Effect of Steel Fibers on the Concrete Strength Grade: A Review

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Abstract. The use of concrete reinforced with steel fibers has emerged as an effective material which has the advantages to be used in the most unconventional situations in reinforced concrete structures. These advantages involve reinforcements in structures that intend to resist loads in extreme conditions or change in the type of use, design and or construction errors, degradation of materials (carbonation or corrosion of reinforcement) and also the possible occurrence of accidents such as fires, floods, gusts of wind and earthquakes. In addition, the increasing use of this reinforcement system requires the development of more conclusive studies regarding the characteristics and behaviour of the steel fibers, as well as a critical evaluation of this material and its techniques. This manuscript presents a review on the interaction between steel fibre and the concrete substrate. Initially, a brief description of some fibers materials is made, followed by a summary of some works on adhesion between steel fibres and concrete under static loads. Finally, a summary of the few works on the main contribution of the steel fibers application to increase the strength after the cracking of concrete matrix during loading.

1. Introduction

The need to guarantee the quality of a structure obligates the designers to consider new loading situations more and more. When a given structure needs to be designed to withstand impact loads, it is essential to understand the behaviour of the concrete subjected to this type of loading as well as the characteristics of a suitable material, capable of withstanding short-term dynamic stresses [1–4]. The use of fibrous materials to improve the mechanical properties of cementitious materials was not exclusively created by man, but rather adapted, since some birds utilize small sticks and grasses (fibrous filaments) to mix them with clay and build their nests, (figure 1) [5].

Similar to birds, there are records that the Egyptians mixed straw and clay to build their shelters. About 5000 years ago, man mixed clay and asbestos (natural silicate whose purest form fibrous minerals), thus making a kind of asbestos cement [6]. In 1971, the first building was built in London using concrete reinforced with steel fibers by 3% of volume [7]. Currently, the use of fibers in civil construction goes far beyond wood, straw and shrubs [8]. In addition to fibers obtained directly from nature, artificial fibers are being widely used, for example, steel, glass and carbon fibers [9]. In addition, vegetable fibers are still used widely in civil construction, either in natural form, or after undergoing...
industrial processes that make it possible to obtain the fibrous filaments themselves, such as sisal, curaua, piassava, and coconut fibers [10–11].

Figure 1. Bird nest.

Staple fibers are used to reinforce concrete material, giving rise to fiber reinforced concrete [12]. Concretes, or mortars, with fibers are generally defined as materials made up of at least two main distinct phases [13]. If we interpret this definition to the letter, we conclude that the fiberless concrete itself is already a composite, since it is formed by cement paste and fine and coarse aggregates [14]. In order not to escape the already established definition of concrete with fibers, the main phases of this material are considered to be the matrix (which is the concrete itself) and the fibers (whether natural or artificial) [15].

Parra-Montesinos et al. presented the mechanism of fiber action on the concrete strength and the main factors that affect the performance of the composite are presented in detail [16]. There are several types of fibers that are added to the concrete, and each type of fiber causes different changes in the mechanical properties of the concrete. The steel fibers and their influence on the mechanical properties of concrete with other types of fibers are presented in this review paper.

2. Types of fibers used in concrete

The types of fibers used in concrete are steel [17], synthetic [18,19] and natural fibers [20,21]. For each application, there is a type of fiber that is most suitable. Among these three categories of fibers, the one that is most popular is steel fiber, however natural fibers and especially synthetic fibers have exhibited an important role in civil construction [22,23]. Steel fibers can be designed in various diameters, lengths, shapes (wavy, straight, straight with hooks at the ends, and with rectangular or circular cross sections) and with different types of steel (high strength or not, high modulus of elasticity or not) [24,25]. Natural fibers are extracted from nature itself, such as coconut, piassava and sisal fibers [26–28]. Synthetic ones, like polyethylene, polypropylene, polyvinyl alcohol, among others, are produced by chemical processes [29,30]. Carbon, and glass fibers are relatively ductile and they exhibit fragile behaviour at break.

Hejazi et al. describe synthetic fibers as being flexible, macroscopically homogeneous, with revealing relationship between length and thickness (aspect ratio) and small cross section [31]. Kajiwara & Ohta presented the main characteristics and indications for the use of the main fibers of polyethylene, polypropylene, acrylic, polyvinyl alcohol, polyamide, aramid, polyester and carbon in order to overcome the weakness of conventional concrete [32]. They affirm that to increase the strength of the composite, the fibers have to possess modulus of elasticity greater than the matrix. For cementitious materials, for which the modulus of elasticity varies between 15 and 30 GPa [33,34], this condition is difficult to achieve for most synthetic fibers.

However, several attempts have been made to develop synthetic fibers with very high modulus of elasticity, to serve as reinforcement for concrete [18,35]. On the other hand, both theoretical and
experimental studies, have shown that even fibers with low modulus of elasticity are capable to increase the deformation capacity, toughness, impact resistance and crack control of concrete [36–38]. They also say that, in many applications, the gain in these properties is much more important than simply increasing the tensile strength, since this property is usually assumed to be not influenced by the addition of these fibers to the matrix.

In their work, Hejazi et al. also described the various types of synthetic fibers and their main applications, but they are not presented here because they are not the subject of this review manuscript [31]. Several authors conducted comparative studies with different types of synthetic fibers, mainly concrete reinforced with nylon fibers [19,39], concrete reinforced with polypropylene fibers [40,41] and concrete reinforced with glass fibers [42–44]. The main characteristics addressed in these studies were crack opening, creep, shrinkage, resistance to compression, flexure behaviour and impact, and crack opening as a function of strain. For each of these mechanical properties, a particular type and volume of fibers were proved to be more efficient.

So far, the main types of synthetic fibers and a comparison between reinforced concretes with these types of fibers have been presented. We now begin to present the behaviour of concrete reinforced with steel fibers. As this is the main type of cementitious composite formed with the addition of fibers, this issue is addressed separately in the following item.

3. Concrete reinforced with steel fibers

One of the common types of fibers most used in concrete is steel fibers, due to its high potential and probably because it is the most easily found on the market [45,46]. Steel fibers made in many countries as addition to concrete have lengths ranging from 13 to 30 mm and some up to 62.5 mm [57,48]. Steel fibers have tensile strength between 345 to 2,100 MPa and an elastic modulus of 200 to 210 GPa [59]. To facilitate their handling, the steel fibers can be grouped in bundles of 10 to 30 fibers glued using water-soluble glue, which dissolves during the mixing process [22].

Ferrari presented the geometric characteristics of steel fibers for the commonly available ones [48]. Isaia showed the main mechanical characteristics of some synthetic steel fibers and the durability of the fibers when it is used in concrete [50]. Figure 2 shows one of the main advantages of steel fibers over other types of fibers, which are the presence of hooks at the ends of the straight fibers and the waviness in the wavy fibers. Both the end hooks and the waviness of the fibers promote the mechanical anchoring of the fibers in the concrete matrix, which allows the steel fibers to be more intensely mobilized during the cracking process of the matrix [50].

| Longitudinal shape | Section | Dimension (mm) |
|--------------------|---------|----------------|
|                    |         | 0.45X0.50      |
|                    |         | 0.50           |
|                    |         | 0.65           |
|                    |         | 1.35X0.50      |

**Figure 2.** Geometric characteristics of steel fibers [50].
Even with the presence of mechanical anchoring in the matrix, both the length of the fibers and their volume that is added to the matrix play a significant role in the performance of the composite. The critical length of the fiber can be defined as the shortest length necessary for the development of adhesion stresses in the fiber, equal to its strength [51]. When the length embedded in the matrix is less than the critical length, it is not enough to generate yield stress or rupture of the fibers, being, therefore, used inefficiently [52]. The critical length \( l_c \) can be defined according to the following equation [49].

\[
l_c = \frac{\sigma_{fu}}{\tau_{fu}} \left( \frac{\tau_{fu}}{2\alpha \beta} \right)^{-\frac{1}{4}}
\]  

(1)

Where \( \sigma_{fu} \) is the ultimate strength of the fiber, \( r \) is the equivalent radius of the fiber, and \( \tau_{fu} \) is the average bond strength at the fiber-matrix interface, calculated from [49].

\[
\tau_{fu} = \left( \sigma_{ct,u} - \gamma \sigma_{cm} V_m \right) \left( \frac{2\alpha \beta}{2} \right)^{-\frac{1}{4}}
\]

(2)

Where \( \sigma_{ct,u} \) being the direct tensile strength of concrete with fibers, \( \gamma = 1.0, \sigma_{cm} \) is the direct tensile strength of the matrix, \( \alpha = 0.41, l/d = \text{fiber shape ratio}, V_f = \text{fiber volume}, V_m = \text{volume of the concrete matrix} (V_m = 1 - V_f) \).

According to Johnston: when \( l < l_c \), the fibers are so short that they are pulled out before sufficient tension is developed to break them; when \( l > l_c \), the length of the fiber embedded in the matrix is sufficient to develop a tension in the fiber equal to its strength, and the rupture of the composite will be predominantly by rupture of the fiber, and; when \( l = l_c \), the maximum toughness of the composite is obtained, since the greatest pull-out resistance is achieved without causing the fiber to break [53].

With the addition of steel fibers to the concrete, a greater mobilization of energy will be necessary to cause the formation of cracks, therefore the resistance of the concrete to creep and shrinkage will be increased, and therefore it allows the application of greater loading. With the increase of the external load more cracks are formed, and this cycle is repeated until the matrix is completely cracked [17,54]. Once the matrix is cracked, the function of the fibers is to inhibit the propagation of cracks, making bridges between their edges, where the forces are transferred from one side to the other of the matrix. At this stage, the volume of fibers that is added to the matrix becomes essential for evaluating the performance of the composite [55].

The passing and filling ability of fiber reinforced concrete mixes with long fibers might be unsatisfactory, especially in congested reinforcing areas. Critical fiber volume refers to the volume that, after cracking, will withstand the load that the composite supported before cracking. For fibers randomly distributed in the matrix, the critical volume \( V_c \) can be calculated by the following equation:

\[
V_c = \frac{2\sigma_m \left( \frac{1}{\tau_{fu} \bar{d}} \right)^{-\frac{1}{4}}}{\alpha \beta}
\]

(3)

Where \( \sigma_m = \text{direct tensile strength of the matrix and } \tau_{fu} = \text{average bond strength at the fiber-matrix interface, calculated from the equation (2).} \)

When the volume of fibers added \( V_f > V_c \), the rupture mode is characterized by multiple cracking of the matrix, and occurs at a tension equal to the resistance to the first crack of the composite. On the other hand, when \( V_f < V_c \), the rupture mode will be by propagation of a single crack, since the volume of fibers added is insufficient to support the load that acted on the matrix before it is cracked. The mixture design methodology of fiber reinforced concrete depends not only on the fiber volume percentage but also on fiber type and aspect ratio. Critical fiber volume is the volume that, after cracking, supports the loading that the composite supported before cracking. In view of this, it is possible to understand why the critical volume of short fibers resulted in a high value. In this case, the matrix for the short fiber is a composite that already contains the long fibers, and consequently the tensile strength of this material is already high, compared to that of concrete without any fiber type. A different mineral admixture composition and chemical admixture also play a vital role [56].

Koenig et al. defined post-hardening as "intended a behaviour characterized by an increase in the residual strength with increasing deformation, which does not exceed the first crack load" [57]. The increase in tensile strength of the composite only occurs if the volume of fibers added is greater than the critical. In practice, the critical volume of fibers is in the range of 1% to 3%, the latter being difficult to
use, since the workability of the concrete decreases considerably, especially in cases where the length of the fibers used is greater than or equal to twice the maximum diameter of the aggregates [58]. According to many researches, the volume of fibers normally added to the matrix, around 1%, contributes only to the post-hardening behaviour of the composite, not increasing the tensile strength of the reinforced concrete [59–61].

4. Application base characteristics of steel fiber reinforced concrete

The application of fiber reinforced concrete is very varied. Some of its main applications which are found in the literature are: industrial floors, tunnels, concrete pipes, compression covers, segmented rings for tunnel lining, road pavement, port pavement, garages and parking, slope stabilization and slopes, fire-resistant structures, explosion-resistant structures, shotcrete, etc. [62]. Basically, in all the applications mentioned above, long steel fibers were the most used, that is, with lengths in the range of 25 mm to 60 mm, depending on the intended use. However, it is known that the use of microfibers in cementitious matrices is able to increase the tensile strength of the composite, depending on the dimensions of these fibers [47,48].

Singh stated that if we consider a reinforced matrix with the same volume of fibers and the same aspect ratio, but with different dimensions, when long fibers are used, only a small increase in tensile strength is obtained. This is probably because the cracking of the matrix starts at a micro level, and if the fibers are far from the micro-cracks, they are not able to contain the micro-cracking. However, when the micro-cracks grow and join together to form a macro-crack, the long fibers are able to contain the spread of this macro-crack and substantially increase the toughness of the composite. On the other hand, if the same volume of micro-fibers are used, depending on their dimensions, they will be much closer to each other, which allows a greater number of micro-cracks to be intercepted by them and, therefore, it is opposing the tendency to open these micro-fissures. Thus, when micro-fibers are added to the matrix, there is a substantial increase in the tensile strength of the composite. However, for the same aspect ratio, the microfibers are smaller and, therefore, are pulled out of the matrix after the micro-cracks are formed, which causes a small increase in post-peak toughness [62]. The author further suggested that a combination of fibers of various sizes may promote increases in tensile strength and post-peak toughness. A combination of short fibers with large fiber factor has a higher passing ability of reinforced concrete than long fibers with a low fiber factor.

A study was conducted by Betterman et al. using polyvinyl alcohol fibers with 4 mm, 7 mm and 12 mm in length, however, due to the fact that fibers of different sizes are mobilized at different stages of loading, regardless of the material they are made of. It is expected that the addition of steel micro-fibers to the concrete will also produce similar results [63]. As steel micro-fibers are not commercially found, there is a great shortage of works in this regard. However, Ferrari (2007) carried out an extensive work seeking to develop a high-performance composite based on Portland cement and steel micro-fibers, to be used as a transition substrate in the flexural reinforcement, with carbon fiber reinforced polymer, in reinforced concrete beams [48].

Another study was carried out by Tamrakar showed that the bond strength decreased in concrete mixtures with short steel fibers ranged from 5.58% to 34.93%, whereas for long steel fibers, it ranged from 4.47% to 83.69%. The control sample showed little increase in bond strength; after initial decrease in current, no current was shown during the entire experiment and the de-passivation started only at the end of the experiment. Therefore, an early stage of corrosion occurred in the control sample, which caused some roughness around the reinforcing bar. Also, a frictional component of bond between the reinforcing bar and the concrete was increased, which might increase bond strength [68]. With the same study carried out by Tamrakar, the concrete mixtures with long steel fibers with 1.2% (12L2) and 1.6% (16L2) fiber volume fraction have higher mass loss of reinforcing bar as well as a greater decrease in bond strength. This may be because of insufficient concrete cover depth as well as higher electrical conductivity of the long steel fiber. The decrease in the bond strength can be verified by the rib profile of the reinforcing bar after pull-out test. However, concrete mixtures with steel fibers (both long and short) in 2.4% fiber volume fraction have identical mass loss and decrease in bond strength for both
long and short steel fibers. This suggests that, even with higher fiber volume fraction, corrosion of the reinforcing bar is limited. The reason behind this is improved alignment of the reinforcing bar. Also, some of the steel fibers, which are randomly distributed in the concrete specimen, might be interconnected with the reinforcing bar [64].

Further studies were conducted by Ramadoss & Nagamani also showed a similar trend. In addition, the secondary absorption rates for mixtures with short steel fibers are lower than for long steel fibers. A possible explanation is that a higher number of short steel fibers per unit volume of concrete (compared to long steel fibers for the same percentage of fiber dosage) might improve bonding of the concrete matrix [65]. One study of corrosion behaviour in concrete showed that the bond strength and degrees of corrosion are governed by many factors such as composition of the bar and deviation in material properties of concrete [66]. A previous study also showed an increase in the bond strength at an early stage of corrosion [67]. As the composite evaluated by Ferrari was composed of long and short steel fibers in the same matrix, a reinforced concrete with different types of fibers, although the material that makes them up is the same seen with steel [48]. For this reason, this subject is addressed in a separate topic, presented below.

5. Interaction between steel fiber and different types of fibers
To obtain the composite, Ferrari used different dosages. Mortar and micro-concrete were used, both with the addition of steel fibers with different lengths. Table 1 presents the characteristics of the fibers used by Ferrari. The fiber dosages for the analysed mortar were from 1% to 2% of type A fiber, from 1% to 2.5% of type B fiber, and combinations with 2% of fibers. There were 0.5% to 1.5% of fiber A and 1.5% to 2.5% of fiber B, and another combination of fibers varying between 1.5% of fiber A and volumes between 0.5% and 3.5% of fiber C. For micro concrete, fiber content A was fixed at 1% and fiber content C was varied between 0% and 2.5% [48].

| Parameters               | Fiber A | Fiber B | Fiber C |
|--------------------------|---------|---------|---------|
| Longitudinal shape       | ![25mm](image1) | ![12mm](image2) | ![13mm](image3) |
| Nominal diameter         | 0.75 mm | 0.60 mm | 0.75    |
| Cross section area       | 0.4418 mm² | 0.2827 mm² | 0.4418 mm² |
| Deformation factor*      | 33      | 22      | 17      |
| Maximum traction stress  | 1100 MPa | 1100 MPa | 1100 MPa |
| Specific weight          | 7850 kg/m³ | 7850 kg/m³ | 7850 kg/m³ |

* Deformation factor refers to an alteration in the shape or dimensions of an object as a result of the application of stress to it.

To assess the structural behaviour of each of the different dosages, three-point bending tests were carried out on prisms with a notch in the middle of the span, in addition to tensile strength tests by diametral compression and simple compression. With the results of the flexural tests, it has three points load curves with a notch opening and fracture resistance curves were plotted. After a careful and detailed analysis of the results of all tests, Ferrari concluded that the mortar which presented the best performance, was the one that had the combination of fibers with 1.5% type A fiber and 1.5% of type C fibers. In the case of micro-concrete, it is concluded that the best performance was achieved by combining 1% type A fibers and 2% type C fibers. Now comparing these two composites, the author concluded that both had very similar responses and the most suitable composite for application in the tensioned beams before the reinforcement with carbon fiber reinforced epoxy is the composite formed by the micro-concrete. And justified the choice simply by the presence of the coarse aggregate, non-
existent in mortar, as this is an important feature in the adhesion of the carbon fiber reinforced epoxy composite blanket to the substrate, as explained above [48].

Still regarding Ferrari study [48], the author concluded that straight and smooth steel microfibers, type B, are inefficient. Due to the loss of adhesion with the matrix, and its consequent slip, led to insignificant increase in the composite toughness. The study has also pointed out that the combination of steel microfibers (with hook at the ends) and conventional fibers would be an interesting alternative in the field of structural recovery. Since its addition to the cementitious matrix is essential to increase the tensile strength in flexural and increase fracture toughness of the material. Ferrari [48] confirmed the hypothesis raised earlier about the similarity between the behaviour of composites formed of steel fibers with different lengths and with PVA fibers, also with different lengths, likewise Betterman et al. [63] suggestion. As previously stated, this confirmation was expected, since the smaller fibers are mobilized in the initial stages of loading and the long fibers are more intensely mobilized in more advanced stages, when the smaller fibers have already broken or slipped from the matrix.

Regarding the reinforcement of concrete beams with the composite developed by Ferrari with carbon fiber reinforced epoxy composite. It was concluded that in the presence of a material with high resistance to fracture in the tensioned flange of the beam, the cracks are more distributed and smaller opening along the extension of the reinforcement. In addition to a significant increase in strength, the bonding of the carbon fiber reinforced epoxy composite blanket to a transition substrate also led to a significant increase in beam stiffness with respect to a beam without transition substrate [48].

6. Conclusion
Researchers have studied reinforced concrete with different kinds of fibers including steel fibers, polyvinyl alcohol fibers, poly-propylene, glass fibers, nylon bundles, and carbon fibers. The use of steel fibers in reinforced concrete is widely applied around the world because it improves the post-peak ductility and the energy absorption capacity of the concrete. The steel fiber reinforced concrete has shown a densified matrix with better bonding between steel and concrete. Therefore, taking the advantage of fresh concrete properties (the ability of the fresh concrete mixture to maintain uniform distribution of mortar paste and aggregates during the construction process) by including steel fibers should provide a positive new feature and a new dimension in concrete technology, which could lead to better behaviour in its mechanical performance in the hardening state. An incorporation of steel fibers (both long and short) successfully enhances the toughness of fibrous concrete mixtures. The post crack strength and flexural strength values can be directly used for design purposes because they provide numerical values regarding the allowable stresses at given deflection based on the load-deflection curve. The hardness and toughness performance of concrete with steel fibers is excellent in presence of the abrasive forces. Overall, the short steel fiber-concrete mixtures perform better than the long steel fiber mixtures with the same fiber dosages. The recommendation for future work is to assess whether this performance is achieved when the models used are larger and increasing the range and weight of the fiber fabrics used.

7. References
[1] Abbood I S, Mahmood M, Hanoon A N, Jaafar M S and Mussa M H 2018 Seismic Response Analysis of Linked Twin Tall Buildings with Structural Coupling International Journal of Civil Engineering and Technology 9 208-19
[2] Mussa M H, Abdulhadi A M, Abbood I S, Mutalib A A and Yaseen Z M 2020 Late Age Dynamic Strength of High-Volume Fly Ash Concrete with Nano-Silica and Polypropylene Fibres Crystals 10 243
[3] Sardar S and Hama A 2018 Evaluation of p-delta effect in structural seismic response. In: MATEC Web of Conferences: EDP Sciences) p 04019
[4] Sardar S, Mahmoud M and Shakir I 2017 Nonlinear Pushover Analysis for Steel Beam-Column Connection Eurasian Journal of Science and Engineering 3 83-98
[5] Heeb P, Kölliker M and Richner H 2000 Bird–ectoparasite interactions, nest humidity, and
ectoparasite community structure, Ecology 81:958-68.

[6] Hartwig M K 2014 A Companion to Ancient Egyptian Art: Wiley

[7] Dixon J and Mayfield B 1971 Concrete reinforced with fibrous wire, Concrete (London)

[8] Triantafillou T 2016 Textile Fibre Composites in Civil Engineering: Elsevier Science

[9] Rai A and Joshi Y 2014 Applications and properties of fibre reinforced concrete, Int. J. Eng. Res. Appl 4:123-31.

[10] Ferreira C R, Tavares S S, Ferreira B H M, Fernandes A M, Fonseca S J G, Oliveira C A d S, Teixeira R L P and Gouveia L L d A 2017 Comparative Study About Mechanical Properties of Strutural Standard Concrete and Concrete with Addition of Vegetable Fibers, Materials Research 20:102-7.

[11] Correia V C, Santos S F, Savastano Jr H and John V M 2017 Utilization of vegetable fibers for production of reinforced cementitious materials, RILEM Technical Letters 2:145-54.

[12] Aydin E 2017 Data for the physical and mechanical properties of staple fibers cement paste composites, Data in brief 14:307-12.

[13] Xiao Y and Wu H 2000 Compressive behavior of concrete confined by carbon fiber composite jackets, Journal of materials in civil engineering 12:139-46.

[14] Choi S-J, Mun J-S, Yang K-H and Kim S-J 2016 Compressive fatigue performance of fiber-reinforced lightweight concrete with high-volume supplementary cementitious materials, Cement and Concrete Composites 73:89-97.

[15] Günay E 2018 Natural and Artificial Fiber-Reinforced Composites as Renewable Sources: IntechOpen.

[16] Parra-Montesinos G J, Reinhardt H W and Naaman A E 2012 High Performance Fiber Reinforced Cement Composites 6: HPFRCC 6: Springer Netherlands.

[17] Atiš C D and Karahan O 2009 Properties of steel fiber reinforced fly ash concrete, Construction and Building Materials 23:392-9.

[18] Oh B H, Kim J C and Choi Y C 2007 Fracture behavior of concrete members reinforced with structural synthetic fibers, Engineering Fracture Mechanics 74:243-57.

[19] Pelisser F, Neto A B d S S, La Rovere H L and de Andrade Pinto R C 2010 Effect of the addition of synthetic fibers to concrete thin slabs on plastic shrinkage cracking, Construction and building materials 24:2171-6.

[20] Reis J 2006 Fracture and flexural characterization of natural fiber-reinforced polymer concrete, Construction and building materials 20:673-8.

[21] Juarez C, Duran A, Valdez P and Fajardo G 2007 Performance of “Agave Lecheguilla” natural fiber in Portland cement composites exposed to severe environment conditions, Building and environment 42:1151-7.

[22] Singh H 2016 Steel Fiber Reinforced Concrete: Behavior, Modelling and Design: Springer Singapore.

[23] Swamy R N and Barr B 1989 Fibre Reinforced Cement and Concretes: Recent developments: Taylor & Francis.

[24] Sengul O 2016 Mechanical behavior of concretes containing waste steel fibers recovered from scrap tires, Construction and Building Materials 122:649-58.

[25] Ackiogene M, Alyamac K E and Ulucean Z C 2013 Fresh and hardened properties of steel fiber reinforced concrete produced with fibers of different lengths and diameters.

[26] Fidelis M E A, Pereira T V C, Gomes O d F M, de Andrade Silva F and Toledo Filho R D 2013 The effect of fiber morphology on the tensile strength of natural fibers, Journal of Materials Research and Technology 2:149-57.

[27] d’Almeida J, Aquino R and Monteiro S 2006 Tensile mechanical properties, morphological aspects and chemical characterization of piassava (Attalea funifera) fibers, Composites Part A: Applied Science and Manufacturing 37:1473-9.

[28] de Andrade Silva F, Chawla N and de Toledo Filho R D 2008 Tensile behavior of high performance natural (sisal) fibers, Composites Science and Technology 68:3438-43.
[29] Pakravan H R and Ozbakkaloglu T 2019 Synthetic fibers for cementitious composites: A critical and in-depth review of recent advances Construction and Building Materials 207 491-518
[30] Naaman A E, Wongtanakitcharoen T and Hauser G 2005 Influence of different fibers on plastic shrinkage cracking of concrete ACI materials Journal 102 49
[31] Hejazi S M, Sheikhzadeh M, Abtahi S M and Zadhoush A 2012 A simple review of soil reinforcement by using natural and synthetic fibers Construction and building materials 30 100-16
[32] Kajiwara K and Ohta Y 2009 Identification of Textile Fibers: Elsevier) pp 68-87
[33] Mondal P, Shah S P, Marks L D and Gaitero J J 2010 Comparative study of the effects of microsilica and nanosilica in concrete Transportation Research Record 2141 6-9
[34] Snoeck D, Smetryns P-A and De Belie N 2015 Improved multiple cracking and autogenous healing in cementitious materials by means of chemically-treated natural fibres Biosystems Engineering 139 87-99
[35] Yang J-M, Min K-H, Shin H-O and Yoon Y-S 2012 Effect of steel and synthetic fibers on flexural behavior of high-strength concrete beams reinforced with FRP bars Composites Part B: Engineering 43 1077-86
[36] Parra-Montesinos G J and Chompreda P 2007 Deformation capacity and shear strength of fiber-reinforced cement composite flexural members subjected to displacement reversals Journal of Structural Engineering 133 421-31
[37] Anggawidjaja D, Ueda T, Dai J and Nakai H 2006 Deformation capacity of RC piers wrapped by new fiber-reinforced polymer with large fracture strain Cement and Concrete Composites 28 914-27
[38] Habel K, Viviani M, Denarié E and Brühwiler E 2006 Development of the mechanical properties of an ultra-high-performance fiber reinforced concrete (UHPFRC) Cement and Concrete Research 36 1362-70
[39] Martínez-Barrera G, Menchaca-Campos C, Hernández-López S, Viguera-Santiago E and Brostow W 2006 Concrete reinforced with irradiated nylon fibers Journal of materials research 21 484-91
[40] Mindess S and Vondran G 1988 Properties of concrete reinforced with fibrillated polypropylene fibres under impact loading Cement and Concrete Research 18 109-15
[41] Gencel O, Ozel C, Brostow W and Martínez-Barrera G 2011 Mechanical properties of self-compacting concrete reinforced with polypropylene fibres Materials Research Innovations 15 216-25
[42] Pehlivanlı Z O, Uzun I and Demir İ 2015 Mechanical and microstructural features of autoclaved aerated concrete reinforced with autoclaved polypropylene, carbon, basalt and glass fiber Construction and Building Materials 96 428-33
[43] Reis J and Ferreira A 2004 Assessment of fracture properties of epoxy polymer concrete reinforced with short carbon and glass fibers Construction and Building Materials 18 523-8
[44] Bischoff P H and Paixao R 2004 Tension stiffening and cracking of concrete reinforced with glass fiber reinforced polymer (GFRP) bars Canadian Journal of Civil Engineering 31 579-88
[45] Pajak M and Ponikiewski T 2013 Flexural behavior of self-compacting concrete reinforced with different types of steel fibers Construction and Building Materials 47 397-408
[46] Khaloo A, Raisi E M, Hosseini P and Tahsiri H 2014 Mechanical performance of self-compacting concrete reinforced with steel fibers Construction and building materials 51 179-86
[47] Yoo D-Y and Yoon Y-S 2015 Structural performance of ultra-high-performance concrete beams with different steel fibers Engineering Structures 102 409-23
[48] Ferrari V J 2007 Reforço à flexão de vigas de concreto armado com manta de polímero reforçado com fibras de carbono (PRFC) aderido a substrato de transição constituído por compósito cimentício de alto desempenho. Universidade de São Paulo
[49] Bentur A and Mindess S 2006 Fibre Reinforced Cementitious Composites, Second Edition: Taylor & Francis
[50] Isaia G C 2005 Concreto: ensino, pesquisa e realizações *São Paulo: IBRACON* 2 953-83
[51] de Alencar Monteiro V M, Lima L R and de Andrade Silva F 2018 On the mechanical behavior of polypropylene, steel and hybrid fiber reinforced self-consolidating concrete *Construction and Building Materials* **188** 280-91
[52] Yi X S, Du S and Zhang L 2017 *Composite Materials Engineering. Volume 2: Different Types of Composite Materials*: Springer Singapore
[53] Johnston C D 2010 *Fiber- Reinforced Cements and Concretes*: Taylor & Francis
[54] Song P and Hwang S 2004 Mechanical properties of high-strength steel fiber-reinforced concrete *Construction and Building Materials* **18** 669-73
[55] Thomas J and Ramaswamy A 2007 Mechanical properties of steel fiber-reinforced concrete *Journal of materials in civil engineering* **19** 385-92
[56] Moavenzadeh F and Cahn R W 1990 *Concise Encyclopedia of Building and Construction Materials*: Pergamon Press
[57] Koenig A, Wuestemann A, Gatti F, Rossi L, Fuchs F, Fessell D, Dathe F, Dehn F and Minelli F 2019 Flexural behaviour of steel and macro-PP fibre reinforced concretes based on alkali-activated binders *Construction and building materials* **211** 583-93
[58] Newman J and Choo B S 2003 *Advanced Concrete Technology Set*: Elsevier Science
[59] Arisoy B and Wu H-C 2008 Material characteristics of high performance lightweight concrete reinforced with PVA *Construction and Building Materials* **22** 635-45
[60] Naaman A and Reinhardt H 1996 Characterization of high performance fiber reinforced cement composites—HPFRC. In: *High performance fiber reinforced cement composites*, pp 1-24
[61] Maalej M, Hashida T and Li V C 1995 Effect of fiber volume fraction on the off-crack-plane fracture energy in strain-hardening engineered cementitious composites
[62] Singh H 2018 *Steel Fiber Reinforced Concrete: Behavior, Modelling and Design*: Springer Singapore
[63] Betterman L, Ouyang C and Shah S P 1995 Fiber-matrix interaction in microfiber-reinforced mortar *Advanced Cement Based Materials* **2** 53-61
[64] Tamrakar N 2012 The Effect of Steel Fibers Type and Content on the Development of Fresh and Hardened Properties and Durability of Self consolidating Concrete *Civil Engineering, Ryerson University, Toronto, ON* 144
[65] Ramadoss P and Nagamani K 2008 TENSILE STRENGTH AND DURABILITY CHARACTERISTICS OF HIGH-PERFORMANCE FIBER REINFORCED CONCRETE *Arabian Journal for Science & Engineering (Springer Science & Business Media BV)* **33**
[66] Bhargava K, Ghosh A, Mori Y and Ramanujam S 2007 Models for corrosion-induced bond strength degradation in reinforced concrete *ACI Materials Journal* **104** 594
[67] Almusallam A A, Al-Gahtani A S and Aziz A R 1996 Effect of reinforcement corrosion on bond strength *Construction and building materials* **10** 123-9