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Case study

Ultra-high-performance fiber-reinforced concrete. Part III: Fresh and hardened properties

Mahmoud H. Akeed [a,*], Shaker Qaidi [b], Hemn U. Ahmed [c], Wael Emad [d], Rabar H. Faraj [e], Ahmed S. Mohammed [c], Bassam A. Tayeh [f], Afonso R.G. Azevedo [g]

[a] *School of Civil and Environmental Engineering, University of Technology Sydney (UTS), Sydney, Australia*
[b] *Department of Civil Engineering, College of Engineering, University of Duhok, Duhok, Kurdistan Region, Iraq*
[c] *Civil Engineering Department, College of Engineering, University of Sulaimani, Sulaimaniyah, KR, Iraq*
[d] *Department of Civil Engineering, Komar University of Science and Technology, Kurdistan Region, Iraq*
[e] *Civil Engineering Department, University of Halabja, Halabja, Kurdistan Region, Iraq*
[f] *Civil Engineering Department, faculty of Engineering, Islamic University of Gaza, Gaza Strip, Palestine*
[g] *Advanced Materials Laboratory, State University of the Northern Rio de Janeiro – UENF, Av. Alberto Lamego 2000, Campos dos Goytacazes, RJ 28013-602, Brazil*

A R T I C L E I N F O

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A B S T R A C T S

Ultra-high-performance concrete (UHPC) refers to cement-based materials exhibiting a compressive strength higher than 150 MPa, high ductility, and excellent durability. Besides, over the last twenty years, remarkable advances have taken place in the research and application of Ultra-High-Performance Fiber-Reinforced Concrete (UHPFRC). Therefore, a comprehensive investigation of the durability characteristics of UHPC is essential to provide fundamental information for material testing requirements and procedures and expand its practical applications. Part I reviewed the developments, principles, and raw materials of the UHPFRC. Part II reviewed the hydration and microstructure of the UHPFRC. This Part III covers the fresh and hardened properties of the UHPFRC. Part IV covers the durability properties, cost assessment, applications, and challenges of the UHPFRC. Part V covers the mixture design, preparation, mixing, casting, and curing of the UHPFRC. This review is expected to advance the fundamental knowledge of UHPC and promote further research and applications of UHPC.

1. Introduction

Concrete's properties have been improved as a result of unforeseen societal demands, such as high-rise buildings, long-span bridges, and high earthquake-resistant concrete constructions, among others. To achieve these expectations, fresh concrete should have exceptional fresh, mechanical, and durability properties. Currently, UHPC and UHPFRC have discovered actual breakthroughs to satisfy the aforementioned standards. UHPC provides excellent performance in terms of extremely low permeability, resulting in

Abbreviations: BSEM, backscattered scanning electron micrograph; UHPC, ultra-high-performance concrete; CC, conventional concrete; UHPFRC, ultra-high-performance fiber-reinforced concrete; DOP, depths of penetration; UHPFRCC, Ultra-High-Performance Fiber-Reinforced Cementitious Composites; GFRP, glass fiber-reinforced polymer; UHSC, ultra-high-strength concrete; ITZ, interfacial transition zone; UPV, Ultra Plus Velocity; RC, reinforced concrete; VMA, viscosity modifying admixtures; RPC, reactive powder concrete SRAShrinkage reducing admixture.

* Corresponding author.
E-mail address: mahmoud.akeed89@gmail.com (M.H. Akeed).

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negligible ingress of harmful substances such as water and chlorides, as well as extremely high compressive strength (greater than 150 MPa), tensile strength greater than 10 MPa, and significant tensile strain hardening and softening behavior. Furthermore, ordinary concrete equipment may be used to cast structural parts made of self-compacting UHPFRC [1–4]. As a result, UHPC has better resistance to severe exposure circumstances, lateral loading resistance with greatly improved structural integrity, and outstanding service life.

Nevertheless the disadvantages of UHPCs include their high cement content (950–1000 kg/m^3), which raises production costs, and their high silica fume (100–250 kg/m^3), which increases CO_2 emissions and global warming [5,6]. Other disadvantages of UHPCs include sensitivity to the quantity of water-to-cementitious materials, superplasticizers-to-cementitious materials, chemical characteristics of materials, and dispersion of fine particles (required for mixers with greater rotation speed). Furthermore, if fibers are not employed, UHPCs, like other high-strength materials, would be exceedingly brittle with a high modulus of elasticity (about 45–60 GPa), which is undesirable. Such issues might be successfully managed by adopting mineral cement alternatives such as slag, rice husk ash, zeolite, fly ash, and metakaolin [7,8]. Furthermore, extra cement ingredients can be employed in UHPCs to minimize production costs while increasing customer appeal and promoting more broad uses.

Several investigators have conducted studies on UHPC, but information on the materials and structural properties of UHPC is still limited. This review includes five parts. Part I reviewed the developments, principles, and raw materials of the UHPFRC. Part II reviewed the hydration and microstructure of the UHPFRC. This Part III covers the fresh and hardened properties of the UHPFRC. Part IV covers the durability properties, cost assessment, applications, and challenges of the UHPFRC. Part V covers the mixture design, preparation, mixing, casting, and curing of the UHPFRC. The purpose of this review is to summarize previous progress and to suggest some needs for future" research.

2. Fresh property

2.1. Workability

Concrete "workability is defined as the effort required to manipulate a freshly mixed quantity of concrete with minimal loss of homogeneity (uniformity) [9–13]. Manipulation refers to the early-age procedures of placing, compacting, and finishing [14]. The technique of increasing the properties and performance of concrete by adding finer mineral admixtures and fibers to the concrete affects its workability. In general, UHPC has a greater viscosity than regular concrete [15]. The viscous flow of UHPC is caused by the radically different design mix composition (close packing of fine components) compared to standard concrete, the characteristics of the materials, and the exceptionally low water-to-binder ratio. Furthermore, the mechanical and durability properties of UHPC are governed by its performance in the fresh" state [16–21].

During the UHPFRC production process, one or more types of fiber, as well as mineral admixtures, are added to the typical concrete components. The workability of UHPFRC is affected by fiber geometry, surface area, volume fraction, and shape [22]. The addition of fibers to the mix reduces the relative droop and increases the air content of UHPC in its fresh state. Reduced cement concentration and suitable particle packing mitigate the unfavorable impacts of fiber addition in UHPC. The inclusion of steel fibers reduces the workability of UHPFRC due to the increased cohesive force between the paste and the fibers [23]. Knowledge of the rheological characteristics of UHPC is required for a better understanding of the cohesion and dispersion of steel fibers in the matrix. Wang, Gao, Huang and Han [22] investigated the effect of ultra-high-performance mortar rheology properties on fiber dispersion. The yield stress, combined with the depth relative to the viscosity of the fresh mix, is the key rheological parameter for a uniform distribution of fiber. Fiber dispersion becomes problematic in a combination with high yield stress and plastic viscosity, whereas too low yield stress and plastic viscosity might result in significant segregation during the casting stage. As a result, the author proposed an ideal range of fresh mix yield stress of 900–1000 Pa, 700–900 Pa, and 400–800 Pa for UHPC mixes with 1%, 2%, and 3% fiber volume fractions," respectively.

According to Kwon, Nishiwaki, Kikuta and Mihashi [24], the "workability of UHPFRC can be estimated using a factor known as the 'fiber factor.' The equation can be used to compute the 'fiber factor'. $\chi_f = V_f \times l_f/d_f$, where V_f is the volume of fiber, χ_f is the fiber factor, l_f is the fiber length, and d_f is the fiber diameter. χ_f is calculated for both straight fibers (S) and hooked fibers (H), and the two χ_f values are added together. The fiber factor range for UHPC development is shown in Table 1. The results reveal that as the fiber factor increases, the slump of UHPFRC decreases with an upper limit of 'fiber factor' in the range of 2–2.5. The similar observation was reported by Marković [25], Naaman and Wille [26]. Khan, Ko, Lim and Kim [27] reported that micro-steel fiber 2% by volume in UHPC is the optimum dosage for a uniform fiber distribution. A uniform fiber distribution is ensured when the optimal mini-V-funnel flow time of suspended mortar is used, i.e., 46 ± 2 s, corresponding to the optimal plastic viscosity (53 ± 3 s). Furthermore, Ferrara, Park and Shah [28] discovered that the type of placing of fresh UHPC in the mold, rather than the casting technique utilized, has a substantial impact

Table 1
Workability measurements and fiber details [24].

Specimens	S1H0.5	S1H1.0	S1H1.5	S1H2.0
Fiber factor (χf)	0.80	1.20	1.60	20
Flow, mm	275 × 260	270 × 260	220 × 220	205 × 200
Vf, %	Hooked 0.5	Hooked 1.0	Hooked 1.5	Hooked 2.0
Shape of fiber	Straight	Straight (S1)	Straight (S1)	Straight (S1)

on uniform fiber distribution. Fresh UHPC is placed from one edge of the mold, letting it to flow to the other end in the longitudinal direction, demonstrating a more suitable fiber" orientation for achieving the greater flexural strength[29–37].

2.2. Homogeneity and porosity

The first property needed for assessing the fresh properties of a concrete mixture is homogeneity, which is defined by concrete properties in all directions. The quantity of micromechanical features of concrete, such as inner cracking, degradation, honeycombing, and material composition differences, can be used to assess homogeneity in cement-based composites [38–45]. The addition of the W/C ratio, which results in a significant volume of pores inside the concrete, can improve the workability of steel fiber-reinforced concrete during casting. Extra water in the fresh stage of concrete can move over the smooth surface of steel fibers, increasing the production of longish air spaces following concrete hardening [46]. In addition to the amount of water used, obtaining a completely clean fiber free of rubber is almost unavoidable during the recycling process of steel fiber, which has the inverse effects of rubber in increasing the porosity and decreasing the mechanical properties of steel fiber-reinforced concrete [47].

The bond "between the fiber and the matrix is a crucial aspect that may allow the fiber to work inside the concrete. This bond could be weakened by generating a significant porosity at the fiber interface, and in some areas, the fiber could be totally disengaged from the cement mix composition. In this case, the fiber and matrix might act separately to withstand external loading. However, the major purpose of utilizing fiber in the concrete mix is to transfer the generated load across different particles and to prepare the load transferring consistency. This consistency could be lowered by weakening the bond between the steel fiber and" the matrix.

Porosity distribution inside the concrete adversely affected the service life of concrete. Since the risk of corrosion of steel fiber can be evidently increased near the voids at the fiber and matrix interface [48]. Besides the corrosion risks, the porosity could increase the occurrence of aggressive ionic attack, and rapid penetration to the concrete such as chloride and sulphate [46].

An essential "issue in mitigating the concerns stated above is the use of extra materials, which might lead to concrete densification. Previously, the effects of various additional materials on the mechanical performance, permeability, and chloride diffusion of a cementitious material with and without fiber reinforcement were investigated. One of these extra materials could be described as having pozzolanic properties. Because pozzolan acts as a cement by combining calcium hydroxide to produce calcium silicate hydrate, it can effectively penetrate the cement matrix the porosity and by spoiling the porosity in the cement matrix, resulting in reducing capillarity and increasing the resistance of concrete to water absorption and chloride ion diffusion. Some studies have highlighted the utility of silica nano powder as a filler in improving the service condition of concrete by dramatically lowering the porosity of concrete in the case of steel" fiber-reinforced concrete [49–56].

Using Ultra Plus Velocity is a reliable and easy nondestructive test among researchers that is independent of material geometry to determine the degree of porosity in concrete (UPV). This test is also beneficial for detecting interior cracking and certain concrete problems, particularly in harsh environments [57]. The level of induced pulses on different areas of the concrete coupons might be used to determine the integrity of the concrete using UPV [58]. A higher received pulse velocity shows that the concrete is of excellent quality, but a lower received pulse velocity indicates that there are some voids or cracks, which cause the pulse to propagate around these discontinuities and cause the route length to be longer. W/C [59], admixture [60], density, and volume of steel fibers can all have an effect on the measured pulse velocity. A recent study found that employing steel fiber in the production of steel fiber-reinforced concrete has a negative impact on UPV. This may be explained by the fact that the presence of steel fiber in the mortar mix increased voids in the microstructure of the cement matrix, while the fiber content raised the UPV less [61].

2.3. Rheology

The best mechanical properties and durability of UHPC over traditional concrete are attributable to the use of a low water-to-binder ratio (w/b) and a high binder concentration, which reduce matrix porosity. Furthermore, the lack of coarse aggregate and the use of fibers in UHPC increase mixture homogeneity and improve mechanical characteristics, cracking resistance, tensile strength, and ductility. Furthermore, the use of high superplasticizer (SP) dose rates in UHPC ensures high fluidity to accomplish self-consolidating uniformity and increase binder system dispersion. In addition to SP, researchers have employed several types of chemical admixtures to improve the mechanical characteristics of UHPC, such as viscosity modifying admixtures (VMA) [62] and air detraining admixtures [63]. These changes in UHPC material composition (compared to CC) result in UHPC having distinct rheological characteristics, as seen in Table 2. Because of these variations, UHPC flow behavior throughout the installation and consolidation stages of construction may differ from that of CC. The rheological properties of UHPC mixes are discussed in depth in the following" sections.

There is little known about the rheological behavior of fiber-reinforced concrete mixes, notably UHPC (mortar + fibers). Martinie, Rossi and Roussel [64] discovered a similar relationship between the rheological parameters of mortar and UHPC to that described in Eq. (1). Furthermore, it was shown that there is a certain concentration of fibers beyond which the rheological characteristics of UHPC improve by many orders of magnitude when compared to mortar or paste combinations [64]. Meng and Khayat [62] investigated the

Table 2
Ranges of typical yield stress and plastic viscosity for various concrete mixes.

Rheological parameter	Conventional concrete[77]	High-performance concrete[78]	UHPC[62,79]	Self-consolidation concrete[80]
Plastic viscosity (Pa.s)	50–100	50–550	20–200	100–400
Yield stress (Pa)	500–2000	50–2000	10–100	5–50

rheological flow behavior of UHPC mixtures and discovered a linear relationship between shear stress and strain rate. Arora, Aguayo, Hansen, Castro, Federspiel, Mobasher and Neithalath [65] also investigated the linear flow behavior of UHPC paste and mortar combinations. The variation in flow behavior (linear and nonlinear) may be related to the material's shear rate ranges during the rheological testing [66] and the mixture ingredients utilized in the various investigations [67]. This change in flow behavior with applied shear rate for UHPC mixes suggests that it is critical to understand the shear rate ranges predicted for a specific material processing in order to effectively estimate rheological characteristics and predict flow behavior.

$$\eta_s = \eta\left(1 + \frac{\varphi}{\varphi_{max}}\right)^{-[\eta]\varphi_{max}} \tag{1}$$

Where η_s is the viscosity of the suspension, i.e., mortar; η is the viscosity of the suspending medium i.e., paste; φ is the volume fraction of the particles; and φ_{max} is the maximum particle packing. φ_{max} represents the volume of the particles at close packing [68] and is taken as 0.65 for monodisperse randomly close-packed spheres [69–76] $[\eta]$ is the intrinsic viscosity, which is taken as 2.5 for non-Brownian rigid spheres.

2.3.1. *Influence of fiber volume fraction*

Increased "fiber content can significantly increase cementitious material yield stress and viscosity due to reduced packing density and increased friction among fibers and their interaction with solid materials. On the other side, when fiber volume grows, it becomes more difficult to distribute them equally, increasing the possibility for fiber interlock. There is a threshold value for fiber concentration over which flowability is significantly diminished. This is due to the fact that when the fiber content exceeds the critical fiber concentration, the fibers might" form clumps and balls.

2.3.2. *Influence of fiber type*

UHPC primarily employs two types of fibers: elastic and rigid fibers. In general, the use of rigid fibers increases yield stress, whereas the use of flexible fibers increases viscosity. Straight, hook, and corrugate fibers are the most common rigid fiber shapes [81]. When compared to straight fibers, the usage of hooked steel fibers has a greater effect on raising yield stress. The deformed shape has both a cohesive and anchoring effect [81–85]. Due to their large aspect ratios, which equal the length of fiber (L_f) divided by the diameter of the fiber (D_f), the inclusion of long rigid fibers can significantly lower the rheological behavior of UHPC. Increased aspect ratio of steel fibers can boost mechanical interaction [86].

Flexible fibers (e.g., polypropylene and polyvinyl alcohol fiber) can increase viscosity through: (1) the deformation of fibers and formation of entangle structure; and (2) shear viscosity increased with the increase of the flexibility of the fibers that enable them to entangle into an S-shape structure and further block movement of particles [87].

2.3.3. *Errors due to fiber migration*

When a coaxial cylinder rheometer is used for UHPC, fibers might migrate to low shear rate zones (i.e., towards the outside wall, as shown in Fig. 1). Water and fine aggregate can also flow in the other direction, as seen in Fig. 1. Particle movement during rheological tests might result in diverse test samples, rendering rheology data incorrect. Long measurement length, high shear rate, and the presence of a wide gap size in the rheometer can all enhance the probability of fiber migration [88]. One method of avoiding particle migration is to remove inaccurate data, which may be assessed using the relationship between the thickness of the sheared zone and the maximum particles zone. Significant particle migration may occur if the thickness of the sheared zone is less than or close to the maximum size of solid components in the combination.

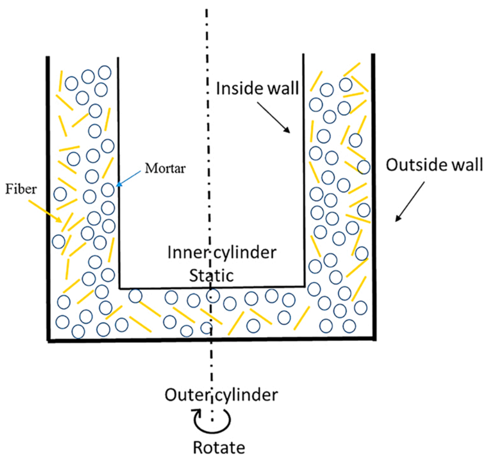


Fig. 1. Concentric/coaxial cylinder rheometer particle movement [88].

3. Compressive behavior

3.1. Effects of steel fibers on compressive strength

Compressive strength is one of the most important properties of UHPC that is often evaluated, as it is of ordinary concrete [89]. Fiber inclusion is required to avoid explosive failure behavior [90]. When compared to standard concrete, the compressive behavior of UHPC containing fibers is not significantly different. The key distinction is increased compressive strength and stiffness. The compressive strength is affected by the component materials, mix proportions", curing conditions, and fiber content [89] (Fig. 2).

This paper analysed over twenty-five included research publications on the influence of steel fibers on compressive strength, including content, shape, length, and fiber combinations. Fig. 2 depicts a comparison of compressive strength enhancement as a function of fiber content vs UHPC without fiber reinforcing. The index is calculated on the basis of a property of reinforced concrete with respect to that of the unreinforced concrete sample [91]. The effect of fiber content on compressive strength differs between research. According to certain research, the introduction of fibers had a rather minor impact on compressive strength (<10%) [92]. According to Arora, Yao, Mobasher and Neithalath [93], compressive strength is mainly reliant on the amount of hydration products and aggregate packing density. Other studies discovered more significant impacts, such as a > 50% increase in compressive strength as a result of fiber incorporation [94]. This increase might be explained by the fibers' capacity to postpone fracture development and propagation [95]. The compressive strength rose as the fiber content increased [81,95]. However, increasing the fiber content could have an unfavorable effect on compressive strength at some point. Meng and Khayat [96] observed this impact when the fiber content approached 3%. Fiber aggregation and entrapped air were responsible for the detrimental influence on compressive strength. Fiber agglomeration was also seen by Le Hoang and Fehling [97] in mixtures containing 3 vol- percent fibers.

To "compensate for the previously noted impact of test specimen geometry, the findings are also shown per specimen type (Fig. 2). According to this, the presence of any volume percentage of fibers has no influence on compressive strength in cylindrical test specimens. The introduction of fibers appears to result in a small improvement in compressive strength for larger cubes (100 mm). However, this effect appears to exclusively distinguish fiber-reinforced UHPC from unreinforced UHPC; it does not appear to be a function of fiber fraction. Only small cubes (40–50 mm) appear to benefit from a 3 vol% increase in fiber volume fraction. Compressive strength appears to fall towards the level of UHPC without fibers at increasing levels. This decrease in compressive strength might be explained by fiber aggregation and decreased workability, resulting in entrapped air. However, it is unclear if any of the observed variances in findings may be explained by arguments about test specimen shape rather than actual fiber effects. Cylinders are thought to have a greater uniaxial stress distribution than cubes. Because of the presence of corners and the smaller height/cross-section dimension ratio, compressive failure in cubes is more impacted by internal shear stress. The most powerful argument to deriving strict conclusions from the comparison of test specimen geometries provided in Fig. 2 is all of the information that is missing. Variances in parameters such as constituent materials, mix percentage, and curing regimes may explain more of the variations in test results than differences in test specimen geometry. The writers of this review study reach the conclusion that there are signs that the shape of the test specimen can impact the outcomes of" studies.

Deformed fibers provide more pullout strength than straight fibers, allowing them to bridge cracks more efficiently [96]. Fig. 3 depicts the effect of employing different shaped fibers in comparison to 13 mm straight micro-steel fibers. The enhanced pullout strength has no effect on the compressive strength of UHPC; all publications indicated that employing deformed fibers had a 15% affect (Fig. 3). Liu, Han, Cui, Zhang, Lv, Zhang and Yang [98] showed minimal variation in compressive strength between macro (l = 30 mm) and micro (l = 13 mm) hooked-end fibers. Yoo, Kim, Kim and Park [99] "discovered that straight fibers had a modest increase in compressive strength when compared to macro deformed fibers. When compared to deformed macro fibers, this impact was explained by the higher number of fibers available to bridge and postpone the spread of micro-cracks. Furthermore, the fiber dispersion was shown to be inferior for the deformed fiber types. Differences in fiber length also had a low amount of" effect (15%) [100–102].

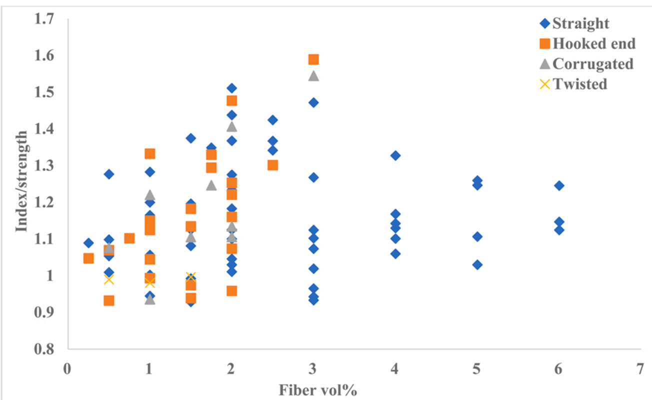


Fig. 2. Improvement of Index for compressive strength of fiber-reinforced UHPC as a function of fiber content [90,92–94,96–98,100,102–112].

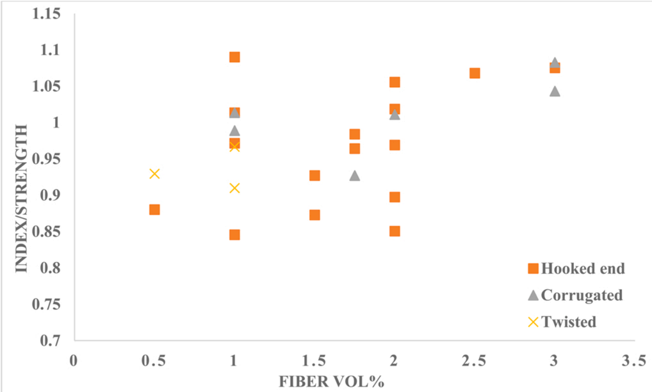


Fig. 3. Improvement of index for deformed fibers on compressive strength as a function of fiber content [81,95,96,98,99,113–115].

3.2. Bond strength and curing impact

One of the most "key characteristics of cement-based products is strength. Depending on composition, casting, and curing conditions, the compressive, tensile, and flexural strengths of UHPC might range from 200 to 800 MPa, 25–150 MPa, and 30–141 MPa, respectively [116,117]. Pre-setting pressure, as predicted, might improve the strength of UHPC" [117,118].

The bonding strength of UHPC with fiber was between 4.8 and 5.5 MPa and increased when silica fume level increased to 30%. The increase in pullout energy caused by silica fume was significantly greater than the increase in bond strength. The increase in pullout energy was about 100% greater in the matrix with 30% silica fume than in the matrix without silica fume. Fibers extracted from a matrix with a high silica fume concentration had a significantly altered microstructure, as illustrated in Fig. 4 [119]. Steel fiber pullout behavior in UHPC is controlled by matrix strength and fiber arrangement (smooth, flat end, or hooked). As matrix strength rose, so did maximum pullout load and total pullout energy [120].

The strength of UHPC after 28 days of conventional room temperature curing could be obtained in 24 h of autoclave curing [121]. When compared to normal curing at 28 days, 24 h of steam curing increased compressive strength by roughly 15–30 MPa. As illustrated in Figs. 5 and 6, after 8 h of autoclave curing, UHPC compressive strength exceeded 200 MPa. Autoclave cured concrete has a greater compressive strength than room temperature water cured sample. However, autoclave steam curing for more than 8 h reduced compressive strength, as seen in Fig. 7. After 6 and 12 days of steam curing, the compressive strength of UHPC was greater than after 28 days of normal water curing. Depending on the fly ash percentage, the strengths of UHPC after steam curing ranged from 89% to 126% of those of UHPC after autoclave curing [122]. After 3 h of autoclaving curing at 180 °C, the compressive and flexural strengths reached 200 MPa and 30 MPa, respectively [123]. Steam and autoclave curing both reduced the flexural strength of UHPC, with steam curing resulting in much lower flexural strength than autoclave curing [124].

The curing regimes have a substantial influence on the interfacial bonding strength of the fiber–matrix. The sequence of interfacial bonding strength is as follows: autoclave curing > steam curing > normal curing. UHPC treated in an autoclave achieved the maximum interfacial bonding strength of 14.2 MPa [125]. However, with autoclaved curing, the bonding strength between prestressed reinforced steel and UHPC was about 50% lower than that between prestressed reinforced steel and ordinary concrete (OC) [126].

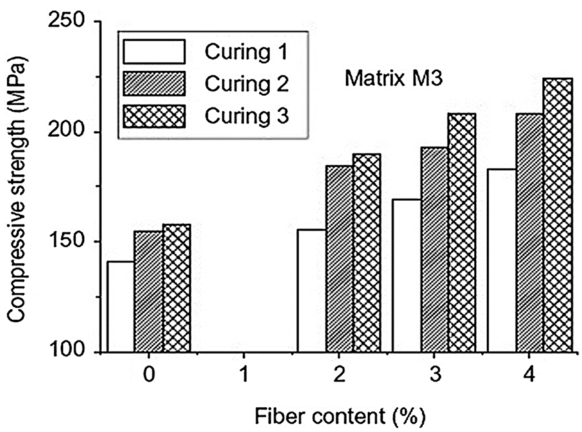


Fig. 4. The effect of curing regimens on UHPC compressive strength [125].

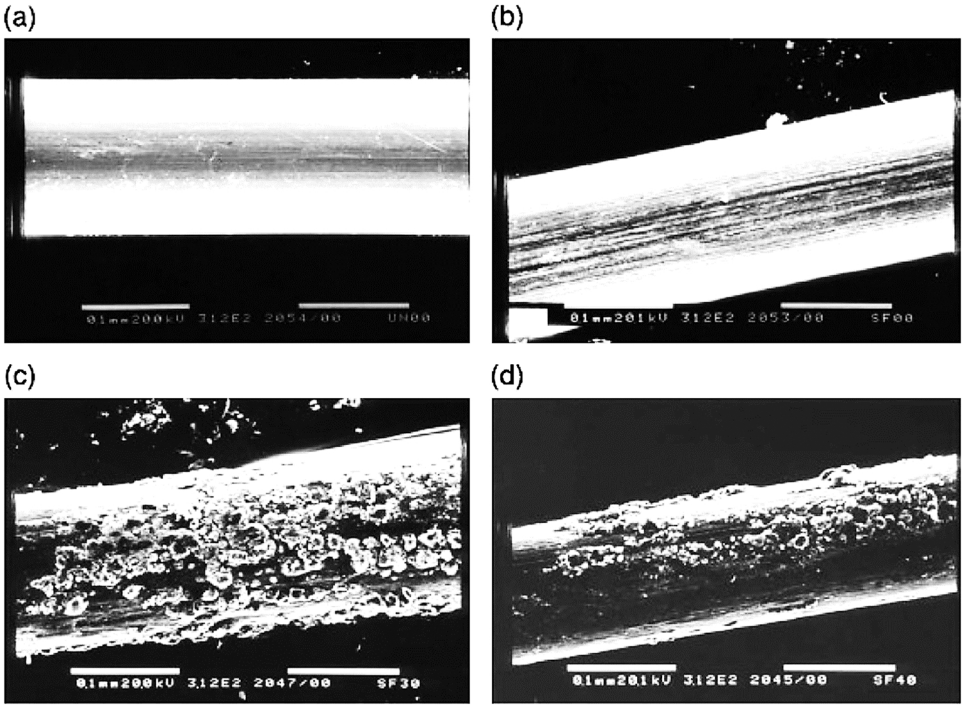


Fig. 5. SEM analysis of the fiber surface under various situations [119].

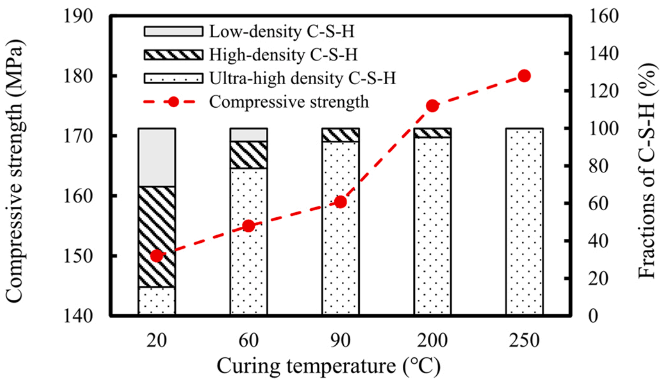


Fig. 6. Heat-curing effects on compressive strength and percentages of various types of C–S–H in UHPC [127].

3.2.1. Fiber–matrix interfacial bond

The "mechanism that controls the fiber–matrix connection is composed mostly of three components: I chemical/physical adhesion (physicochemical adhesion); (ii) friction; and (iii) mechanical anchoring [128,129]. Physical adhesion is often stronger than chemical adhesion because no chemical reaction occurs between steel fiber and UHPC matrix. At the fiber–matrix contact, chemical/physical adhesion, and friction act. Mechanical anchoring can have a significant impact on the bond via fiber interlock (entanglement), plastic deformation of the fiber, and extra normal force pressure. The three primary bonding mechanisms of fiber incorporated in UHPC are identical to those of regular" concrete.

The bond mechanisms are affected by the stress transition. The fiber–matrix interface bond can be classified as shear (parallel to the interface) or tensile (perpendicular to the interface) based on the alignment of stress transferred along the interface relative to the fiber [130]. These can be stated as follows:

$$\tau = \frac{p}{\pi d_f L_E} \tag{2}$$

$$\sigma = \frac{N}{\pi d_f L_E} \tag{3}$$

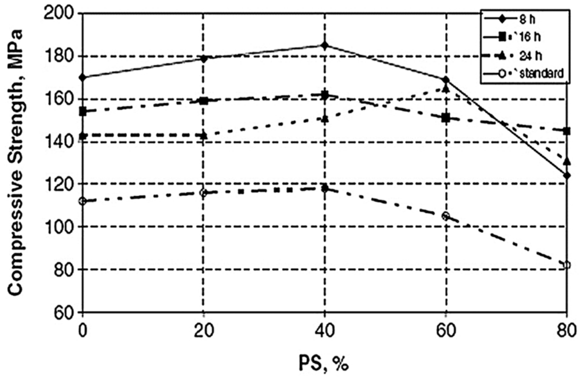


Fig. 7. The effect of autoclave curing time on UHPC compressive strength [122].

where P, D_f, L_E and N are the pullout force (N), diameter of fiber (mm), length of fiber in matrix (mm), and normal force (N), respectively.

Fig. 8 depicts the distribution of pullout and normal forces on an implanted fiber in a cementitious matrix. Shear bond resists withdrawal force and is one of the major elements influencing UHPC mechanical failure behavior. The shear bond transfers stress between the fiber and the matrix prior to fracture. Bridging "fibers at the cracking region carry the load in a cracked UHPC, while the shear bond transfers stress to the uncracked matrix. Shear bonds are divided into elastic and friction bonds [131]. Elastic bonds help to securely transfer stress without debonding or fiber slippage when the pullout force is less than the critical pullout force for slipping. Once the critical pullout force is reached, the balance is destroyed, and axial and peripheral relative displacement between fiber and matrix ensues. When elastic bonds break, friction bonds form, which resist displacement at the interface parallel to the length of the fiber. When the frictional bond strength is more than the ultimate elastic shear bond, fiber–matrix debonding occurs gradually; however, when the frictional bond strength is less than the ultimate elastic shear bond, a fast rise in stress can cause rapid" debonding. The friction coefficient at the fiber–matrix interface, normal force per unit length of fiber, and Poisson's ratio all have a significant impact on the strength of friction bonds [132].

Tensile bond resists the normal force exerted by the lateral contraction of fibers in the matrix. Under the normal force, a complete debonding occurs immediately when tensile stress exceeds the tensile bond strength. Considering that the tensile bond strength is higher than the transverse strength of matrix or even the transverse splitting strength of fiber, a tensile failure may occur in the adjacent area of matrix or at the cross-section of fiber parallel to the fiber length (the latter is unlikely due to the high transverse strength of fiber).

Because the bond exists at the fiber–matrix interface, the microstructure of the interface has a substantial impact on the mechanical characteristics of a composite. The bond behavior of smooth fibers is principally determined by the density of the interfacial transition zone (ITZ) and C–S–H gel via physicochemical adhesion and friction. The ITZ between steel fiber and matrix in UHPC with a 28-day compressive strength of 110 MPa is dense and homogenous due to the low water-to-binder ratio (w/b) and considerable number of fine materials [133], as demonstrated in the BSEM picture in Fig. 9 [134]. In general, no micro-cracks are seen surrounding the fiber. However, due to the wall and bleeding action during hydration, the interface may still be porous and susceptible to micro-cracks [135, 136]. Because of inadequate contact between the fiber and matrix, the porous zone and micro-cracks at the interface might result in poor bond strength [137]. Increase the quantity of binder material, reduce w/b, add supplemental cementitious admixtures, fiber surface treatment, high energy mixing, and improve aggregate and fiber distribution to improve the qualities of the fiber–matrix bond interface [138].

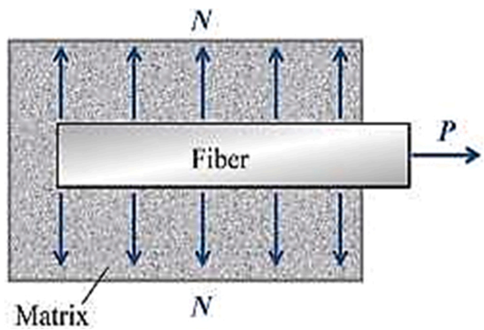


Fig. 8. Pullout and distributed normal forces on an implanted fiber in a cementitious matrix during fiber pullout [131].

Fig. 9. Image of ITZ between steel fiber and UHPC matrix obtained using a BSEM [134].

3.2.2. Fiber-bridging and failure mode

A bridging fiber in the "fiber-bridging and pullout model avoids the formation of microcracking in the matrix and bears tensile stress, especially following cracking in concrete. Fiber pullout or fiber rupture are the failure modes of fiber-bridging [139]; matrix spalling can occur in any situation. Matrix spalling often happens prior to fiber withdrawal or rupture, and bond strength is reduced as a result of significant matrix degradation. A substantially stronger connection can cause fiber rupture and matrix spalling. When the bond tension in a dense ITZ exceeds the ultimate strength of the surrounding matrix, spalling occurs. Fiber rupture happens when the bond strength surpasses the ultimate tensile strength of the fiber [140]. Fiber pullout is the most commonly seen failure mode under stress due to the weak fiber–matrix contact and high tensile strength of steel fiber. Fiber rupture caused by overuse of fiber tensile strength and brittle matrix failure should be avoided [141].

Finally, fiber-bridging has a considerable influence in influencing UHPC post-cracking behavior. Nonetheless, the softening behavior of the matrix in UHPC including fibers becomes less brittle because the cracking pattern is altered by the fibers [142]. As a result, the matrix's contribution should be considered when determining" post-cracking behavior.

3.2.3. Comparison of bond behaviors in normal concrete and in UHPC

UHPC has a compressive strength of more than 120 MPa [143] and typically demonstrates good bond characteristics when compared to conventional concrete. According to Cao and Yu [144], a quick steep decline after the peak load in standard concrete was not seen in UHPC due to the thick microstructure of UHPC, as illustrated in Fig. 10 [145,146].

In contrast to the slip-softening behavior of conventional concrete, the slip-hardening behavior of brass-coated straight fibers increases bond toughness following debonding in UHPC. Extensive surface scratching, as seen in Fig. 11(a) [141], can be induced by micro sand particles in the UHPC matrix [147] or fiber surface treatment applied perpendicularly to the fiber axis [148]. Because of kinetic friction, the abraded surface of the fiber produces extra resistance. Furthermore, when the bond is much stronger than the weak ITZ or matrix, the slip-hardening behavior in UHPC can be related to local matrix "destruction in pullout behavior [149]. Fiber is pushed out, surrounded by a pile of damaged matrix, as seen in Fig. 11(b) [141,150]. Several micro-cracks can be seen on the surface of the matrix linked to the fiber. As a result, the channel through which the fiber is drawn out gets obstructed, and the surface becomes rougher. The coefficient of kinetic friction and sliding friction between fiber and matrix are enhanced. Fiber surface abrasion and

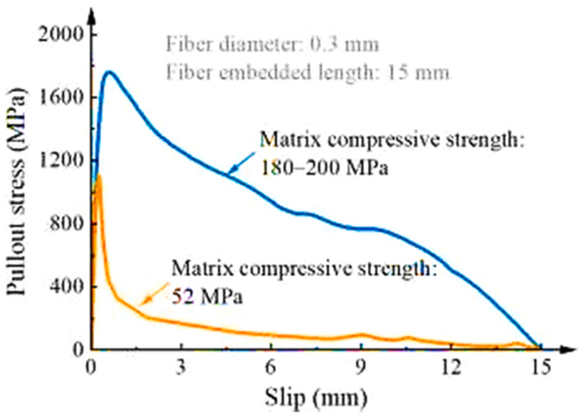
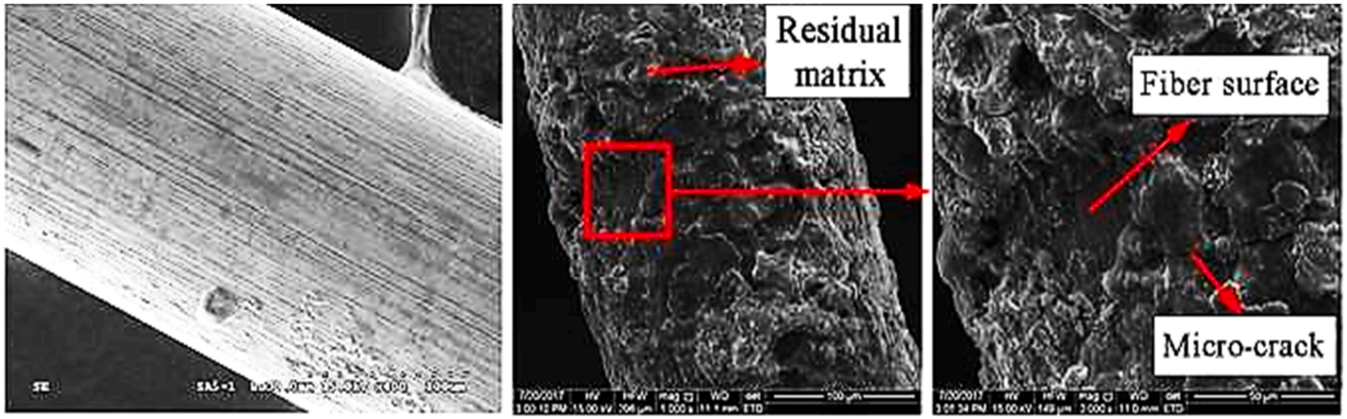


Fig. 10. Pullout stress vs slip of straight fibers in normal concrete (compressive strength of matrix: 52 MPa) [146] and UHPC (compressive strength of matrix: 180–200 MPa) [145].



(a) (b)

Fig. 11. Surface microstructure of steel fibers after pullout: (a) surface scratching [141]; (b) residual matrix adhered to the surface [150].

matrix jamming can both occur at the same time. Because of the significant friction and mechanical force in the whole pullout process, this slip-hardening tendency is particularly visible for severely deformed fiber, such as twisted fiber [147], along the entire" fiber length.

Fiber rupture can occur when the fiber is pulled out of the UHPC, in addition to the increasing sliding friction caused by fiber scratch and matrix jamming during the pullout process. In contrast, the fiber embedded in ordinary concrete can be totally extracted even if it is not fully straightened. As a result, for UHPC, the entire stress–slip curve should be evaluated rather than just the peak pullout stress.

3.3. Stress–strain relationship

Concrete compressive stress–strain relationship is one of its most fundamental constitutive relationships, and it is required for nonlinear analysis of concrete structures [151]. Fig. 12 depicts the hardening behavior of FRC, HPFRCC, and UHPFRC, as well as normal tensile strain softening. However, research into the uniaxial compressive stress–strain constitutive relationship for UHPC is still in its initial stages. Under uniaxial compression, the failure mechanisms of UHPC were identical to those of steel fiber concrete [152]. The peak strain of UHPC rose dramatically as concrete strength increased. The ultimate stress corresponded to the peak stress, and the ultimate strain corresponded to the peak strain [153]. Peak strain increases with increasing steel fiber percentage for a given water/binder ratio. Increased steel fiber content had minimal influence on specimen toughness when the water/binder ratio was excessively high (up to 0.24). When the water/binder ratio is high, a water film can easily develop on the surface of the fiber, resulting

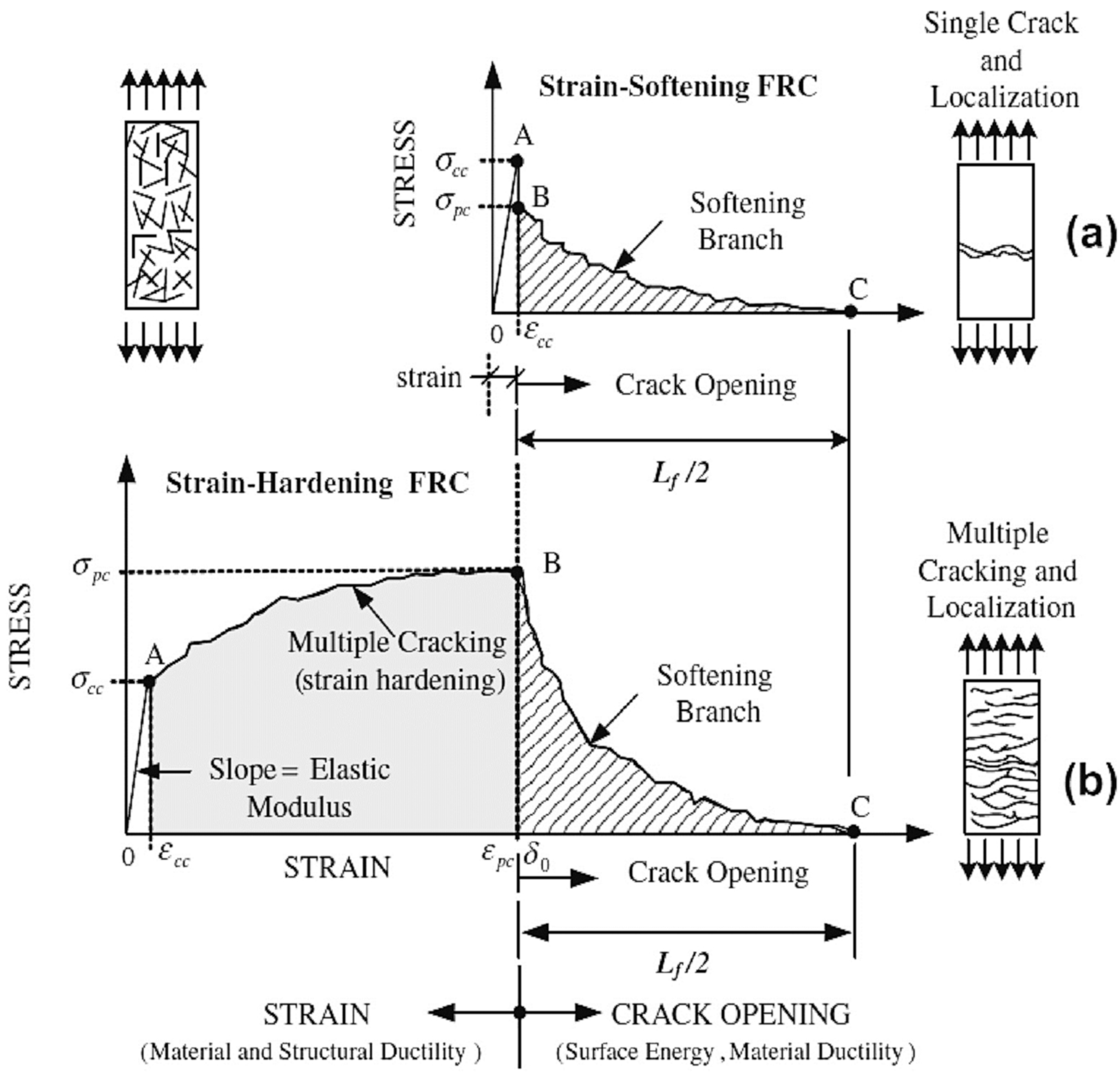


Fig. 12. FRC, HPFRCC, and UHPFRC hardening behavior and typical tensile strain softening [126].

in a more porous ITZ. The elastic proportional limit of the ascending branch of the stress–strain curve of UHPC was around 83–95% of the peak stress attributable to the dense and homogenous internal structure of UHPC [154], which was greater than the elastic proportional limit of OC (40–50%). The ultimate strain of UHPC with steel fibers of length 13 mm was found to be greater than that of steel fibers of length 6 mm. The latter's failure mode was major pulling-off rather than" pulling-out [155].

Due to the integration of steel fiber, UHPC has a substantially greater flexural loading carrying capacity after the peak load. The addition of blast furnace slag raised the maximum bending loads due to higher bonding strength between the matrix and the fibers [156]. The displacement at maximum load for all combinations was between 0.42 and 0.49 mm, which was marginally lower than the displacement for slag-incorporated mixtures.

4. Flexural/tensile properties

UHPC can accomplish "strain hardening behavior by adding high-volume reinforcing fibers (≥2% by volume of mixture). Aside from the expensive cost, however, a high fiber content might present handling concerns (e.g., difficult to mix and limited workability owing to fiber aggregation) [157,158]. Innovative strategies have been developed to reduce fiber content while keeping or increasing flexural/tensile properties: (1) improving fiber dispersion and orientation; and (2) adding multi-scale" reinforcements.

4.1. Impact of fiber shape

Straight, hooked, corrugated, and twisted metallic fibers have been employed in the UHPC [81,96]. Deformed fibers, in particular, outperform in terms of improving the tensile/flexural characteristics of UHPC [140]. The load-slip curves of various shaped steel fibers were summarized in Fig. 13 [159]. Fig. 14 depicts an improvement index for employing deformed fibers on prism flexural tensile strength as a function of fiber content. In contrast, Fig. 15 shows an improvement index for peak flexural tensile strength of fiber-reinforced UHPC as a function of fiber content. The pull-fiber behaviors of straight fibers are governed by debonding and friction at the fiber–matrix contact [160]. Mechanical anchorage/interlock can give extra resistance for deformed fibers [161]. Various forms induced different load-slip reactions after the elastic stage (before A1, A2, and A3). Peak load (B1) was followed by debonding (B1–C1) for straight fiber. The fiber was then extracted from the matrix using friction (C1–S) [160]. After the pullout load declined from the peak, a stable zone (C3-D3) with a constant load was found for the hooked fiber, which can be attributed to the mechanical anchorage/interlock given by the hooked-end [162]. Finally, the fibers were yanked from the matrix by friction (D3-S). Because the curved form caused straightening processes capable of holding prolonged loads, numerous stable areas (C2 and D2) were discovered for the corrugated fiber [159].

The researchers estimated the effect of fiber geometry on fiber–matrix bonding strength [163]. Corrugated and hooked fiber bond strengths were 200% and 600% greater, respectively, than straight fiber bond strengths. Flexural strengths of UHPC with corrugated fibers and hooked fibers were 5% and 20% higher, respectively, than those of UHPC with straight fibers. The bonding strength between the UHPC matrix and twisted triangular fibers was 40% more than that between the UHPC matrix and straight circular fibers. As a consequence, UHPC with twisted triangular fibers had a 35% higher tensile strength than UHPC with straight circular" fibers.

4.2. Impact of fiber dispersion

Fiber "dispersion in UHPC indicates the arrangement of the reinforcing fibers and is measured as the deviation of the number of fibers per unit area from the total number of fibers in the whole cross-section. According to Fig. 16, evenly dispersed fibers increase the flexural strength of UHPC beams [166], because an even fiber dispersion improves the encapsulation effect of the UHPC mortar on the fiber surface and increases the fiber–matrix interfacial" characteristics [167].

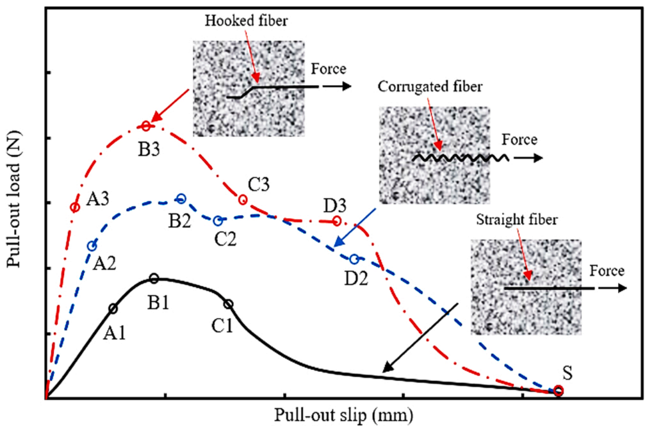


Fig. 13. Comparison of the typical pullout load-slip curves of different shaped steel fibers [159].

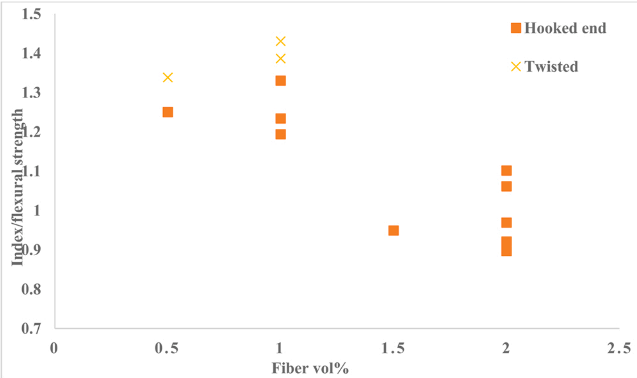


Fig. 14. Improvement index for using deformed fibers on flexural tensile strength of prisms as a function of fiber content [96,99,110,114,115].

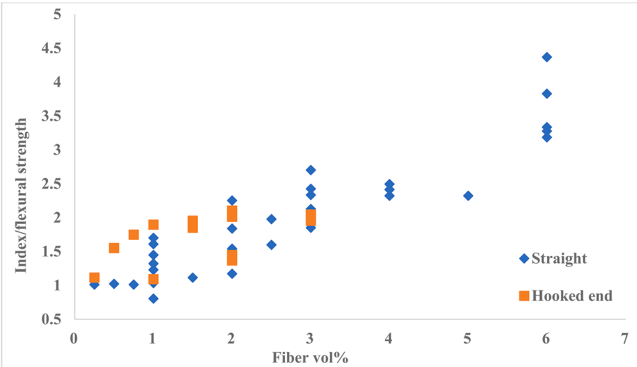


Fig. 15. Improvement index for peak flexural tensile strength of fiber-reinforced UHPC as a function of fiber content [93,100,102,103,106,108,164,165].

The viscosity of the UHPC suspending mortar can be used to regulate fiber dispersion [62]. Teng, Meng and Khayat [168], found that the coefficient of fiber dispersion increased with the plastic viscosity of UHPC mortar, as seen in Fig. 17 (a). Meanwhile, as demonstrated in Fig. 17, the flexural strength and toughness rose with the coefficient of fiber dispersion (b). Flexural strength was somewhat reduced because to an increase in entrapped air in the UHPC matrix caused by the excessive inclusion of VMA.

4.3. Impact of fiber aspect ratio

The aspect ratio "is the proportion of fiber length (L_f) to fiber diameter (D_f) [170]. Steel fibers having a greater aspect ratio, in most

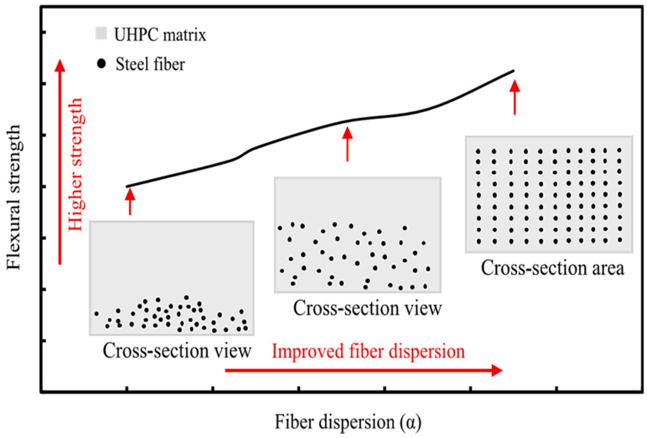


Fig. 16. The relationship between fiber dispersion coefficient and UHPC flexural strength [169].

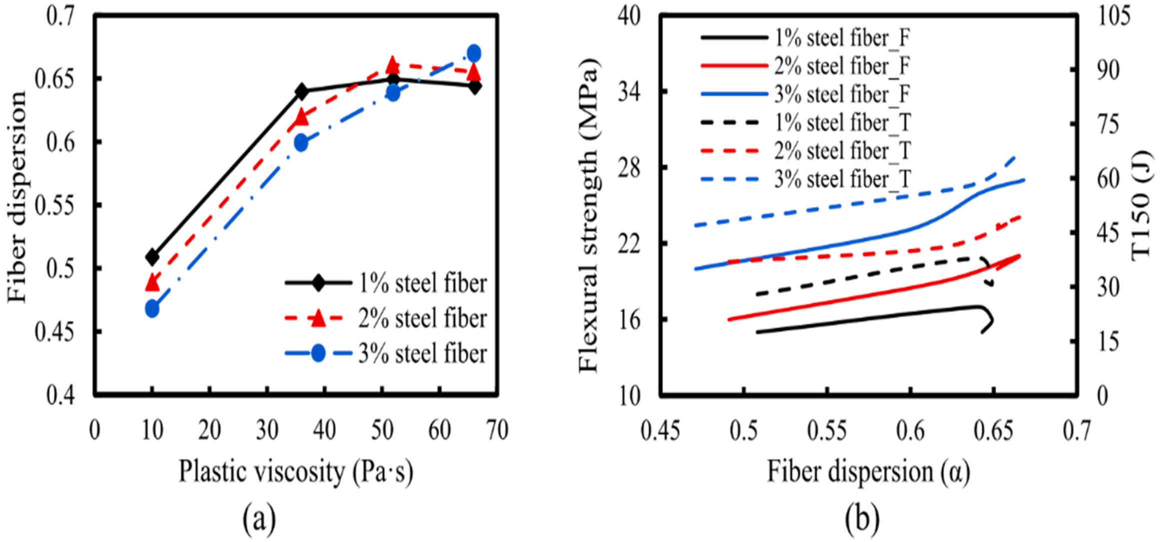


Fig. 17. Results of rheology control for UHPC: (a) the plastic viscosity of UHPC suspension mortar versus fiber dispersion; and (b) fiber dispersion versus the flexural strength of UHPC [168].

circumstances, provide improved flexural performance (e.g., flexural strength, deflection capacity, and toughness) [114]. This is due to the fact that reinforcing fibers with a greater aspect ratio have a bigger effective fiber–matrix bond area, which results in superior post-cracking behavior [171]. Yoo, Kim, Park, Park and Kim [114] discovered that increasing the fiber aspect ratio from 65 to 97.5 increased the flexural strength and toughness of UHPC by 40% and 105%, respectively, when the amount of steel fibers was fixed at 2% [114]. Furthermore, the number of cracks in UHPC with steel fiber ($L_f/D_f = 97.5$) increased by 125%, while the average crack spacing decreased by" 45%.

4.4. Impact of fiber orientation

The optimal fiber orientation aligns the reinforcing fibers with the tensile stress vector [172]. The fibers in UHPC cast using the traditional process are randomly orientated [173]. When the single-fiber pullout test findings show that when the.

When the angle of the reinforcing fibers is greater than 30 degrees off the tensile direction, the energy dissipation capacity and bond strength are dramatically reduced [174]. Higher flexural characteristics of UHPC can be achieved when additional fibers are orientated in the tensile direction, as shown in Fig. 18 [62].

Casting processes have a considerable impact on fiber orientation [175,176]. Allowing UHPC to flow from one side to the other side of a beam induces self-orientation of fibers, which is the optimum approach for casting a UHPC beam. Because of UHPC's high viscosity, the velocity gradient of the shear flow of fresh UHPC causes the fibers to be orientated along the flow direction [62]. It is worth noting that the fiber orientation is dictated by the specimen size [177]. As illustrated in Fig. 19, Huang, Su, Gao and Yang [178] found

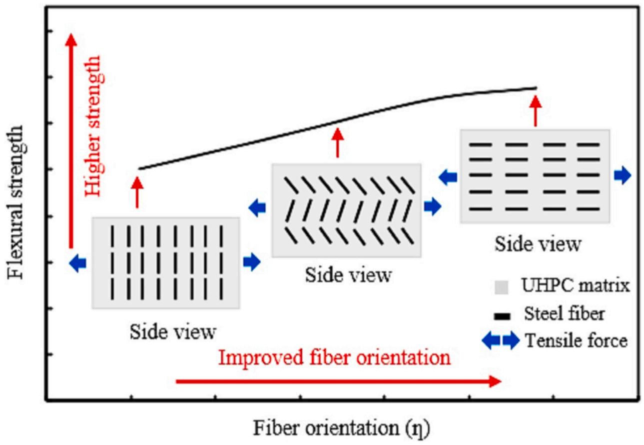


Fig. 18. Relationship between the fiber orientation and the flexural strength of UHPC [169].

that the free rotation of fibers was hampered near the formwork borders, such that fiber orientation near the formwork is better than that far from the formwork walls (i.e., wall effect). The thickness of the wall effect zone is determined by the mold dimensions [178], and thinner specimens have better fiber orientation when the same casting procedure is used.

Furthermore, Song, Yu, Shui, Wang, Rao, Lin and Wang [177] discovered that increasing the length of the casting mold increased fiber orientation in UHPC. The casting mold was separated into three zones: (1) adjusting zone, where fibers begin to re-orient; (2) optimal zone, where most fibers align to the flow direction; and (3) re-disorder zone, where fibers become disordered as flow velocity decreases. Because a low Saver (average fiber area) signifies good fiber orientation, the Saver value reduces with increasing flow distance and increases at the other end of the mold. The length of the optimum zone rose from 0 mm to 280 mm as the casting length increased from 400 mm to 1000 mm.

4.5. Impact of fiber surface condition

Aside from "deforming the fibers, roughening the fiber surface can also strengthen the fiber–matrix connection [179] Several treatment procedures, including chemical solution immersion [163], sandpaper [148], and cold gas plasma, have been developed [163]. According to the quantitative examination of atomic force microscope pictures, the roughness of steel fibers rose by 290% after 6 h of immersion in an ethylenediaminetetraacetic acid solution, as illustrated in Fig. 20(a) and (b) (Yoo et al., 2021). As a result, the tensile strength and strain capacity of UHPC with roughened steel fibers were raised by 15% and 16%, respectively, when compared to UHPC with untreated steel fibers, as shown in" Fig. 20 (c).

5. Shrinkage properties

UHPC differs from "conventional concrete in terms of fine particle content (cement and finer pozzolanic material), aggregate content, and water-to-binder ratio. A changed composition with a larger cementitious content and a low water-to-binder ratio, for example, results in greater shrinkage and early-age cracking [180]. The larger the total shrinkage (early-age, autogenous, drying) the lower the structural performance capabilities. Autogenous shrinkage causes dimensional instability and premature cracking [181]. Early-age cracking allows chemicals and moisture from the environment to enter and reduces serviceability [182]. As a result, thorough research, and knowledge of the impacts of pozzolanic materials and fibers (mono/hybrid state) on the shrinkage behavior of UHPC are" critical.

Because of the integration of "steel fiber, the drying shrinkage of UHPC after steam curing is quite low in general [183]. For UHPC, higher shrinkage rates were developed from 1 to 14 days. The shrinkage rate gradually increased from 14 to 100 days, then gradually decreased from 100 to 130 days. The shrinkage of concrete treated with silica fume was greater than that of concrete treated with slag. Chemical admixtures are known to impact the porosity of hardened cement paste, both total porosity and pore size distribution, hence affecting the shrinkage behavior of the concrete. In the presence of retardation or a high superplasticizer dosage, both autogenous shrinkage and evaporation increased, as did drying shrinkage" and hence the fracture propensity, as illustrated in Fig. 21 [184].

Concrete drying shrinkage could be reduced by lowering the water/binder ratio, inserting steel fiber, and employing heat-curing [185]. Increasing the stress-to-strength ratio from 40% to 60% increased the tensile creep coefficient by 44% and the specific creep coefficient by 11%, respectively, while using fibers and heat-curing could reduce drying shrinkage by more than 57% and 82% after 14 days of loading, as shown in Fig. 22 [186]. The incorporation of coarse particles may reduce UHPC drying shrinkage. Furthermore, there was no swelling in the specimens formed from UHPC with coarse aggregates after the initial shrinkage, but swelling was detected in the UHPC without coarse particles [187]. The addition of shrinkage reducing admixture (SRA) resulted in a considerable decrease in drying shrinkage due to a decrease in surface tension in the water at the pores, resulting in decreased capillary strains. However, these chemical admixtures may have detrimental side effects such as decreased early strength and a minor delay in setting time [184]. The incorporation of fly ash could reduce concrete shrinkage because the unhydrated cementitious material functioned as aggregate, restricting shrinkage [188,189].

Soliman and Nehdi [16] added "wollastonite microfibers at 0%, 4%, 8%, and 12% as partial volume replacements for cement. Three varied sizes of wollastonite fiber, MF1 (length 152 μm, diameter 8 μm), MF2 (length 50 μm, diameter 5 μm) and MF3 (length 15 μm, diameter 3 μm), were used. The maximum improvement has been observed in the UHPC containing MF1. The increment of MF1 from 4% to 12% reduces the 7 days total shrinkage up to 16%, whereas, for MF2, 2–9% is the reduction in the total shrinkage as compared to that of the control mixture. MF3 exhibited a less significant reduction in the total shrinkage compared to that of the control mixture. The presence of wollastonite microfibers reinforced the matrix at micro level and curb the shrinkage of the UHPC. Hence, there is less UHPFRC shrinkage as compared" to that in UHPC.

6. Impact resistance

UHPC without "steel fiber is extremely brittle. Steel fiber incorporation may boost split tensile strength and flexure strength while decreasing brittleness. The fracture energy of UHPC with fiber may be four times that of OC [190]. The penetration depth and crater width in target specimens under impact load decreased overall as the compressive strength of UHPC increased. The trend, however, was nonlinear. Steel fiber concentration increased lowered crater diameter and crack propagation but had no effect on" penetration depth.

Some researchers "investigated UHPC's dynamic axial tensile properties and splitting tensile properties. The impact splitting tensile strength of UHPC including fibers (3% and 4%) rose by one time when compared to plain concrete, while the impact axial tensile

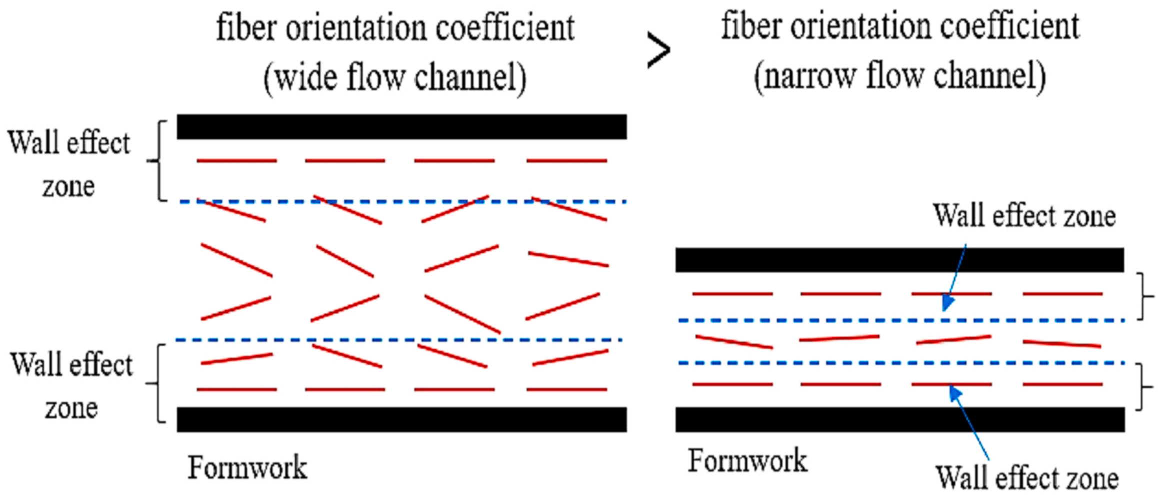


Fig. 19. The illustration of the mechanism of the wall effect [178].

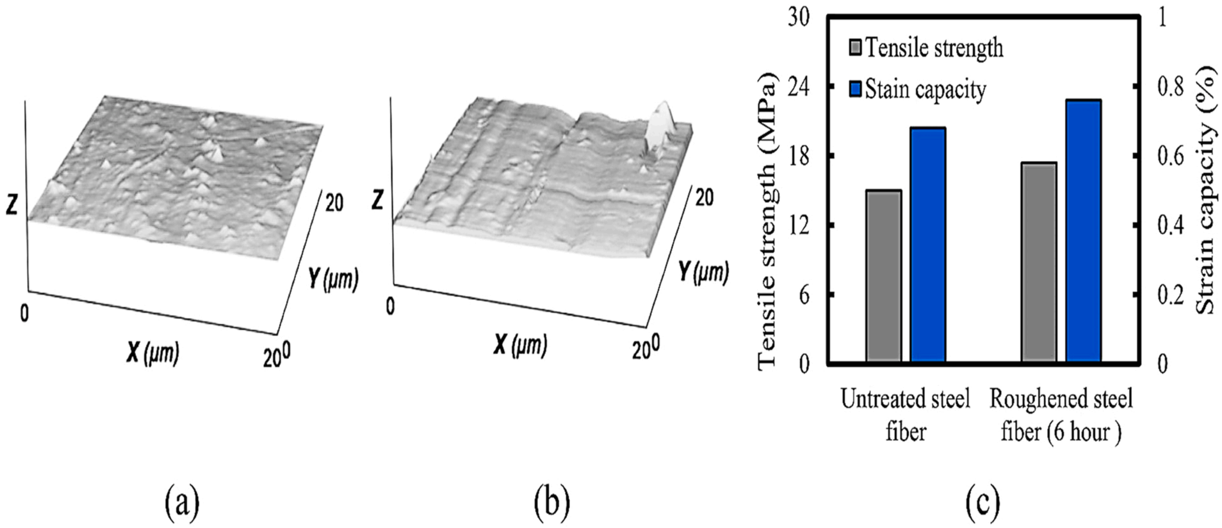


Fig. 20. Effect of surface roughness of steel fibers and tensile properties: (a) atomic force microscope image of untreated steel fibers surface; (b) image of roughened steel fibers surface (6-h immersion); and (c) results of tensile properties of UHPC with different roughness of fibers [163].

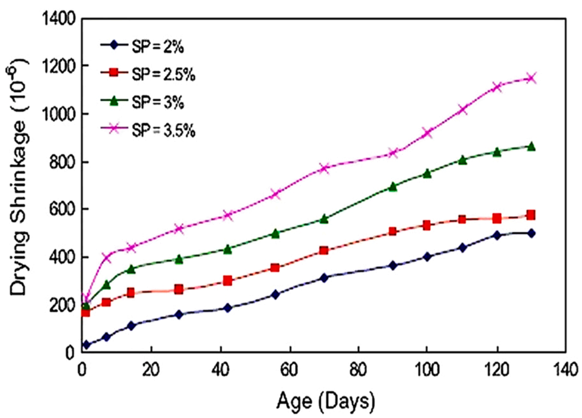


Fig. 21. Drying shrinkage for UHPC with different SP dosages [184].

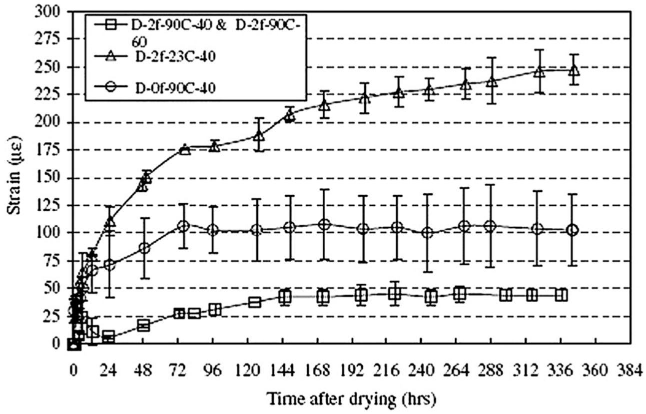


Fig. 22. Free shrinkage of different UHPC mixes; drying started at 7 days of age [186].

strength increased by about 1.5 times. It was discovered that the fracture surface fibers were dragged out rather than ripped off. As a result, the specimen was destroyed due to insufficient binding strength between matrix and steel" fibers [191].

The usage of "fiber materials, particularly steel fibers, has a significant impact on UHPC projectile impact resistance. Li, Brouwers and Yu [192] investigated the performance of UHPFRC when struck by a NATO armor-piercing bullet at velocities of 843 mm/s and 926 mm/s. A particle packing model and two types of steel fibers were used to create the UHPFRC (13 mm straight steel fibers and 30 mm hooked ended fibers). Depths of penetration (DOP) were measured for plain UHPC, UHPFRC with 30 mm hooked steel fibers, and UHPFRC with 13 mm straight steel fibers, respectively. When compared to the 30 mm hooked steel fibers, the 13 mm straight steel fibers performed better in terms of DOP reduction. This is due to the increased number of fibers per kg (number density) in 13 mm straight steel fibers compared to 30 mm steel fibers. Better uniform dispersion was also a factor, contributing to the achievement of higher compressive and tensile strength in UHPFRC. The ideal percentage of steel fiber in UHPFRC for efficient projectile impact resistance is 2% by volume" of concrete.

Aside from the DOP, the most prominent phenomena of concrete due to projectile impact include spalling and scabbing [192]. The front and back faces of an impact-resistant wall withstand compressive and tensile loading, respectively [193]. Tension stress on the back face causes scabbing and an increase in impact velocity due to the wide dispersion of fractured concrete components [194]. This action may be regarded as a secondary source of damage in the surrounding areas. The use of hybrid fiber in the development of UHPC results in reduced scabbing and a decrease in DOP.

7. Toughness

Steel fibers are "the most prevalent fibers utilized in UHPC [96,195]. Meng and Khayat [96] found that increasing the steel fiber concentration from 0% to 2% (by mass of mixture) boosted the 28-day flexural strength and toughness of UHPC by 120% and 3360%, respectively. Steel fibers, on the other hand, have disadvantages such as (1) high initial cost, (2) corrosion potential [196], (3) negative impact on structural surface finishing [197], and (4) high density" (add dead load).

Steel fiber "content has a considerable impact on UHPC toughness due of its cracking resistance [198]. When the steel fiber volume content was 3%, the toughness index (g_{c30}) improved by more" than 80%.

Yoo, Kim, Park, Park and Kim [114] discovered that increasing the fiber aspect ratio from 65 to 97.5 increased the flexural strength and toughness of UHPC by 40% and 105%, respectively, when the amount of steel fibers was fixed at 2%. The ratio of ultimate strain to peak strain was lowest, or the toughness of samples was highest, when two steel fibers (2% 13 mm + 1% 6 mm) were blended [155].

Furthermore, the "additional manufacturing process of deformed fibers raises the cost of UHPC using deformed fibers [114]. As a result, it is advised to blend deformed fibers with straight fibers. Meng and Khayat [96] discovered that when the steel fiber content was fixed at 2%, a hybrid of 1% straight steel fiber and 1% hooked steel fiber provided the best flexural performance. When compared to UHPC with 2% mono straight steel fiber and UHPC with 2% mono hooked steel fiber, the 28-d flexural strengths and toughness were raised" by 25% and 30%, respectively.

Mineral admixtures "improved bond strength between matrix and fibers, increasing toughness in all curing regimes by 18–46% for ordinary room temperature curing, 24–44% for steam curing, and 23–39% for autoclaved curing. The curing regime is another aspect that influences the hardness of UHPC. The hardness of UHPC increased in the following order: normal curing > autoclave curing > steam curing [124]. It was discovered that 3D fabric improved the durability of cement-based composites up to 200 times more than short fiber [199]. Pre-setting pressure, as expected, might greatly improve the toughness" of UHPC [200].

8. Conclusions

Based on the review and discussions above, it can be summarized as follows:

1. In UHPC matrice's, steel fibers are often employed. Proper fiber dosage could improve mechanical properties and reduce autogenous shrinkage in UHPC. Furthermore, a combination of macro and micro-steel fibers could result in tensile strain hardening behavior. However, the higher fiber content may cause balling and reduce the workability of the" combination.
2. For constructability, the workability of UHPC should be managed. The physical and chemical controls are explained in order to effectively increase the flowability of UHPC and ensure its self-consolidating characteristic. It is suggested that the amount of viscosity modifying agent in UHPC suspending mortar be changed to reduce fiber separation and the floating of light raw materials.
3. The type of mixer has the "greatest impact on the workability of steel fiber-reinforced concrete. Higher fiber doses resulted in lower workability while using a typical mixer. In contrast, mixing with a planetary mixer on the vertical axis resulted in larger slump values and little slump decrease as fiber content" increased.
4. Because of the smaller particle size and higher superplasticizer concentration in UHPC, the matrix viscosity increases, and a quick loss of workability occurs, limiting the use of UHPC in practical applications. When fiber is introduced to the matrix, the loss of workability becomes alarming. Due to the absence of high workability necessary for constructions such as tunnels and super-high-rise buildings, a stiff mix of UHPC and UHPFRC restricts its utilization. More refined rheology testing shows that the viscosity yield stress represents fresh behavior better than UHPC viscosity.
5. The rheological properties of the UHPC mixture ingredients are significantly influenced. Binder materials' chemical composition, particle size distribution, content, particle shape, surface texture, and specific surface area, as well as w/b, can all have a significant impact on rheological characteristics.
6. A higher fiber volume fraction improves rheological characteristics. Deformed fiber mixtures have higher yield stress and viscosity than straight fiber mixtures. Chemical admixtures have a significant impact on rheology. While SP is required to ensure low yield stress and lower w/b, VMA can be employed to change the viscosity of the suspending mortar and improve fiber dispersion.
7. Fiber types "have been studied, ranging from micro to macro fibers, straight or deformed (hooked-end, twisted, or corrugated). High-strength steel fibers (tensile strength > 2000 MPa) were generally employed for all fiber shapes. The cumulative results for compressive strength suggest that employing deformed fibers rather than straight ones has no effect. Deformed fibers appear to increase flexural tensile strength at low fiber volumes. Straight fibers, on the other hand, perform better at higher fiber volumes. As a result, the optimal fiber type appears to be determined by the fiber volume" percent.
8. UHPC toughness can be improved by pre-setting pressure, heat-curing, and the use of mineral admixtures. The highest toughness was obtained after 28 days of ordinary room temperature curing, while steam curing produced the lowest. Mineral admixtures may improve toughness following typical room temperature curing. UHPC without steel fiber is extremely brittle. Steel fiber incorporation could boost UHPC yield split tensile strengths.
9. The shrinkage of UHPC mixture is more than that of regular concrete. The usage of several types of fibers in mono or hybrid conditions, on the other hand, controls the shrinkage behavior of UHPC. In the context of projectile impact, hybrid fiber-contained UHPC provides greater protection than mono-state or without fiber UHPC. The use of hybrid steel fibers in UHPC results in greater control over depth of penetration," spalling, and scabbing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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