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Ultra-high-performance fiber-reinforced concrete: Fresh properties

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Abstracts

UHPC is a cement-based composite that is used in new construction and/or renovation of existing structures to increase their service life. It is a unique composite material that may be used as an alternative to concrete in harsh conditions. Following decades of research and development, a wide range of commercial UHPC compositions are now accessible across the world to fulfill the growing number of applications and demand for high-quality construction materials. Although UHPC has significant advantages over conventional concrete, its use is limited because of rigid design restrictions and excessive pricing. As a consequence, a detailed analysis of UHPC's durability qualities is necessary to provide critical information for material testing requirements and methods, as well as to widen its practical applications. The goal of this study is to learn more about UHPC and to encourage more research and use of UHPC.

Keywords

Ultra-High-Performance Fiber-Reinforced Concrete; Fresh properties

1. Introduction

Concrete is the most widely used synthetic material on the globe, and it will remain in high demand for the near future. It is estimated that global concrete output is over 6 billion cubic meters per year, with China now utilizing approximately 40% of global concrete production [1-3]. Concrete's superior properties, such as its strength and durability, capacity to be laid in a variety of forms, and low cost, have made it the most well-known and vital material in the building industry. Concrete is generally employed because of its high compressive strength. Over the last few decades, considerable progress has been made in the field of concrete development. Intensive scientific attempts to improve concrete's compressive strength began in the 1930s [4-6].

Ultra-High-Performance Concrete (UHPC) is an innovative cement-based composite material that outperforms traditional concrete in terms of mechanical and durability [7-11]. UHPC is gaining popularity in research and commercial applications. Although UHPC applications have been successfully proven in many nations, mainstream adoption remains a challenge. Several impediments are identified, including a lack of understanding of structural behavior, material characterization processes, and generally accepted design codes. The ability to design lightweight and slender structures is one of the driving elements behind increased utilization [12-15] . Others include lower costs, a smaller environmental footprint, and fewer maintenance requirements.

Existing codes for conventional concrete production and structural application do not fully apply to UHPC. Several nations, including Germany [16], Switzerland [17], Australia [18], Canada [19], Spain [20] and Japan [21], are developing design guidelines or recommendations for UHPC. Each of these nationally evolving design guidelines has various material characterization needs, and each takes a different approach to the design process. Already in 2002, the Association Française de Génie Civil (AFGC) issued design recommendations for UHPC [22]. In 2016, a version of this was adopted in France as a national appendix [23-28] to the ordinary concrete design code (Eurocode 2).

Generally these different properties of fiber yield different effects when added to their respective concretes. For the microstructure of concrete, Marković [29] indicated that the micro fiber (shorter than 0.1 mm) has a more homogenous distribution in concrete, leading to a higher packing density of cement matrix. Keer [30] reported that synthetic fiber increases the permeability of concrete due to their porous interfacial transition zone (ITZ). As far as the mechanical performances of concrete are concerned, various researchers [15, 31-35] have studied the fibers' effect on concrete under compression or tension. They have reported that the fibers increase the tensile strength of concrete, but not necessarily its compressive

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strength. They have also found that the macro fiber has an efficacious capacity against the macro cracking of concrete in the post-peak phase. Nataraja, et al. [36] reported that fibers with a greater ratio of L/f yield a higher compressive strength in the concrete. Zheng and Feldman [37] showed that fibers with higher tensile strength and higher elastic modulus could significantly improve the mechanical performance of concrete [38-43].

Many researchers have conducted studies on UHPC, but information on the materials and structural properties of UHPC are still limited. This review includes four parts. The purpose of this review is to summarize previous research 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) [15, 33-35, 44]. Manipulation refers to the early-age procedures of placing, compacting, and finishing [45]. 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 [46]. 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 [8, 9, 47-50].

During the UHPFRC manufacturing 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 [51]. 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 [52]. 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, et al. [51] 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, et al. [53], 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 [29], Naaman and Wille [54]. Khan, et al. [55] 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 ± 2s, corresponding to the optimal plastic viscosity (53 ± 3s). Furthermore, Ferrara, et al. [56] discovered that the type of placing of fresh UHPC in the mold, rather than the casting technique utilized, has a substantial impact on uniform fiber distribution [57-61]. 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 [62-70].

Table 1. Workability measurements and fiber details [53].

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)

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. 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 [71-77]. 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 [78] [79-82]. 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 [83-87].

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 [88-91]. 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 [33, 38-40, 92].

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 [93]. 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 [78] [94-96].

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 [89-91, 94-96]. 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 [24-26, 97-101].

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 [102]. The level of induced pulses on different areas of the concrete coupons might be used to determine the integrity of the concrete using UPV [103]. 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 [104], admixture [105], 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 [106].

2.3. Rheology

The better 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) [107] and air detraining admixtures [108]. 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 [73-77, 88]. 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, et al. [109] 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 [109]. Meng and Khayat [107] investigated the rheological flow behavior of UHPC mixtures and discovered a linear relationship between shear stress and strain rate. Arora, et al. [110] 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 [111] and the mixture ingredients utilized in the various investigations [79-82, 112]. 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 [41-43, 57, 59, 113].

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

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 [114] and is taken as 0.65 for monodisperse randomly close-packed spheres [η] is the intrinsic viscosity, which is taken as 2.5 for non-Brownian rigid spheres [84-87].

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

Rheological parameter	Conventional concrete [115]	High-performance concrete [116]	UHPC [107, 117]	Self-consolidation concrete [118]

Plastic viscosity (Pa.s)	50–100	50–550	20–200	100–400
Yield stress (Pa)	500–2000	50–2000	10–100	5–50

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 [119]. 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 [13, 61, 119-121]. 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 [122].

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 [123-126].

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 [124-127]. 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 [60, 61, 71, 72].

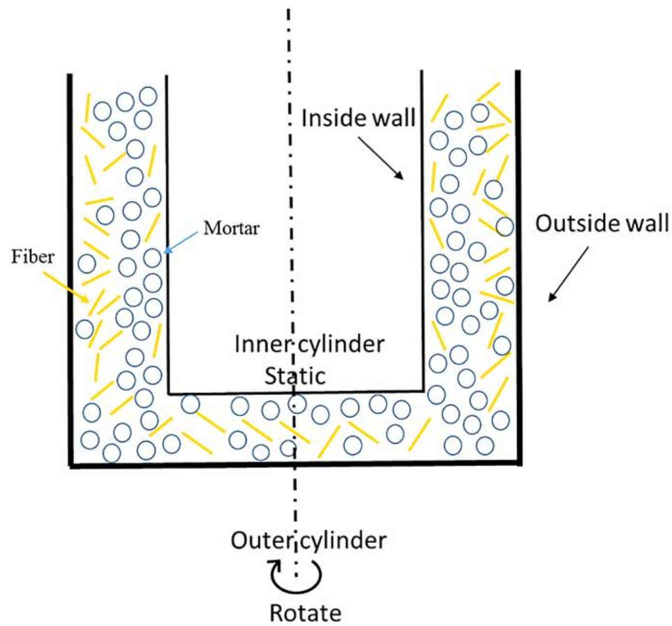

Fig. 1. Concentric/coaxial cylinder rheometer particle movement [127].

3. Conclusions

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

1. In UHPC matrices, 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

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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.

Conflicts of interest / Competing interests

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.

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