large equivalent diameters have higher flexural stiffness and a higher effect on aggregates' consolidation during mixing and placement [14]. Fibre length affects the workability and aggregates' size to be used. Including the length and equivalent diameter effects into consideration, the aspect ratio showed effects on the flexural performance and workability, among others; if we took the case of straight fibres, the fibres with the highest aspect ratio were more effective in improving the flexural performance than those with lower aspect ratios [7]. On the other hand, the workability decreases with an increasing aspect ratio. Aspect ratios above 100 will be challenging to mix and achieve a uniform mix [15]. Combining various aspect ratios to improve the mechanical properties is more effective than a single aspect ratio [16].

3. Mix design

Fibres are added to improve the concrete, and the concrete mixture will vary significantly in many cases, including size graduation, binder type, admixtures, water/binder ratio, and additives. Fibres have no conditions for the type of cement and water to be used other than that for regular concrete. Fibres addition affects the physical characteristics of aggregates and their overall gradation. Such; lightweight and porous aggregates that should not be used due to their high absorption, enlarging the workability issue. Generally, the SFRC has higher cement, and fine-to-coarse ratio than regular concrete and the maximum coarse aggregate size affects the minimum cement dosage [17]. To avoid taking each part indivisibly, we try to look at the main parameters when using SFs. Workability is one of the critical issues that face the use of fibres, and bond strength is a very influencing parameter to the overall properties of SFRC.

Workability

Workability is the leading property of the fresh concrete we consider when dealing with SFRC. The addition of SFs reduces workability and accelerates the stiffening of fresh concrete. Both volume fraction and aspect ratio affects it. Some improvements to the concrete properties require a sufficient volume fraction to be used, which will result in a decrease in workability. Some adjustments are necessary when using a large volume fraction to maintain workability. Increasing the water volume to reach better workability will cause a reduction in mechanical strength and durability (larger porosity). The workability solution should not affect the water/cement ratio. It can be constant by increasing water and cement volume (reducing the fibres volume fraction) or adding additives that will increase the fine volume. Additives like pozzolans, fly ashes, calcium filler and micro silica. All with lower bulk specific gravity than cement. Fine volume has an optimum proportion to avoid segregation. If we exceed this portion, the amount absorbed by the fine will reduce the workability. If we are below the optimum, the internal friction between coarse aggregates and fibres will also lessen the workability. Fine-to-coarse aggregates ratios are obtained by adjusting the overall gradation to some gradation curve.

Another way is by adding water-reducing admixture (superplasticisers) to minimise the viscosity of the slurry [18]. New superplasticisers with the enhancement of workability can also maintain the plasticity of the mixture for a more extended period. The risk of “balling” should be kept in mind, as with the increase of the fibre volume fraction, the separation between the fibre is reduced.

Bond strength

Thinking of SFs as small, randomly distributed, non-continuous bars along with the mixture when considering the bond helps to understand the importance of the bond strength and how much it controls the effect of the reinforcements added.

The bond strength controls the tensile strength of the SFRC. If the bond strength is low, debonding (pull-out) failure is expected. Debonding failure makes the high strength of SFs go to waste, as the fibre cannot help resist the stresses. The bond can be strong till the failure is a rupture in the fibre, but it is unlikely to happen [2]. Between the two cases lies a bond strong enough to transmit stresses after matrix failure if the stresses have not exceeded the bond strength. This way, the fibres can bridge the cracks and help in post-cracking strength and resistance to crack propagation.

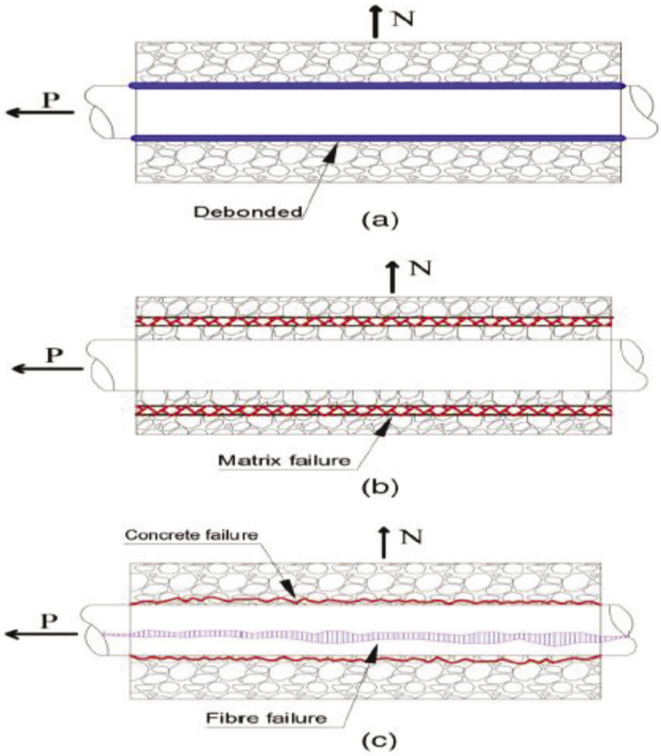

Fig. 5 *Tensile failure modes under normal forces* [2]
5. ábra *Szakítósérülési módok normál erők mellett* [2]

When designing the mixture, fibres length affects the maximum aggregate size; to ensure an efficient anchorage for the fibres, the maximum aggregate size should be less than (two-thirds/half) of the fibre length [18]. The increased size and volume of the aggregate particles greater than 5 mm will reduce the workability [15]. The shape and the properties of the fibres should be based on the bond strength that can be achieved, taking into consideration the mixture portions.

4. Mechanical properties

The fibres' role in the mixture should be cleared to understand the effect of SFs on the mechanical properties. Fibres improve the mechanical properties in concrete at different ratios. Flexural strength is more sensitive to the addition than compressive and tensile strength. Fibres help in the post-cracking strength, the toughness of the concrete, and the shear strength improvement.

Compressive strength

When it comes to compressive strength, the addition of fibre does not improve significantly. Still, as the fibres help bridge post-cracking stresses, the post-peak behaviour improves with the increased fibre volume fraction. The increase in fibre content improves the post-peak behaviour, and a more extended softening branch is observed [12], [15].

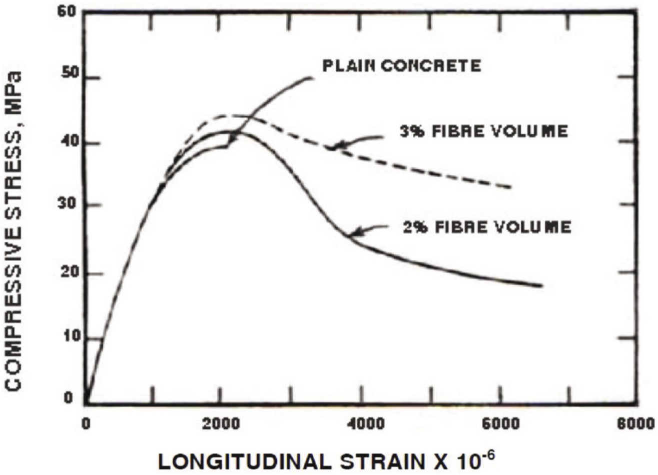

Fig. **6** *Stress-strain for compression for SFRC* **[19]**
6. ábra *Acélszálerősítésű beton σ-ϵ diagramja* [19]

Tensile strength

The tensile strength of the fibres is critical when choosing the fibre to use. The bond strength controls how much will be utilised from the fibres. Going back to the analogy of small randomly distributed non-continuous bars as a representation of SFs, the SFs' orientation to the tensile stresses significantly influences how much the fibres improve the direct tensile strength of the matrix. Fibres aligned with stress transformation increase the direct tensile strength.

At the first crack, the tensile strain can be increased as much as 100%, with 20-50 times the ultimate strain of plain concrete [12].

Flexural strength

Flexural strength is highly affected by adding fibres with high elastic modulus. Fibres with low elastic modulus improve the impact resistance and not much for the flexural [12]. The increase in flexural strength depends on the tensile strength of the fibres, orientation, volume fraction, shape, and aspect ratio. With a larger aspect ratio, the increase is better [7] three different types of steel fibers were considered, and three different aspect ratios were applied for the case of straight fibers. To quantitatively evaluate the cost effectiveness of reducing the fiber content of UHP-FRCC, cost analysis was also performed. Test results indicated that at low fiber volume fractions (Vf ≤ 1.0%). The deformed bars have improved the flexural strength more by achieving a better bonding within the mixture. One of the very well-known applications of fibres is the pavement. The improvement in the flexural strength allows a decrease in the pavement's thickness required [15].

Other properties

The addition of steel fibre improves the toughness of the concrete; the concrete has better ductility, which means it can absorb higher energy prior to failure.

The durability of the concrete has improved with the addition of SFs. Corrosion is reduced in the SFRC as the fibres help to control the cracks. The SFRC have a better impact resistance of SFRC against dynamic loads. The higher the volume fraction of SFs, the higher the fatigue strength. SFs addition delays the onset of flexural cracking. Shear strength is significantly improved with the addition of SFs [16], [20], [21].

5. Conclusions

Steel fibre-reinforced concrete has the steel fibre as a new component in the material composition, which in order affects the material behaviour. The shape, aspect ratio, and volume fraction of SFs highly affects the degree of influence SFs have on the concrete. Shape of SFs controls the integration of the new material components and how well it will alternate the overall behaviour. Having deformations enhance the mechanical anchorage increasing the bond strength and the influence of the fibres. Aspect ratio of the SFs and volume fraction affect the workability and the mixing and placing of the concrete. Workability of fresh concrete decreases with the increase of SFs volume fraction and aspect ratio. Flexural performance is also improving with the increase of the aspect ratio and the volume fraction.

The bond strength between the fibres and the surrounding matrix is essential to improve the mechanical properties. If the bond is weak, debonding will happen, the fibre will not transfer stresses, and the tensile strength of the fibre will not be efficiently utilised.

Mechanical properties have seen improvement with the addition of SFs, and flexural strength is the most affected by the fibres' addition, and tensile, durability, toughness and shear strength are improved.

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