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The Effect of Fibre in Ultra High-Performance Concrete (UHPC): A Review

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Abstract

Ultra high-performance concrete (UHPC) is a novel material with superior strength, durability, and ductility compared to conventional concrete. The addition of fibers to UHPC enhances its mechanical properties, improves its ductility, and enhances its resistance to cracking and spalling. This review paper provides a comprehensive overview of the effect of fibers on the properties of UHPC. The intention is to give an overview of the research field and supply guidance for future research. The paper describes the different types of fibers that can be added to UHPC and their characteristics. The review examines the effect of fiber content, length and aspect ratio on the mechanical properties of UHPC.

Keywords: *Ultra High-Performance Concrete (UHPC), fibre reinforcement, Compressive strength, Orientation, aspect ratio.*

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I. INTRODUCTION

Ultra-high-performance concrete (UHPC) is a relatively new material that has gained popularity in recent years due to its exceptional mechanical properties, such as high compressive strength, low permeability, and high durability. UHPC is an advanced fiber-reinforced concrete that consists of a high volume of cement, silica fume, fibers, superplasticizer (SP) and other supplementary cementitious materials. It is designed by the dense packing theory of solid materials, and keeping the water content very low (w/b < 0.2). These features lead to the high compressive strength of UHPC (>150 MPa, approximately 3–16 times higher compared to normal concrete), as well as excellent ductility and energy absorption properties [1].

However, UHPC has some drawbacks, such as its brittleness and natural tendency to form shrinkage cracks. One strategy for overcoming these restrictions and improving UHPC performance is fibre reinforcement. In the past few decades, there has been a lot of research on the use of fibres in UHPC, and the findings are encouraging. Research has been done on the effects of various fibre types on the characteristics of UHPC, including steel, polypropylene, glass, carbon, natural fibres, etc. Although UHPC applications have been successfully demonstrated in several nations, their use remains less widespread. There are a number of known challenges, such as a lack of understanding of structural behaviour, methods for material characterization, and widely used design standards. Possibility of designing light and thin structures is one factor encouraging increased use [2].

UHPC is a type of concrete that has high compressive strength (150–200 MPa), a lower water to cement ratio of 0.2 or less, high bending strength, tensile strength >7 MPa, a maximum aggregate diameter of less than 1 mm, superior ductility in tension and bending, high fracture toughness, and low maintenance requirements. It has a high workability (200 mm) and maintains its pumpability despite having a low water to cement ratio [6–9]. Due to its superior compressive and tensile strengths and toughness performance, UHPC has been a desirable alternative material for high elevation buildings, pre-stressed girders, as well as long span bridges [10,11].

II. FIBRE REINFORCEMENT IN CONCRETE

Fiber reinforced concrete (FRC) has been used in modern construction for more than 60 years [12]. However, the idea of adding fibres (like straws and horsehair) to brittle materials to strengthen them was developed more than a thousand years ago [13]. The construction industry now uses a variety of fibre reinforced concrete types for various applications [14]. One of them is UHPC with fibre reinforcement, also known as UHPFRC. Reducing the brittleness of the cementitious matrix is one goal of using fibres. Fibers can control the brittle fracture process, affect cracking behaviour, and provide strength and toughness after cracking [12].

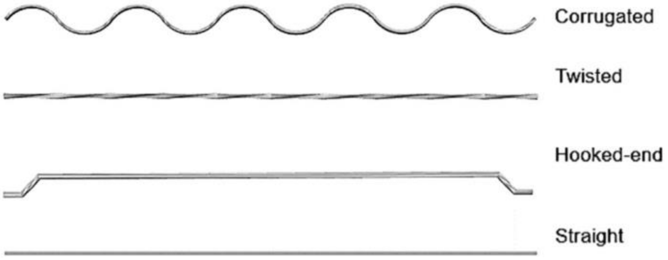


Figure 1: Some frequently used steel fibres [16]

The fibre reinforcement can be characterised by differences in material (steel, mineral or synthetic fibres), geometry, aspect ratio (fibre length divided by fibre diameter) and mechanical properties [15]. Different sizes of straight fibres as well as different deformed fibres, such as hooked-end, corrugated, and twisted fibres, are available in a variety of geometrical lengths and shapes (Fig. 1). The volume fraction or percentage (vol.-%) is the standard way to express the fibre content. For the same volume fraction, smaller fibre geometry will produce more fibres than larger geometry. Longer fibres can increase the ultimate strength by being able to control the propagation of macrocracks, whereas a high number of smaller fibres are more densely distributed in the cementitious matrix and can effectively control the development of microcracks [13]. When compared to commercially available UHPC-mixes, the fibre volume fraction in conventional FRC frequently ranges from 0.25 to 2 vol-% [16, 17], whereas it has been reported that between 2 and 6 vol-% of fibres are present in UHPC-mixes [18]. The mechanical properties are anticipated to be impacted by both fibre content and geometrical variations (shape, length, aspect ratio).

III. IDEAL UHPC

Three factors affect the strength of UHPC: the pore structure of the cement paste, the quality of the aggregate, and the structure of the aggregate-matrix and fiber-matrix interfaces. The interface area, which is the weakest of these qualities, could be strengthened by lowering the water to cement ratio and keeping aggregate diameter below 1 mm. Both techniques have upper bounds, though. Fly ash, slag, and silica fume are examples of cementitious materials that not only reduce production costs but also improve strength [4, 19, 20]. High strength concrete is directly impacted by the aggregate quality. UHPCs are not generally used when traditional concrete is productive because of its elevated manufacturing price, providing the required output. In this regard, researchers identified three key elements that can be reduced to lower costs without sacrificing product quality, namely the amount of high-strength fibre added to the mixture, the amount of powder, and the curing [21,22]. In most cases, natural sand can be used in place of silica sand while maintaining superior mechanical performance and ductility. UHPC strength is unaffected significantly using natural sand [22]. The fibre content can vary significantly depending on the concrete type and application.

The fibres in concrete are typically a mixture of several short fibres and a few longer fibres when the workability attribute is crucial [23]. However, it has been shown that 2.5% steel fibres with an aspect ratio of 40 to 60 produce the best results in terms of fresh and hardened concrete characteristics. To ensure low porosity, the fibres' length should be set to the largest aggregate diameter. The length of the fibre should be at least ten times the maximum overall diameter. The UHPC can't be used unless high-performance plasticizers are added. The ability of the fibres to mix into the concrete and the workability of the concrete are significantly influenced by the aspect ratio of the fibres. Particularly as the aspect ratio rises, workability declines. There are four requirements that must be met in order to get the best performance out of UHPCs: (1) using sand with a grain size of 150 to 600 mm to increase homogeneity, (2) adding cement and silica fume to increase density, (3) adding steel fibres to increase ductility, and (4) applying temperature treatment (90 °C) to enhance the UHPC microstructure and increase early age durability [24,25].

IV. PROPERTIES OF FIBRE REINFORCEMENT

Several investigations examined the effect of fibre content by increasing the content from 0 up to 2–3 vol-%. Only five of the investigations reviewed [26, 27] examined the impact of fibres above 4 vol%. Numerous studies have looked into the impact of fibre shape [26, 28, 29, 30] and compared it to various deformed fibre types (hooked-end, corrugated, twisted, and spiral) of various lengths and diameters. Hooked-end fibres with a length of 30 mm and a diameter of 0.3 to 0.6 mm were frequently investigated among the deformed fibres [26, 28, 29]. Micro hooked-end and corrugated fibres were investigated in some studies [28].

Straight microfibers with a diameter of about 0.2 mm and a length of 12–13 mm was the most frequently studied type of fibre [26, 27, 28, 29, 30]. Eleven of the papers that were included reported on hybrid combinations

[26], whereas many papers [27, 28, 29, 30] reported on the effects of single fibre combinations. The following provides a summary and discussion of the findings from all of those.

V. COMPRESSIVE STRENGTH

5.1 TEST SETUP

In order to measure compressive strength, cylinders or cubes are subjected to increasing compressive loads until failure. The dimensions of the test specimens and the loading rates for conventional concrete are governed by a number of standards. With minor adjustments and requirements, these procedures are frequently suitable for UHPC [1]. The included studies used cubes ranging in size from small cubes (40-50 mm) [26, 27, 28, 29, 30] to larger cubes (100-150 mm) [26, 27, 28, 29, 30] for compressive testing. Additionally, compressive strength tests on cylindrical specimens of various sizes were conducted [26, 27, 28, 29, 30]. It has been noted that the test specimen size variations can affect the results of compressive strength [26, 27]. A study by Josef and Bílý´ [30] showed that size dependency decreases with increasing strength and varies for different mix composition, making the issue of size effect rather complicated. The included papers do not completely address the question of whether variations in size and geometry affect the effectiveness of fibre reinforcement. Only three studies [31, 32, 33] looked into the effects of using cylinders and different-sized cubic samples (50 mm and 100 mm cubes). In the majority of investigations, compressive strength measurements were taken in accordance with a standardised process. This might be the Eurocode (EN 12390–3:2009–7) [34], the ASTM standard C39 [41,42], the Korean standard (KS F 2405) [62] or the Chinese standard (GB/T 17671-1999) [36]. Other studies used the ASTM standard C1609 [37] or the Chinese standard CECS 13:2009 [38] as standards for fibre reinforced concrete. Chinese standard GB/T 31387-2015 for reactive powder concrete has been used in two studies [39]. No study made use of a standard specifically created to measure the compressive strength of UHPC. The French standard for the production of UHPFRC [35] and Swiss recommendation for UHPFRC [4] are both referring to the European standard for conventional concrete, EN 12390-3 [34]. A practise standard for the production and testing of UHPC has been published by ASTM [40]. Also, this standard refers to a test method for conventional concrete, ASTM C39/C39M Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [41]. Other UHPC standards could also be referencing conventional concrete standards.

5.2 EFFECTS OF STEEL FIBRES ON COMPRESSIVE STRENGTH

Like conventional concrete, compressive strength is one of the most significant and frequently measured properties of UHPC [1]. To prevent explosive behaviour at failure, fibre inclusion is crucial [32, 25, 30, 35]. UHPC with fibres exhibits compressive behaviour similarly to conventional concrete with only minor differences. The increased stiffness and compressive strength make the biggest difference. The constituent materials, mix proportions, curing circumstances, and fibre content all affect compressive strength [1]. Many of the included research papers discussed how steel fibres affected compressive strength.

In different studies, the effect of fibre content on compressive strength has been examined. According to some studies, fibre inclusion only had a 10% or less impact on compressive strength [21, 32, 35, 39]. According to Arora et al. [24], the volume of hydration products and the packing density of aggregates have a significant impact on compressive strength. More significant effects were discovered in other studies; the addition of fibres increased compressive strength by more than 50% [31]. The capacity of the fibres to postpone the development and spread of cracks may help to explain this increase [31, 45]. The compressive strength increased in line with an increase in fibre content [31, 33, 27, 45]. However, adding more fibres might eventually have a negative impact on compressive strength. This effect was described by Meng and Khayat [26] when the fibre content was greater than 3 vol-%. Fiber agglomeration and trapped air were used to explain the detrimental effect on compressive strength. Le Hoang and Fehling [35] reported that the mixes with 3 vol-% of fibres also exhibited fibre agglomeration.

It is clear from the cited papers that the inclusion of any volume fraction of fibres has little impact on the compressive strength of cylindrical test specimens. The presence of fibres appears to result in a slight boost in compressive strength for large cubes (100 mm). However, this effect does not appear to depend on the fibre fraction; rather, it appears to only distinguish between UHPC that has been reinforced with fibre and one that has not. Small cubes (40–50 mm) are the only ones that appear to benefit from an increase in the volume fraction of fibres up to 3 vol%. The compressive strength appears to be decreasing for higher levels towards the level of UHPC without fibres. Possible explanations for this decline in compressive strength include fibre agglomerations, decreased workability, and trapped air. A significant question, though, is whether some of the observed variations in results can be attributed to test specimen geometry rather than actual fibre effects. In comparison to cubes, cylinders are generally thought to represent a more uniaxial stress distribution. Due to the presence of corners and lower height/cross-section dimension ratio, internal shear stress has a greater impact on compressive failure in cubes. The variations in test results may be better explained by variations in factors like constituent materials, mix proportion, and curing regimes than by variations in test specimen geometry. As a result, we can say there is a possibility that the geometry of the test specimen may have an impact on the results of investigations but it is to be proved for the same.

Deformed fibres can more effectively span cracks because they have higher pull-out strength than straight fibres [26, 27]. The improved pull-out strength is not evident on the compressive strength of UHPC; all papers concluded that the influence of using deformed fibres was within ± 15%. Little difference in compressive strength was discovered by Liu et al. [36] when they compared macro (l = 30 mm) and micro (l = 13 mm) hooked-end fibres. Yoo et al. [42] observed a slight increase in compressive strength for straight fibres compared to macro deformed fibres. This result was explained by the greater number of fibres available to bridge and postpone the spread of microcracks in comparison to deformed macro fibres. Furthermore, a worsened fibre distribution was seen for the deformed fibre types. Differences in fibre length were also found to have a low level of influence (±15%) [20, 23, 35, 39, 42].

VI. EFFECTS OF FIBER GEOMETRY, LENGTH, AND VOLUME CONTENT

An innovative form of twisted steel fibre known as "Torex fibre" was created by Naaman [51] in the late 1990s. This fiber's polygonal cross-sectional geometry, which allows for twisting along its axis, is made possible by the use of very high-strength steel wire.

The fibre intrinsic efficiency ratio, which is closely related to the post-cracking strength of composites, was the fundamental concept used to determine the cross-sectional geometry of the Torex fibre. Compared to a circular fibre with an identical cross-sectional area, triangular or square-shaped fibres are 28% and 12% more effective at raising the value of the FIER, respectively [52, 53]. The adhesion and frictional bonding elements improved as the FIER value increased, and twisting the fibres improved the mechanical bond. Figure 3 [48, 54] depicts the typical fibre stress and slip curves for straight, hooked-end, and twisted steel fibres embedded in a UHPFRC matrix.

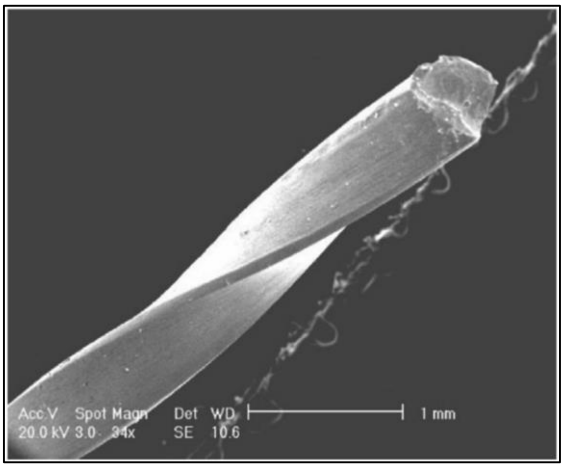


Figure 2: Typical example of Torex twisted triangular steel fiber [43]

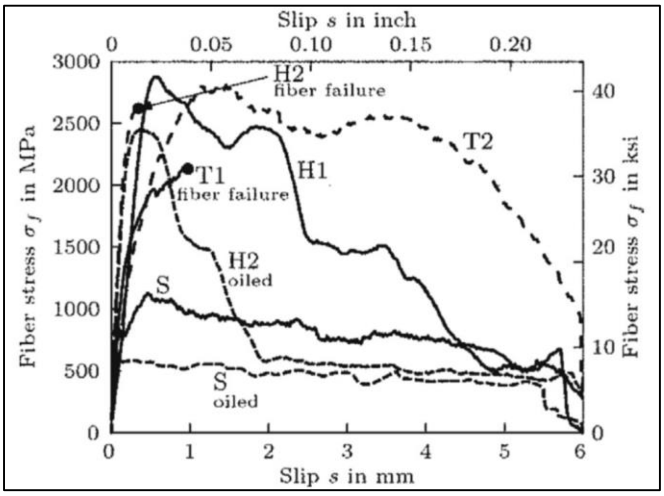


Figure 3: Effect of fiber geometry on pullout behavior of steel fibers embedded in UHPFRC matrix (S = straight, H = hooked-end, and T = twisted) [44]

As shown in the figure, Wille and Naaman [48] stated that the use of twisted (and hooked-end) steel fibres produced a maximum fibre stress that was three times greater than that of the short straight steel fibres (df = 0.2 mm and Lf = 13 mm); sf,max = 2900 MPa vs. sf,max = 1100 MPa, respectively). With the use of the deformed (twisted and hooked-end) steel fibres, as opposed to the short straight steel fibres, the tensile strength and post-cracking strain capacity of UHPFRC were also significantly improved [7, 54].

Tensile strength and strain capacity of the specimens with 2 vol% of twisted steel fibres were 14.9 MPa and 0.61%, respectively; these values are roughly 32% and 205% higher than those of the specimens with 2 vol% of short straight steel fibres (Fig. 4).

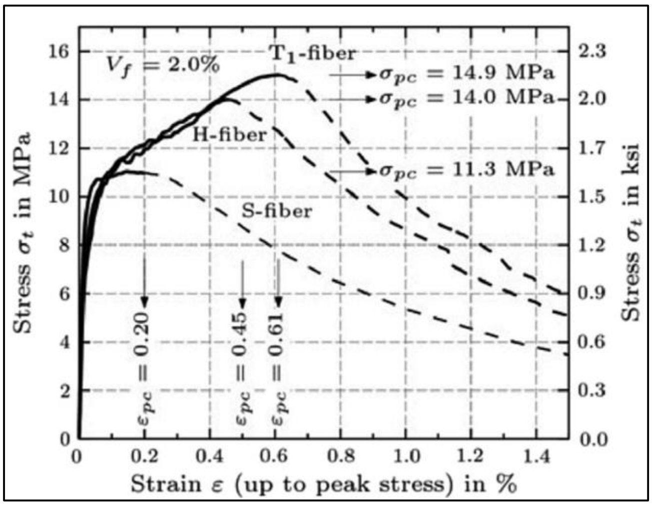


Figure 4: Comparison of direct tensile response of UHPFRC with different types of steel fibers at Vf = 2.0% [45]

Additionally, according to Yoo and Yoon [49], UHPFRC beams with twisted steel fibres have a flexural strength that is roughly 1.7 times greater than beams with short straight steel fibres. By using twisted steel fibres instead of short, straight steel fibres, the compressive behaviours, such as the compressive strength, strain capacity, and elastic modulus, were also improved. However, the improvement was relatively negligible in comparison to what was seen for the tensile and flexural performance. Using long, straight steel fibres, Yoo et al. [3, 50, 54] recently proposed a different technique for enhancing the flexural performance of UHPFRC under uniaxial and biaxial stress states as well as its fracture energy capacity.

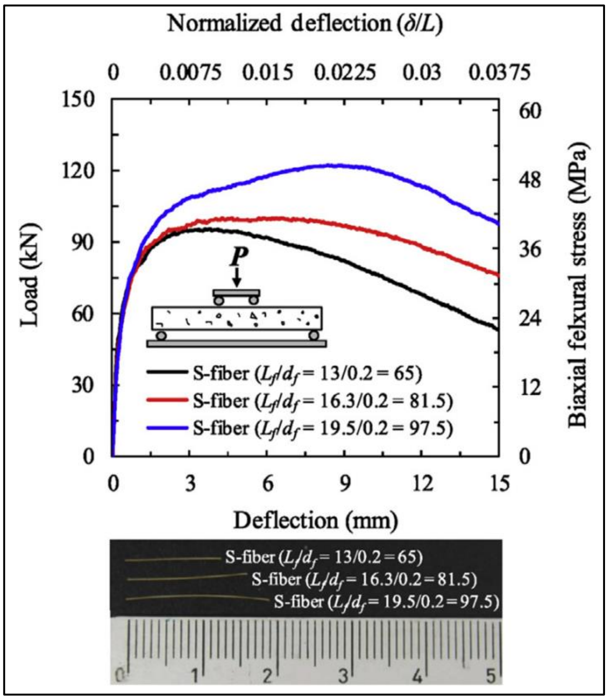


Figure 5: Biaxial flexural response of UHPFRC panels (placing concrete at the center) [46]

As seen in Fig. 5, lengthening the fibres significantly increased the flexural strength, deflection capacity, and toughness of UHPFRC. The flexural strength and deflection capacity of UHPFRC panels with long straight steel fibres (Lf/df = 19.5/0.2 = 97.5) were respectively 26% and 13% higher than those with medium (Lf/df = 16.3/0.2 = 81.5) and short (Lf/df = 13/0.2 = 65) straight steel fibres. Additionally, compared to medium and short steel fibres, fracture energies that were almost 121% and 35% higher were obtained when using long steel fibres [3]. This is primarily brought on by the fact that using longer steel fibres expands the area where the fibre and matrix are bonded, which increases the fiber's capacity to carry load and slip [51]. Additionally, the fibre length at the same diameter had a negligible impact on the number of fibres at crack surfaces, which is a significant factor influencing the post-cracking tensile behaviour. For instance, the numbers of fibers per unit area were found to be 34.00/cm2 for short fibers, 33.12/cm2 for medium fibers, and 35.79/cm2 for long fibers [3]. Although the actual number of fibres included in the mixture decreases with fibre length at an identical volume fraction (because the fibres are included in the mixture based on their volume content), the likelihood that fibres will be present at crack surfaces increases with fibre length, which accounts for the negligible change in the number of fibres detected per unit area. As the fibre volume fraction increased, the post-cracking flexural strength, strength factors in the tri-linear (or bi-linear) tension-softening curve, and fracture energy increased almost linearly. In contrast, the fibre volume fraction had little impact on the first-cracking flexural strength and the corresponding deflection [31,52,53].

Up to a fibre volume fraction of 3%, adding more steel fibres marginally increased the elastic modulus and compressive strength [53]. The ideal fibre volume fraction that yields the highest compressive strength varies depending on the researcher because the homogeneity of the fibre dispersion has a significant impact on compressive strength. According to Prabha et al. [54], UHPFRC with 2 vol% of 13-mm-long straight steel fibres provided the highest compressive strength up to a fibre volume fraction of 3%, while Yunsheng et al. [31] reported that the compressive strength continuously increased with an increase in the fibre volume up to 4% (the specimen with 4 vol% of steel fibres exhibited a compressive strength that was 30–50 MPa higher than that without fibres). Additionally, by including up to 2 vol% of steel fibres in the matrix, the performance of the fibre pullout was enhanced [53]. Tensile strength and strain capacity of UHPFRC were increased from 8 to 14 MPa and 0.17 to 0.24% for straight steel fibres and from 8 to 15 MPa and 0.33 to 0.61% for twisted steel fibres, respectively, by increasing the fibre volume from 1.5 to 2.5%. The tensile strength of UHPFRC increased with increasing fibre volume from 9 to 14 MPa in the case of hooked-end steel fibres, but the strain capacity remained constant at roughly 0.46% [7].

VII. EFFECTS OF FIBER ORIENTATION

UHPFRC has been used to fabricate structures using a variety of placement techniques due to its high fluidity and suitable viscosity to prevent fibre segregation from the cement matrix [55-58]. According to Boulekbache et al.'s study [59], which is depicted in Fig. 6, different flow velocities cause the fibres in flowable fiber-reinforced concrete to rotate. The fibres are affected by the fluid's forces and moments, which causes them to be aligned either parallel to the flow direction (shear flow in Fig. 6(b)) or perpendicular to the flow direction (radial flow in Fig. 6(a)).

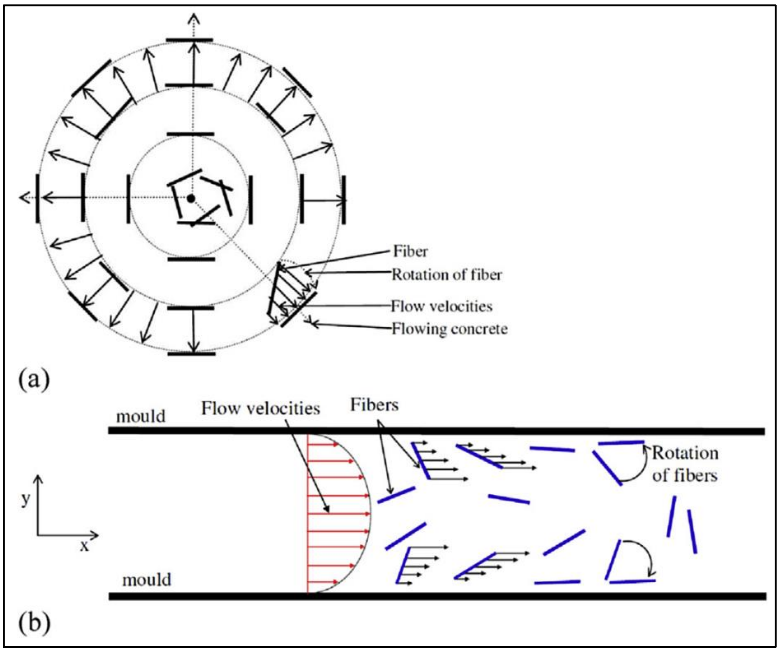


Figure 6: Schematic view of fiber orientation in (a) fountain (radial) flow, (b) canal channel (shear) flow [47]

Using two different placement techniques, Yang et al. [55] constructed steel bar-reinforced UHPFRC beams: (1) placing concrete at one end of the forms and letting it flow to the other end, and (2) placing concrete at the centre and letting it flow to both ends. According to their test results, the beams with concrete placed at one end were able to support a maximum load that was 15% greater than those with concrete placed in the middle. This results from more fibres being oriented in the direction longitudinal to the beam length due to UHPFRC's flowability. Along with producing rectangular slabs using various placement techniques, Ferrara et al. [56] and Kwon et al. [57] also looked into the impact of fibre orientation on the flexural performance of UHPFRC. The beams (T series) placed in the vertical direction of the flow direction performed poorly in comparison to the beams (L series) placed in the parallel direction in the case where concrete was placed at one short edge of the mould and allowed to flow [56]. This resulted from the fibres' perpendicular alignment to the beam length, as depicted in Fig. 7.

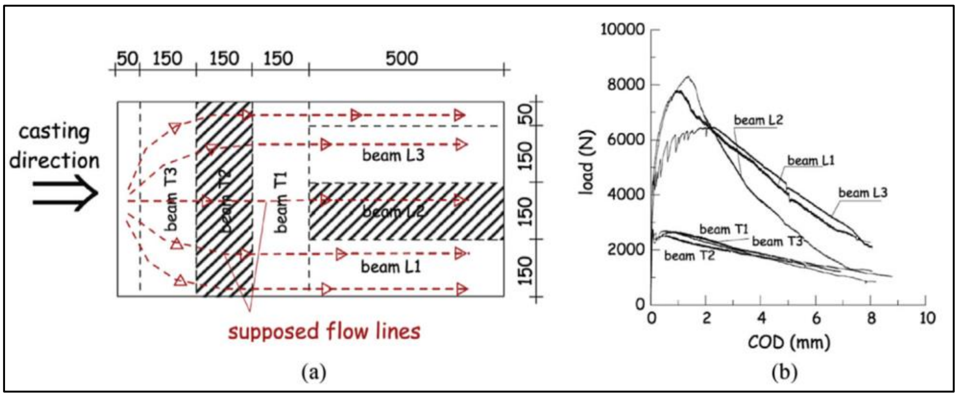


Figure 7: Effect of fiber orientation on the flexural response; (a) schematic view of slab casting and beam cutting, (b) flexural load-COD curves [48]

The beams placed parallel to the flow direction also demonstrated significantly lower load carrying capacities than the beams in other areas for the case where concrete was placed at the centre (radial flow) [57]. Additionally, they displayed deflection softening behaviour, which is unusual for UHPFRC flexural behaviour. The aforementioned observations make it abundantly clear that the characteristics of the fibre orientation have a big impact on the mechanical and structural performance under tension and flexure. In order to quantitatively assess how the fibre orientation characteristics, affect the mechanical properties of UHPFRC, a number of studies [3,4,50,51,56] were carried out and produced some insightful results. The flexural behaviour of uniaxial UHPFRC beams was studied by Wille and Parra-Montesinos [60] in relation to the casting method (layer-casting and middle-casting) and casting speed of a layer-casting method. They claimed that by speeding up the casting process, it was possible to avoid a snake-like flow pattern and obtain a thinner layer with a preferred fibre alignment in the beam axis, which enhanced flexural performance. Additionally, the middle-cast beams showed a middle flexural strength value between the layers-cast beams with a high casting speed and the middle-cast beams with a low casting speed. Similar to this, Yoo et al. [3] reported that beams cast in the middle provided higher flexural strength than beams cast in the edge; however, the casting method had no appreciable impact on the fracture energy because the advantage of the higher strength was counterbalanced by a steeper decrease in the post-peak stress. As shown in Fig. 8, they also carried out image analysis in order to rationally analyse the test results and confirmed that the beams cast in the middle contained more steel fibres than the beams cast in the edge did (at the region of maximum moment).

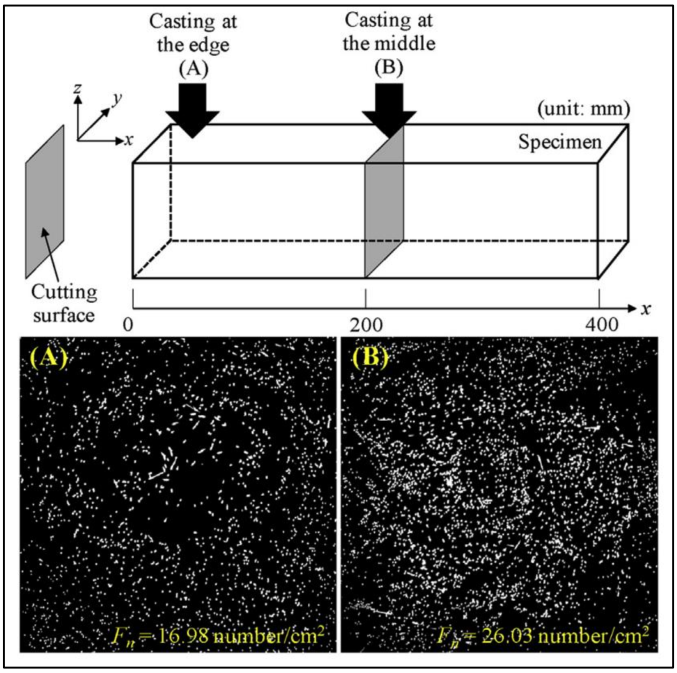
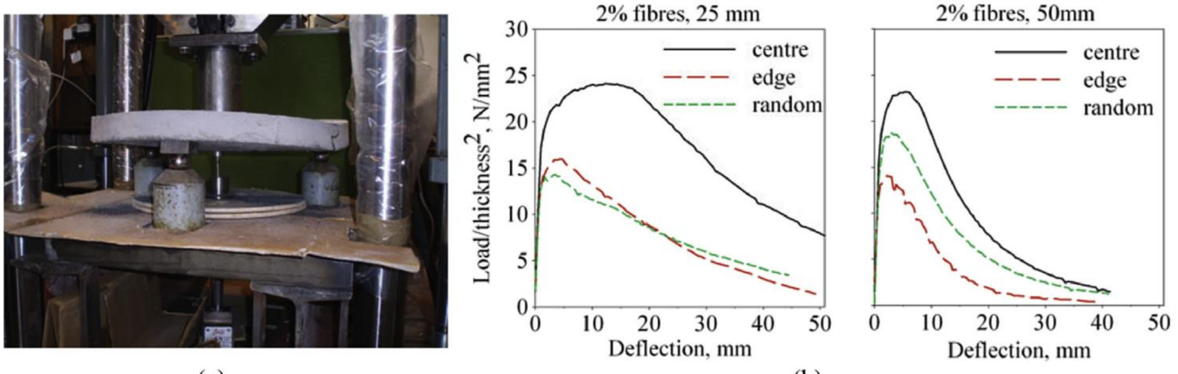


Figure 8: (a) schematic description of cross-sectional saw cut of UHPFRC beams, (b) transformed binary images obtain at the middle of beams with a size of 100x100x400 mm3 (using straight steel fibers with a length of 30 mm and a diameter of 0.3 mm) [49]

In comparison to panels cast using other placement techniques, such as casting randomly, casting at one edge, and casting at various points around the panel's perimeter, UHPFRC panels cast in the centre demonstrated noticeably higher flexural strengths. Fig. 9 displays the test outcomes from ASTM C 1550.



(a) (b)

Figure 9: Round panel tests; (a) picture for test setup (ASTM C 1550), (b) biaxial flexural behaviors [50]

Barnett et al.'s [4] analysis of X-ray computed tomography (CT) helped to explain their findings. As an alternative, Yoo et al.'s [50] image analysis was carried out using binary images at the crack surfaces that were transformed from RGB images obtained with a high-resolution camera. From these analyses, they deduced that, in contrast to other panels with different placement techniques, a greater proportion of the steel fibres in the panels cast in the centre were aligned perpendicular to the flow direction because of the gradient of the flow velocity. The panels cast in the centre had greater flexural strength and toughness compared to their counterparts as a result of the improved fibre alignment. Based on Jeffery's equation [65] and the supposition that there were no interactions between the fibres, Kang and Kim [62] numerically examined the rotational motion of the fibres. They claimed that as the flow distance increased, the fibres gradually grew more perpendicular to the flow direction (for radial flow) and parallel to the flow direction (for shear flow). These numerical outcomes are in line with the outcomes of the shear and radial flow image analysis performed by Yoo et al. [3,51].

VIII. CONCLUSION

The research papers were analysed by using a structured literature search to look at the effects of fibre content, type, and combination on the compressive strength of UHPC. The study's findings demonstrate that:

- Despite the development of specific UHPC standards, standardised practises for conventional or fibre reinforced concrete are frequently used. Even the dedicated UHPC standards refer to conventional concrete standards for some tests, like compressive strength.
- The test results are frequently said to be affected by geometry differences. It is evident from the analysis of the total results from all the papers included in this review that the geometry affects compressive strength.
- There have been investigations into different fibre types, from micro to macro, straight or deformed (hooked-end, twisted or corrugated). High strength steel fibres (tensile strength > 2000 MPa) were primarily used for all fibre geometries. The cumulative results indicate little difference between using straight and deformed fibres for compressive strength. At at higher fibre volumes, straight fibres perform better. As a result, the ideal fibre type appears to be influenced by the fibre volume fraction. The strength decreases at high content levels. Fibre agglomeration and air trapped inside the fibres may help to partially explain this.
- In UHPC, fibre reinforcement is required to prevent explosive behaviour during failure. Several investigations reported that the compressive strength was affected by the inclusion of fibre reinforcement, giving UHPC higher strength. However, there was little discussion of the effects of variations in test specimen geometry and other variable factors. When the individual results are contrasted, it appears that adding fibres has little impact on compressive strength when tested on cylinders but more significant effects when tested on large cubes (100 mm). For small cubes (40–50 mm) there seems to be an increase in compressive strength as a function of fibre content up to 3 vol-%.

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