

Review

Fiber-reinforced cementitious composites: recent advances and future perspectives on key properties for high-performance design

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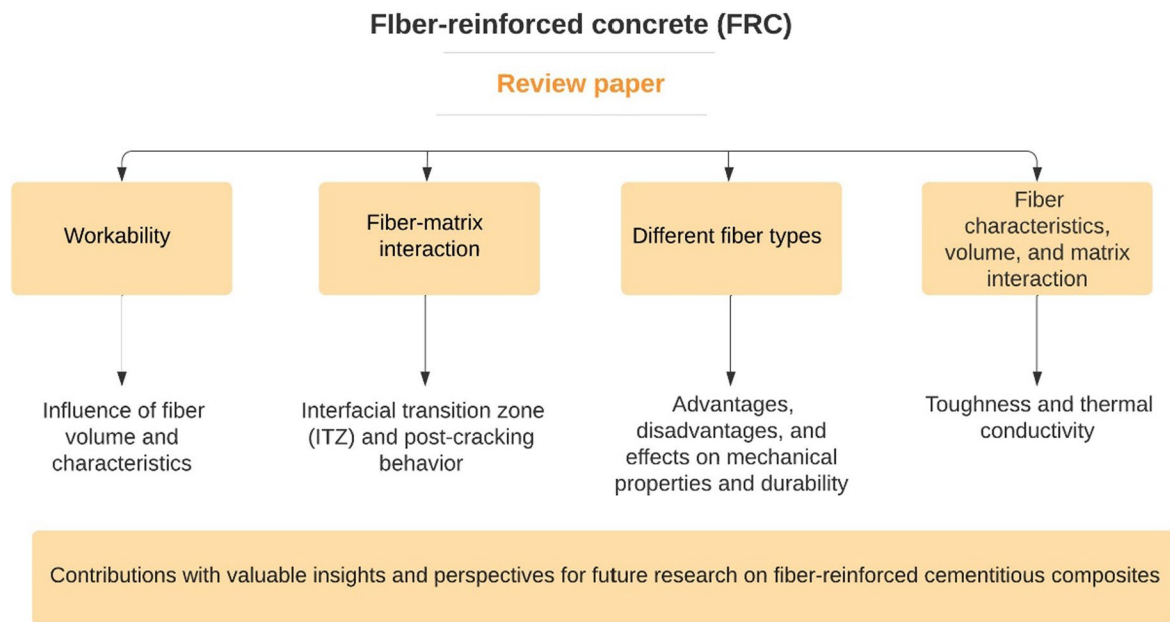
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Abstract

This paper comprehensively reviews fiber-reinforced concrete (FRC), focusing on workability, fiber-matrix interaction, mechanical properties, and thermo-mechanical behavior. The study investigates the influence of fiber volume and characteristics on workability. It explores the role of fiber-matrix interaction within the interfacial transition zone (ITZ) and its impact on post-cracking behavior. Different fiber types, including steel, polypropylene, natural, and synthetic fibers, are analyzed to identify their advantages, disadvantages, and effects on mechanical properties and durability. The paper discusses the influence of fibers on concrete's tensile strength, ductility, flexural strength, and impact resistance. The relationship between fiber characteristics, volume, and matrix interaction is examined, highlighting their combined effect on composites' toughness and thermal conductivity. The findings emphasize the need for further research to optimize fiber-reinforced composites and explore potential applications in civil construction for improved thermal comfort in buildings. This review contributes valuable insights and offers perspectives for future research in fiber-reinforced cementitious composites.

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Graphical abstract

Keywords Cement-based materials · Durability · Fibers · Interfacial transition zone · Sustainability

1 Introduction

Modern society consumes about 10 billion tons of engineering materials annually, among which concrete stands out as the most consumed worldwide, especially in developing regions [1, 2]. Moreover, the production of Portland cement, the main component of concrete, has increased at rates higher than population growth since the twenty-first century [3], and there are several reasons for such expansion (Fig. 1). Its components are easily found in most places and are relatively cheap; its production is simple and applicable in various works [4].

It is also important to mention the increased concern by the technical and scientific community with sustainability, which has become one of the biggest challenges for the construction industry. Most conventional concretes used in engineering works contain Portland cement, whose production emits large amounts of carbon dioxide (CO₂) into the atmosphere, intensifying the greenhouse effect and leading to global warming [5]. Some studies point out that, although its CO₂ emissions are lower than those of steel, wood, glass, and other construction materials [6], concrete production is responsible for about 7% of global CO₂ emissions [2]. The construction industry has increasingly explored alternative materials and techniques, such as reducing the clinker content in cement and incorporating industrial by-products to address these environmental challenges [7]. However, implementing these measures requires overcoming technical and economic barriers, highlighting the need for innovative solutions like fiber-reinforced concrete, which offers improved performance and sustainability [8].

In this context, the constant development of new construction materials, especially concrete, has originated cementitious composites with characteristics focused on specific environments, which are not only related to strength but also to better durability, higher resistance to external agents, high energy absorption, better appearance, among others [9]. It happens because conventional concrete can no longer meet all current needs due to environmental aspects, the complexity of the projects, the structures themselves, and sometimes their execution. To build long bridges and tall buildings made of reinforced or prestressed concrete, for example, more efficient cementitious materials are required, which provide high strength and greater ductility than conventional ones, which can be applied on-site and have competitive prices in the market [10, 11].

Considering the concrete's mechanical behavior, its brittleness has been studied for many decades since it is the main reason for the frequent repair and rehabilitation of concrete structures. In this aspect, the use of additions to the

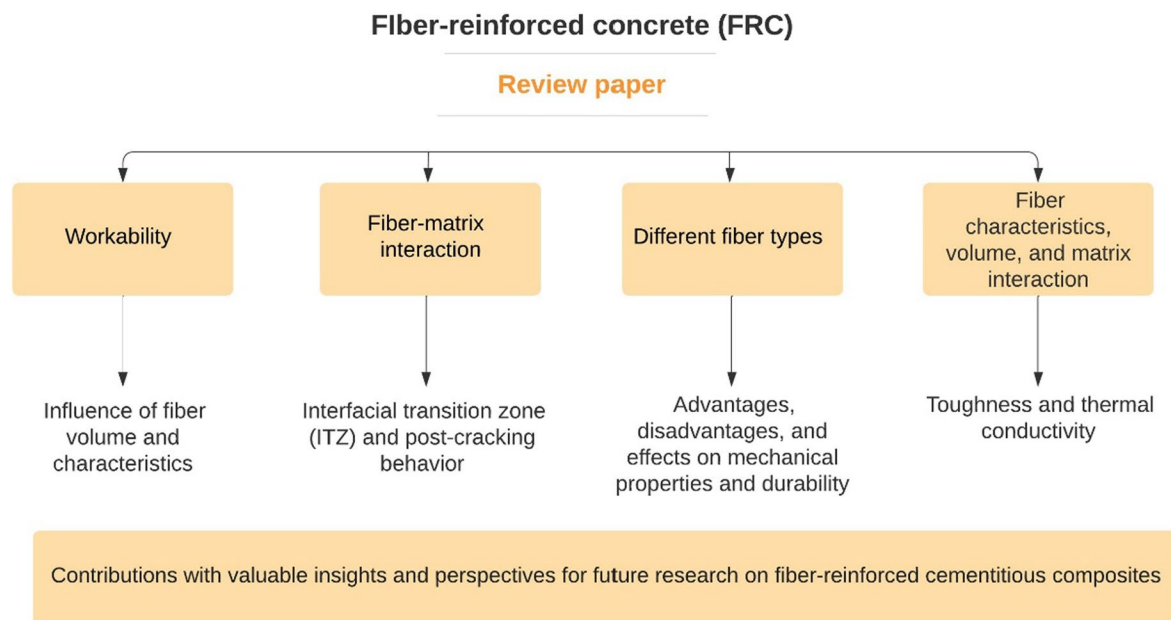


Fig. 1 Main topics and contributions of the current review

cementitious matrix has improved its mechanical properties [12, 13], with the fibers an alternative that improves the concrete's fracture toughness by increasing its deformation capacity by tensile stresses [12]. Currently, the fibers most used as reinforcement in cement-based materials are steel, glass, carbon, and synthetic polymeric fibers—polypropylene, polyethylene, polyvinyl alcohol, acrylics, polyamide, and polyester. Specifically, the main properties to be improved by incorporating fibers are tensile strength, flexural strength, fracture toughness, fatigue, impact, and thermal shock resistance [14]. Notably, some fiber types, such as carbon fibers, have an inert surface that can hinder load transfer between the fibers and the matrix. For this reason, some studies suggest modifying their surface [15, 16]. Regardless, the environmental impact of fiber production, including the energy consumption and emissions associated with their manufacture, remains a critical concern that requires further research and mitigation strategies.

According to Bentur and Mindess [17], steel fibers (SF) are widely used in cementitious composites because they act as a stress-relief bridge in the fracture region. In other words, they increase the composite's strength by transferring loads and stresses through cracks. In addition, they provide energy absorption mechanisms related to fiber debonding and slippage. These factors imply an upward stress–strain curve after crack formation, a behavior also known as strain hardening. However, Sadrinejad et al. [18] point out some of SF's limitations, such as corrosion and the effect on electric and magnetic fields, which limit their use, and they cite the high bulk density as a disadvantage. Considering these characteristics, these authors suggest synthetic fibers as a practical alternative.

In this sense, Söylev and Özturan [19] state that polypropylene fibers (PPF) are restricted to a non-structural reinforcement to reduce the growth of cracks due to plastic shrinkage by drying (hydraulic shrinkage), not contributing to the concrete's load capacity. Recent studies indicate that PPF benefits high-strength concrete (HSC) submitted to high temperatures. According to Kalifa et al. [20], the cement matrix assimilates the melted fibers, typically melting around 170 °C, creating a network of tiny empty spaces that facilitate the release of vapor pressure. Resende et al. [21] ratified this theory by experimentally studying the behavior of HSC reinforced with PPF at temperatures up to 800 °C. The authors showed that adding these fibers to HSC improves its residual mechanical properties, i.e., compressive strength (up to the range of 400 °C), tensile strength (up to 200 °C), and modulus of elasticity (at room temperature). At high temperatures (600 °C and 800 °C), all tests showed similar performance in mechanical properties, regardless of whether using synthetic fibers.

Polymeric fibers (PF), in turn, have a specific density about six or seven times lower than SF [22], have a significantly lower cost when compared to conventional SF, and are also advantageous in reducing the strength loss of cementitious materials exposed to high temperatures [23].

With this perspective, new components and technologies developed for specific purposes are now partly applied in daily production in ready-mixed concrete plants. Generally, fiber-reinforced concrete (FRC) is becoming a highly technological material that provides excellent performance but requires appropriate design and execution. Real-world

applications of FRC face challenges such as ensuring uniform fiber dispersion, addressing compatibility between fibers and the cement matrix, and balancing the cost–benefit ratio in large-scale projects. Therefore, theoretical and experimental investigations into its concern have been increasingly found in the literature [9, 24, 25]. Emerging fiber technologies, such as nanofibers and bio-based fibers, are gaining attention for their potential to enhance mechanical properties, sustainability, and adaptability in specialized cementitious composites. Figure 2 shows the growing number of studies involving FRC production.

Therefore, various frontiers of knowledge concerning FRC studies can still be debated. The studies referenced in this review were selected through a systematic search of the Web of Science and Scopus databases over the past twenty years, complemented by theses, dissertations, and books to provide a more comprehensive portfolio. As depicted in Fig. 1, this study examined the main characteristics of FRC and discussed an analysis of workability variations based on the volume and characteristics of the fibers. Subsequently, the study investigated the interaction between fiber and matrix and the post-cracking effect, particularly in the interfacial transition zone (ITZ). Once the fiber-matrix relationship was understood, the study focused on FRC's primary mechanical properties and thermo-mechanical behavior. Finally, the paper deliberated on the key advantages and disadvantages of fiber usage and provided perspectives on future research in this field.

2 Fiber-reinforced concrete overview

Concrete produced with Portland cement is the world's most widely used building material and has various civil infrastructure applications. The fresh and hardened state properties can meet many design specifications by varying the type and amount of individual constituents in the concrete mixture (e.g., cement, water, aggregate, and admixtures) [22]. Besides these variations, another possible adjustment to tailor its hardened state properties is the fiber addition in its matrix, characterizing the material as FRC [17]. It is worth mentioning that fibers have been used to reinforce cementitious material since ancient times when straw was incorporated into clay bricks. Thus, FRC can be understood as an advanced model of this technology, in which straw and clay are replaced by natural or synthetic fibers and cement, respectively [26–28].

FRC has appropriate integrity and cohesion and can act as a pseudo-ductile material to produce structural components in various geometries. Using fiberglass, polypropylene, steel, and carbon, associated with producing different composite types, gives cementitious materials desirable engineering properties for various industrial applications, making them very attractive to the construction industry [26]. SF and glass fibers (GF) were first incorporated into concrete in the mid-1950s. At that time, they were straight and smooth, but since then, more complex geometries have been developed, mainly to modify the bond with the cementitious matrix. For example, modern steel can be manufactured in hook shape or deformed ends, occurring as packed filaments or laminated films [10, 17].

Concerning their materials, fibers are divided into four basic groups: steel, glass, synthetic, and natural fibers [29]. Synthetic fibers, in particular, have gained significant popularity in recent years due to their versatility, cost-effectiveness, and ability to enhance concrete properties. These fibers' physical and mechanical properties are crucial as they directly influence the concrete's performance, durability, and bonding with the matrix [30, 31]. Table 1 presents the physical (density and aspect ratio – length/diameter) and mechanical properties (tensile strength, Young's modulus, and elongation) of polymeric, polyvinyl alcohol, and polyethylene fibers based on values reported in the literature. These properties are key to understanding the effectiveness of synthetic fibers in concrete applications.

Fig. 2 Evolution of research on FRC

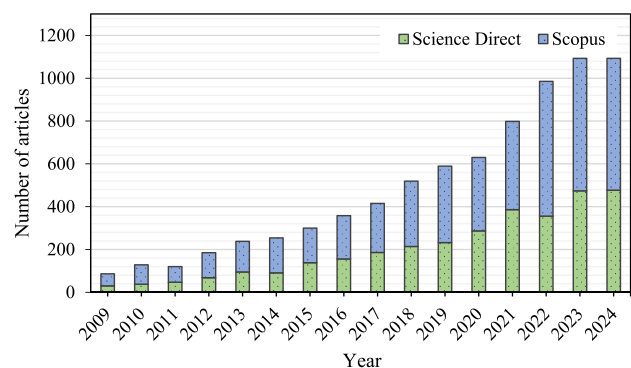


Table 1 Physical and mechanical properties of synthetic fibers

Fiber	Density (g/cm ³)	Aspect ratio	Tensile strength (MPa)	Elastic modulus (GPa)	Elongation (%)	Ref
Acrylic	1.17	–	207–1000	14.6	7.5–50.0	[32]
Aramid	1.44	–	3620	62.0	4.4	[32]
High-modulus aramid	1.44	–	3620	117.0	2.5	[32]
Nylon	1.16	–	965	5.2	20.0	[32]
Polyester	1.34–1.39	–	896–1100	17.5	–	[32]
Polypropylene	0.90–0.91	–	310–760	5.5–4.9	15.0	[32]
Polyethylene	0.96	–	200–300	5.0	3.0	[32]
Polyethylene	–	453.6	3000	100.0	3.1	[33]
Polyethylene	–	600.0–642.9	2900–3800	100.0–120.0	2.0–3.0	[34]
Polyethylene	–	1500.0	2700	88.0	–	[35]
Polyvinyl alcohol	–	307.7	1620	42.8	6.0–8.0	–*

*The values for polyvinyl alcohol fibers were consistently reported across most of the references consulted

Moreover, according to Sadrinejad et al. [18], depending on their geometry, they are classified into two main types: microfibers, defined as short fibers with a diameter of 100 μm or less and a specific surface area greater than 500 cm^2/g , and macrofibers, which, compared to microfibers, are larger in diameter and length and have a specific surface area of approximately 10 cm^2/g .

Within this context, it is worth mentioning that despite concrete having high levels of strength, workability, and durable performance, its heterogeneous structure has some undesirable effects. Its complex structure can lead to many zones of internal stress concentration, creating conditions where some internal voids can occur in fresh or hardened concrete. Even before any load or weathering application, microcracks may exist at the interfaces between the aggregate and the matrix [36]. In addition, external factors such as structural loads and environmental effects can increase cracks in size and quantity. Crack propagation in the matrix and crack bridging produce larger cracks, which may fail [37]. In this sense, the fiber incorporation can act in two ways in cement-based composites: as primary reinforcement, to improve their flexural and tensile strength through the bridging effect for stress transfer, as exemplified in Fig. 3, and as secondary reinforcement, to prevent the creation and propagation of microcracks by shrinkage. Thus, both mechanisms generate optimized results [36, 38, 39].

It should also be noted that fiber-matrix interfacial interactions influence the mechanical properties of cement-based materials, especially in engineered cementitious composites (ECC) produced with small-sized sands, fillers, fibers, and complementary cementing materials. ECCs were developed in the 1990s, with the first ones having moderate tensile strengths of 4–6 MPa and higher ductilities of about 3%–5%. One outstanding characteristic of ECC is its capacity for multiple microcracking during the strain hardening process—the microcracks have an opening smaller than 100 μm —making it a highly efficient material [38]. To achieve optimized properties, the fibers used nowadays have a high modulus of elasticity, such as carbon, steel, and polyvinyl alcohol. For instance, researchers recently have used ultra-high molecular weight polyethylene fiber to develop ultra-high performance engineered cementitious composites (UHP-ECC). Achieving

Fig. 3 Steel fibers acting as a bridge for stress transfer in a mortar specimen ruptured in the flexural test



compressive and tensile strength of 120–150 MPa and 15–20 MPa, respectively, the authors showed that UHP-ECC has excellent development prospects in all kinds of civil engineering applications [40].

In contrast, the fibers must have a higher modulus of elasticity than the matrix to optimize the mechanical behavior. For cementitious materials, where this modulus varies between 15 to 30 GPa, this condition may be difficult to find in most synthetic fibers. In this scenario, even in front of attempts to develop fibers with a very high modulus of elasticity, some studies have indicated that considerable improvements in strain capacity, toughness, impact strength, and crack control can be obtained in composites even with low-modulus fibers, with the betterment of these properties being much more significant than the modest increase in flexural tensile strength in many applications [32].

Furthermore, some parameters influence the fiber's effectiveness as a reinforcement material, most related to its dispersion in the matrix, such as content, orientation, and fluidity. Dispersion is affected by fiber geometry and its interaction effects, concrete yield stress in the fresh state, concreting and compaction procedures, concrete mold geometry, and size. The fiber orientation is the parameter that most influences the FRC ductility, as it needs to be in the direction of tensile stresses to act as a bridge for stress transfer [41].

In general, each fiber type has its advantages and disadvantages when incorporated into cement-based materials. SF can significantly improve mechanical behavior, but their electrical, magnetic, and thermal conductivity properties make them unsuitable for some special applications, and corrosion can be harmful and rapidly deteriorate the composite. GF, in turn, has excellent strengthening effects but poor alkali resistance. Natural fibers, such as wood, sugarcane bagasse, and plant fibers, are cheap and readily available but have poor durability. Synthetic fibers, such as acrylic, aramid, and carbon, can avoid plastic shrinkage cracks and improve post-cracking behavior but generally present low modulus [36].

3 Workability

It is impossible to produce high-quality cementitious composites if the fresh state does not have satisfactory properties, one of the most important being workability, which brings together several characteristics of the fresh concrete. A workable cementitious composite presents adequate consistency for application, is compatible with the compaction and finishing that will be adopted, and does not present segregation or exudation. Moreover, the workability is affected by the rheological characteristics of the composite itself, represented by its consistency, which corresponds to the plasticity degree and ability to remain homogeneous [42, 43].

In this aspect, it should be noted that adding fiber to concrete reduces the mixture's workability and makes molding difficult. This condition can lead to unsatisfactory consistency and high volumes of incorporated air, reducing strength and durability. However, some research points out that the current FRC can be designed for high workability, allowing fluidity, pumping, and filling of complex molds without segregation occurring [37, 44].

Fresh concrete workability can be determined through the slump test, regulated by the Brazilian standard NBR NM 67 [45]. The results of this test have indicated that fiber addition reduces the slump—the difference in height between the axis of the test specimen and the height of the conical mold—, thus decreasing the fresh concrete workability. This fact is because the fiber incorporation can form a network structure in the concrete matrix, restricting flow. Furthermore, due to the high volume and fiber's large surface area, the concrete viscosity increases. Thus, to improve the FRC workability, commonly employed measures are to limit the fiber content in the mixture. In the case of PF, for example, a range of 0.1–1.0% and adding more water are recommended, but adding more water will negatively affect the concrete's strength. This scenario leads to another alternative to improve workability, the use of plasticizer additives, which discards the need for more water [36, 46].

With this perspective, several authors have recently developed works investigating the influence of various fiber types and contents in different concrete classes. Ortega-López et al. [47] studied the effects of adding hybrid SF (0.5%–1.5% by volume) and recycled tire polymer fiber (RTPF, 0.1%–0.4%) on concrete workability through slump test and reported that the incorporation of either SR or RTPF reduced the workability by 28.3–81.2%. Tibebe et al. [48] also used the slump test to experimentally measure the workability behavior of chopped glass fiber reinforced concrete (GFRC), with fiber contents ranging from 0.05%, 0.1%, 0.15%, to 0.2% (by weight of cement). The authors noted that the GFRC slump reduced as the fiber content increased because of the increase in the reinforcement binding nature of GF. Zhang et al. [49] studied lightweight cement concrete (LCC) workability. Briefly, the SF addition reduced the fluidity and slightly increased LCC density, whereas the PPF addition significantly decreased both fluidity and density. Ye et al. [50], in turn, studied the influence of polyethylene fiber content on the 3D-printed ultra-high ductile concrete (UHDC) workability.

These authors reported that all the fiber contents studied (1.0%, 1.5%, and 2.0% by volume fraction) showed favorable workability in 3D printing.

Wu et al. [51] investigated the effects of SF content and form on some mechanical properties of ultra-high performance fiber-reinforced concrete (UHP-FRC). As depicted in Table 2, the results indicated that incorporating 1%, 2%, and 3% straight SF reduced the flowability by 14.9%, 25.6%, and 38.1%, respectively, due to the increase in the specific surface area associated with the increased amount of fibers. The authors also reported that the flowability of mixtures with hooked SF was reduced by 20.9%, 35.8%, and 51.2% for the same aforementioned contents and in the same order compared to those with the same amount of straight fibers. For mixtures with deformed fibers, the reduction was 17.7%, 31.2%, and 45.1%, respectively, due to the greater friction between fibers and aggregates, which increases adherence with the matrix and thus reduces fluidity. In addition, the change in shape makes the fibers more likely to cluster [51].

Sadrinejad et al. [18] evaluated the mechanical and durability properties of concrete containing hybrid synthetic fibers, polyolefin fibers with continuous embossed surface texture, in macro size, 48–50 mm in length and 1.0–1.5 mm in diameter, and PPF, in micro size, 12 mm in length and 0.02 mm in diameter. Incorporating 0.5%, 1.0%, and 1.5% of polyolefin fiber in contents reduced the rebate value by 20%, 40%, and 75%, respectively. In comparison, in that order, PP fibers in contents of 0.1% and 0.2% caused a reduction of 15% and 25%. The authors reported higher slump loss when considering the samples with hybrid fibers in equal amounts. They attributed this finding to the larger specific surface area of the fibers relative to aggregates. In other words, the fibers need more cement paste to cover their surface, increasing the mixture's viscosity and reducing the concrete workability [18].

Yogesh et al. [52] investigated the workability characteristics of hybrid bamboo and steel FRC through a flow table test. The authors used SF of hooked end and bamboo fibers ranging from 3 to 5 mm. They varied their contents between 0%, 0.5%, 0.75%, and 1.0% (per volume of concrete) and reported a maximum workability reduction of 20.98% when they incorporated 1% bamboo fiber, followed by 1% SF. Overall, the authors mentioned that reducing the fiber content, especially bamboo fiber, consistently increased the concrete workability.

Matar and Assaad [53], in turn, studied the simultaneous effects of replacing natural aggregate with recycled concrete aggregate (RCA) and adding PPF on the self-consolidating concrete (SCC) workability. The authors made specimens containing 25%–100% RCA and 0.25%–1.75% PPF and reported 1.75% PF as the maximum feasible content for reference specimens—with natural coarse aggregate (NCA)—produced with water/cement (w/c) ratio of 0.50, and 0.5% PF for specimens containing 100% RCA aggregates made with w/c ratio of 0.38. The authors also indicated that PF incorporation required a higher amount of high-range water reducer (HRWR) to improve the cement matrix dispersibility due to the need to counterbalance the formation of fiber clumps and the increase of internal friction due to RCA.

Therefore, workability plays a crucial role in ensuring the practical application of the composite. The addition of fibers directly influences this characteristic, leading to the formation of a network structure and an increase in viscosity. Accordingly, careful consideration should be given to the volume and shape of the fibers used and the potential need for plasticizing additives. Failing to control these effects can significantly impact the composite's mechanical properties and durability.

4 Fiber-matrix interaction

The fiber contribution to the strength of the matrix starts when the concrete's cracking is initiated and can also improve the post-cracking behavior, with the load increase being the primary responsibility for the development and propagation of the cracks [54]. When cracks begin in FRC, the fibers act as a stress-relief bridge, bridging the cracked sections (Fig. 3), distributing the excessive stresses to the matrix, and reducing the stress at the crack propagation front. The fracture

Table 2 Effects of steel fiber (SF) content and shape on the flowability measured by the spread of fresh ultra-high performance fiber-reinforced concrete (UHP-FRC) mixtures [51]

SF shape	UHP-FRC flowability (mm)*			
	0% SF	1% SF	2% SF	3% SF
Straight	215	182	160	132
Deformed	215	175	148	117
Hooked	215	171	140	105

*The approximate values were extracted from the graph presented by Wu et al. [51] and are reported here in table form

process can lead to fiber slippage if these stresses exceed the fiber-matrix bond strength. If the stresses exceed the fiber tensile strength, it can lead to fiber breakage. In this case, as a progressive crack approaches a fiber, bond breakage is triggered at the fiber-matrix interface due to the tensile stresses occurring in the region in front of the crack [54–56].

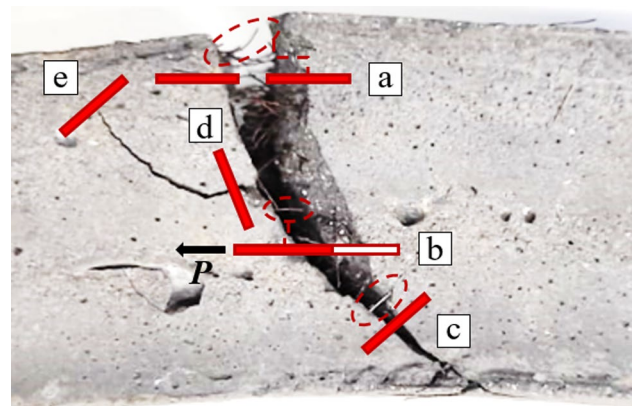
Figure 4 illustrates the different failure modes of FRC as follows: (a) the fiber reaches its tensile strength limit and breaks; (b) the bond between the cementitious matrix and the fiber is lost, causing the fiber to be pulled out; (c) the fiber bridges the crack and reduces the stress intensity at the crack tip. Additionally, the fiber bridging can decrease crack width, which may prevent the entrance of water and contaminants into the concrete matrix, thereby protecting the reinforcement steel from corrosion and mitigating concrete degradation; (d) fiber/matrix debonding occurs, which helps absorb and dissipate energy, stabilizing crack propagation within the concrete; (e) the fiber prevents the propagation of a crack tip. In addition to these mechanisms, small cracks are distributed throughout the matrix. As Yin et al. [36] reported, while each fiber contributes only marginally, the overall reinforcing effect is cumulative. Therefore, fibers can effectively control crack growth, maintaining the integrity of the concrete and transforming its behavior from inherently brittle and fragile to a tougher material with greater crack resistance and improved pseudo-ductility. According to these authors, to achieve significant reinforcement, fibers must possess high tensile strength and a high Young's modulus [36].

It is worth mentioning the importance of the interface between the reinforcement and the matrix during the stress transfer between the phases for the composite's effective working. In addition to the aggregate and cement paste phases, cement-based materials own the ITZ, a thin layer around the aggregate with different chemical and mechanical properties region whose microstructure differs from those further away from the ITZ [57]. The particulate nature forms water-filled spaces around the fibers due to the inefficient packing of cement grains at this interface. Thus, the matrix is much more porous around the fiber [14]. Some authors even suggest studies on adding nanomaterials to FRC to reduce the paste phase's porosity around the fiber [58]. Therefore, if fibers are incorporated into concrete, they act as a separate phase surrounded by an ITZ with mechanical and microstructural properties different from those of the cementitious matrix. The ITZ properties, in turn, vary with the local w/c factor, confinement, and different boundary conditions [57].

Before any cracking has occurred in the matrix, during the initial stages of loading, the interaction between fiber and matrix is elastic. The stress developed at the interface is a shear stress required to distribute the external load between the fibers and the matrix. This elastic shear transfer is the primary mechanism to be considered to predict the pre-cracking tensile behavior of fiber-reinforced composites, and the elastic stress distribution along the fiber-matrix interface is not uniform. In FRC, the primary role fibers play is in the post-cracking zone, i.e., once any cracking occurs, the cracked matrix does not resist tensile loading; only the fibers do [59].

Thus, the FRC tensile strength can be quite variable due to its dependence on the strength of the fiber-matrix interfacial bond. Fiber pull-out is likely to occur at low loads with weak bonds. Thus, the fiber does not contribute much to resisting crack propagation. On the other hand, if the bond is strong enough, fiber disruption can occur before it fully contributes to post-cracking strength [36]. Two main types of bonding develop between the matrix and the fibers: the physicochemical, through adhesion and friction at the interface, and the mechanical, through the anchoring effect of the interconnected fibers. The ITZ properties and fiber surface predominantly determine the former. This bonding type is the first mechanism to be activated in the pull-out process and determines the pull-out strength of straight fibers. There is only the physicochemical bonding for perfectly straight fibers, i.e., without curvature or preformations. In contrast, for pre-deformed fibers, such as steel ones, the mechanical interlock arises from the geometric deformation in the fiber length [56].

Fig. 4 Scheme of failure mechanisms in fiber-reinforced concrete: (a) fiber rupture; (b) fiber pull-out; (c) fiber bridging; (d) fiber/matrix debonding; (e) fiber preventing cracking propagation



Considering the aforementioned mechanisms, it should be noted that the fiber efficiency in transferring the applied stress to the matrix depends on the continuity of the ITZ, which is generally the weakest phase of the composite due to its porous nature. The microstructure of the ITZ between fiber and matrix has a calcium hydroxide $\text{Ca}(\text{OH})_2$ layer that contributes to a less dense dispersion of cement particles around the fiber in the fresh state. Consequently, voids are partially filled with hydration products, decreasing the ITZ stiffness and strength compared to a matrix without fibers [60]. Abdallah et al. [56] indicate that reducing the w/c factor and using fillers, e.g., silica fume, can contribute to ITZ densification and increase its hardness. However, these are not entirely effective measures to improve interfacial bond strength.

In addition, microstructure and ITZ depend on the mixture composition and the added fibers. SF tends to exhibit a wall effect consisting of a surrounding cement paste phase, while PF does not. This occurrence is due to the physical trapping of water particles in contact with SF. Since SF cannot absorb water, physical and physicochemical forces may be the main reason for attracting non-chemically bound water. Such forces include electrostatic, magnetic, and Van der Waal forces. During hydration, water is consumed by a chemical reaction, forming calcium silicate hydrate (C–S–H) gels. On the other hand, synthetic fibers reduce the concrete's capillarity and block possible pathways for evaporation or loss of water to the atmosphere by retaining the water within the matrix. Unlike SF, synthetic ones have no magnetic or electrostatic forces that can resist capillary water transport due to the hydration of the neighboring cement particles, allowing them to hydrate thoroughly. This characteristic leads to a similar strength of a reference mixture due to water retention. For both fiber types, some interlock occurs with the surrounding mortar. However, the most pronounced interlock is observed between the concrete and SF. Although this interlock exists in both mixtures, SF's rough surface and surface angularity differ from synthetic ones [61].

Sun and Xu [60] investigated the mechanisms and consequent effects of PPF addition on the concrete's physical and mechanical properties with this perspective. The authors reported that PPF significantly altered the concrete's microstructure by reducing the crystallization and orientation of $\text{Ca}(\text{OH})_2$. Specifically, the PPF formed a network that restricted the growth of $\text{Ca}(\text{OH})_2$ and reduced microcracks in the aggregate-cement ITZ, condensing the concrete's microstructure. As a result, increased compressive strength, flexural strength, fatigue life, and improved dynamic performance were observed in the concrete samples, as well as reduced water penetration and abrasion mass loss. Barluenga [62], in turn, studied fiber-matrix interaction at early ages of concrete with short fibers. The authors considered different contents (600–1200 g/m³) and lengths (6, 12, and 18 mm) of alkali-resistant glass fiber (ARGF) and two different fiber coatings. According to their research, considering the contents studied, 900 g/m³ was the one that produced the maximum tensile stress in the perpendicular direction to the fiber. Furthermore, the authors indicated that the shorter the fiber length, the lower the stress, and that for some combinations (fiber content and fiber length), the reduction of the cracked area reached up to 95%, indicating that the inclusion of small contents of ARGF is an effective measure to control early age cracking.

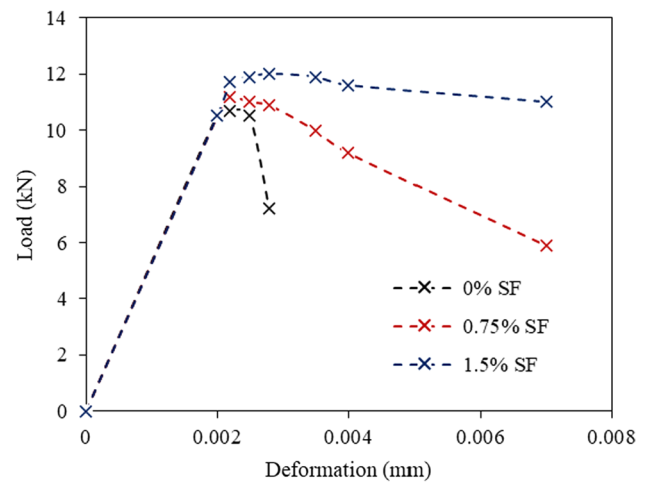
Hence, the fiber acts as a bridge to alleviate the applied stresses on the FRC, decreasing crack propagation. The interaction between the fiber and the matrix is closely tied to the failure mechanism of the composite. It is crucial to be particularly attentive to the ITZ, which represents the most porous region of the composite. The packing is less effective in this region, making it more susceptible to failures. Consequently, thoroughly analyzing the matrix composition and fiber properties is necessary to establish a competent interaction among the composite components, ultimately enhancing the mixture's properties.

5 Mechanical properties

5.1 Compressive strength and modulus of elasticity

In general, the fiber addition does not seem to significantly affect the concrete's compressive strength (f_c), which is usually excellent [26, 63]. However, ordinary concrete exhibits a rapid decrease in f_c in the post-peak loading region, which causes a brittle failure mode, a behavior that tends to accentuate the higher the f_c . In this sense, fiber addition is one strategy to improve the concrete's pseudo-ductility without sacrificing its compressive strength [64]. Sarzalejo et al. [65] incorporated SF in the volumetric content of up to 1.5% to concrete and reported accentuated pseudo-ductility and a modest increase in f_c , as illustrated in Fig. 5. From this figure, it can be noted that increasing the SF content led to increased strength for the same deformation levels. Hannawi et al. [66], in turn, investigated the effect of adding fibers of different natures (steel, mineral, and synthetic), dimensions (macroscopic or microscopic), and mechanical properties in cementitious composites. The authors mainly reported that longer fibers had more effect on concrete macro-cracks in the

Fig. 5 Load vs. deformation curves for compression tests in fiber-reinforced concrete with different steel fiber contents (approximate representation based on data from Sarzalejo et al. [65], created independently for illustrative purposes)



post-peak phase, that fibers with a greater aspect ratio (length/thickness) produced higher f_c , and that fibers with greater tensile strength and greater modulus of elasticity can significantly improve the concrete's mechanical performance.

Ding et al. [67] conducted a study on ECC reinforced with high-modulus polyethylene (HMPE-ECC) fibers and monitored the patterns of cracks occurring during mechanical testing. Cylindrical specimens measuring 100×200 mm (height $\times$ diameter) were used, and f_c between 43 and 115 MPa were obtained. The authors observed that as the external load increased, microcracks appeared and propagated in the matrix; however, the fiber bonding effect was activated, and lateral restriction was provided to the specimen as the cracks extended. In addition, the cracks were relatively small but numerous near the main crack. The authors reported a delay in the failure from brittle to ductile [67]. Corinaldesi et al. [68], in another approach, conducted experimental tests to evaluate the high-performance concrete's mechanical behavior at an early age (up to 28 days) by adding SF with anchoring at the ends—dosages of 1.5%, 1.75%, and 2.0% by volume—and calcium oxide-based expanding agent to the mix. As can be seen in Table 3, the authors verified that the different fiber dosages did not influence the f_c .

It should also be emphasized that there is a direct relationship between density and modulus of elasticity in homogeneous materials, a property that describes the initial elastic response of specimens under uniaxial compression. In heterogeneous multiphase materials, such as concrete, the density, the modulus of elasticity of the main constituents, and the characteristics of the ITZ determine the behavior of the composite's modulus of elasticity. In this sense, the studies on the FRC modulus of elasticity performed so far present controversial results since some researchers have reported gains and also losses in this property from the addition of SF [69]. In contrast, others reported negligible effects from SF and PF addition on compressive strength and modulus of elasticity in cementitious composites but cited an improvement in the behavior after fracture in the SF-reinforced composite [61].

Zhou et al. [40] experimentally studied ECC reinforced with recycled polyvinyl alcohol fibers (PVA-ECC) and found that PVA fibers make the mortar more ductile under uniaxial compression, and the failure mode changes from brittle fracture to ductile shear failure. The authors reported that the PVA-ECC modulus of elasticity increased with compressive strength and attributed the lack of aggregates to the fact that the PVA-ECC modulus of elasticity was lower than that of conventional concrete with similar f_c . Hassan et al. [70], in turn, experimentally studied the UHP-FRC compressive response at early ages (up to 28 days). The authors also reported that SF addition provided little influence on compressive strength

Table 3 Effects of steel fibers (SF) on the compressive strength of high-performance concrete at early ages [68]

SF content	Compressive strength (MPa)*				
	1 day	3 days	7 days	14 days	28 days
1.50% SF	58	72	95	102	116
1.75% SF	55	68	94	103	115
2.00% SF	53	70	92	103	115

*The approximate values were extracted from the graph presented by Corinaldesi et al. [68] and are reported here in table form

and modulus of elasticity, regardless of the age of the samples, corroborating the conclusions of the aforementioned works.

Several other studies involving the compressive strength of FRC are found in the literature. Prasad et al. [71] studied the influence of crimped SF, PPF, and basalt fibers (BF) on the compressive strength of geopolymer concrete (GPC). Among several conclusions, the authors reported that the optimum content of crimped SF, PPF, and BF for GPC to achieve 35–40 MPa compressive strength is 0.55%, 0.1%, and 0.3% by volume of cement, respectively. Besides, they found that the GPC with BF showed higher compressive strength than the samples with SF and PPF. Sharaky et al. [72] carried out an experimental study on the compressive strength of HSC with SF (0%, 0.25%, and 0.5%) and metakaolin (0%, 10%, 15%, 20%, 30%, 40%, and 50% as replacement of cement content). These authors reported increased compressive strength when the SF content increased from 0 to 0.5% and also when the metakaolin (MK) content increased from 0 to 15%, between 20 and 50%; however, the strength decreased. The maximum improvement occurred for a composition with 15% MK and 0.5% SF.

Therefore, the discussion surrounding the impact of fiber addition on composites' compressive strength and modulus of elasticity remains inconclusive, with no consensus among the scientific community. The variations observed can be attributed to differences in experimental conditions, such as the type of fiber used (e.g., steel, polypropylene, or recycled fibers), fiber dosages, matrix composition, specimen curing age, and testing methods. These factors can have distinct impacts on compressive strength and modulus of elasticity, contributing to the controversy in the literature. However, as previously discussed, fibers have demonstrated their potential to enhance post-peak behavior and induce a pseudo-ductile effect in FRCs, though substantial improvements in compressive strength are not observed. Similarly, findings concerning the modulus are conflicting. Given the complexity of fiber effects, more research is needed to clarify these aspects and provide more straightforward directions for using fibers in concrete.

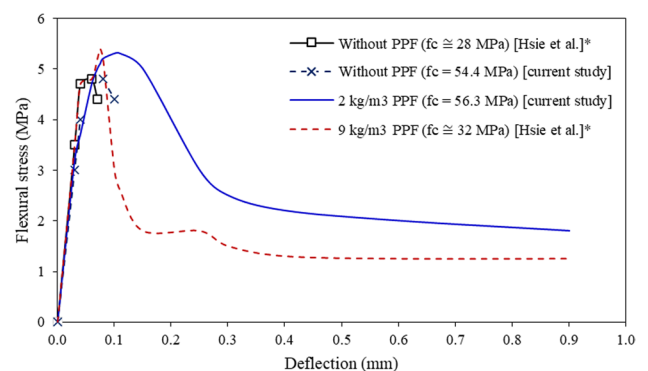
5.2 Flexural strength

As mentioned before, concrete has excellent compressive strength, making it quite convenient to meet the design requirements in the construction industry. However, these high levels are not observed in tensile strength (f_{ct}) [73], which usually has only approximately 10% of the compressive strength [74]. This property is directly related to the concrete's heterogeneous structure, which can present voids in the fresh or hardened state and generate internal stress concentration zones, favoring microcrack formation at the interface between aggregate and matrix. Moreover, external factors, such as structural loads and environmental effects, can cause cracks to grow in size and number. With this perspective, fiber inclusion in the matrix improves concrete's ductility and tensile and/or flexural strength [37].

In the case of FRC, the main benefit of fiber addition is the improvement of ductility in the post-cracking region and the concrete's flexural toughness [66]. When the first crack appears, the body usually fractures and collapses almost suddenly, with minimal deformation; however, failure can progress with bending but without sudden collapse. In other words, when concrete fails, the load is transmitted to the fibers, preventing crack propagation and delaying collapse [36].

Figure 6 presents load vs. deflection curves for PPF fiber-reinforced and plain concretes from preliminary tests conducted in this study and the literature. The literature data is from Hsie et al. [75], who tested the flexural strength of FRC through a three-point bending test on beams measuring 150 mm × 150 mm × 530 mm. The monofilament PPF fibers used had a diameter of 1 mm and a length of 60 mm. The concrete had an approximate f_c of 30 MPa at 28 days. The current study, in turn, used monofilament PPF fibers with a length of 12 mm and a diameter of 25 μ m. The same flexural test was

Fig. 6 Load vs. deflection curves of polypropylene (PP) fiber-reinforced concretes ('approximate representation based on data from Hsie et al. [75], derived from their curves and created independently for comparison purposes)



performed, but the beams measured 160 mm × 160 mm × 640 mm, and the concrete had an f_c of approximately 55 MPa at the same age—mix proportion: 1:1.4:1.4;0.35 (cement: natural sand: gneiss gravel: water) by weight, with a cement consumption of 569 kg/m³. Three specimens were tested for each sample, and the curves represent the average results.

As shown in Fig. 6, plain concrete exhibited brittle failure regardless of the study. The flexural strength reached its maximum at a deflection of approximately 0.05 mm, with no post-crack performance. In the study by Hsie et al. [75], adding 9 kg/m³ of PPF fibers slightly increased the maximum flexural strength to 5.5 MPa, occurring at the same deflection point as the plain concrete. However, after reaching the maximum flexural stress, the load was transferred to the PPF fibers, stabilizing at around 1.5 MPa. In the current study, plain concrete failed at a stress level similar to that reported by Hsie et al. [75] but with a deflection of approximately 0.08 mm. For the FRC with 2 kg/m³ of PPF fibers, the maximum stress reached 5.3 MPa at a deflection of 0.10 mm. Unlike plain concrete, this fiber-reinforced beam exhibited higher post-peak residual strength, stabilizing at around 2.0 MPa after deflection of 0.40 mm, likely due to its higher f_c .

It is worth noting that both fiber-reinforced concretes exhibited flexural strength of similar magnitude despite one having double the f_c of the other. This result can be attributed to the higher dosage (9 kg/m³ vs. 2 kg/m³) and longer PPF fibers (60 mm vs. 12 mm) used by Hsie et al. [75]. In other words, even with a lower f_c , the greater fiber length and higher dosage effectively enhanced the bridge effect during tensile stress transfer. Additionally, the smaller beam dimensions used by these authors likely limited the allowable deflection, which may have further influenced the comparison, as shorter beams naturally exhibit lower deflections under similar loading conditions.

In this context, Said and Razak [22] stated that more significant deformations of ECCs can be achieved by improving the composite's microstructure, taking into account micromechanical characteristics, such as the mechanical interactions between the PF, the cementitious matrix, and the interfacial surface. For instance, this improvement can be done by producing concrete with fine silica sand with a maximum particle size of 200 µm and discrete PF with a diameter of less than 50 µm and in 2% content. On the other hand, although they can be manufactured with such a small diameter, SF would lead to excessive cost [22].

It is worth mentioning that the fragility of a composite is exposed when it is subjected to tension or bending because, in this situation, the cracks start to develop until its tensile strength is reached, leading to failure [76]. Adding fibers improves the composite's fracture toughness. However, it is still necessary to improve the strain hardening—the material's ability to resist loading even after reaching the yield strength—to achieve ductility since ductile concretes are inherently tough, but tough concretes are not necessarily ductile. Therefore, there is a difference between improving the concrete's fracture toughness and imparting tensile ductility [12]. To obtain strain-hardening behavior, the post-cracking strength—determined by the fiber bonding capacity—must be greater than the tensile strength—influenced mainly by the tensile strength of the matrix [77, 78].

In this scenario, Deb et al. [79] investigated the improvement of the concrete's pseudo-ductility by incorporating two different types of commercially available PPF: fibrillated and monofilament fibers. The authors found that the fibrillated ones improved the mixture's tensile strength and flexural capacity but led to less significant gains in ductility than the monofilament ones. On the other hand, the combination of the two fiber types improved the sample's tensile strength and ductility.

Lee et al. [80] investigated the effect of high-strength PPF – in contents between 0.25 and 1%—on the flexural strength of concretes with compressive strength equal to 30, 40, and 60 MPa. According to the authors, the fibers act before fracture, helping to resist external loads and significantly preventing the growth of tensile cracks in the concrete. This flexural strength after cracking is called residual strength. The authors reported, among other conclusions, that the concrete with greater f_c showed lower flexural strength than the others, considering 0.25% of fibers, and greater flexural strength when the fiber content was equal to or higher than 0.5%. These results, obtained for f_{ck} of 30 MPa, are similar to those reported by Hsie et al. [75] for FRC with the same strength class.

In addition to the aforementioned work, some FRC research has used not-so-conventional fibers. Solanke et al. [81] conducted an experimental study to evaluate the flexural strength of concrete with sugarcane bagasse ash (SCBA) and SF. The authors made mixtures varying the replacement content of cement by SCBA between 5%, 10%, 15%, and 20%, and the addition of SF between 0.5%, 1%, and 1.5% by volume. It was evidenced that using SF concomitant with SCBA dramatically improved concrete's tensile and flexural strength. Specifically, the authors mentioned that the mixtures that led to the best results of these properties were those with higher SF content and 10% SCBA. They also highlighted that SCBA use in concrete is an eco-friendly alternative since it helps conserve the environment by reducing solid waste. Kavi priya et al. [82], in turn, used sisal fibers in lightweight geopolymer concrete to measure its flexural strength. The authors used mixtures with the replacement of bamboo aggregates by coarse aggregates (10%, 20%, and 30% replacement) and

added sisal fibers at levels of 0.25%, 0.5%, 0.75%, and 1.0% by volume of concrete. In summary, the authors concluded that replacing up to 30% does not affect the concrete's strength, but adding fibers at levels up to 0.75% does.

Thus, it is understood that the presence of a heterogeneous structure and the influence of external factors contribute to the low tensile strength of concrete. Consequently, adding fibers becomes crucial to enhance FRC's ductility and tensile and/or flexural strength. These beneficial effects are associated with the retardation of crack propagation, thus preventing the sudden collapse of the composite material. To achieve higher levels of deformation prior to rupture, it is essential to focus on improving the microstructure of the composite. In conclusion, increasing the toughness and promoting enhanced strain-hardening in FRC is necessary, resulting in post-cracking strength that surpasses its tensile strength.

5.3 Impact strength

Concrete elements are subjected to impact loads in many applications, including piles, hydraulic structures, airfield floors, protective shelters, industrial floor coverings, and marine structures. Impact strength represents concrete's ability to withstand repeated blows and absorb energy. As it is a brittle material, it has a relatively low energy absorption capacity under repeated impact loads, which severely limits its use under high strain rate loads due to the possibility of crack formation and growth. In this sense, the fiber addition to concrete can effectively prevent these cracks, raising its impact resistance under these load types [83].

Obtaining rapid and precise methodologies to determine the impact behavior of FRC is considered an important research focus in materials science between 2020 and 2030, as stated by the United States National Academy of Sciences [84]. Studies using reinforcements explicitly focusing on increasing the energy absorption capacity under impact have been carried out. SF, PF, and carbon fibers are increasingly employed in concrete, but there is a numerical superiority in the research using SF and PPF. Flexible fibers, such as PF, can improve concrete's crack and impact strength due to their high ductility [85]. Research on high modulus polyethylene (HMPE) and polyester (PES) FRC, on the other hand, is even more incipient. Despite this, studies on the concrete's impact response are at an early stage compared to quasi-static loading investigations [86].

In this context, Lu et al. [87] researched the impact resistance in PVA-ECC and ECC reinforced with recycled polyethylene terephthalate fibers (PET-ECC). They evaluated the impact energy absorption capacity using the modified Charpy impact test, in which the notch was removed due to the cementitious composites' low impact strength and relatively brittle nature. The authors reported that PET-ECC dissipated a similar amount of energy as PVA-ECC. The proposed model showed that stronger adhesion strength between fiber and matrix does not always lead to higher energy absorption under impact loading, which is consistent with the test result.

Considering HSC, it should be noted that due to its increased compressive strength, concrete becomes brittle and relatively less ductile, with potentially more catastrophic failures. However, the HSC brittle behavior can be overcome by adding SF to its mixture. They reinforce and compensate for such brittleness by sewing the microcracks and assuming the subsequent tensile strains act on the concrete. Thus, among other objectives, adding fibers to a concrete matrix increases the energy absorption capacity of hardened concrete, making it more suitable for use in structures subjected to impact and seismic loads. In HSC, therefore, this reinforcement seems to be an efficient process, giving the hardened material a relatively better ductility [41]. With this, it is expected that the insertion of high-strength PF into the cementitious matrix will lead to the same effects. Besides the type of fiber, various factors contribute to the energy absorption potential of FRC, including fiber orientation, hybridization, and composite thickness [88–90].

In this sense, several kinds of research in the current literature have addressed impact strength. Mohammed and Karim [91] studied it in HSC containing polyethylene terephthalate (PET) waste fiber with different lengths (10, 20, and 40 mm) and contents (0.50%, 0.75%, 1.00%, 1.25%, and 1.50% by volume). The authors reported impressive results regarding impact strength, with improvements of up to 300% in first crack impact and up to 833% in ultimate load impact when the longer length and higher fiber content were employed. Poongodi and Murthi [92], in turn, studied the impact strength enhancement of banana fiber-reinforced lightweight self-compacting concrete (LWSCC). The authors used contents of 0.25–1.50% by volume of concrete and reported gains of up to 23% in the impact strength of LWSCC to the reference samples (without fibers) when using the content of 1.25%, the best result obtained. Among other parameters, Bhogayata and Arora [93] evaluated the impact strength of concrete reinforced with metalized plastic waste (MPW) fiber lengths between 5 and 20 mm and contents between 0 and 2%. The authors reported an excellent improvement in the impact strength of the concrete with 2% MPW fibers 20 mm longer than conventional concrete. They attributed this betterment to the increased crack resistance and stress distribution among the hardened concrete constituents.

Therefore, impact resistance is vital in various concrete applications within civil construction. It is well-established that incorporating fibers improves the concrete's ability to absorb impact, mainly due to its inherently brittle nature. Among the commonly used fiber types, steel and polypropylene fibers are prevalent. In the case of HSC, the increase in compressive strength can potentially reduce ductility, resulting in a heightened susceptibility to critical failures during impact events. However, adding steel fibers enhances the energy absorption capacity, and a similar effect is expected when incorporating high-strength polymeric fibers.

5.4 Flexural toughness

The concept of toughness is associated with the work dissipated by a material up to a certain deflection level, specifically for composites; it can be understood as the energy absorbed by that material due to the loadings before and after cracking. Simply put, it is the ability to deform before rupture [94].

According to Kang and Kim [59], the most important advantage of adopting FRC is the increase in tensile strength and toughness, the latter due to the strain-hardening behavior after the first crack. Wang et al. [95] studied the effects of SF at 1.5%, 2.0%, 2.5%, and 3.0% on the flexural strength of ultra-high performance concrete with coarse aggregate (CA-UHPC). The authors reported that the 1.5% and 2.0% contents showed the best flexural toughness results. Zeyad [96] investigated the influence of different fibers – hook-end steel, mild steel, carved steel, basalt rock, and polypropylene fiber – on the flexural toughness of self-compacting concrete, keeping the content of 0.25% of the concrete volume fixed. The author observed that the concrete with fibers had better strength than those without fibers and that the fiber type greatly affected the flexural toughness. According to the author, adding hook-end and carved-steel fibers led to the highest toughness values, indicating their greater propensity to energy absorption.

From another perspective, Mezzal et al. [97] studied the effect of using discarded hybrid steel fibers (DSF) on the flexural toughness of high-strength self-compacting concrete (HSCC) exposed to elevated temperatures (300 °C, 500 °C, and 700 °C). The authors noted an expressive increase (1300%) in the toughness of the HSCC samples with DSF. They added that after 2 h of exposure to the samples at 700 °C, the HSC became more brittle, lost strength, and showed fine cracks on its surface. On the other hand, Jang and Yun [98] investigated the combined effect of SF and coarse aggregate size on the flexural toughness of HSC (60 MPa). The authors made specimens with different aggregate sizes and SF contents ranging from 0.5%, 1.0%, 1.5%, and 2.0% by volume. In general, the authors concluded that the mechanical properties of HSC with SF are more related to fiber content than aggregate size, and flexural toughness increased significantly with increasing fiber content.

Still, Sadrinejad et al. [18] studied the properties of concrete reinforced with polyolefin fibers and PPF and reported that only specimens with polyolefin fibers significantly increased toughness. In comparison, Halvaei et al. [38] incorporated nylon and PPF and found an improvement in flexural toughness. These studies show that the results obtained are still controversial and point to the need for further investigations.

Hence, the significance of incorporating fibers to improve the toughness of composites and enhance tensile strength is well recognized. The effectiveness of the addition is contingent upon fiber characteristics, volume, and interaction with the matrix rather than the aggregate size. Care should be taken when adding DSF exposed to high temperatures, as the material may become more brittle. Moreover, further studies are required to analyze the toughness of composites with the inclusion of PPF, nylon, and polyolefin fibers.

6 Thermo-mechanical behavior

The thermal conductivity (λ) of a material is the property that determines the heat flow by conduction that passes through it in a unit of time, through a unit of thickness, and a unit area of the material due to a temperature gradient between different points in it. It is directly associated with density, the solid matter being more conductive than the air in its pores, its chemical nature, amorphous materials being generally less conductive than crystalline materials, and the material's moisture content. Thermal conductivity also varies with temperature, and thermal energy in materials increases as temperature increases [99, 100].

In concrete, specifically, thermal conductivity is greatly affected by the mix proportion, types, and sources of aggregates, as well as the dry state's moisture content and unit weight. Among these parameters, the most influential on the concrete's thermal conductivity are the aggregates' volume fraction and the moisture condition of the sample. The age

factor, in turn, hardly affects this property except at a very early age, i.e., around two days. In the case of mortars and pastes, thermal conductivity is more affected by the additive type and amount of cement [101–104].

In this context, it is known that the thermal conductivity of a building material is an essential criterion to ensure the thermal comfort of the occupants because a building material with low λ provides a slower heat transfer, preventing a rapid temperature accumulation inside the building. Considering the application directed to non-structural building material, studies indicate that the PPF incorporation and acrylic PF with additions greater than 0.3% by volume provide a reduction in thermal conductivity. In addition, the building material needs to exhibit a certain resistance to high temperatures, which can occur in the event of a fire. This occurrence could potentially be life-saving, as the high-temperature resistance would delay the collapse of the structure due to fire, which allows occupants sufficient time for escape [23]. With a similar perspective, Manco et al. [105] affirm that adding carbon fibers to concrete enhances the structures' resistance and reduces deflections when exposed to high temperatures, potentially delaying collapse during fires.

According to Fraternali et al. [106], the reduced thermal conductivity of recycled fiber-reinforced concrete (RFRC), compared to ordinary concrete, allows the production of structural components capable of reducing the environmental impact and improving the energy performance of buildings. These authors performed an experimental study of thermal conductivity. They examined the influence of adding to concrete industrially extruded polyethylene terephthalate macro fibers from recycled PET bottle flakes with different properties and mechanical profiles. They employed a volumetric dosage of 1% fiber and observed marked improvements in thermal resistance, with an 18% reduction in RFRC thermal conductivity compared to concrete without reinforcement. Wang et al. [107], in turn, investigated the effect of high temperatures (400–1000 °C) on the thermal conductivity of glass fiber concrete. The authors used fibers with two lengths, 0.60 cm, and 2.54 cm, and in contents of 0.5%, 1.0%, and 1.5% cement by weight. The authors reported that using GF led to concrete with a lower thermal conductivity than the reference one, and the greater the length and fiber content, the greater such reduction was. In addition, it was noted that the 400–500 °C range led to the largest decreases in thermal conductivity. Finally, it is worth highlighting that thermal stresses are one of the main factors leading to localized plastic flow, which can result in premature structural failure. Therefore, studying thermally induced deformations and stresses in composites is truly important to understand the limitations of the structure [108].

Hence, thermal conductivity is closely tied to the material's density, chemical composition, and moisture content, escalating as the temperature rises. In concrete, its components' mixture composition and moisture levels exert the most significant influence on thermal conductivity fluctuations. As for mortars, the impact originates from additives and the quantity of cement used. Studies have already demonstrated the capability of incorporating polypropylene and polymeric fibers to decrease conductivity, as evidenced in RFRCs. Consequently, the inclusion of these fibers and the utilization of RFRC to enhance thermal comfort in buildings showcase the immense potential for applications in civil construction.

7 Main remarks

This paper comprehensively reviews fiber-reinforced cementitious composites, focusing on workability, fiber-matrix interaction, mechanical properties, and thermomechanical behavior. The following remarks can be drawn:

- i. The workability of the composite is significantly influenced by the addition of fibers, which create a network structure and increase viscosity. Proper consideration of fiber volume, shape, and the potential need for plasticizing additives is crucial to maintaining desired mechanical properties and durability.
- ii. Fibers act as bridges to reduce applied stresses and crack propagation in fiber-reinforced composites. The interaction between fibers and the matrix, particularly in the ITZ, is crucial for overall composite performance. A thorough analysis of matrix composition and fiber properties is necessary to establish a competent interaction and enhance mixture properties.
- iii. The impact of fiber addition on compressive strength and modulus of elasticity in composites remains inconclusive, with varying findings among researchers. However, fibers have shown potential in enhancing post-peak behavior and inducing pseudo-ductile effects in fiber-reinforced composites, while improvements in compressive strength are not consistently observed.
- iv. Fibers are essential for enhancing fiber-reinforced concrete's tensile strength, ductility, and flexural strength. By retarding crack propagation and improving the microstructure, fibers promote higher deformation prior to rupture, increasing toughness and post-cracking strength.

- v. Incorporating fibers in concrete significantly improves its impact resistance, making it more capable of absorbing energy. Steel and polypropylene fibers are commonly used for this purpose, with steel fibers enhancing energy absorption capacity and high-strength polymeric fibers expected to have a similar effect.
- vi. Adding fibers is crucial for improving composites' toughness and tensile strength. Fiber characteristics, volume, and interaction with the matrix play a more significant role than aggregate size. Care should be taken when using fibers exposed to high temperatures, as they may become more brittle. Further research is needed on the toughness of composites with different types of fibers.
- vii. Thermal conductivity in concrete and mortars is influenced by mixture composition, moisture levels, additives, and the amount of cement used. Incorporating polypropylene and polymeric fibers, as demonstrated in reinforced fiber composites (RFRCs), can decrease thermal conductivity, which opens up potential applications in civil construction to enhance thermal comfort in buildings.

8 Scope for future research

Based on the main remarks of this research, the following topics are suggested for further research:

- i. The influence of fiber volume, shape, and different types of plasticizing additives on the workability and mechanical properties of fiber-reinforced composites.
- ii. The role of the ITZ and the interaction between fibers and the matrix to optimize composite performance and enhance mixture properties while encouraging future studies to integrate advanced microscopic testing techniques, such as scanning electron microscopy or nanoindentation, for deeper insights.
- iii. The impact of fiber addition on compressive strength and modulus of elasticity in composites, aiming to establish consistent findings and identify factors contributing to the observed variations.
- iv. Further investigating how fibers enhance post-peak behavior and induce pseudo-ductile effects in fiber-reinforced composites, focusing on understanding the relationship between fiber characteristics and these improvements.
- v. The performance of different types of fibers (beyond steel and polypropylene) in improving the impact resistance of concrete, exploring their energy absorption capacity and potential applications in various civil construction scenarios.
- vi. The effect of fiber characteristics, volume, and matrix interaction on composites' toughness and tensile strength, including studying the behavior of different fiber types under high-temperature conditions to enhance their durability.
- vii. The impact of incorporating various fiber types, such as PPF, nylon, and polyolefin fibers, on the thermal conductivity of concrete and mortars, focusing on developing more energy-efficient and comfortable building materials for thermal insulation purposes.
- viii. The transport properties and durability of fiber-reinforced composites under aggressive conditions, such as freeze–thaw cycles and high humidity, to assess their long-term performance in real-world applications.

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Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

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