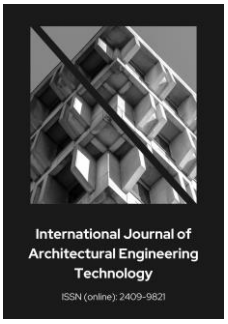
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Fiber Types, Properties, and Vibration Effects in Fiber-Reinforced and Ultra-High Performance Concrete: A Review

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ABSTRACT

This paper presents an overview of the different types, geometries and important characteristics of fibers that have been used or proposed for use in fiber-reinforced concrete (FRC) and ultra-high performance concrete (UHPC). The effects of these fibers on the mechanical properties, durability and workability of FRC and UHPC are then outlined. While the addition of the proper amount of fibers has the beneficial effect of enhancing the material properties and durability of concrete, challenges such as cost, need for more stringent quality control, issues with mixability and workability, and the use of proper vibration during the mixing and pouring phases need to be addressed. Insufficient vibration can lead to voids, reduce fiber dispersion, and weaken the concrete. Conversely, excessive vibration can cause segregation and fiber misalignment, thereby compromising the structural integrity of the final product. Based on a critical review of existing literature, four areas of further research have been identified. They are: (1) determining the optimal dosage of fibers given their types, geometries and intended applications, (2) identifying the most efficient method to enhance mix workability for a given fiber type, geometry, and volume fraction, (3) correlating vibration parameters such as vibration time, frequency and amplitude with the mechanical properties of FRC and UHPC, (4) incorporating other advanced technologies such as artificial intelligence and multiscale modeling techniques to gain a better understanding of how fiber alignment, distribution, pore structure, and interfacial interaction between fibers and matrix affect the mechanical performance, ductility and durability of FRC and UHPC.

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1. Introduction

Concrete is a widely used construction material worldwide. While it is strong in compression, it has relatively low tensile strength and tends to fail in a brittle manner. As a result, reinforcements in the form of reinforcing bars and fibers need to be used. Fiber-reinforced concrete (FRC) is a composite material comprised of a concrete matrix reinforced with discrete, randomly oriented fibers. These fibers, which can be made from steel, synthetic or natural materials, are introduced into the concrete mix during the mixing process. The fibers provide enhanced tensile strength, toughness, and crack resistance to the concrete, making it suitable for a much wider range of applications. FRC gained prominence through research conducted by Romualdi and Batson [1] and Romualdi and Mandel [2]. Afroughsabet *et al*. [3] and Isabai *et al*. [4] highlight FRC's benefits in improving mechanical properties (tensile strength, flexural strength and ductility), reducing shrinkage and creep, while also noting potential drawbacks like negatively impacting workability, electrical resistivity, and chloride penetration resistance. Despite these challenges, American Concrete Institute (ACI) 544.1R96 [5] affirms that FRC offers potential for enhancing overall concrete performance.

The primary purpose of adding fibers to concrete is to control cracking and shrinkage. This, in turn, significantly enhances the durability of concrete structures. Gouri *et al*. [6] and Hassan and Saeed [7] conducted a comprehensive review of fiber-reinforced concrete and concluded that it offers superior structural performance compared to traditional non-fiber reinforced concrete.

According to *fib* [8] incorporating fibers into concrete has a minimal impact on compressive strength, especially for fiber volumes up to 1%. However, as the fiber content increases, the concrete's post-cracking behavior becomes more ductile, exhibiting increased toughness. The most significant impact of fibers lies in enhancing the residual tensile strength after cracking, which is a crucial factor for designing structures using fiber-reinforced concrete.

A study by Grija *et al*. [9] has shown that tiny cracks, or early-age cracks, can form in fresh concrete within the first day due to internal stresses from settling and drying. Over time, continued drying can lead to larger cracks, compromising the concrete's structural integrity and limiting its overall performance. Fiber reinforcement improves the concrete mix's post-cracking behavior, leading to better strength, toughness. For instance, Mohod [10] studied steel FRC (SFRC) and reported the following observations:

1. Increasing the percentage of steel fibers reduces the workability of SFRC.
2. Increasing the steel fiber percentage increases the compressive and flexural strengths of SFRC. The optimum values of fiber content for compressive and flexural strength enhancements were determined to be about 1%. And 0.75%, respectively.
3. During testing, it was observed that plain cement concrete specimens showed a typical crack propagation pattern which led to splitting of the beam in two pieces. However, cracking did not progress after the addition of steel fibers in concrete, and displaying some ductile behavior.

In addition to steel fibers, other types of fibers (e.g., glass, synthetic, natural) have also been used [11, 12]. While they provide different attributes, their addition often enhances the performance of concrete.

In recent years, the use of fibers in ultra-high performance concrete (UHPC) has accelerated. UHPC is a special type of concrete that possesses compressive strength >120 MPa, sustained post-cracking tensile strength >5.2 MPa, and modulus of elasticity exceeding 50 MPa [13, 14]. It is made from mixing high early strength cement with water (at a very low water-to-cement ratio <0.25), fine to very fine well-graded aggregates, ultra-fine silica, metallic or synthetic discontinuous fibers, superplasticizers, anti-foaming agent and other additives, but without coarse aggregates [15]. Because UHPC has a discontinuous pore structure, it is more resistant to liquid ingress and freeze-thaw cycles. It is also less susceptible to scaling, and chloride attack. It is often used in high-rise buildings, long-span bridges, liners and infrastructures that require enhanced durability [16]. The presence of fibers in UHPC contributes to its strain hardening behavior, ductility, and toughness [17].

These and other studies have shown that the use of fibers in concrete can lead to:

- Improved Strength and Toughness: Concrete with fibers embedded in the matrix exhibits superior tensile strength compared to plain concrete. The fibers bridge cracks, preventing them from propagating and enhancing the overall toughness of the material. This translates to better impact resistance and a higher load-bearing capacity.
- Enhanced Durability: The presence of fibers improves the concrete's resistance to cracking caused by factors like shrinkage, freeze-thaw cycles, and chemical attacks. This leads to a longer lifespan and lower maintenance costs.
- Greater Design Flexibility: The ability of concrete with fibers to be molded into intricate shapes opens doors for innovative and visually striking architectural designs. Additionally, its lighter weight compared to traditional concrete allows for creative applications where weight reduction is crucial.
- Improved Crack Control: Fibers in concrete serve as micro-reinforcement and allow stress to be distributed more evenly throughout the concrete matrix. This significantly reduces the likelihood of shrinkage cracks, leading to a more aesthetically pleasing and structurally sound final product.
- Reduced Permeability: Improved crack control by fibers minimizes pathways for water and other substances to penetrate the concrete, enhancing its longevity.
- Minimized Bleeding: Fibers help reduce the separation of water from the concrete mix, leading to a more uniform structure.

Despite these advantages, some challenges associated with the use of FRC remain. They are:

- Higher Initial Cost: The inclusion of fibers adds to the material cost of FRC compared to plain concrete. This can be a significant factor, especially for large-scale projects.
- Special Handling Considerations: Mixing and placing may require some specialized techniques or equipment compared to conventional concrete. This can necessitate additional training for construction crews.
- Limited Fire Resistance: While research is still ongoing, concrete with fibers generally exhibits lower fire resistance compared to concrete reinforced with traditional steel rebar. This may limit its use in certain building applications with strict fire safety regulations.
- Importance of Quality Control: The effectiveness of fiber reinforced concrete heavily relies on proper mixing and fiber dispersion throughout the concrete matrix [18], ensuring consistent quality control measures are crucial for achieving optimal performance.
- Need for Standardization: Although some general guidelines are available [19-22], when compared to traditional reinforced concrete, design codes and standards for concrete reinforced with different fiber types are still evolving. This can create uncertainties for engineers and designers when incorporating this promising material into their projects.

2. Methodology

This review began with a thorough literature search on ResearchGate, Google Scholar, and Syracuse University (SU) Libraries to identify important studies and standards related to fiber reinforced and ultra-high performance concrete. ResearchGate has a scale that displays research interest score, number of citations, recommendations and reads which facilitates the determination of the relevance of the publications. Google Scholar allows for full text or metadata search of scholarly literature using keywords, authors' names and/or article titles, as well as provides information on citations and h-indices of authors. SU Libraries offers easy access to online databases such as ProQuest, Scopus and Web of Science for online views or hardcopy downloads of publications relevant to the current research.

Keywords used in the search included: fiber reinforced concrete, ultra-high performance concrete, fiber types, sampling methods, vibration time and consolidation of FRC and UHPC. The reviews, taking into considerations the degree of relevance, citation counts and publication year, were focused on assessing established guidelines, particularly those from American Society for Testing and Materials (ASTM) and European (EN) standards, to identify gaps in protocols tailored to FRC and UHPC. One major criterion used in the selection of relevant literature is whether the study contributes towards the standardization of FRC samplings and applications. Emphasis was also placed on the effect of vibration on sample preparation. The search prioritizes empirical evidence and research that directly examines the performance and behavior of FRC and UHPC under various conditions.

To gain a better understanding of the existing challenges in mixing, fiber distribution, and workability of FRC and UHPC, the selected references were reviewed in chronological order and a systematic, evidence-driven strategy to ensure relevancy and accuracy was used to identify old and recent publications that establish standardized practices for the preparation and usage of this type of construction materials.

Based on these reviews, some important information and observations on FRC and UHPC are summarized and presented in what follows.

3. Fiber Types and Characteristics

The way FRC behaves depends on the type and volume of fibers used in the mix [23]. The inclusion of fibers in concrete mix is not meant to replace the main reinforcement, but primarily enhances post cracking strength. For beams, they provide improved resistance to tensile and flexural stresses. Adding fibers to columns decreases the amount of extra reinforcement needed and enhances their ability to perform well under repeated loading cycles [24]. Nowadays, steel, carbon, glass, aramid and basalt are some of the most commonly used fibers in FRC. According to terminology adopted by Zollo [25] and the American Concrete Institute (ACI) Committee 544 [5, 20, 26], four groups of fibers used in FRC are identified. They are:

- Steel fibers: The most common type, offering good strength and crack control.
- Silica/Glass fibers: Often considered synthetic, glass fibers improve impact resistance and control shrinkage cracks.
- Synthetic fibers: Includes carbon fibers, offering high strength and reduced permeability.
- Natural fibers: Fibers like sisal or coconut are known for their sustainable and ability to improve crack control.

Table **1** summarizes some physical and mechanical properties of these fibers [27-30]. Steel fibers can come in different shapes and geometries (as discussed in the following section) while the other fibers are available only in straight profile. They all possess crack bridging capacity, especially for steel fibers with non-straight geometries which provide mechanical anchorage into cement matrix. Steel fibers also have good thermal resistance, but they do expand and contract with changes in temperature, and are prone to corrosion. Glass fibers do not corrode. They have good thermal resistance up to about 700°C - 900°C, but they are susceptible to alkali attack. As a result, glass fibers used in FRC are often treated with zirconium dioxide (zirconia) to prevent the fibers from degrading under a high-alkaline environment in concrete [31]. Synthetic fibers (e.g., carbon) possess high tensile strength, high elastic modulus and have low to near-zero coefficient of thermal expansion. They are also chemically inert and non-corrosive. Another aspect of carbon fibers that are considered desirable is that they possess electrical conductive properties and can therefore be used in structural health monitoring of smart concrete structures. Except for basalt, natural fibers have relatively low mechanical properties. They are hydrophilic and are susceptible to chemical attacks. Compared to the other fibers, natural fibers have the advantages of providing a sustainable, environmental-friendly and cost-effective alternative to reinforcing the cement matrix in FRC.

Although glass fibers can be considered as a type of synthetic fibers [11], their historical significance, distinct properties, established practices, and industry recognition makes it more appropriate for them to be classified as a distinct group.

Table 1: Physical and mechanical properties of the four major fiber groups.

Fiber Group	Length (mm)	Aspect Ratio	Density (kg/m^3)	Tensile Strength (MPa)	Elastic Modulus (GPa)	Common Dosage (% by volume)
Steel	7 - 75	20 - 100	7850	1000 - 1200	200 - 210	0.3 – 2.5
Silica/Glass	6 - 20	400 – 1000	2500 – 2680	1000 - 3400	29 – 85	1 - 2
Synthetic/Carbon	5 - 12	1000 - 1200	1600 – 2200	3000 - 7000	200 - 900	0.1 - 1.5
Natural	10 - 75	30 - 75	700 -1650	200 - 1000	5 - 130	0.3 - 3

In addition, hybrid (mixing of two or more of the above) fibers and nanofibers (tiny fibrils measured in nanometer to micrometer scale) can also be used. Over the years, new materials and fabrication methods have been used to produce these fibers. Some important characteristics as well as advantages and disadvantages of using these fibers in FRC and UHPC will be discussed in the following sections.

3.1. Steel Fibers

Steel fibers are one of the first fiber types for use in FRC [32, 33]. Steel fibers used today come in different shapes and forms as summarized in Table **2**. Steel fibers that have nonuniform or non-straight geometries are very effective in bridging cracks since they provide good anchorage in addition to bond strength between the fibers and cement matrix. According to Wadekar and Pandit [34], the efficiency of the bond between the steel fibers and the matrix in the tensile zone of fiber reinforced concrete beams can vary from 1.0 to 2.2. It should be noted that the use of straight, smooth fibers had become obsolete [35], with modern fibers featuring rough surfaces, hooked ends, crimps, or undulations to enhance performance through shape modification. According to *fib* [8], fibers with specialized shapes (like hooked ends, varying thicknesses, or wavy forms) demonstrate superior performance in resisting small cracks compared to straight fibers of the same length. These mechanically anchored fibers are particularly advantageous in lower strength concretes. Conversely, straight fibers tend to exhibit better performance in high-strength concretes with strong bond between the fiber and the surrounding matrix.

Incorporating steel fibers into concrete offers a significant improvement in its overall performance [11]. Studies by Jhatial *et al*. [36] indicate that using around 3% steel fibers by volume of cement can lead to a notable increase in both compressive and flexural strength. The addition of steel fibers also enhances other key properties such as: Toughness [37, 38], ductility and crack resistance [38], improved shear strength and impact resistance [39], impact resistance [11], durability and cold weather performance [32].

While steel fibers offer numerous benefits, there are some potential challenges to consider, which include: susceptibility to corrosion, reduce workability [39] and higher material cost when superplasticizers are used to increase workability of the mix.

3.2. Silica/Glass Fiber Group

Silica fibers are made from sodium silicate. Glass fibers are made from silica sand and other oxides such as aluminum, boron, calcium, iron and sodium. They both have high tensile strength, and are resistant to temperature and chemicals, but silica fibers are stronger and can withstand higher temperatures than glass fibers.

3.2.1. Silica Fibers (Fig. 2a)

While silica is a naturally occurring mineral, silica fibers are considered synthetic since they are produced by a manufacturing process by which silica is melted then drawn into fibers. The resulting strands are primarily composed of silicon dioxide. Silica fibers are commercially divided into chemical glass (C-glass), structural glass (S-glass), electrical glass (E-glass), and alkali-resistant glass (AR-glass) fibers [17]. In construction, S-glass fibers are used in the production of FRC and UHPC. In situations of high alkalinity, AR-glass fibers can be employed in the mix formulation to allow for more tolerance in high alkaline environment.

Table 2: Characteristics and usage of steel fibers.

Fiber Type	Characteristics	Notes on Usage
Cold-drawn wire fibers (Fig. **1a**)	These fibers have good strength and durability as well as enhanced flexibility and smooth and consistent surface finish. However, limited production rate and high die costs are considered disadvantages.	Cold drawing is a metalworking process that significantly enhances the mechanical properties of rolled steel wire, particularly for low-carbon steels. The most widely available cold-drawn wire fibers are Type I [35].
Cut sheet fibers (Fig. **1b**)	Manufactured by shearing steel sheets into smaller pieces [35], they can be produced with either a smooth or deformed surface finish. If the sheets are deformed before being cut, the deformation processes can alter the internal grain structure of the material, potentially affecting its ability to resist pulling forces (tensile strength).	Cut sheet fibers offer a valuable benefit for concrete slabs. Due to their unique shape, they act as a reinforcing system that helps address restrained shrinkage. Restrained shrinkage occurs when concrete slabs are prevented from freely contracting during the curing process, which can lead to cracking. Cut sheet fibers help mitigate this issue by distributing stress more evenly within the concrete.
Melt-extracted fibers (Fig. **1c**)	Good for withstanding thermal shock, extreme temperature changes, and mechanical impact. Workability is enhanced as a result of the full annealing process, making these fibers exceptionally pliable and manageable. The optimized aspect ratio also ensures better flow and easier separation during mixing.	These fibers are ideal refractory material widely used in fire clays, torpedo ladles, precast concrete, and concrete repair applications as they can potentially double the lifespan of refractory materials, and thus significantly reducing their replacement needs [35].
Flat end steel fibers (Fig. **1d**)	Also known as fishtail fibers, they are straight steel fibers with widened ends. The increased surface area at the end enhances their anchorage within concrete by providing improved grip beyond mere friction.	The fiber content is typically measured by volume fraction (VF), ranging from 0.1 to 3% in industry standards. They are particularly suited for shotcrete and used to bolster the structural integrity and crack resistance of precast components such as floors, tunnels, and buildings [8].
Hook tain/end steel fibers (Fig. **1e**)	Renowned for their exceptional tensile strength, they feature hooks at their extremities with a straight central section.	Employed in the construction of tunnels, dams, expressways, and towering structures like wind turbine supports [40].
Crimped steel fibers (Fig. **1f**)	Produced from low-carbon steel and exhibit a wavy, curved configuration. When incorporated into concrete, they help control temperature and shrinkage cracking, bolster flexural and shear strengths, and enhance toughness.	Flat crimped steel fibers are made from steel wires that are flattened and then crimped to create a specific shape. They are widely used in industrial floors, road pavements, highway construction, dams, bridges, and have recently gained traction in tunnel construction. Round crimped steel fibers are cylindrical in shape with a crimped profile, designed to optimize bonding with concrete and enhance overall performance.
Glued steel fibers (Fig. **1g**)	These fibers are constructed from high-quality, cold-drawn steel wire bundled together using a water-soluble adhesive. This unique configuration promotes exceptional dispersion within concrete, preventing clumping and ensuring uniform distribution.	They provide significant enhancements in tensile strength, flexural strength, abrasion resistance, impact resistance, fatigue resistance, toughness, and crack resistance to unreinforced concrete.
Twisted steel fibers (Fig. **1h**)	These fibers are helical in shape and thus offer superior anchorage, strength, and resistance due to their unique shape [17, 41, 42].	The helical twist creates a crucial feature on mechanical anchorage. As concrete cracks and fiber extraction begins, the twist unwinds, generating a wedging effect that surpasses the bonding capabilities of straight fibers [43].



(**a**) Cold-drawn steel fibers (**b**) Cut sheet steel fibers (**c**) Melt-extracted steel fibers

(**d**) Flat end steel fibers (**e**) Hook tain/end steel fibers (**f**) Crimped steel fibers

(**g**) Glued steel fibers (**h**) Twisted steel fibers

Figure 1: Various types of steel fibers.

Despite its numerous advantages, silica fibers face challenges such as nonlinear effects at high stress levels and the need for efficient fiber joining. As technology advances, silica fibers remain a vital component of future communications, industrial and civil infrastructures, driving innovation and progress.

3.2.2. Glass Fibers (Fig. 2b)

While technically synthetic, glass fibers are considered as a major group herein because of their historical significance and distinct material properties. The construction industry often recognizes Glass Fiber Reinforced Concrete (GFRC) as a distinct category due to its established applications and familiarity among engineers and contractors. The use of glass fibers actually began centuries ago [44] and their compositions and applications in the glass industry are described in ASTM C162 [45]. Glass fibers offer a different set of benefits compared to other synthetic fibers like carbon or aramid. For instance, they excel in impact resistance, shrinkage crack control, and aesthetics (sometimes used for architectural applications due to their finer profile). GFRC has a longer history of use compared to other synthetic fibers in concrete and is well known for its high compressive strength-to-weight ratio. It has high flexural strength (bending strength) and high tensile strength, plus load bearing quality. Also, because of its widespread use, specific standards and practices have been developed for GFRC.

Glass fibers enhance concrete performance in several aspects such as:

- Enhanced Tensile Strength and Reduced Steel Corrosion: Glass fibers increase the tensile strength of concrete, reducing the reliance on steel reinforcement [46]. This is particularly beneficial in marine environments and hydraulic structures, where steel is susceptible to corrosion.
- Improved Durability: Glass fibers enhance fatigue resistance, flexural strength, and crack behavior by reducing crack width [47]. Additionally, GFRC exhibits better impact strength and absorbs more energy compared to plain concrete [48].

- Temperature Resistance: While not significantly affecting compressive strength [49], glass fibers can improve fire safety. Studies using the finite element analysis software ANSYS have shown that a higher volume fraction of glass fibers leads to a slower rate of temperature increase within concrete at high temperatures. This can help protect steel rebars by lowering their core temperature during a fire event [50].
- Sustainable Benefits: The use of industrial glass waste as a fiber source not only enhances the flexural and tensile strengths of GFRC but also provides an efficient and sustainable method for waste disposal [51].

  Despite these advantages, glass fibers can be negatively impacted by the alkaline substances present in cement [52]. Research on glass fibers has demonstrated that alkali present in cement can attack and embrittle the fibers. To enhance their alkali resistance, glass fibers can be treated with zirconia to form Alkalin-Resistant (AR) glass fibers for use in FRC [31].



(**a**) Silica fibers (**b**) Glass fibers

Figure 2: Silica and glass fibers.

3.3. Synthetic Fiber Group

Synthetic fibers are engineered fibers produced from various chemicals, resulting in a range of unique properties. Common examples include carbon, nylon, polyester, acrylic, and polyurethane. These fibers offer several advantages. Bhaladhare *et al*. [32] indicated that, although synthetic fibers were not as strong as steel, they enhanced the pumpability of concrete by preventing it from clogging pipes. Additionally, they maintain stability in varying temperatures, reducing the risk of cracking. Synthetic fibers do not swell under heat or contract in the cold which helps to control cracking. However, some potential drawbacks of synthetic fibers are their environmental impact during production and their contribution to microplastics when they shed. In what follows, some commonly used synthetic fibers are briefly described.

3.3.1. Carbon Fibers (Fig. 3a)

Carbon fibers, when incorporated, create a material known as spatial micro-fiber reinforced concrete. This technology has proven effective in strengthening existing bridges. Carbon Fiber Reinforced Polymer (CFRP) concrete prevents premature debonding of CFRP composites from the concrete surface and demonstrates fatigue resistance [11, 53]. In addition, crack bridging by these fibers enhances post-cracking ductility in concrete structures [54]. Studies have shown increased stiffness, ductility, and bearing capacity in reinforced concrete columns strengthened with CFRP [55].

While compressive strength remains largely unaffected, the inclusion of carbon fibers can double the flexural capacity when compared to normal concrete [56]. This makes CFRP a cost-effective solution for rehabilitating and strengthening deep reinforced concrete beams, which are susceptible to degradation from weathering and chemical attacks [57]. The bonded CFRP layer on pre-cracked beams effectively restrains the element, preventing the development of shear cracks at the ends [58].

CFRP boasts a low density, offering high resistance to segregation in the concrete mix. However, it can decrease the slump flow, a measure of workability [11, 59]. Additionally, CFRC performs best for enhancing flexural strength when used without an air-entraining agent, which introduces microscopic air bubbles to improve freeze-thaw

resistance. The observed increase in flexural toughness is attributed to the combined effects of improved strength and ductility [60].

3.3.2. Plastic Fibers (Fig. 3b)

Plastic fibers offer a promising approach to construction by acting as a reinforcing material. Studies by Baldenebro-Lopez *et al*. [61] indicate that replacing a portion of cement with waste plastic fibers (around 1.5%) can reduce construction costs. Additionally, Mistry and Rane [62] studied the effect of polyethylene terephthalate (PET) fibers on concrete compressive strength and found that a specific arrangement (continuous plastic fiber reinforcement) had a beneficial effect as it enhances the bond between the concrete mix and the fibers. In addition, PET fibers increase the concrete's tensile strength, promote a more ductile failure mode (resisting brittle cracks), and improve flexural behavior (bending resistance) as reported by [11, 61, 63, 64].

However, a crucial consideration is the effect of PET fibers on the flow properties of the concrete mix. Their inclusion can hinder flowability, potentially leading to spalling (flaking) during placement, as noted by Bheel *et al*. [65]. Also, they are non-biodegradable, heat sensitive and have low resistance to strong acids and alkalis. The use of too much plastic fiber may decrease the compressive strength of concrete. However, this effect can be countered by incorporating additives like silica fume and metakaolin, as demonstrated by Kandasamy and Murugesan [66].

A special type of plastic fibers is polypropylene fibers. Polypropylene fibers are lightweight, highly crystalline, and exhibit high stiffness [67]. They offer superior resistance to chemical and biological degradation. Concrete reinforced with polypropylene fibers is highly beneficial for use in public spaces like parks, roads, and beaches that are exposed to harsh environmental conditions, impact damage and surface abrasion [68].

3.3.3. Aramid Fibers (Fig. 3c)

Aramid fibers, known for their superior tensile strength, are made from long-chain synthetic polyamides, engineered by hand lay-up molding with the addition of gel and resin coatings, and topped with a reinforcement layer to a mold, adding layers as required, followed by curing, releasing, and trimming. They are lightweight and have super high strength, high modulus, high temperature, acid and alkali resistance, and possess other excellent properties such as high resistance to impact and damage, and can withstand wear and tear better than most other materials. The enhanced performance of aramid fibers (with modulus ~112,400 MPa and density ~1.44 g/cm^3) is attributed to their compact molecular structure, hydrogen-bonding, and high crystallinity [69]. Their strength is 2 to 3 times that of steel wires or glass fibers, and their toughness is comparable to that of steel wires. Their weight is only about 1/5 of the steel wire, and they do not decompose or melt at a temperature up to 560^{o}C. They have good insulation and anti-aging properties and have a long-life cycle. Aramids are used in advanced products where lightweight, yet high strength and enhanced impact resistance are needed, such as automobiles, aerospace and marine structures, ballistics, protective wear.

There are, however, a few cons that need to be considered. Because of their very complex manufacturing process, Aramid fibers are more expensive than most of its substitutes. Also, aramids are brittle and can crack under high impact or stress loads.



(**a**) Carbon fibers (**b**) Plastic fibers (**c**) Aramid fibers

Figure 3: Synthetic fibers.

3.4. Natural Fiber Group

Due to their lightweight, low cost and sustainability, natural fibers are promising reinforcements for use in concrete and are easily procured in many countries [70]. However, the use of natural fibers as structural components should be properly evaluated as they could affect concrete durability since they can decompose [32]. Some commonly available natural fibers are discussed herein.

3.4.1. Wheat Straw Fibers (Fig. 4a)

Straws were used to strengthen sunbaked bricks in ancient civilizations. In the United States, a pueblo dwelling constructed around 1540 utilized sun-backed adobe reinforced with straw [5]. Wheat straw fibers exhibit a "sewing effect" within the concrete, thus allow it to resist crack propagation and improve its overall energy absorption capacity [11]. Some advantageous aspects of wheat fibers are:

- Enhancing Pavement Performance: Studies by Anas *et al*. [11] have shown that Wheat Straw Reinforced Concrete (WSRC) offers significant advantages for pavements, particularly in terms of early-age behavior. WSRC pavements experience a notable reduction in the severity and number of shrinkage cracks compared to conventional concrete pavements [70]. While the addition of wheat straw reduces the workability (slump) of the concrete mix, it demonstrably improves flexural, tensile, and compressive strengths [71]. This translates to increased ductility and a more ductile failure mode, limiting crack width and enhancing post-cracking behavior. Furthermore, pavements constructed with at least 1% wheat straw content exhibit superior compressive behavior compared to plain concrete pavements [11, 70].
- Benefits to Environment and Economy: Utilizing wheat straw in concrete reduces the environmental hazard associated with crop burning [11, 72]. Additionally, wheat straw is a readily available and cost-effective alternative material, potentially leading to reduced construction costs.

3.4.2. Sugarcane Fibers (Fig. 4b)

Sugarcane fibers offer a two-fold benefit: they reduce the thermal conductivity of the concrete matrix, leading to lighter weight concrete [11], and sugarcane bagasse ash (SCBA) can be used as a partial replacement for ordinary Portland cement. Studies by Gebreyouhannes and Geremew [73] indicate that SCBA can enhance the flexural, compressive, and tensile strengths of concrete composites. This improvement comes with the added benefit of a slower setting time and reduced hydration temperature during the curing process. Furthermore, the composite exhibits good thermal stability, maintaining its properties up to a temperature of 450°C [74].

Research by Ghazali *et al*. [75] using electron beam radiation and scanning electron microscopy techniques suggests that incorporating around 6% sugarcane bagasse into concrete leads to a significant increase in the material's elastic modulus. This translates to improved overall mechanical behavior due to a reduction in voids within the concrete matrix.

3.4.3. Sisal Fibers (Fig. 4c)

Sisal fibers are extracted from leaves of sisal plants and have been shown to be a reliable material for structural applications with minimal health risks [76]. Concrete reinforced by sisal fibers performs well in compression, tension, and flexural strength tests [11], making them suitable for applications like drainage plates. A significant advantage is its cost-effectiveness, with a reported 1.85 times lower cost compared to ordinary steel reinforcement.

While adding sisal fibers can decrease the mix's workability, they also increase the stress required to initiate cracks [77]. This translates to improved overall strength compared to conventional concrete. Additionally, Rahuman and Yeshika [78] showed that a significant (>50%) increase in compressive strength of M20 and M25 grade concrete was observed with just a 1.5% addition of sisal fiber. Mbereyaho *et al*. [79] and Anas *et al*. [11] identified an optimal replacement percentage of cement with ground granulated blast furnace slag to be around 20%, potentially offering further benefits in the mix design.

3.4.4. Jute Fibers (Fig. 4d)

Jute fibers are collected from the phloem of plants such as hemp, linseed and ramie. They can be used to improve key properties of concrete beams and slabs [11]. While stiffness and ductility decrease slightly with increasing fiber content and thickness [80], Jute Fiber-Reinforced Concrete (JFRC) exhibits significant gains in toughness, ultimate flexural strength, and load-carrying capacity. Studies by Anas *et al*. [11] and Bharathi Murugan *et al*. [81] report a 12.92% increase in initial cracking load and a 6.94% increase in ultimate load for beams reinforced with natural jute fibers throughout the concrete.

The improvements in JFRC properties translate to enhanced resilience, making it a suitable material for structural slabs. Jute fibers contribute to this resilience by increasing flexural strength [82], enhancing initial crack energy and toughness [11], and promoting better bonding between concrete fibers and the matrix, as evidenced by improved bridging patterns [82]. Furthermore, the use of natural jute fibers offers economic and durability benefits for construction projects [83].

3.4.5. Bamboo Fibers (Fig. 4e)

Incorporating bamboo fibers can significantly increase both the compressive and split tensile strengths of concrete by 22% and 17%, respectively [11]. This improvement is attributed to the “bridging action” of the fibers, which effectively hinders crack propagation within the hardened concrete mix. In addition, when used in place of steel in slabs, bamboo fiber reinforcement achieved 82% and 93% of the strength and ductility, respectively [84]. These findings suggest that bamboo fibers have the potential to serve as a viable alternative to steel reinforcement in certain concrete applications. Nevertheless, additional research to study the mechanical properties of bamboo-reinforced concrete is needed to determine what the optimal mix design should be.

3.4.6. Basalt Fibers (Fig. 4f)

Basalt fibers are derived from volcanic rocks melted at high temperatures (1500-1700°C) [85]. They are durable and cost-effective reinforcements for concrete [17]**.** Basalt fibers have gained popularity in concrete reinforcement as they offer many advantages such as:

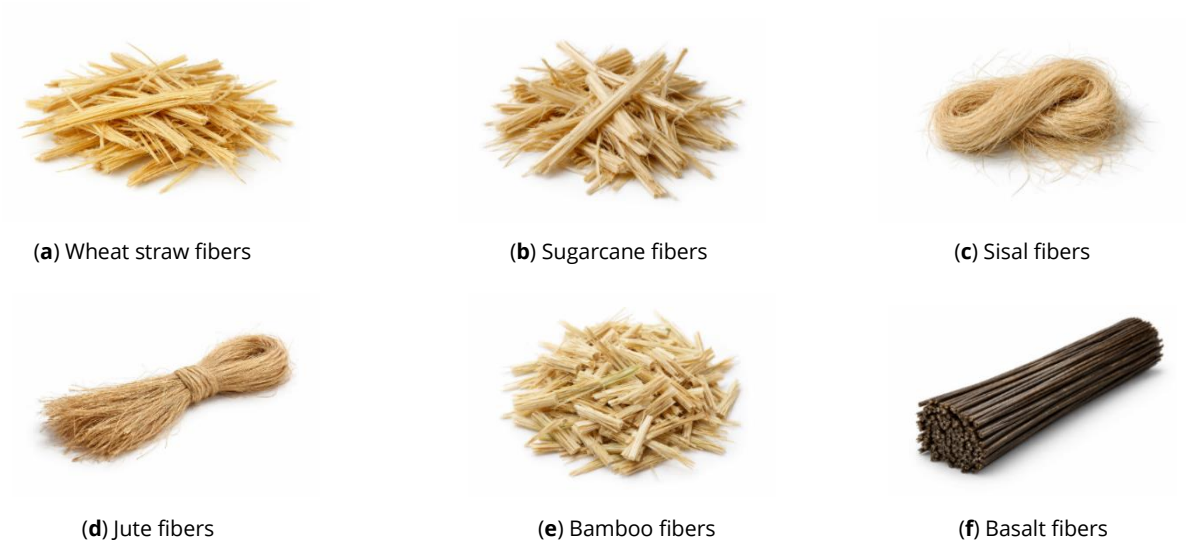
- Durability and Chemical Resistance: Basalt fibers exhibit excellent inert behavior, making them resistant to degradation from harsh environments like acidic regions [86].
- Exceptional Abrasion Resistance: Their high Mohs hardness between 8 and 9 [85] translates to superior resistance to wear and tear, making them ideal for high-traffic areas.
- Superior Thermal Performance: Concrete reinforced with basalt fibers performs well in extreme temperatures, ranging from -200°C to 700-800°C [87]. This makes them suitable for applications exposed to high heat or extreme cold.
- Sustainability: Basalt, a volcanic rock, is readily available and requires minimal processing for fiber production. They are non-toxic, recyclable, and require no harmful additives during manufacturing.
- Superior Mechanical Properties: Basalt fibers offer high strength and modulus, as well as excellent resistance to temperature (remaining functional from -269°C to 650°C), corrosion, and chemicals. Compared to glass fibers (like E-glass), basalt fibers exhibit superior performance in many areas, including breaking load, Young’s modulus, and environmental stability.
- Applications and Advantages: Their high strength, chemical stability, and corrosion resistance make them ideal for reinforcing concrete and structures in harsh environments, including marine applications. Additionally, basalt fibers have replaced asbestos in brake pads and other friction applications due to their superior flame and abrasion resistance.

Beyond their mechanical performance, basalt fibers offer other advantages that include:

- Cost-Effectiveness: Compared to high-performance options like carbon fibers, basalt fibers are significantly more cost-effective.

- Lightweight: Basalt fiber composites can be lighter than traditional materials like aluminum, offering benefits in applications like wind turbine blades, camera tripods, and snowboards.
- Acoustic Absorption: The automotive industry has found that basalt fiber-reinforced systems exhibit good acoustic absorption properties, adding another dimension to their utility.

Overall, basalt fibers offer a compelling combination of sustainability, excellent mechanical properties, versatility, and cost-effectiveness. They are considered sustainable and versatile for reinforcement [88]. As research and development continue, one can expect to see even wider adoption of basalt fibers across various industries. The challenge faced with basalt fibers is the difficulty they pose in cutting. Due to the inherent hardness and heat resistance of basalt, cutting the cured fibers can be challenging. This may require specialized tools or techniques during construction.



(**a**) Wheat straw fibers (**b**) Sugarcane fibers (**c**) Sisal fibers

(**d**) Jute fibers (**e**) Bamboo fibers (**f**) Basalt fibers

Figure 4: Natural fibers.

3.5. Hybrid Fibers

Hybrid fiber technology offers a powerful tool for concrete engineers. By strategically combining different fiber types, they can create concrete with tailored performance, enhanced crack resistance, improved toughness and ductility, and potential for cost reduction. Since each fiber type offers unique properties, combining them creates a synergistic effect [17, 89-91]. In particular, these combinations can improve the rheology, compressive strength, tensile strength, and durability of UHPC [92, 93]. Common fiber types used in hybrid combinations include:

- Steel fibers: They provide high tensile strength, crack bridging, and improved toughness.
- Polypropylene fibers: They enhance workability, reduce plastic shrinkage cracking, and improve impact resistance.
- Glass fibers: They contribute to crack control, improve flexural strength, and can offer some fire resistance benefits.

Some examples of the beneficial effects of hybrid fibers are:

- Flexural Toughness: Combining steel fibers, short-chopped fibers (Korta), and small hooked fibers (bar chips) enhances the UHPC's ability to absorb energy and resist bending without failure [94].
- Chloride Resistance: A hybrid combination of polypropylene fibers, carbon fibers, and glass fibers reduces the penetration of chloride ions, which can corrode steel reinforcement within the concrete [94].
- Fire Resistance: Combining nylon and polypropylene fibers improves the UHPC's performance in high-temperature environments [95].

- Bond Strength: Mixing macro and micro straight steel fibers increases the force required to pull the fibers out of the concrete matrix, leading to a stronger bond and improved performance [96].
- Energy Absorption and Strain Hardening: Combining steel fibers and polyethylene fibers enhances the UHPC's capacity to absorb energy and resist deformation under stress [97].

Researchers are continually exploring new hybrid fiber combinations to optimize UHPC for various applications.

3.6. Nanofibers

Nano fiber reinforced concrete (NFRC) is concrete reinforced by tiny fibers on the micrometers (μm) to nanometers (nm) scale. These fibers are usually added to the concrete mix in the range of 0.05% to 0.5% by weight. The three most commonly used fibers in NFRC are carbon nanofibers, carbon nanotubes, and cellulose nanofibrils.

Carbon nanofibers [98, 99] are cylindrical or cone shaped nanostructures (Figs. **5a** and **5b**), typically 50 to 500 nm in diameter and several microns (μm) long, arranged in stacked cup, plate, or platelet graphene layers. They provide excellent mechanical strength, electrical conductivity, and thermal properties. The use of carbon nanofibers in NFRC not only enhances the tensile strength and durability, but offers electrical conductivity potential of concrete [100, 101].

Carbon nanotubes are graphene (sheets of pure carbon atoms) rolled up into tiny, hollow cylinders. Carbon nanotubes can be single-walled or multi-walled (Figs. **5c** and **5d**). Single-walled carbon nanotubes are made from a single rolled sheet of carbon atoms with diameter and length in the range of 0.7 to 2 nm and 1 to 50 μm, respectively. Multi-walled carbon nanotubes are made from multiple nested or layered tubes inside one another with diameter and length in the range of 2 to 100 nm and 5 to 30 μm, respectively. The addition of carbon nanotubes allows dense internal nano fiber networks to be formed in the cement matrix, which results in a noticeable increase in strength and stiffness [102, 103].

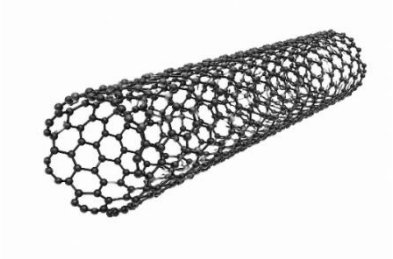
Cellulose nanofibrils are ultra-fine, naturally derived bio-based fibers with widths of 2 to 20 nm and lengths of 0.1 to several μm. There are three types: (1) nanofibrillated cellulose (NFC), (2) nanocrystalline cellulose (NCC), and (3) bacterial nanocellulose (BNC). The nanofibrils used in FRC are NFC and NCC (Figs. **5e** and **5f**). These fibrils are biodegradable and offer high mechanical strength and lightweight properties [104, 105]. Being derived from natural material, they are sustainable and offer a low-carbon option to improve the hydration and durability of concrete.

Nano FRC possesses higher compressive, flexural, and tensile strengths as well as toughness when compared to standard concrete. This is because the nanofibers bridge tiny fissures before they can coalesce into larger cracks. NFRC is also more durable due to its low internal porosity and thus more resistant to chemical attacks.

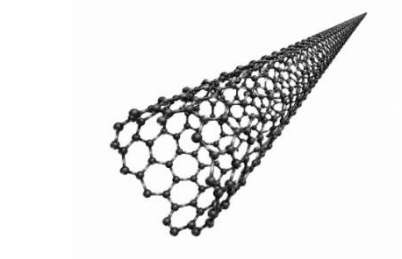
Some disadvantages of using nanofibers include high cost, difficulty in achieving a uniform mix, low workability, potential health hazards due to inhalation and respiratory risks, and complexity in mixing. To produce good quality NFRC, the use of special chemical dispersants and high-shear mixers to separate and spread the fibers evenly are often needed. Moreover, the wearing of protective gears as well as adherent to strict quality and safety control protocols are required.

4. Fiber Reinforced Concrete and Ultra-High Performance Concrete

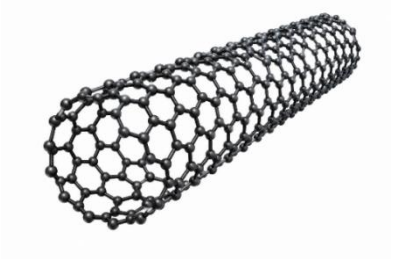
Reinforced concrete, one of most commonly used construction materials, is prone to surface cracking, particularly in areas where tensile forces dominate. These surface cracks allow water and other corrosive agents to reach the reinforcing steel, accelerating its corrosion and significantly compromising the long-term durability and performance of the structure. To address this issue, fibers can be incorporated into the concrete mix to arrest these cracks.



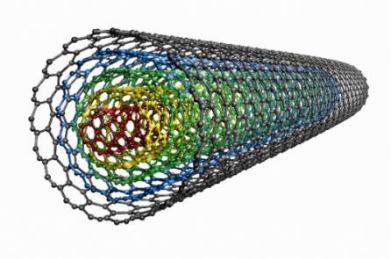
(**a**) Cylindrical-shaped carbon nanofiber



(**b**) Cone-shaped carbon nanofiber



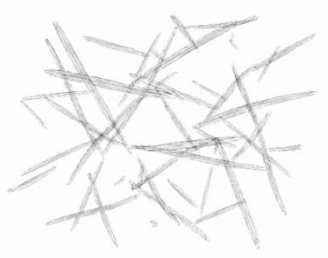
(**c**) Single-walled carbon nanotube



(**d**) Multi-walled carbon nanotube



(**e**) Nanofibrillated cellulose



(**f**) Nanocrystalline cellulose

Figure 5: Nanofibers.

Fiber-reinforced concrete (FRC) is a versatile material for use in modern construction due to its enhanced durability, crack resistance, and ability to withstand demanding environmental conditions. FRC addresses the limitations of traditional reinforced concrete, particularly in controlling crack propagation and improving post-cracking behavior [106]. Its cost-effectiveness, versatility, and proven performance in various demanding conditions have made it a material of choice by many engineers. Recent advances in FRC include exploring their potential for sustainability and eco-friendliness [107, 108].

Ultra-high performance concrete (UHPC) is a cementitious composite material made from mixing water with high early strength cement, fine/ultra fine aggregates, microsilica/silica fume, superplasticizers, other special additives and fibers. Because of its dense microstructure, UHPC has high compressive strength (>120 MPa), high stiffness (>50 MPa), high abrasion and chemical resistance and low permeability. UHPC is currently being used primarily in high-rise buildings, long span bridges, and liners for culverts and pipes, but research on expanding their use is ongoing [109, 110] including the use of 3-D printed UHPC in engineering practice [111].

Liu *et al*. [112] and Yoo *et al*. [113] provided reviews of the use of nanomaterials (ranged in size from 0.1 to 100 nm) in UHPC to enhance its mechanical properties and durability. Zaid *et al*. [114] conducted experimental and analytical study of UHPC modified with egg shell and nano-silica. They concluded that the use of 5% by weight of these ingredients significantly increased the effectiveness of double hooked end steel fibers in split tensile and flexural strengths of concrete.

To reduce cost and limit environmental impact, Farahzadi *et al*. [115] performed sustainability assessment of UHPC made with various volumes of ground granulated blast furnace (GGBF) slag and fly ash and concluded that incorporating up to 50% GGBF slag as supplementary cement material could significantly reduce the environmental impact of UHPC without compromising its mechanical and durability characteristics.

Below are some typical applications of FRC and UHPC across various sectors:

4.1. Civil Engineering and Infrastructure

- Roads and Highways: FRC and UHPC improve the longevity of pavements and road surfaces under repetitive loading conditions, thereby reducing maintenance needs.
- Bridges: The material provides superior crack control and high tensile and flexural strength, critical for load-bearing structures.
- Tunnels, Diversion Chambers, and Shafts: Enhances water resistance and durability in underground construction
- Water-Related Structures: The primary purpose of adding fibers is not only to increase the tensile capacity of the concrete but also to control crack propagation, which is especially critical in structures that either transport or retain water such as dams, reservoirs and pipes. Khayat and Roussel [116] and Khayat *et al*. [117] highlighted the importance of fibers in enhancing the post-cracking behavior of concrete, demonstrating their effectiveness in controlling crack development and extending the lifespan of structures exposed to such environmental stresses.

4.2. Buildings and Construction

- Foundations: Provides resistance to cracking due to ground movements.
- Slabs and Suspended Floors: Enhances load distribution and reduces the risk of cracking.
- Walls and Panels: Offers better tensile strength and durability for structural and partition walls.
- Precast Concrete Components: Improves production efficiency and structural performance.

4.3. Industrial Applications

- Factory Floors: Enhances durability and impact resistance in high-traffic areas.
- Containment Structures: Improves crack control and reduces risk in hazardous material storage.
- Pipeline and Tank Linings: Provides additional protection against leaks and corrosion.

4.4. Other Applications

- Shotcrete and Sprayed Concrete: Widely used in tunnel linings and slope stabilization for its quick application and crack resistance [118].
- Marine Structures: Offers resistance to chloride attack and corrosion in saline environments.
- Agricultural Structures: Improves the durability of silos, barns, and water retention systems.

5. Fiber Effects on FRC and UHPC

Over the years, various researchers have performed research on FRC and UHPC, some important research of fiber effects on concrete is presented below.

Effect of specimen size and the compressive strength of high-strength fiber-reinforced concrete (HSFRC): A comprehensive experimental study by Fladr and Bily [119] to investigate this effect with a 16 mm maximum aggregate size has shown that the size dependence of compressive strength decreases as concrete strength increases, with near-size independence observed for materials exceeding 130 MPa. However, flexural strength tests on two HSFRC mixes with different sized prismatic specimens revealed a size dependency, regardless of the anticipated compressive strength. These findings are valuable for researchers and practitioners working with coarse-aggregate HSFRC, as they enable the use of smaller specimens, simplifying sample preparation, handling, and testing procedures.

Impact of fiber type, length and volume on concrete mixability: Studies by Ramakrishnan *et al*. [120], Soroushian and Bayasi [121] and Khan and Abbas [122] have resulted in the following key findings:

- Fiber type and volume significantly affect concrete mixability.
- An optimized combination of fiber types can significantly improve crack resistance.
- Hooked-end fibers are more prone to balling, especially at higher volumes (above 1%).
- Corrugated steel fibers exhibit superior mixability, even at higher volumes (up to 2%).
- Straight steel and polypropylene fibers can cause balling and air entrapment, especially at higher volumes (2%).
- Using 0.5-1.5% by volume of steel fibers significantly enhances the compressive and tensile strengths on concrete.
- Industry standard fiber volume often ranges from 0.1% to 3%.

These findings highlight the importance of carefully selecting fiber type and volume to ensure optimal concrete mixability. To achieve a homogeneous mixture, they recommended the following be considered.

- Fiber Type: Corrugated steel fibers appear to offer the best balance of mixability and potential performance benefits. However, the specific application and desired properties should dictate the final choice.
- Fiber Volume: Adhering to industry standards (0.1-3%) is generally recommended. However, the optimal fiber volume for a specific application may vary and should be determined through testing.
- Mixing Techniques: Employ effective mixing techniques to disperse fibers evenly and prevent balling. This may involve adjustments to mixing time, speed, or the use of specialized mixing equipment.

Impact of fiber orientations on the accuracy of FRC test results: A study by Dayaa *et al*. [123] has shown that fiber orientation affects the performance of SFRC beams with hooked-end steel fibers oriented in the direction of maximum normal stress provide the best enhancement in load capacity. Using glass fibers, Zhang *et al*. [124] also made the same conclusion. The authors of another study [125] have noted that traditional concrete mold filling and consolidation techniques could lead to fiber reorientations, potentially resulting in inaccurate test data and non-compliance with industry standards. To mitigate this issue, industry standards such as the American Society of Testing and Materials (ASTM), American Concrete Institute (ACI), and Fiber Reinforced Concrete Association (FRCA) have shifted away from tamping rods, promoting external consolidation methods such as rubber mallets or vibrating tables. The vibration method, whether external or internal, directly impacts fiber geometry, distribution, mixing, and orientation, highlighting the intricate connection between these factors.

Workability and properties of steel fiber-reinforced concrete (SFRC): By using slump tests, Gencel *et al*. [126] have shown that while all mixes exhibited good fluidity and self-compacting characteristics, fiber inclusion reduced the mixture's ability to flow and fill molds when the European Federation of Nozzlemen and Apprentice Concrete Sprayers (EFNARC) high-volume fiber limit is exceeded. Increasing cement content, fine aggregates, or employing pozzolanic/chemical admixtures could enhance SFRC flowability. In addition, several key findings include:

- Higher fiber content correlates with improved ductility under flexural, splitting tensile, and compressive loads.
- Fibers prevent catastrophic concrete failure.
- SFRC exhibits enhanced crack resistance.
- Fiber addition significantly improves energy absorption and compressive ductility.
- Toughness increases with rising fiber content.

Effect of glass fibers on the workability, mechanical properties, and free shrinkage of fiber reinforced self-consolidating cementitious material: Results obtained from an experimental program by Mehdipour *et al*. [127] have shown that mechanical performance was strongly related to the fresh state properties and fiber dispersion characteristics.

Fiber concentration and shape influence the number of contacts form between fibers. An equation that describes the relationship for thin, rigid fibers shows that the average number of contacts per fiber c depends on the fiber volume fraction (ϕ) and aspect ratio r. The equation is given by $c = \phi r(\frac{4}{r} + \frac{3r}{3r+2})$; and when the aspect ratio is high ($r >> 1$), the equation simplifies to $c \approx \phi r$. This means the number of contacts is directly proportional to the fiber factor F, which is also equal to ϕr. The fiber factor is a main factor that controls the rheology (flow behavior) and workability of fiber suspensions. In simpler terms, the higher the concentration and aspect ratio of fibers (reflected by the fiber factor), the more the suspension's flow and workability are affected.

The workability and mechanical performance of fiber-reinforced suspensions are strongly affected by fiber concentration. When fiber concentration is low, fibers exist as isolated entities, failing to bridge or prevent cracks effectively, leading to suboptimal performance. Increasing fiber concentration results in the formation of a fiber network. This network formation can improve some material properties, but it may also make the material more difficult to process or shape. Fiber clumping becomes pronounced at very high concentrations, hindering even dispersion and severely impacting workability. To better understand this fiber effect on performance and workability of FRC, the following two parameters can be used.

- Critical volume fraction (F_c): This is the fiber concentration below which the fibers have minimal interaction, and the suspension behaves like a simple cement paste. The critical fiber volume (CFV) in FRC is the minimum fiber volume fraction required to significantly improve the concrete's tensile strength and crack resistance. It's a crucial parameter that determines the effectiveness of fibers in enhancing the material's performance. Factors affecting CFV are:
    - Fiber Type: The type of fibers (e.g., steel, glass, synthetic) and its properties (e.g., length, diameter, aspect ratio) influences the CFV.
    - Concrete Mix: The properties of the concrete matrix, including its strength, workability, and aggregate characteristics, also affect the CFV.
    - Loading Conditions: The type of loading (e.g., tension, flexure, impact) and the rate of loading can influence the CFV.
- Dense volume fraction (F_d): This is the concentration where fiber clumping becomes significant, negatively impacting workability.

Keeping the fiber content below F_c ensures good workability and allows the cement paste to dominate the rheology (flow behavior) of the suspension. In summary:

A better fiber distribution and bridging efficiency can be obtained by having fiber factor (defined as the volume of the fiber multiplied by the aspect ratio) near the optimum value and preventing the fibers from clumping. The result is a higher flexural and tensile strength with optimum workability properties.

1. Increasing the fiber factor has the following effects.
    a. Flowtime becomes more dominant than slump flow.
    b. Shrinkage is significantly decreased; but for fiber factor higher than F_d, fibers are not sufficiently distributed and connected to efficiently transfer the stress, which then results in lower shrinkage reduction.
2. Lowering the fiber factor and below F_c, the fibers cannot bridge cracks during loading and transfer the load. Fiber volume fraction and aspect ratio shall be selected in such a way that the fiber factor is higher than the minimum value to reach the appropriate hardened properties.

3. When the fiber factor is between F_c and F_d, significant improvement in hardened properties is gained and the mixture is still workable enough to flow under its own weight without any signs of instability and fiber balling. In this case, better fiber distribution and bridging efficiency can result in higher mechanical properties.
4. When the fiber factor is above F_d, the fibers tend to become entangled together and form clusters due to the fiber balling, which can lead to poor mechanical properties.

Impact of steel fiber length and dosage on the mechanical and durability properties of UHPC: A study by Abbas *et al*. [128] has led to the following key findings:

- Mechanical Properties:
  - Compressive Strength: Slightly increased with fiber addition, but fiber length had minimal impact.
  - Splitting Tensile and Flexural Strengths: Significantly improved with higher fiber dosage. Shorter fibers led to higher peak load and enhanced strain hardening compared to longer fibers.
- Durability Properties:
  - Chloride Ion Penetration Resistance: UHPC exhibited excellent resistance due to low porosity and dense microstructure. Fiber length had no significant impact.
  - Mechanical Degradation: No significant deterioration observed after exposure to various chloride ion solutions. Higher fiber dosage slightly improved durability.

Impact of fibers on concrete performance: Some key aspects of a study by Anas *et al*. [11] are: adding fibers enhance mechanical properties of concrete including tensile and flexural strength, ductility, and crack resistance while reducing shrinkage and creep. Fiber aspect ratio, length, and shape significantly influence creep behavior, with high aspect ratio fibers generally providing superior performance regardless of fiber content. Synthetic fibers like polypropylene excel in energy absorption and crack control but contribute less to load-bearing capacity compared to other fiber types. Longer fibers outperform shorter ones, emphasizing the importance of aspect ratio in fiber selection for FRC. However, fiber addition compromises concrete workability. Achieving uniform fiber distribution without segregation is challenging, especially at higher fiber contents. Laboratory mixing often employs wire mesh baskets to disperse fibers evenly. Jassim and Anwar [129] reported negative impacts of polypropylene fibers on mixing and handling despite improving compressive strength.

Effect of steel and synthetic fibers on the workability, mechanical properties, and durability of UHPC: A study by Ravichandran *et al*. [17] has shown that:

- Fiber Types
  - Discontinuous Fibers: Short fibers (3-5 μm diameter) enhance toughness and ductility.
  - Continuous Fibers: Long, continuous fibers (e.g., monofilament) improve tensile strength and flexural stiffness.
  - Particulates: Small particles enhance compressive strength and impermeability.
  - Whiskers: Short, high-aspect-ratio fibers improve tensile strength and fracture toughness.
- Fiber Orientation and Geometry
  - Fiber Orientation: Aligned fibers enhance load resistance, while random distribution is suitable for multi-axial loading.
  - Fiber Geometry: Pre-deformed fibers with mechanical anchoring (e.g., hooks, crimps) provide superior bond with the matrix.
- Key Factors Influencing Fiber Efficiency
  - Material Compatibility: Fibers and the matrix must be compatible to ensure optimal performance.

- Fiber-Matrix Interaction: Strong bonding between fibers and the matrix is crucial for effective stress transfer.
- Aspect Ratio: The ratio of fiber length to diameter impacts post-cracking behavior.
- Fiber Nature, Combination, Orientation, Mechanical Properties, and Geometry: These factors collectively determine the overall performance of UHPC.

- Mechanical Properties and Durability
  - Compressive Strength: Increases with fiber content up to 3%, with hooked-end steel fibers providing superior performance.
  - Tensile Strength: Enhanced by up to 38% with steel fibers, while synthetic fibers may reduce it due to insufficient orientation.
  - Durability: UHPC exhibits excellent impermeability to carbonation and chloride ions and high resistance to freeze-thaw cycles.

In addition, a study by Liu *et al*. [112] on the durability of UHPC under salt water exposure and freeze-thaw cycles has shown that UHPC is highly effective in marine structures as it provides good corrosion protection for being resistant to chloride ion penetration.

6. Fibers, Vibration and Sampling of FRC and UHPC

Based on the above studies, it can be concluded that the addition of fibers impacts both the concrete mix and final product. In particular, the authors of this paper have identified three key areas – fiber geometry/distribution/mixing/orientation, vibration, and sampling – to expound on and explicate their influence on the production, properties, and behavior of concrete with embedded fibers.

6.1. Fiber Geometry, Distribution, Mixing and Orientation

The performance of concrete with embedded fibers is significantly influenced by the geometry, distribution, mixing, and orientation of the fibers within the concrete matrix. These factors play a crucial role in determining the mechanical properties, durability, and overall effectiveness of the composite material.

Fiber Geometry: The shape and size of the fibers can impact the mechanical properties of concrete. With reference to Fig. (**6**):

- Straight fibers are typically used to enhance the tensile strength and toughness of concrete.
- Hooked-end fibers tend to provide improved bond with the concrete matrix, leading to enhanced tensile strength and fracture energy.
- Crimped fiber can improve the workability of the concrete mix and provide additional reinforcement.

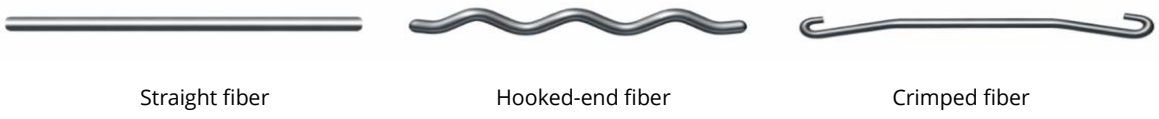


Figure 6: Commonly used fiber geometries.

Fiber Distribution: Uniform fiber distribution throughout the concrete matrix is essential for optimal performance. Non-uniform distribution can lead to localized variations in strength and durability. Factors influencing fiber distribution include:

- Fiber dosage: The amount of fibers added to the concrete mix.

- Mixing process: The efficiency of the mixing process in dispersing fibers evenly.
- Concrete placement techniques: The methods used to place and consolidate the concrete.

Fiber Mixing: Proper mixing of fibers into the concrete mix is critical to achieve uniform distribution and prevent fiber balling. Effective mixing techniques can help to:

- Disperse fibers: Break up fiber clumps and ensure individual fiber dispersion.
- Orient fibers: Align fibers in the desired direction to optimize performance.
- Avoid segregation: Prevent the separation of fibers from the concrete matrix.

Fiber Orientation: The orientation of fibers within the concrete matrix can significantly impact the mechanical properties, particularly the tensile strength and toughness. Fiber orientation can be:

- Unidirectional, where fibers are aligned in a single direction, provides maximum strength in that direction but limited strength in other directions.
- Bidirectional, with fibers aligned in two perpendicular directions, offers improved strength and stiffness in both directions.
- Multidirectional, with fibers aligned in multiple directions, provides enhanced strength and toughness in various load conditions.
- Random, where fibers are distributed randomly, offers isotropic properties and improved impact resistance.

The choice of fiber orientation depends on the specific application and desired performance characteristics. Factors influencing fiber orientations include:

- Mixing process: The mixing technique can induce some degree of fiber orientations.
- Concrete placement: The placement method can affect the final orientations of fibers.
- External forces: External forces, such as vibration or compaction, can influence fiber orientations.

6.2. Effects of Vibration

The effectiveness of embedding fibers in concrete is heavily influenced by the consolidation process, particularly vibration. By compacting the concrete mixture, vibration removes air voids, aligns fibers, and enhances the overall homogeneity of the material. While vibration is essential for optimal performance, it must be carefully controlled. Insufficient vibration can lead to voids, known as “bug holes,” which weaken the concrete and reduce its fiber dispersion. Conversely, excessive vibration can cause segregation of materials and fiber misalignment, compromising the structural integrity of the concrete.

Impact of vibration on mixing and casting: Based on slump tests performed on conventional and Ultra-High Performance Fiber Reinforced Concrete (UHPFRC), Sudarshan and Chandrashekar [130] revealed that vibration significantly improves the workability of both types of concrete. Additionally, they showed that vibration positively influences the compressive strength of UHPFRC. While ultrasonic pulse velocity measurements indicate no substantial effect of vibration on the dynamic modulus of elasticity of UHPFRC, the overall conclusion is that vibration is a valuable tool in concrete construction, particularly for UHPFRC, as it enhances workability and strength without compromising other properties. Vibration promotes even distribution of steel fibers within the concrete matrix, thereby enhancing strain-hardening properties crucial for high-density, ductile behavior, and delaying structural collapse.

Internal vibration applied to freshly mixed concrete effectively removes entrapped air, primarily by expelling larger natural voids to the surface and release them to the atmosphere [131-133]. While moderately sized entrained air voids may also rise with intense and prolonged vibration, the critical spacing of smaller voids which are crucial for concrete’s durability remains largely unaffected. Optimal vibration, characterized by sufficient intensity and duration for consolidation without excessive air removal, is essential for achieving the desired concrete properties.

Concrete slump could affect the extent to which vibration can alter air content [134]. Slumps exceeding 5 inches may experience up to 4% air loss after 30 seconds of vibration. Conversely, external, vigorous vibrations can introduce larger air voids, reducing concrete quality. For slip-form operations (continuous concrete placement), a vibration frequency of 8000 vibrations per minute is generally recommended for paver speeds exceeding 3 feet per minute.

Importance of material proportions, mixing and consolidation: Inadequate consolidation reduces strength, but vibration can mitigate the effect [135] and self-consolidating concrete eliminates this requirement [136, 137]. Bleeding and segregation can weaken concrete, especially in upper specimen sections with higher water-cement ratios. Mold type also impacts strength, with rigid steel molds producing higher results than cardboard or plastic alternatives [138, 139].

High specific surface area and elongated fiber shape significantly increases the cohesiveness of fiber-reinforced concrete (FRC) mixes [140]. This characteristic often leads to an overestimation of workability issues when using the static slump test. In contrast, many FRC mixes with low slump values exhibit good flowability under vibration, a condition commonly encountered during concrete placement. Consequently, dynamic workability tests that simulate vibration are generally considered more representative of actual placement conditions than the traditional slump test.

Hover [141] stated that discrepancies can arise between air content measurements of fresh and hardened concrete due to factors such as mixing, handling, and consolidation. Air voids in fresh concrete are dynamic and can be influenced by vibration, pressure, and temperature. While vibration is often used to reduce air content, it can also introduce air during placement. Various studies [142-153] have confirmed the variability in air content measurements and the complex interplay between these factors.

Impact of vibration stirring: By comparing traditionally stirred SFRC with vibration-stirred SFRC, Zhang *et al*. [154] showed that vibration stirring significantly enhances the mechanical properties of SFRC, particularly in terms of compressive strength, elastic modulus, splitting tensile strength, and flexural strength, especially at lower fiber volume fractions. Mixing by vibration stirring refines the microstructure of the interface between the concrete matrix and the steel fibers, improving adhesion and fiber distribution. Optimal mechanical performance is achieved with a steel fiber volume fraction below 1%. While higher matrix strengths generally contribute to improved properties, excessive vibration can hinder the dispersion of fine particles in high-strength matrices. Vibration-stirred SFRC exhibits superior failure behavior with fewer cracks and reduced spalling due to improved fiber distribution and interfacial bond. Vibration stirring is therefore a powerful technique for enhancing the mechanical performance and durability of steel fiber-reinforced concrete. By optimizing the microstructure and fiber distribution, vibration stirring offers a promising means for producing high-performance concrete composites.

Effect of vibration time: The mechanical properties of SFRC with varying levels of flowability was investigated by Zhao *et al*. [155]. Their study involved compacting SFRC specimens with different slump values (80 to 200 mm) using three distinct vibration times (10s, 30s, and 60s). The key findings from their research are:

- Optimal Vibration Time and Flowability: The optimal vibration time was found to decrease as the flowability of the concrete increased. This suggests that high-flowability SFRC requires shorter vibration durations to prevent segregation and achieve a dense, well-compacted structure.
- Mechanical Property Impact: The compressive strength, flexural strength, and flexural toughness of the SFRC were significantly influenced by the optimal vibration time. Specimens with a 120 mm slump and a 30-second vibration time exhibited the best overall mechanical performance, demonstrating superior flexural toughness and load-carrying capacity.
- Fiber Distribution and Segregation: Excessive vibration, especially in high-flowability SFRC, can lead to steel fiber segregation, where the fibers tend to settle at the bottom of the specimen. This can negatively impact the mechanical properties.

- Practical Implications: To achieve consistent mechanical properties and prevent segregation, it is essential to adjust the vibration time according to the flowability of the fresh SFRC. Further research is needed to establish relationships between fiber distribution and vibration factors (time, frequency, amplitude) to optimize the compaction process.

This study illustrates the importance of tailoring the vibration time to the flowability of SFRC to achieve optimal mechanical performance. By understanding the interplay between vibration time, flowability, and fiber distribution, it is possible to produce high-quality SFRC with enhanced durability and strength.

Double-axis vibration mixing technology: Introduced by Zheng *et al*. [156] to enhance the performance of UHPC, this vibration mixing technology improves the distribution of steel fibers within the concrete matrix, leading to more uniform and efficient mixing. The key findings of this research can be summarized as follows:

- Improved Fiber Distribution: The vibration mixing technology enhances the uniformity of fiber distribution, reducing agglomeration and increasing the percentage of fibers favorably oriented for tensile strength.
- Enhanced Mechanical Properties: This technology improves both static and dynamic mechanical properties of UHPC, including compressive strength, tensile strength, flexural strength, impact resistance, and toughness.
- Early Strength Improvement: The vibration mixing technique significantly improves the early-age strength of UHPC.
- Potential for Resource Efficiency: This technology may enable a reduction in the number of raw materials, such as cement, required to achieve the same mechanical properties, leading to lower costs and reduced carbon emissions.

6.3. Sampling of Low Slump Concrete

Herein, sampling refers to the collection of representative samples of freshly mixed concrete dispersed with reinforcing fibers to evaluate its consistency, workability, air content, and mechanical performance. Effective sampling is fundamental to ensuring that the finished structures meet industry standards and perform reliably in real-world applications. Accurate property assessment requires adherence to standardized testing procedures, as outlined in guidelines such as ASTM and EN standards.

Reference [157] highlighted a potential issue with high fiber dosages (macro-synthetic fibers at 3.0 pounds per cubic yard or higher) when using the pressure vessel method for air content determination. Fiber bridging within the vessel can lead to entrapped air, even with proper consolidation. To accurately measure air content at these elevated fiber levels (including steel fiber dosages of 65.0 pounds per cubic yard or higher), the article recommends using the ASTM roll-o-meter test [158] in conjunction with the ASTM standard pressure vessel method [159].

According to CEN [160], test specimens are to be cast and cured in accordance with the guidelines outlined in CEN [161] and CEN standards [162], unless specific alternative procedures are provided. These standards ensure uniformity, reliability, and accuracy in the preparation and testing of concrete samples. The process of placing the concrete mixture into the mold is carried out in two distinct increments. The first increment accounts for approximately two-thirds of the total volume, which is double the volume of the second increment. This method ensures proper layering and minimizes the potential for air entrapment, which can affect the strength and integrity of the specimen.

Initially, the mold is filled to roughly 90% of its total capacity before beginning the compaction process. This approach allows sufficient space for effective compaction, which is critical for eliminating voids and ensuring a dense, uniform structure. During compaction, the remaining volume is filled with the second increment of concrete. This final layer is leveled to create a smooth, even surface, ensuring consistency across specimens and promoting reliable testing outcomes.

For traditional concrete, external vibration is used for compaction. However, self-compacting metallic fiber concrete requires no additional compaction beyond filling and leveling the mold.

Based on CEN [161], concrete compaction can be achieved by the use of:

- Internal vibrator (Fig. **7a**): A high-frequency (minimum 120 Hz) device with a diameter not exceeding one-quarter of the cone's smallest dimension.
- Vibrating table (Figure **7b**): Operates at a minimum frequency of 40 Hz.
- Compacting (tamping) rod (Fig. **7c**): A circular metal rod, approximately 16 mm in diameter and 600 mm long, with rounded ends.
- Compacting (tamping) bar (Fig. **7d**): A square metal bar, approximately 25 mm x 25 mm in cross-section and 380 mm long.



(**a**) Internal vibrator



(**b**) Vibrating table



(**c**) Tamping rod



(**d**)Tamping bar

Figure 7: Concrete compaction equipment.

Compaction can be performed using any one of the following methods [162]:

- Compacting with internal vibration: Apply the vibration for the minimum duration necessary to achieve full compaction of the concrete. Avoid over-vibration, which may cause loss of entrained air.
- Compacting with vibrating table: Apply vibration for the minimum duration necessary to achieve complete concrete consolidation. Securely fasten or hold the mold to the vibrating table to prevent movement. Excessive vibration can lead to loss of entrained air, impacting concrete quality.
- Hand compaction: Compaction with rod or bar: Distribute the strokes evenly across the mold's cross-section, avoiding forceful impact on the mold base for the bottom layer. Apply at least 25 strokes per layer. After each layer, gently tap the mold to release trapped air and eliminate rod or bar imprints.

Jeknavorian [163] described a standardized approach for the preparation of concrete test specimens, which play a critical role in assessing the mechanical and physical properties of concrete. He addresses a wide range of concrete types, including standard concrete, high-strength concrete, low-slump concrete, self-compacting concrete (SCC), roller-compacted concrete (RCC), and specialty concretes including FRC. This process involves collecting concrete samples directly from delivery trucks and placing them into molds where they are allowed to cure before testing. The method of consolidation used during this process is essential to ensure the removal of air voids and achieve uniform density within the specimen. The choice between rodding or vibration as the consolidation technique depends on the concrete's slump, as defined by ASTM C143/C143M-20 [164].

For concrete with a slump greater than 25.4 mm (1 inch), either rodding or vibration can be used as an effective method of consolidation. However, for concrete with a slump of less than 25.4 mm (1 inch), vibration is required to achieve proper compaction. Low-slump concretes, such as roller-compacted concrete (RCC), present unique challenges due to their stiff, dry consistency. To address this, specialized vibration techniques are required, as outlined in ASTM C1176/C1176M-20 [165] and ASTM C1435/C1435M-20 [166]. These standards provide detailed guidance on the type, duration, and intensity of vibration necessary for effective consolidation of such concretes. It is important to note that this standardized procedure does not apply to all types of concrete. Specifically, concretes that cannot be effectively consolidated using either rodding or vibration are excluded from this process. Additionally, the procedure does not accommodate specimens that require non-standard dimensions, as these may demand alternative preparation and testing methods. This limitation highlights the need for tailored approaches when dealing with unique concrete formulations or specialized testing requirements.

Daniel [167] used the Vebe apparatus to measure the consistency of stiff concrete mixes. This method involves filling a cone with concrete, removing the cone, and measuring the time required for vibration to reshape the concrete into a cylinder. While suitable for dry concrete, its accuracy diminishes for concrete with slumps exceeding 2 inches (50.8 mm), thus suitable for FRC. Alternative consistency tests include the Thaulow Concrete Tester and the Compacting Factor test**.** These methods offer varying degrees of suitability for different concrete consistencies, with the Thaulow test being particularly effective for low-slump concrete.

- Vebe Apparatus [168]: The Vebe apparatus shown in Fig. (**8a**) measures the workability and consistency of low-slump concretes, particularly stiff mixes like roller-compacted concrete (RCC), which cannot be assessed using traditional slump tests. It consists of a vibration table, a cylindrical mold, a weighted tamper, and a timer. Fresh concrete is placed in the mold, and the tamper rests on its surface. When the vibration table is activated, the concrete compacts as air is expelled. The time it takes for the concrete to fully settle and make contact with the tamper is recorded as the Vebe time, with shorter times indicating higher workability and longer times reflecting stiffer mixes [169]. The modified Vebe apparatus is essential for testing low-slump concretes like RCC and FRC, where accurate workability measurement is critical for quality control. It ensures proper compaction, which is necessary to achieve the desired density, strength, and durability. By offering a standardized approach to assess workability, the Vebe test supports better production control and ensures performance requirements are met in large infrastructure projects like pavements, dams, and industrial flooring.
- Thaulow Concrete Tester [170-172]: This tester shown in Fig. (**8b**) is a tool designed to assess the workability of low-slump concrete, particularly mixtures that are too dry to be evaluated with a standard slump cone. It functions similarly to the Vebe consistometer and Powers remolding test but can measure concretes with greater workability. The apparatus includes a 10-liter cylindrical container, which is narrower than those used in other tests. Concrete is placed into the cylinder using a slump cone, and a handle at the top strikes the container's sides. For low-slump mixtures, a drop table is used, and the number of drops needed to remold the concrete to a 5-liter mark is counted. This dynamic process offers a direct measure of concrete's workability. While the Thaulow tester excels at handling high-workability concretes, it requires a stable base to absorb the vibrations from the drop table, limiting its practical use in field conditions.
- Compacting Factor Tester [173]: This test apparatus shown in Fig. (**8c**) is designed to assess the workability of fresh concrete, particularly for stiff or low-slump mixes that are challenging to evaluate with traditional slump tests. The apparatus consists of two conical hoppers and a cylindrical container. Concrete is first placed in the upper hopper, from where it falls into the lower hopper and then into the cylindrical container. The difference in height between the initial and compacted concrete is measured, and the compacting factor is determined by dividing the weight of the compacted concrete by the weight of the original volume. This method provides a more accurate assessment of the concrete's ability to compact under its own weight, making it particularly useful for high-strength or self-compacting concrete. The test is preferred when slump tests are ineffective for low-workability mixes, offering a reliable measure of the concrete's ease of placement and compaction.



(**a**) Vebe apparatus (**b**) Thaulow concrete tester (**c**) Compacting factor tester

Figure 8: Test apparatus for concrete workability and consistency.

For lightweight concrete with oven-dry densities exceeding 800 kg/m³ (50 lb/ft³), compressive strength testing should adhere to ASTM C330/C330M-23 guidelines [174]. To ensure proper consolidation, one needs to gently tap the cylindrical mold sides with a rubber hammer during concrete placement. Alternatively, as suggested by Fouad [175], light vibration of the mold can be employed. His research on lightweight concrete material makes it suitable for sampling FRC.

Preparing test cylinders for RCC according to Adaska [176] requires specialized compaction methods to replicate field conditions. Standard concrete consolidation techniques are inadequate due to RCC's low workability. He indicated that several methods have been developed to address this, including the following:

- Vibrating table: ASTM C1176/C1176M-20 [165] as shown in Fig. (**9a**) provides a detailed set of guidelines for creating, maintaining, and examining concrete samples in real-world building sites where precise lab conditions aren't feasible. The standard ensures that the concrete used in construction is strong, long-lasting, and consistent. The key steps include preparing molds, pouring concrete, and controlling the curing process to allow proper hardening. A major part of the standard is about consolidation techniques, which are crucial for eliminating air bubbles and achieving even density. Two primary methods are outlined: rodding and vibration. The choice of method hinges on the concrete's slump. For concrete with a slump exceeding 1 inch (25.4 mm), either method is suitable, while slumps of 1 inch (25.4 mm) or less demand vibration. This is particularly important for low-slump concretes like RCC, which need special vibration methods to ensure adequate compaction. Proper consolidation guarantees that the final sample accurately represents the concrete's performance in its final position, aiding in better structural quality control.
- Vibrating hammer: The ASTM C1435/C1435M-20 standard [166] provides a detailed procedure for creating cylindrical specimens of roller-compacted concrete (RCC) using a vibrating hammer (Fig. **9b**). This standardized approach ensures uniform and reliable testing of RCC, a concrete type commonly used in large-scale infrastructure projects like dams, bridges, and foundations. The process involves placing fresh RCC into a cylindrical mold, compacting it with a vibrating hammer to achieve the required density, and curing the specimen under controlled conditions. These specimens are later tested to determine the compressive strength of the RCC, a key indicator of its structural integrity. Adhering to this standard is vital for quality control and research, promoting the safety and durability of RCC structures.
- Modified Proctor: ASTM Modified Proctor [177] outlines the Modified Proctor Test (Fig. **9c**) used to determine the maximum dry density and optimum moisture content of soil for construction projects like roads, foundations, and embankments. The test involves compacting soil in five layers using a 10-lb (4.54 kg) hammer dropped from 18 inches (457 mm), applying a higher compaction effort than the Standard

Proctor Test. By measuring density and moisture at different levels, engineers identify the optimal conditions for soil compaction, ensuring stability, load-bearing capacity, and resistance to settlement. This method is essential for quality control in earthworks, promoting stronger, more durable structures. Adaska [176] states that the modified Proctor compaction test [177] is a widely recognized method for soil compaction and can also be applied to Roller-Compacted Concrete (RCC).

- Pneumatic tamper: A pneumatic concrete tamper (Fig. **9d**) is a compressed-air tool used to compact and level concrete. It delivers rapid impacts or vibrations through a flat tamping foot, eliminating air pockets, increasing density, and creating a smooth finish. Key parts include an air-powered piston, tamping foot, ergonomic handle, and impact mechanism. Adjustable models allow control of speed and intensity for different tasks. Commonly used in construction for slabs, precast products, and large surfaces, it enhances concrete strength and durability while reducing labor effort compared to manual tamping.
- Gyratory compaction: Gyratory compaction [178] is a technique used to compress and shape materials like asphalt, soil, and other granular substances, especially in road construction and laboratory testing. A sample is placed in a cylindrical mold, where it undergoes both vertical pressure and rotational motion to replicate real-world conditions. The gyratory compactor (Fig. **9e**) includes key components like the mold, pressure system, and gyration mechanism, along with a control system to monitor the process. This method is essential for asphalt mix design, quality control, and pavement research, ensuring materials meet necessary density and strength requirements. It helps identify potential issues like cracking or rutting, improving the durability and performance of roads.



(**a**) Vibrating table



(**b**) Vibrating hammer



(**c**) Modified Proctor



(**d**) Pneumatic tamper



(**e**) Gyratory compactor

Figure 9: Concrete compaction apparatus.

6.4.Sampling of FRC and UHPC

FRC and UHPC offer enhanced strength, impact resistance, and durability, but their performance depends on the uniform distribution and proper orientation of fibers, making accurate sampling critical. Key challenges

include fiber segregation, misalignment, and variations caused by specimen size and shape. On-site methods such as batch sampling, core drilling, and direct molding, as well as lab-based techniques like controlled casting and cutting from larger blocks, help address these issues. Proper compaction, vibration, and multi-point sampling further promote uniform fiber distribution.

When casting concrete in situ, internal vibration using an electric vibrator is a common practice. The vibrator is inserted into the concrete to remove trapped air and improve consolidation, which is critical for achieving optimal strength. However, in precast concrete systems, external vibration is predominantly used. External vibration consolidates the concrete by vibrating the entire mold, a technique especially useful in FRC production to ensure uniform fiber dispersion. The choice of vibration system varies depending on the size of the precast product, with electric vibrators being used for smaller products and pneumatic vibrators recommended for larger or heavier structures.

During sampling, it is essential to avoid excessive vibration, as this can cause the heavier mortar fraction to settle beneath the surface, leading to an uneven finish. Consolidating fresh concrete has been thoroughly addressed in standards, which recommend using rodding or a combination of rodding and vibration to produce concrete with the most desirable properties. For concrete embedded with fibers, external vibration is the preferred method as internal vibrators can disrupt the random distribution and alignment of fibers. External vibration provides several advantages for consolidation such as:

- Uniform Consolidation: It ensures a more even distribution of forces throughout the concrete mass, which helps in achieving better fiber distribution.
- Reduced Fiber Damage: External vibration minimizes the risk of damaging fibers that could occur from direct contact with internal vibrators.
- Avoidance of Segregation: Excessive internal vibration can cause the concrete mixture to segregate, separating cement paste from aggregates and fibers. External vibration helps mitigate this risk.
- Accessibility: External vibration is often easier to apply, especially for large or complex structures, making it a more practical choice for many projects.

The sensitivity of plain concrete samples to vibration is well-documented, though the samples are often tested remotely by third-party agencies for quality control and assurance. Current standards suggest storing concrete samples close to the placement area to ensure consistency in setting conditions, particularly in terms of temperature and moisture. However, at active construction sites, this is not always feasible. Instead, lab-controlled environments attempt to mimic field conditions, though this introduces its own set of challenges. For FRC and UHPC, particularly in precast applications, this issue is mitigated by the fact that samples and products are often cured under the same controlled conditions.

While guidelines for determining vibration duration for plain concrete are well-established, based on concrete slump and other factors, determining the appropriate vibration duration for FRC and UHPC can be more challenging due to the variability in workability. Over- or under-vibration can occur because of the difficulty in assessing the workability of the mix. The duration of vibration is often dependent on the technician, even though many researchers have suggested safe time ranges for stopping the vibration. More research is therefore needed in this area.

In summary, vibration mixing technology offers a promising approach to producing higher-quality GRC and UHPC with improved performance and reduced environmental impact. Studies by Uygunoglu *et al*. [179] noted that electric tables offer better precision and consistency, which is crucial for laboratory testing of FRC.

Vibration time, frequency and amplitude should be carefully controlled. Prolonged vibration time tends to cause heavier fibers (such as steel) to settle, but insufficient vibration time could result in non-unform blending of the mix ingredients. A study by Zhao *et al*. [155] has shown that a vibration time from 5 to 10 s gives optimal compressive and flexural strengths for steel FRC.

Research by Mindess *et al*. [139] revealed that excessive amplitude could cause fiber segregation, while low amplitude might be insufficient to achieve proper compaction. High amplitude and high frequency vibration lower the plastic viscosity of wet cement paste. While this allows the fibers to rotate more freely, it could result in fibers orienting themselves in the direction of vibration, which may not be desirable.

Fiber volume fraction, aspect ratio, shape and geometry affect the ease with which the fiber moves in the cement paste [180-182]. Fibers having high aspect ratio, non-straight non-smooth geometries and used with high volume fraction tend to entangle more easily. The use of proper vibration energy (a combination of vibration time, frequency and amplitude) to avoid fiber balling and localized voids without causing vibration-induced realignment is crucial in obtaining a uniform mix. Unfortunately, the optimal energy that should be used has not been established and research is still needed to address this aspect of FRC and UHPC.

7. Summary

The use of fibers to enhance the performance of concrete has undergone rapid developments over the years. Macro, meso and nanofibers of synthetic or natural origins are currently being used to alter the strength, durability, ductility, toughness and other properties of concrete. As summarized in Table **3**, research performed by various scholars has demonstrated that the addition of fibers to concrete can improve its mechanical properties, make it more resistant to impact and abrasion, and help inhibit crack formation and propagation. However, some challenges such as higher cost, the possibility of fiber balling and clumping during mixing, and uncertain response to fire and chemicals need to be resolved. Given that various types of fibers are available for use in fiber reinforced concrete, the degree to which each fiber type can affect the mechanical and thermal properties of the finished product and the optimal amount of fibers that need to be added to the mix in order to obtain the desired properties remain a challenge.

Table 3: Advantages and challenges of concrete with embedded fibers.

Advantages	Challenges
Enhance tensile, flexural, and shear strengths	Higher cost
Control crack, shrinkage and spalling	Problems with mixability and workability
Increase impact and abrasion resistance	More stringent quality control
Improve durability, ductility and toughness	Uncertainties with fire and chemical resistance
Reduce creep and permeability	Lack of codifications

In Table **4**, important pros and cons for the six fiber groups discussed in this paper are summarized. In terms of unit cost and as of this writing, nanofibers are the most expensive, followed by carbon and silica fibers, then glass and steel fibers, with synthetic and especially natural fibers cost the least. However, it should be noted that cost is just one aspect of the design, the whole spectrum of pros and cons should be carefully considered in determining the type of fibers for use in a given project.

Fibers (mostly steel, but also S-glass and synthetic) are used in ultra-high performance concrete (UHPC). They bridge and arrest cracks, reduce spalling, help transfer stresses within the concrete matrix, as well as improve strength and enhance ductility.

Regardless of the types of fibers used, proper mixing and consolidation are essential for ensuring the structural integrity, durability, and performance of FRC and UHPC. While both rodding and vibration can be used for mixing and placing or ordinary concrete with slump larger than 1 inch (25.4 mm), the use of vibration, especially external vibration, is preferred as rodding and internal vibration can disturb the random distribution and alignment of fibers. While vibration during consolidation plays a crucial role in reducing voids and improving homogeneity, improper vibration duration can lead to detrimental effects such as fiber misalignment, segregation, or surface irregularities. Despite its significance, the optimal consolidation duration for FRC remains an underexplored area in current research, with limited studies considering the interaction between vibration

parameters (e.g., frequency, amplitude, duration) and FRC-specific factors such as fiber type, size, and distribution. Existing methods often rely on subjective judgment or generalized guidelines that fail to address the complexities of FRC behavior. There is a critical need for more systematic, research-based approaches to objectively determine the optimal vibration duration based on these factors. Addressing these research gaps will not only improve the consistency and reliability of FRC testing but also contribute to the development of more efficient and effective construction practices. By establishing evidence-based standards for vibration duration, future research can optimize consolidation processes, minimize material waste, and enhance the overall performance and reliability of FRC in practical applications.

Table 4: Pros and cons of each fiber groups.

Fiber Group	Pros	Cons
Steel	High strength; high stiffness; high toughness; good impact resistance and ductility; able to withstand extreme temperature range.	Susceptible to corrosion; high density (results in higher dead weight for the structure); high cost.
Silica/Glass	Corrosion-proof; lightweight (when compared to steel fibers); high strength-to-weight ratio; good impact and temperature resistance.	High cost (silica fibers); brittle; glass fibers (except for AR glass) are susceptible to alkali attack; nonlinear effect under high stress.
Synthetic/Carbon	Corrosion-proof; very high strength and modulus; lightweight; high resistance to chemical and biological degradation (PET and aramid fibers); stable in varying temperature; carbon fibers possess electric conductivity (can have applications in smart structures).	Expensive to produce; brittle; plastic fibers are heat sensitive; and their production can create microplastics which could contaminate the environment.
Natural	Corrosion-proof; very lightweight; low cost; sustainable.	Hydrophilic; susceptible to environmental degradation (except for basalt fibers); not very strong.
Hybrid	Offer multi-scale crack bridging capacity; enhance strength, ductility, toughness and reduce cost when metallic and non-metallic fibers are used together; improve durability by reducing porosity and permeability; enhance fire and chemical resistance and increase workability (when metallic and polypropylene fibers are used).	Increase mix design complexity (determining the proper proportions and mixing sequence of each fiber type can be quite challenging); potential for negative synergistic effect when fibers that exhibit totally opposite characteristics are used (e.g., mixing polyvinyl alcohol fibers which are hydrophilic with polypropylene fibers which are hydrophobic); complicate the quality control process.
Nano	Delay micro-crack initiation at the molecular level; accelerate Calcium-Silicate-Hydrate (C-S-H) gel formation; strengthen chemical bonding between the fibers and the matrix; improve durability (by reducing porosity and water and chloride permeability due to the formation of a highly densified fiber-matrix network.	High cost; propensity for fiber balling (due to their large surface area-to-volume ratio and high surface energy); reduce workability (require high doses of superplasticizers); complex quality control to achieve the desired final product.

8. Future Research

Despite the voluminous amount of research on FRC and UHPC, some research gaps remain. They are separated into four categories and are discussed as follows:

1. **Fiber Related Research:** Different fibers and different dosages affect the performance of concrete differently [183]. Although commonly used dosages or volume fractions based on experience are available (see last column of Table **2**), codes and specifications are not specific in addressing the most appropriate type and the optimal dosage of fibers to be added to the cement paste to achieve the desired material properties. If empirical or semi-empirical equations can be developed to relate dosage and fiber types, fiber geometries (shape, length, aspect ratio) with enhanced FRP or UHPC mechanical or other desirable engineering properties (such as compressive and tensile strengths, ductility, durability), this will be an important step toward standardization and codification.

2. **Research on Enhancing Workability:** Adding fibers to cement mix decreases its workability. Research on the most efficient method or a combination of methods to enhance workability for a given fiber type, geometry, volume fraction is needed. Some suggestions include using chemical admixtures (superplasticizers, viscosity-modifying agents, polymer-based workability enhancers), manipulating mix content (increasing the cementitious content, using very well graded fine aggregates, limiting the size of coarse aggregates), managing fiber parameters (use nano and shorter fibers, different combinations of fiber lengths and sizes, fiber coating/lubrication, new fiber geometries), and controlling fiber insertion and placement (adding fibers to the mix in a predetermined sequence and rate). With the advent of 3-D printing, tailor-designed synthetic fiber geometries that have been known to lessen entanglement (e.g., fibers that are straight, with flat, oval or circular cross-sections and have small aspect ratios) can be fabricated relatively easily and experimented to determine what the optimal geometries are for increasing workability.

3. **Research on Vibration Control and Technique:** By carefully controlling vibration parameters such as vibration time, frequency and amplitude of electric and pneumatic vibration systems, external vibration can be used to achieve adequate consolidation of FRC while preventing issues such as fiber balling, segregation or material damage. Electric and pneumatic vibration methods differ in their effectiveness for consolidating FRC due to variations in their operational mechanisms and the type of forces they generate.

   Electric vibration systems typically offer more controlled and adjustable frequencies, making them suitable for fine-tuning the consolidation process. They can be particularly effective in achieving consistent consolidation for a variety of FRC mixes. However, they face limitations in providing the necessary intensity for larger or denser samples. Pneumatic vibration methods, on the other hand, use air-driven systems that can deliver higher amplitude vibrations, which might be more effective for consolidating thicker or more rigid FRC mixes. However, these systems lack the precision of electric methods, leading to less control over vibration parameters.

   There is a critical need for objective, standardized methods to determine the optimal vibration parameters such as frequency, amplitude, and vibration duration for FRC based on its unique material properties, such as fiber type, size, and distribution. The absence of clear guidelines has led to inconsistent vibration practices, resulting in variability in the consolidation process and unreliable test results. While existing standards like ASTM C192/C192M-24 (2024) provide guidance for vibrating ordinary concrete, they fail to address the distinct challenges posed by FRC and UHPC.

   Given that vibration duration, frequency and amplitude are all related to energy, developing an energy-based multi-axis vibration method to determine if a single vibration parameter (energy) can be used to achieve the desired mix results would be an important contribution to the field of FRC and UHPC.

4. **Integration of Existing with Emerging Technologies:** Over the years, a number of important developments in materials research have been developed and reported. Combining FRC with self-healing concrete, incorporating fibers in carbon absorbing concrete, using artificial intelligence and multiscale modeling methods to assess the macro, meso and micro structural characteristics of FRC and UHPC, as well as to study the effects of fiber alignment, fiber distribution, pore structure, and interfacial transition zones between fibers and matrix to gain a better understanding of how they affect mechanical performance, ductility and durability of FRC and UHPC will be valuable endeavors.

Conflict of Interest

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