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Review article

The influence of steel fibres on compressive and tensile strength of ultra high performance concrete: A review

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HIGHLIGHTS

- Effects of fibres on compressive and tensile strength of UHPC are reviewed.
- A variety of specimen geometries, sizes and procedures are applied.
- Fibres have potential to improve the tensile strength of UHPC.
- Effects on tensile strength depend on fibre content, type and hybrid combination.
- The influence of fibres on compressive strength is questionable.

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ABSTRACT

This review paper presents the effects of steel fibre reinforcement regarding the compressive and tensile strength of UHPC. The intention is to give an overview of the research field and supply guidance for future research. Relevant papers were identified through a systematic literature search. An accumulation of the results shows that fibres have potential for improving the tensile strength of UHPC. The effect depends on fibre content, type and hybrid combinations. The effect of fibres on compressive strength seems to be questionable. Variations in test specimen geometry and other factors might also influence the results.

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1. Introduction

Ultra High Performance Concrete (UHPC) is an advanced cement-based composite material with improved mechanical and durability properties compared to conventional concrete [1]. There is an increasing interest for research and commercial use of UHPC. Although applications of UHPC has been successfully demonstrated in several countries, widespread use is still limited. Several obstacles are known, including lack of understanding of the structural behaviour, procedures for material characterisation and generally accepted design codes. One driving force for increased use is the potential to design low-weight and slender structures [2]. Others are reduced cost and environmental footprint and low maintenance requirements.

The existing codes for production and structural use of conventional concrete are not fully applicable for UHPC. Design guidelines or recommendations for UHPC are currently emerging in several countries, including Germany [3], Switzerland [4], Australia [5], Canada [6], Spain [7] and Japan [8]. Each of these nationally emerging design guidelines has different requirements for material characterisation, and each approaches the design process differently. The Association Française de Génie Civil (AFGC) published design recommendations for UHPC already in 2002 [9]. In 2016, a development of this was adopted in France as a national appendix [10] to the design code for conventional concrete (Eurocode 2).

An essential constituent in UHPC is discontinuous fibre reinforcement. The inclusion of fibres is necessary to impose the ductility in compression, required for structural safety. Fibres prevent a brittle behaviour and might also improve several other material properties, e.g. provide exploitable tensile strength and increase the energy absorption capacity. Multiple types of fibres are used, varying in size, shape and material. Numerous factors cause variations in the distribution and orientation of the fibres, including the rheological properties of the fresh UHPC, the placement methods and the geometrical conditions shaped by the formwork. Variations in fibre content, geometry, combination, distribution and orientation are all central contributors to making the structural design of UHPC complex. Fibres are also one of the main reasons for the high unit cost and carbon footprint of UHPC. Consequently, increasing the knowledge on the effects of fibre reinforcement is an essential step towards the development of commonly accepted design codes and widespread use of UHPC.

Some review papers cover the mechanical properties of UHPC [2,11–13], but none focus specifically on the effects of steel fibre reinforcement on compressive and tensile strength. This study aims at contributing by presenting the state-of-the-art in research, based on a literature review. A preliminary version of this paper was presented and discussed on the 5th International Federation of Structural Concrete (fib) Congress in Melbourne 2018 [14]. The preliminary paper demonstrated that the research conclusions diverge considering the effects of fibres on the mechanical properties of UHPC. Enriched by the discussion at the fib Congress, this paper presents the results from a comprehensive literature review on the impact of steel fibre reinforcement on the compressive and tensile strength of UHPC.

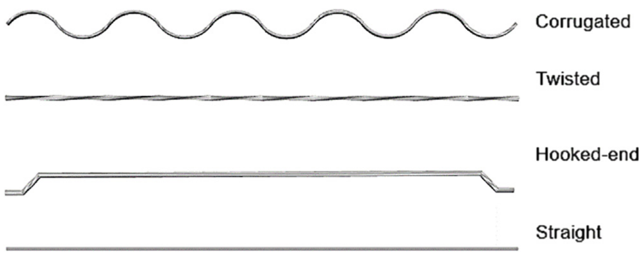


Fig. 1. Some frequently used steel fibres.

2. Fibre reinforcement in concrete

More than 60 years have passed since fibre reinforced concrete (FRC) were introduced in modern times [15]. However, the concept of strengthening brittle materials with fibres (e.g. straws and horsehair) was developed for more than a thousand years ago [16]. Multiple types of fibre reinforced concretes are now used for various applications in the construction industry [17]. One of them is fibre reinforced UHPC, often denoted UHPFRC.

One aim of using fibres is to reduce the brittleness of the cementitious matrix. Fibres can influence cracking behaviour, control the brittle fracture process and provide post-cracking strength and toughness [15]. 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 [18]. A variety of geometrical forms and lengths exists, from different sizes of straight fibres to various deformed fibres (Fig. 1), including hooked-end, corrugated and twisted fibres. The fibre content is normally stated as the volume fraction or percentage (vol.-%). Smaller fibre geometry will give a higher number of fibres than larger geometry, for the same volume fraction. The high number of smaller fibres are more densely distributed in the cementitious matrix and can efficiently control the development of microcracks, while longer fibres can improve the ultimate strength by being able to control the propagation of macrocracks [16]. The fibre volume fraction in conventional FRC often ranges from 0.25 up to 2 vol-% [19], while commercially available UHPC-mixes have been reported to contain between 2 and 6 vol-% of fibres [1]. Both geometrical differences (shape, length, aspect ratio) and the fibre content are expected to affect the mechanical properties, as discussed later in this review paper.

3. Review methodology

The objective of this literature review was to identify the effects of steel fibre reinforcement on compressive and tensile strength of UHPC. The review focused on the following questions:

- What experimental methods are used to find the impact of fibre reinforcement on compressive and tensile strengths?
- What are the effects of different fibre contents, types and hybrid combinations on the compressive and tensile strength?

3.1. Search terms and search strategies

Relevant research papers were found through a systematic literature search in Scopus and Web of Science (WoS). Both databases are widely used in engineering. Three main search categories were

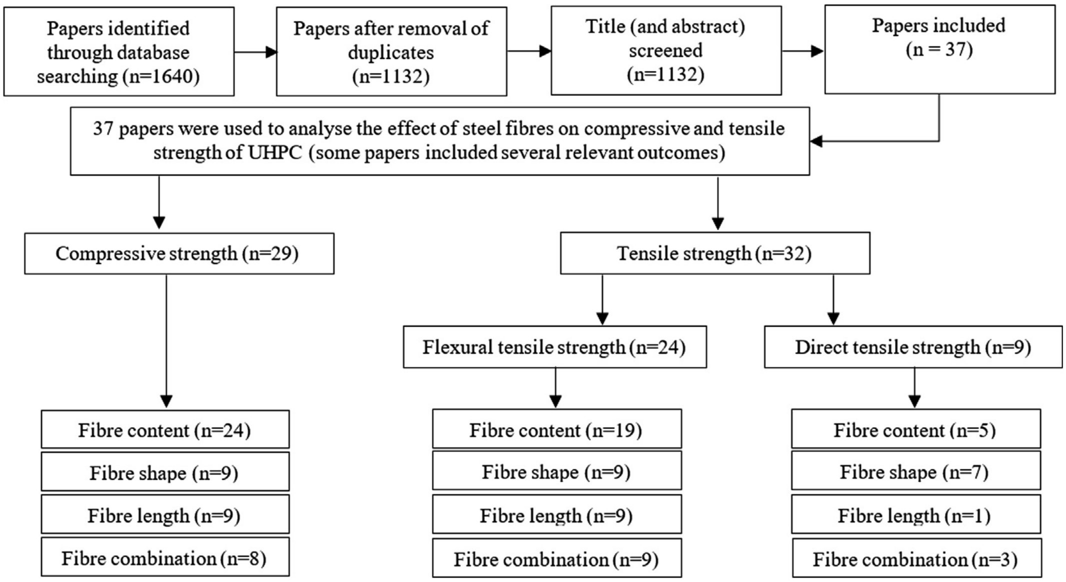


Fig. 2. Flow chart of the search process and results.

Table 1
Exclusion and inclusion criteria.

Exclusion criteria	Inclusion criteria
- Non-English language - Other document types than research papers (e.g. books, book-sections, reviews) - Numerical or analytical studies - Structural members (e.g. slabs, beams) - Other loadings than compressive and tensile strength (e.g. impact, blast, shear, fatigue) - Non-steel fibre reinforcement - Investigations of extreme conditions or curing conditions or autoclave curing	- English language - Journal or conference papers - Experimental research paper - Tensile strength or compressive strength - Investigations on the effect of fibre content, fibre shape, fibre length or hybrid fibre combinations

identified: i) Ultra High Performance Concrete, ii) steel fibre reinforcement and, iii) compressive and tensile strength. A block of keywords represented each of these search categories. The different search terms within each search block were combined with the Boolean operator “OR”. The keywords (including synonyms) were refined by finding indexed keywords or author keywords in Scopus and WoS. Each search block was searched separately, and in the end, the search blocks were combined with the Boolean operator “AND”. The search was done in Title, Abstract and Keywords (referred to as “Topic” in WoS). The search was updated in November 2019. Fig. 2 shows the flow chart of the search process and results.

After removal of duplicates (using EndNote) and studies in other languages than English, 1132 papers were identified (conference and journal papers). The titles and/or abstracts of these papers were assessed against the inclusion and exclusion criteria (Table 1). Only papers fulfilling the inclusion criteria were included for further analysis.

3.2. Data extraction and analyses

Thirty-seven papers were finally included. Relevant information from the included research papers was extracted and divided into different categories (Fig. 2). The two main categories were: “Compressive strength” and “Tensile strength”, the latter covering both “Flexural tensile strength” and “Direct tensile strength”. Each of those categories was then divided into four sub-categories: i) “Fibre content”, ii) “Fibre length”, iii) “Fibre shape” and iv) “Fibre combination”. Fibre combination refers to the use of hybrid fibre reinforcement. Relevant strength values were also extracted and analysed. Some papers had only presented the results in diagrams, not including exact values. In these cases, values were recorded as readouts from the diagrams. In cases where different test ages were presented, 28 days-strength results were extracted. For the papers investigating various parameters (e.g. w/b-ratios, type of binders, amount of superplasticiser), one parameter was chosen and kept constant.

4. Results

4.1. Properties of fibre reinforcement

Table 2 list all included papers with information about the fibre reinforcement and the measured properties (compressive strength, flexural tensile strength and direct tensile strength).

Several investigations examined the effect of fibre content by increasing the content from 0 up to 2–3 vol-% (Table 2). The effect of fibres above 4 vol-% was studied in only five of the investigations [20,28,33,38,41]. Most of the papers have reported steel fibre tensile strengths above 2000 MPa [20,23,27,29,31,33–37,39,40,42,43,45–56]. Many have investigated the effect of fibre shape [27,29,34,36–38,40,46–48,50,52–54,56], using straight micro fibres as a reference and compared it to different types of deformed fibres (hooked-end, corrugated, twisted and spiral) – all in different lengths and diameters. Amongst the deformed fibres, hooked-end with a length of 30 mm and a diameter 0.3–0.6 mm were frequently studied [26,27,29,32,34,36,38,40,43,46,47,52–55]. In some studies, micro hooked-end and corrugated fibres were investigated [23,36,37,48,50]. The most frequently studied fibre type were straight micro fibres with a length of 12–13 mm and a diameter of around 0.2 mm [20–22,24,27,30,31,33–56]. Hybrid combinations were reported in eleven of the included papers [27,34,37,38,40,43,44,49,52,55,56], while the effect of single fibre combination was reported in twenty-six [20–26,28–33,35,36,39,4

Table 2
Fibre characteristics of the included research papers.

Author(s) (year)	Relevant properties	Fibre volumes	Fibre combination	Fibre shape	Aspect ratio (l/d)*	Fibre tensile strength [MPa]	Ref.
Abbas et al. (2015)	Compressive strength, flexural tensile strength	0%, 1%, 3%, 6%	Single	Straight	8/0.2	2850	[20]
					12/0.2	2850	
					16/0.2	2850	
Allena et al. (2012)	Compressive strength, flexural tensile strength	0%, 1.5%	Single	Straight	13/**	**	[21]
Alsalman et al. (2017)	Compressive strength	0%, 3%	Single	Straight	12.7/0.2	**	[22]
Arel (2016)	Compressive strength	1.9%	Single	Hooked-end	8/0.2	2500	[23]
					13/0.2	2500	
					16/0.2	2500	
Arora et al. (2019)	Compressive strength, flexural tensile strength	0%, 1%, 3%	Single	Straight	13/0.2	1900	[24]
Bae et al. (2016)	Compressive strength	0%, 0.5%, 1%, 2%	Single	**	**	**	[25]
Chkheiwer & Kadim (2019)	Compressive strength, flexural tensile strength	0%, 0.5%, 1%, 1.5%, 2%, 2.5%	Single	Hooked-end	30/0.5	850	[26]
Chun & Yoo (2019)	Direct tensile strength	2%	Single + Hybrid	Straight	13/0.2	2788	[27]
					30/0.3	2580	
				Hooked-end	30/0.375	2900	
				Twisted	30/0.3	2428	
Erdoğdu et al. (2019)	Compressive strength, flexural tensile strength	0%, 3%, 4%	Single	Straight	6/0.15	1100	[28]
Gesoglu et al. (2016)	Compressive strength, flexural tensile strength	0%, 0.25%, 0.5%, 0.75% 1%, 1.5%, 2%	Single	Straight	6/0.16	2250	[29]
				Hooked-end	30/0.55	1345	
Hassan et al. (2012)	Compressive strength, direct tensile strength	0%, 2%	Single	Straight	13/0.2	**	[30]
Ibrahim et al. (2017)	Compressive strength, flexural tensile strength	0%, 0.65%, 1.4%, 2%	Single	Straight	13/0.2	2160	[31]
Jin et al. (2018)	Compressive strength, flexural tensile strength	0%, 1%, 2%, 3%	Single	Hooked-end	30/0.6	1100	[32]
Kazemi & Lubell (2012)	Compressive strength	0%, 2%, 3%, 4%, 5%	Single	Straight	13/0.2	2500	[33]
Kim et al. (2011)	Flexural tensile strength	1%, 1.5%, 2%, 2.5%	Single + Hybrid	Straight	13/0.2	2788	[34]
					30/0.3	2580	
				Hooked-end	30/0.375	2311	
					62/0.775	1891	
				Twisted	30/0.3	2428	
Le Hoang & Fehling (2017)	Compressive strength, direct tensile strength	0%, 1.5%, 3%	Single	Straight	9/0.15	2500	[35]
					13/0.175	2500	
					20/0.25	2500	
Liu et al. (2016)	Compressive strength, direct tensile strength	0%, 1%, 1.75%, 2.5%	Single	Straight	13/0.2	2940	[36]
				Spiral	13/0.2	2860	
				Hooked-end	13/0.2	2940	
					30/0.6	1890	
Ma et al. (2019)	Compressive strength, flexural tensile strength	2.5%	Single + Hybrid	Straight	13/0.2	2850	[37]
				Hooked-end	13/0.2	2850	
Meng & Khayat (2018)	Compressive strength, flexural tensile strength, direct tensile strength	0%, 1%, 2%, 3%, 4%, 5%	Single + Hybrid	Straight	13/0.2	1900	[38]
				Hooked-end	30/0.5	1900	
Park et al. (2017)	Compressive strength, flexural tensile strength	0.5%, 1%, 1.5%, 2%	Single	Straight	13/0.2	2788	[39]
					19.5/0.2	2500	
					30/0.3	2580	
Park et al. (2012)	Direct tensile strength	1%,1.5%, 2%, 2.5%	Single + Hybrid	Straight	13/0.2	2788	[40]
					30/0.3	2580	
				Hooked-end	30/0.375	2311	
					62/0.775	1891	
				Twisted	30/0.3	2428	
Pourbaba et al. (2018)	Compressive strength	0%, 1%, 2%, 3%, 4%, 5%, 6%	Single	Straight	13/0.16	**	[41]
Prem et al. (2015)	Compressive strength, flexural tensile strength	0%, 2%, 2.5%	Single	Straight	6/0.16	2000	[42]
					13/0.16	2000	
Ryu et al. (2012)	Compressive strength, flexural tensile strength	2%	Hybrid	Straight	13/0.2	2700	[43]
					16.3/0.2	2700	
					19.5/0.2	2700	
				Hooked-end	30/0.375	2311	

Table 2 (*continued*)

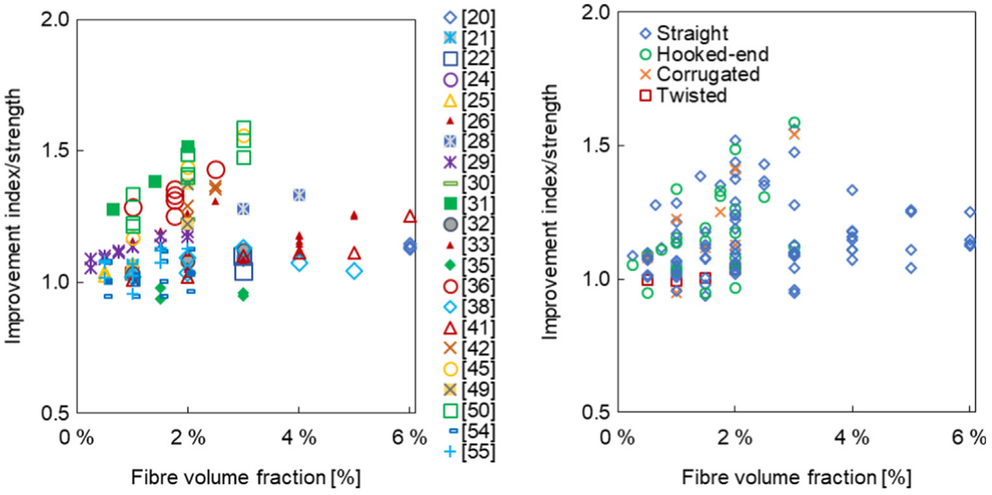
Author(s) (year)	Relevant properties	Fibre volumes	Fibre combination	Fibre shape	Aspect ratio (l/d)*	Fibre tensile strength [MPa]	Ref.
Ryu et al. (2011)	Compressive strength, flexural tensile strength	1.5%, 2%	Hybrid	Straight	13/0.2	**	[44]
					16.3/0.2	**	
					19.5/0.2	**	
Wang & Gao (2016)	Compressive strength, flexural tensile strength	0%, 1%, 2%, 3%	Single	Straight	13/0.2	2850	[45]
Wille et al. (2014)	Direct tensile strength	1.5%, 2%, 2.5%, 3%	Single	Straight	13/0.2	2600	[46]
				Hooked-end	30/0.38	2900	
				Twisted	18/0.3	2100	
Wille et al. (2011)	Direct tensile strength	1.5%, 2%, 2.5%	Single	Straight	13/0.2	2600	[47]
				Hooked-end	30/0.38	2900	
				Twisted	30/0.3	2100	
					30/0.3	3100	
Wu et al. (2018)	Flexural tensile strength	0%, 2%	Single	Straight	13/0.2	2800	[48]
				Hooked-end	13/0.2	2800	
				Corrugated	13/0.2	2800	
Wu et al. (2017)	Compressive strength, flexural tensile strength	0%, 2%	Single + Hybrid	Straight	6/0.2	2800	[49]
					13/0.2	2800	
Wu et al. (2016)	Compressive strength, flexural tensile strength	0%, 1%, 2%, 3%	Single	Straight	13/0.2	2800	[50]
				Hooked-end	13/0.2	2800	
				Corrugated	13/0.2	2800	
Yoo et al. (2016)	Flexural tensile strength	2%	Single	Straight	13/0.2	2500	[51]
					16.3/0.2	2500	
					19.5/0.2	2500	
Yoo et al. (2017 a)	Compressive strength, flexural tensile strength	2%	Single + Hybrid	Straight	13/0.2	2788	[52]
					19.5/0.2	2500	
				Hooked-end	30/0.38	2500	
				Twisted	30/0.3	2428	
Yoo et al. (2019)	Direct tensile strength	2%	Single	Straight	13/0.2	2788	[53]
				Hooked-end	30/0.375	2900	
					25/0.375	2900	
				Twisted	30/0.3	2428	
Yoo et al. (2017b)	Compressive strength, flexural tensile strength	0%, 0.5%, 1%, 1.5%, 2%	Single	Straight	13/0.2	2788	[54]
					19.5/0.2	2500	
					30/0.3	2580	
				Hooked-end	30/0.38	2500	
				Twisted	30/0.3	2428	
Yoo et al. (2017c)	Compressive strength, flexural tensile strength	0%, 0.5%, 1%,1.5%, 2%	Single + Hybrid	Straight	13/0.2	2788	[55]
					19.5/0.2	2500	
					30/0.3	2580	
Zhang et al. (2018)	Compressive strength, flexural tensile strength	2%	Single + Hybrid	Straight	13/0.2	2940	[56]
				Hooked-end	20/0.25	2860	
					20/0.35	2810	

*Length/diameter in mm **not stated

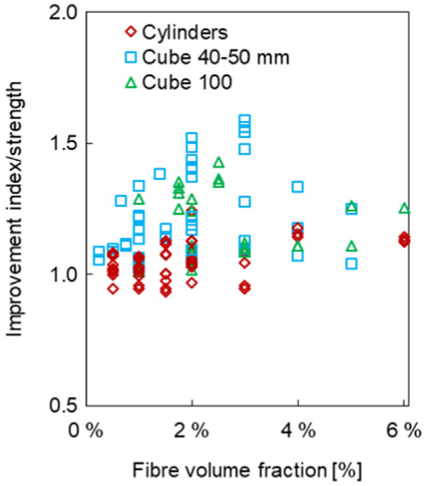
Table 3
Standards and test specimen geometry used for compressive strength tests.

Author(s) (year)	Standard	Specimen size	Ref.
Abbas et al. (2015)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [61] (ASTM International)	75 mm × 150 mm cylinders	[20]
Allena et al. (2012)	BS 1881-116, Testing concrete. Method for determination of compressive strength of concrete cubes	50 mm cubes and 100 mm cubes	[21]
Alsalman et al. (2017)	ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) [69] (ASTM International)	50 mm cubes 75 mm × 150 mm cylinders	[22]
Arel (2016)	EN 12390-3:2009-7, Testing hardened concrete. Compressive strength of test specimens [59] (European standard)	150 mm cubes	[23]
Arora et al. (2019)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [60] (ASTM International)	75 mm × 150 mm cylinders	[24]
Bae et al. (2016)	KS F 2405, Standard Test Method for Compressive Strength of Concrete [62] (Korean standard)	100 mm × 200 mm cylinders	[25]
Chkheiwer & Kadim (2019)	**	Cube (size not stated)	[26]
Erdoğdu et al. (2019)	EN 196-1:2016, Methods of testing cement - Part 1: Determination of strength [70] (European standard)	40 mm cubes*	[28]
Gesoglu et al. (2016)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [61] (ASTM International)	50 mm cubes	[29]
Hassan et al. (2012)	Purposed method	50 mm × 100 mm cylinders	[30]
Ibrahim et al. (2017)	** Loading rate given	50 mm cubes	[31]
Jin et al. (2018)	CECS 13:2009, Standard test methods for fiber reinforced concrete [65] (Chinese standard)	100 mm cubes	[32]
Kazemi & Lubell (2012)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [61] (ASTM International) ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) [69] (ASTM International)	50 mm, 75 mm and 100 mm cylinders 50 mm and 100 mm cubes	[33]
Le Hoang & Fehling (2017)	EN 12390-3:2009-7, Testing hardened concrete. Compressive strength of test specimens [59] (European standard)	150 mm × 300 mm cylinders	[35]
Liu et al. (2016)	GB/T 31387-2015, Reactive powder concrete [66] (Chinese standard)	100 mm cubes	[36]
Ma et al. (2019)	EN 196-1, Methods of testing cement—Part 1: Determination of strength [71] (European standard)	40 mm cubes*	[37]
Meng & Khayat (2018)	ASTM C109, Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or [50-mm] Cube Specimens) [69] (ASTM International)	50 mm cubes	[38]
Park et al. (2017)	** Loading rate given	100 mm × 200 mm cylinders	[39]
Pourbaba et al. (2018)	**	100 mm cubes	[41]
Prem et al. (2015)	ASTM C1609, States that this standard is used: Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading) [72] (ASTM International)	100 mm cubes	[42]
Ryu et al. (2012)	KS F 2405, Standard Test Method for Compressive Strength of Concrete [62] (Korean standard)	100 mm × 200 mm cylinders	[43]
Ryu et al. (2011)	**	**	[44]
Wang & Gao (2016)	GB/T 17671-1999, Method of testing cements – Determination of strength [63] (Chinese standard)	40 mm cubes*	[45]
Wu et al. (2017)	GB/T 17671-1999, Method of testing cements – Determination of strength [63] (Chinese standard)	40 mm cubes*	[49]
Wu et al. (2016)	** Loading rate given	40 mm cubes*	[50]
Yoo et al. (2017 a)	**	**	[52]
Yoo et al. (2017b)	ASTM C39, Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens [60] (ASTM International)	100 mm × 200 mm cylinders	[54]
Yoo et al. (2017c)	** Loading rate given	100 mm × 200 mm cylinders	[55]
Zhang et al. (2018)	GB/T 31387-2015, Reactive powder concrete [66] (Chinese standard)	100 mm cubes	[56]

*Specimens are the remaining parts of prisms, after splitting through flexural tensile strength test **Not stated.



(a) Sorted by author (b) Sorted by fibre type



(c) Sorted by specimen geometry

Fig. 3. Improvement index for compressive strength of fibre reinforced UHPC as a function of fibre content. The improvement index is calculated following Pakravana & Ozbakkaloglu [73]: the value of fibre reinforced concrete relative to that of the unreinforced concrete sample. The data is obtained from all relevant research papers in Table 2.

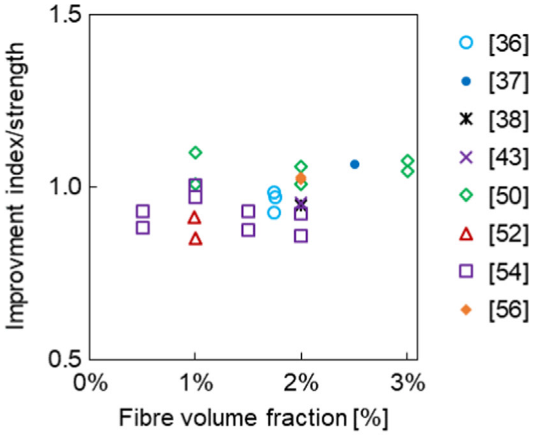
1,42,45–48,50,51,53,54]. The results from all those are summarised and discussed in the following.

4.2. Compressive strength

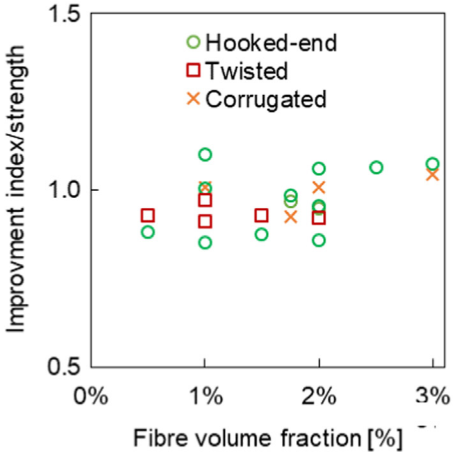
4.2.1. Test setup

For compressive strength measurements, cylinders or cubes are exposed to increasing compressive load until failure. Various standards regulate the size of the test specimens and the loading rates for conventional concrete. These procedures are often appropriate for UHPC, sometimes with small modifications and requirements [1]. The size of cubes used for compressive testing varies between the included studies; from small cubes (40–50 mm) [21,22,28,29,31,33,37,38,45,49,50] to larger ones (100–150 mm) [21,23,32,33,36,41,42,56]. Also cylindrical specimens of different sizes were used to test compressive strength [20,22,24,25,30,33,35,36,39,43,54,55]. The size variations in the test specimens have been reported to influence the compressive strength results [57,58]. A study by Josef and Bílý [57] showed that size dependency decreases with increasing strength and varies for different mix composition, making the issue of size effect rather complicated. Whether differences in size and geometry influence the impact of fibre reinforcement is not fully answered in the included papers. Only three of the studies have investigated the effect of using different size of cubic samples (50 mm and 100 mm cubes) [21] and cylinders [22,33].

Table 3 shows the different test standards and test specimen geometry used to measure compressive strength. In most investigations, the measurements of the compressive strength were done according to a standardised procedure. This might be the Eurocode (EN 12390–3:2009–7) [59], the ASTM standard C39 [60,61], the Korean standard (KS F 2405) [62] or the Chinese standard (GB/T 17671-1999) [63]. In other studies, standards for fibre reinforced concrete was used; the ASTM standard C1609 [64] or the Chinese standard CECS 13:2009 [65]. Two studies have used a Chinese standard for Reactive Powder Concrete (GB/T 31387-2015) [66]. None of the studies used a standard developed explicitly for compressive strength measurements of UHPC. The French standard for the production of UHPFRC [67] and Swiss recommendation for UHPFRC [4] are both referring to the European standard for conventional concrete, EN 12390-3 [59]. ASTM has published a standard for practice on production and testing of UHPC [68]. Also, this standard refers to a test method for conventional concrete, ASTM C39/C39M *Standard Test Method for Compressive Strength of Cylindrical Concrete*



(a) Sorted by author



(b) Sorted by fibre type

Fig. 4. Improvement index for deformed fibres on compressive strength as a function of fibre content. The improvement index is calculated for different deformed fibres relative to 13 mm straight fibres for corresponding volume fractions. The data is obtained from all relevant research papers presented in Table 2.

Specimens [60]. Other standards for UHPC might also be referring to standards for conventional concrete. However, this remains unknown to the authors of the present paper.

4.2.2. Effects of steel fibres on compressive strength

Compressive strength is one of the most important and frequently measured properties of UHPC [1], as it is for conventional concrete. Inclusion of fibres is essential to avoid explosive behaviour at failure [22,25,30,35,55]. The compressive behaviour of UHPC with fibres is not substantially different compared to conventional concrete. The main difference is the improved compressive strength and stiffness. The compressive strength is dependent on the constituent materials, mix proportions, curing conditions [1] and fibre content (Fig. 3).

Twenty-nine of the included research papers reported the effect of steel fibres on compressive strength (Fig. 2). Fig. 3 shows a comparison of improvement of compressive strength as a function of fibre content, relative to UHPC without fibre reinforcement. All data points are collected from the included papers and are sorted by author (Fig. 3(a)), fibre type (Fig. 3(b)) and specimen geometry (Fig. 3(c)). The influence of fibre content on compressive strength varies between the different studies. Some studies found that inclusion of fibres yielded relatively low levels of influence on compressive strength (<10%) [21,22,35,39]. Arora et al. [24] stated that the compressive strength is highly dependent on the volume of hydration products and the packing density of aggregates. Other investigations found more substantial effects; >50% increase in compressive strength as a result of the inclusion of fibres [31,45,50]. Such an increase might be explained by the ability of the fibres to delay the formation and propagation of cracks [31,45]. By increasing the fibre content, the compressive strength increased accordingly [31,33,41,45,50]. However, at some point, increasing the fibre content could have an adverse effect on the compressive strength. Meng and Khayat [38] reported this effect when the fibre content exceeded 3 vol-%. The negative impact on the compressive strength was explained by fibre agglomeration and entrapped air. Le Hoang and Fehling [35] also experienced fibre agglomeration for the mixes with 3 vol-% of fibres.

The results are also presented sorted by specimen type, to accommodate the aforementioned influence that test specimen geometry might have (Fig. 3(c)). According to this, cylindrical test specimens show little effect on compressive strength, from the inclusion of any volume fraction of fibres. For large cubes (100 mm), a slight increase in compressive strength seems to be the result of the inclusion of fibres. However, this effect seems only to differentiate fibre reinforced from not reinforced UHPC – it does not seem to be a function of fibre fraction. Only small cubes (40–50 mm) seem to benefit from an increase in the volume fraction of fibres up to 3 vol-%. For higher levels, the compressive strength seems to decrease towards the level of the UHPC without fibres. This reduction in compressive strength might be explained by fibre agglomerations and reduced workability, leading to entrapped air. However, a major concern remains on whether some of the demonstrated variations in results can be explained through discussions on test specimen geometry rather than actual fibre effects. Cylinders are generally accepted to represent a more uniaxial stress distribution than cubes. A compressive failure in cubes is more influenced by internal shear stress, both because of the presence of corners and the lower height/cross-section dimension ratio. The most influential objection towards drawing strict conclusions from the comparison between test specimen geometries presented in Fig. 3(c) is, however, all the information that is not included. Differences in factors like constituent materials, mix proportion, and curing regimes might explain more of the differences in test results, than test specimen geometry. The authors of this review article settle with a conclusion that there are indications that the test specimen geometry might influence the results from investigations.

Deformed fibres have higher pullout strength than straight, giving them the ability to bridge cracks more effectively [38,56]. Fig. 4 shows the effect of using different shaped fibres relative to using 13 mm straight micro steel fibres. The improved pullout strength is not evident on the compressive strength of UHPC; all papers concluded that the influence of using deformed fibres was within ± 15% (Fig. 4). Liu et al. [36] investigated macro (l = 30 mm) and micro (l = 13 mm) hooked-end fibres and found little difference in compressive strength. Yoo et al. [52] observed a slight increase in compressive strength for straight fibres compared to macro deformed fibres. This effect was explained by the increased number of fibres available to bridge and delay the propagation of microcracks compared to that of deformed macro fibres. In addition to this, a poorer fibre distribution was observed for the deformed fibre types. Low level of influence (±15%) was also shown for differences in fibre length [20,23,35,39,42,49,54,55].

4.3. Tensile strength

4.3.1. Test setups

Three or four-point bending tests are often used to determine the tensile properties of UHPC. These tests are easier to execute than testing direct tensile strength. Due to the fibre reinforcement,

Table 4
Standards and test specimen geometry used for flexural tensile strength tests.

Author(s) (year)	Standard	Specimen size [mm^3]	Ref.
Abbas et al. (2015)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[20]
Allena et al. (2012)	ASTM C78, Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Third-Point Loading) [75] (ASTM International)	Prisms 75 × 100 × 400	[21]
Arora et al. (2019)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 457 Prisms 50 × 65 × 380	[24]
Chkheiwer & Kadim (2019)	**	Prism **	[26]
Erdoğdu et al. (2019)	EN 196-1:2016, Methods of testing cement – Part 1: Determination of strength [70] (European standard)	Prisms 40 × 40 × 160	[28]
Gesoglu et al. (2016)	RILEM 50-FMC/198, Determination of fracture energy of mortar and concrete using three-point bend tests on notched beams [76]	Prisms 70 × 70 × 280 (notched)	[29]
Ibrahim et al. (2017)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 50 × 50 × 300	[31]
Jin et al. (2018)	CECS 13:2009, Standard test methods for fiber reinforced concrete [65] (Chinese standard)	Prisms 100 × 100 × 400	[32]
Kim et al. (2011)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[34]
Ma et al. (2019)	EN 196-1, Methods of testing cement—Part 1: Determination of strength [71] (European standard)	Prisms 40 × 40 × 160	[37]
Meng & Khayat (2018)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading) [72] (ASTM International)	Prisms 76.2 × 76.2 × 304.8	[38]
Park et al. (2017)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[39]
Prem et al. (2015)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam With Third-Point Loading) [72] (ASTM International)	Prisms 70 × 70 × 350 (notched)	[42]
Ryu et al. (2012)	** Loading rate given	**	[43]
Ryu et al. (2011)	** Loading rate given	**	[44]
Wang & Gao (2016)	GB/T 17671-1999, Method of testing cements – Determination of strength [63] (Chinese standard)	Prisms 40 × 40 × 160	[45]
Wu et al. (2018)	** Loading rate given	Prisms 40 × 40 × 160	[48]
Wu et al. (2017)	GB/T 17671-1999, Method of testing cements – Determination of strength [63] (Chinese standard)	Prisms 40 × 40 × 160	[49]
Wu et al. (2016)	**Loading rate given	Prisms 40 × 40 × 160	[50]
Yoo et al. (2016)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[51]
Yoo et al. (2017 a)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[52]
Yoo et al. (2017b)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[54]
Yoo et al. (2017c)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[55]
Zhang et al. (2018)	ASTM C1609, Standard Test Method for Flexural Performance of Fiber-Reinforced Concrete (Using Beam with Third-Point Loading) [64] (ASTM International)	Prisms 100 × 100 × 400	[56]

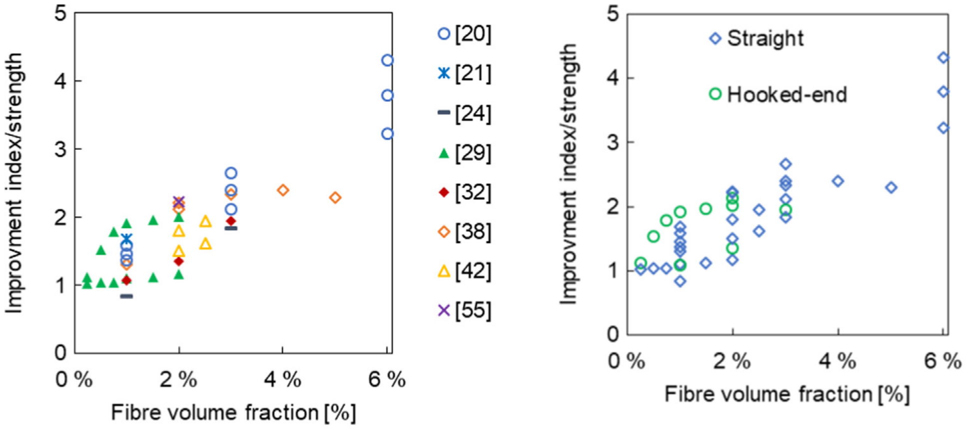
*Span length **Not stated.

Table 5
Standards and test specimen geometry used for direct tensile strength tests.

Author(s) (year)	Standard	Specimen size* [mm^2]	Ref.
Chun & Yoo (2019)	According to recommendations from JSCE [77]	Dog-bone 30 × 13	[27]
Hassan et al. (2012)	No standard, test setup described	Dog-bone 50 × 26	[30]
Le Hoang & Fehling (2017)	No standard, Leutbecher (2008) [78]	Prisms 40 × 40 (notched)	[35]
Liu et al. (2016)	No standard, Park et al. (2012) [40]	Dog-bone 100 × 50	[36]
Meng & Khayat (2018)	No standard, Meng & Khayat (2016) [79]	Dog-bone 50 × 25	[38]
Park et al. (2012)	No standard, loading rate and test setup described	Dog-bone 100 × 50	[40]
Wille et al. (2014)	AASHTO T 132–87 Standard Method of Test for Tensile Strength of Hydraulic Cement Mortars [80] and Sujivorakul (2002) [81]	Dog-bone 25 × 25	[46]
Wille et al. (2011)	According to Sujivorakul and Naaman [82]	Dog-bone 50.8 × 25.4	[47]
Yoo et al. (2019)	According to recommendations from JSCE [77]	Dog-bone 30 × 13	[53]

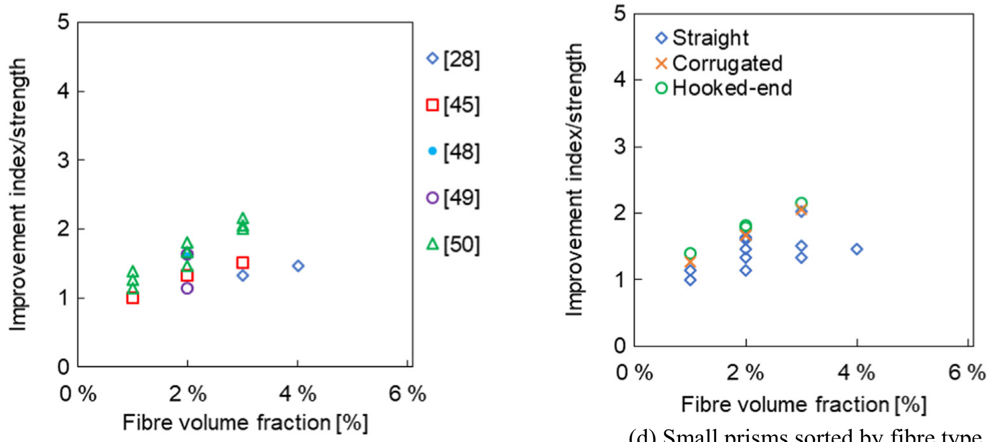
*Cross-sectional testing area.

UHPC can exhibit considerable tensile strength compared to conventional concrete, even after first-cracking. The capacity of both pre- and post-cracking strength are central properties to measure. Hence, standards for conventional concrete are less applicable for measuring the tensile strength of UHPC, as these standards usually only provide a first-cracking strength value. This shortcoming is, however, expected to change through revisions, e.g. the coming revision of the Eurocode 2 aims at including regulations for structural use of fibres in conventional concrete. The new addition entails values for post-cracking strength. The included papers report the use of different standards to determine the flexural tensile strength (Table 4). ASTM C1609 [64] is the most frequently applied standard for testing the effects of fibres on flexural tensile strength of UHPC (Table 4). This is a standard for fibre reinforced



(a) Large prisms sorted by author

(b) Large prisms sorted by fibre type



(c) Small prisms sorted by author

(d) Small prisms sorted by fibre type

Fig. 5. Improvement index for peak flexural tensile strength of fibre reinforced UHPC as a function of fibre content. The figure differentiates between large test prisms (length ≥ 280 mm) and small test prisms (length ≤ 160 mm). Both are sorted by author and fibre type. The improvement index is calculated in accordance with Pakravana & Ozbakkaloglu [73]: the value of fibre reinforced concrete with respect to that of the unreinforced concrete sample. The data is obtained from the relevant research papers in Table 2.

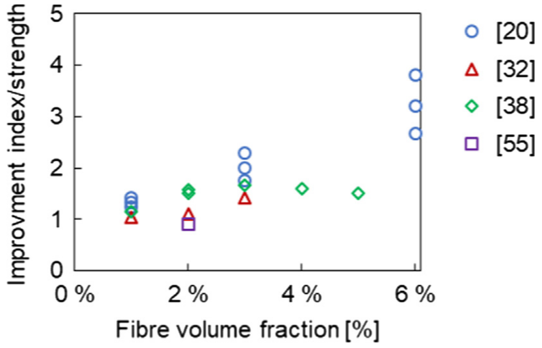
concrete, using large prisms (length > 350 mm). Some studies used standards for testing cement; the Chinese standard, *Method of testing cements – Determination of strength* [63] and the European standard *Methods of testing cement - Part 1: Determination of strength* [70]. Both standards use small prisms of 40 × 40 × 160 mm^3. The use of such small test specimens excludes the use of macro fibres, as there is no room for free orientation of those fibres. In ASTM C1609 [64], the requirement for test specimen size is that both the depth and width should be at least three times the maximum fibre length. Differences in specimen size have been reported to influence the results [57,74]. One main reason is that differences in the specimen geometry might induce differences in fibre distribution [74]. Josef and Bílý [57] collected data in former studies, reporting a clear size dependency for flexural strength. In the following analysis, the results from testing the flexural tensile strength are presented in two separate figures: one for the small prisms and another one for the larger prisms.

Only nine of the research papers investigated the effect of fibre reinforcement using direct tensile strength tests. One reason might be that the test setup is more complicated than the three or four-point bending tests. Table 5 provides information about the test setups for direct tensile strength. The applied test setups are often based on earlier studies, and standards are rarely referenced. Only one investigation applied a standard as the basis for the test setup [46], while two referred to a recommendation [27,53]. The specimen geometry varies between investigations, from one study using prisms to others using differently sized and shaped dog-bones. All variations in geometry are expected to influence the results.

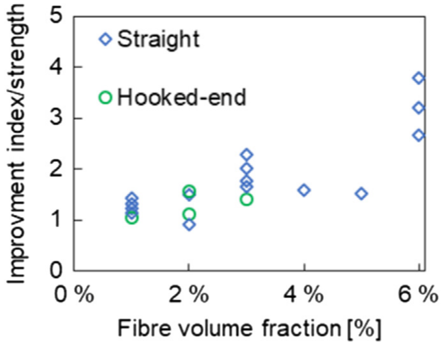
4.3.2. Effects of steel fibres on flexural tensile strength

In structural design codes for conventional concrete, the tensile strength is often considered to be zero. Concrete can resist tensile loads. However, this capacity is low. Fibres enable the concrete to sustain structural integrity towards tensile load after first cracking by bridging cracks and transferring the load across the cracks. Fig. 5 presents the improvement of flexural tensile strength as a function of fibre content, relative to the same UHPC without fibre reinforcement. Due to the expected size dependency on flexural strength [57], the figure differentiates between large test prisms (length ≥ 280 mm) and small test prisms (length ≤ 160 mm). However, the figures do not separate on other differences between investigations, like constituting materials, mix proportions, curing regimes, etc.

Most studies report an improvement in flexural tensile strength corresponding to an increase in fibre content (Fig. 5). An explanation might be that at higher fibre contents, the fibres are more closely spaced [20]. Consequently, more fibres are spanning each crack [54]. This gives a higher bonding area between the matrix and the fibres [54] and more effective control of crack propagation [20]. Park et al. [39] observed 3 times higher peak strength for

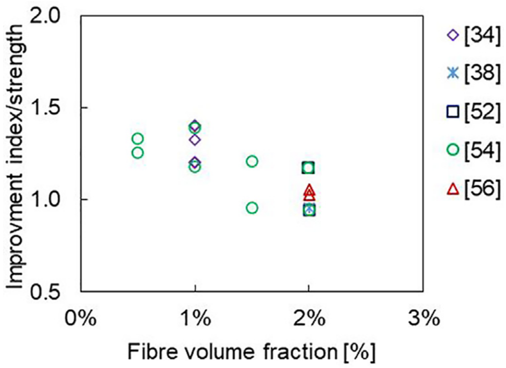


(a) Large prisms sorted by author

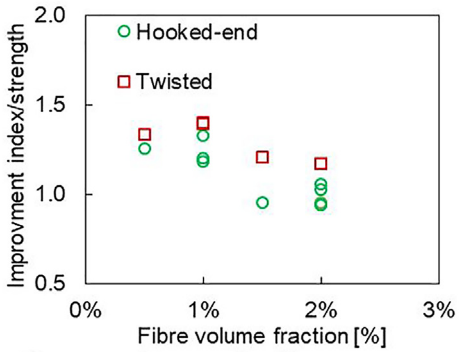


(b) Large prisms sorted by fibre type

Fig. 6. Improvement index for first-cracking flexural tensile strength of fibre reinforced UHPC large prisms (length ≥ 280 mm) as a function of fibre content. The improvement index is calculated in accordance with Pakravana & Ozbakkaloglu [73]: the value of fibre reinforced concrete with respect to that of the unreinforced concrete sample. The data is obtained from the relevant research papers in Table 2.



(a) Large prisms sorted by author



(b) Large prisms sorted by fibre type

Fig. 7. Improvement index for using deformed fibres on flexural tensile strength of large prisms (≥280 mm) as a function of fibre content. The improvement index is calculated by deformed fibres relative to that of 13 mm straight fibres for corresponding volume fractions. The data is obtained from the relevant research papers presented in Table 2.

prisms with 2 vol-% of fibres compared to the ones with 0.5 vol-%. For some studies, the flexural tensile strength did not continuously improve with fibre content [29,38]. Meng and Khayat [38] observed fibre agglomeration for high fibre contents (>3 vol-%), giving an adverse effect on flexural tensile strength. Abbas et al. [20] observed only slightly reduced flowability even for high contents of fibres (up to 6 vol-%) and reported a considerable increase in peak load for high dosages of fibres. This supports the idea that the effects of fibres are influenced by additional factors, like the constituent materials and mix proportion, affecting the rheological properties of the UHPC material. Extended curing time might provide a denser microstructure and a higher degree of hydration around the fibre, creating better bond strength between the fibres and matrix [83]. Greater bond properties can also be achieved by increasing the amount of silica fume [48,84]. The inclusion of silica fume contributes to creating more hydration products, which may reduce the weakness of the Interfacial Transition Zone (ITZ) around the fibres, and hence enhance the bond strength to the fibres [83]. Using more coarse aggregates can give defects in the microstructure, thus lower the bond strength between the fibres and the matrix [36]. Additionally, the use of coarse aggregates may impair the fibre dispersion, giving lower flexural strength.

Fig. 6 shows the improvement of first-cracking flexural tensile strength as a function of fibre content, relative to UHPC without fibre reinforcement. Park et al. [39], Wu et al. [50] and Yoo et al. [55] observed that the first-cracking strength was not influenced by an increase in fibre content or variations in fibre type. According to Yoo et al. [55], the first-cracking strength is strongly dependent on the tensile cracking strength of the cementitious matrix. The fibres are mainly activated after the first-cracking strength is reached [42]. Meng and Khayat [38] found an increase in first-cracking strength as a function of fibre content, but a plateau was identified for volume fractions above 3 vol-%. Some reported improvement in first-cracking strength with fibre content [20,32], even up to 6 vol-% [20]. Abbas et al. [20] explained this effect by the formation of multiple microcracks that delay the growth of macrocracks, leading to higher first-cracking strength.

Fig. 7 compares the effect of using different deformed fibres relative to 13 mm straight micro fibres. Based on the results in Fig. 7, the influence of using deformed fibres varies from 5% decrease [52,54] up to 40% increase [34,52]. However, the effect of using deformed fibres seems to decline after reaching 1 vol-%. As discussed earlier, deformed fibres have higher pullout strength, making them able to bridge cracks more efficiently [38,56]. Kim et al. [34] observed an increase of 20 to 40% for 1 vol-% of three different deformed fibres in comparison to using only micro straight steel fibres. Gesoglu et al. [29] reported flexural tensile strength of notched prisms using 6 mm micro fibres as reference. The study showed that using macro hooked-end fibres (l = 30 mm), improved the flexural tensile strength more efficiently than using the micro straight fibres. However, regardless of the higher pullout strength, some investigations observed reduced capacity or little effect of using 2 vol-% of hooked-end fibres [52,56]. Yoo et al. [52] found that 2 vol-% of twisted fibres (l = 30 mm) increased the flexural tensile strength, while hooked-end (l = 30 mm) fibres gave similar results as using micro straight steel fibres (l = 13 mm). They also observed that using long straight fibres (l = 30 mm) gave even higher flexural tensile strength, although resistance to fibre pullout was lower than for the deformed fibres. Another study by Yoo et al. [54] found that at lower fibre content (≤1 vol-%), deformed fibres showed the highest strength, while at higher fibre dosages

(≥1.5 vol-%) the straight fibres (l = 19.5 mm) performed better. According to Yoo et al. [54], this might be caused by the formation of split cracks in the cementitious matrix. As the fibres are pulled out of the matrix, the high bond strength of the deformed fibres leads to the formation of split cracks in the surrounding matrix. For higher fibre contents, a higher number of split cracks are formed which will weaken the pullout capacity of the nearby fibres, and consequently reduce the capacity.

Wu et al. [48,50] and Ma et al. [37] investigated the effect of variations in fibre shape using small prisms and deformed micro fibres (l = 13 mm). Wu et al. [48,50] observed a noticeable increase for two types of deformed fibres compared to using only straight fibres up to 2 vol-%, while the results from Ma et al. [37] showed a slight decrease of strength for 2.5 vol-% of fibres.

Nine of the included papers reported results on the effect of fibre length on the flexural tensile strength of UHPC [20,34,39,42,49,51,52,54,55]. Several found that the flexural tensile strength can be increased by >20% when using longer straight fibres [39,42,49,51,52,54,55]. Yoo et al. [51] explained this effect with the improved fibre bridging capacity of longer fibres, as the bonding area between the fibre and the matrix is increased. They also reported a higher number of microcracks and lower average cracks spacing for the test beams with longer fibres. Abbas et al. [20] experienced the highest flexural capacity when using the smallest fibres (8 mm). The increased strength can be explained by the increased number of short fibres present to bridge the cracks compared to the number of the longer fibres.

4.3.3. Effects of steel fibres on direct tensile strength

Nine papers presented direct tensile strength results [27,30,35,36,38,40,46,47,53]. Only one investigation reported on the effect of fibre content relative to UHPC without fibres [30]. Hassan et al. [30] observed that the strength was nearly doubled compared to unreinforced UHPC. Four of the studies investigated the effect of fibre content without having unreinforced UHPC as a reference [35,36,46,47]. All investigations found that the peak flexural tensile strength improved with higher fibre content.

Wille et al. [47] reported a considerable improvement in the direct tensile strength by using deformed fibres compared to straight fibres. Park et al. [40] found minor differences for 1 vol-% of two types of hooked-end fibres (l = 30 mm and l = 62 mm) compared to using long straight ones (l = 30 mm), but considerable improvements in tensile strength for the twisted fibres. Liu et al. [36] reported that macro hooked-end fibres (l = 30 mm) gave lower tensile strength than micro hooked-end fibres (l = 13 mm). The decreased capacity was explained with the reduced frictional bonding and the low number of fibres at the same fibre volume fraction. Despite the higher pullout strength for deformed fibres, the results from some investigations showed minor effects (≤15%) of using deformed fibres compared to straight ones [36,38,46]. Yoo et al. [53] observed a considerable decrease in tensile strength for two types of macro hooked-end fibres (>40%) and macro twisted fibres (15%) compared to the straight micro fibres (l = 13 mm). Chun and Yoo [28] reported similar results. This could be explained by fibre congestion and high bond strength causing matrix damage [53].

Only Le Hoang and Fehling [35] reported on the effects of fibre length on direct tensile strength. They achieved the highest tensile strength for the 13 mm fibres compared to 9 mm and 20 mm fibres.

4.4. Hybrid combinations of fibres

Hybrid fibre combinations include both short and long fibres, aiming at synergetic effects benefitting from all the included fibre types. Short fibres bridge microcracks more efficiently, as they are small and numerous for the same fibre volume, whereas the longer fibres have better pullout properties and can more efficiently prevent the propagation of macrocracks [85]. This might minimise the fibre content while maintaining performance.

The method of combining longer and hooked-end fibres with micro fibres was investigated in several of the included research papers [27,34,37,38,40,43,52,56]. Some investigated the hybrid combination of different straight fibres [44,49,55]. Fig. 8 shows the effect of using hybrid combinations of fibres on compressive strength and flexural tensile strength of larger prisms. Several hybrid combinations were found to efficiently improve the flexural tensile strength of UHPC compared to using only one type of fibres (Fig. 8). Meng and Khayat [38] reported that hybrid fibre combinations were more effective in improving the compressive strength than increasing the fibre content. Similar results were shown for flexural tensile strength. In many studies, it was found that although some hybrid combinations improved the flexural tensile strength, others gave similar or lower results [34,43,44,49,52,55]. Disadvantages of deformed macro fibres are the creation of damaging split cracks in the matrix, while straight micro fibres have limited pullout strength [52]. Yoo et al. [52] found an optimal ratio of macro twisted and straight micro fibres to be 1:1. This combination effectively compensated the weakness of both types of fibres. The optimal combination of fibres differs between the studies. Only a few hybrid combinations were found to provide improved flexural tensile strength while also giving increased compressive strength (Fig. 8). Ma et al. [37] observed that only the compressive strength was enhanced for the hybrid combinations. However, most of the included papers showed a relatively low influence (<15%) on compressive strength compared to using 13 mm fibres [38,43,44,49,52,56].

Three papers reported on the effect of using hybrid combinations on direct tensile strength [27,38,40]. Chun and Yoo [27] compared the use of hybrid fibre combination with different macro fibres. They observed that the tensile strength was improved with the increasing replacement ratio of macro hooked-end and twisted fibres by micro straight fibres. However, using only straight macro fibres showed better or similar tensile strength results compared to the various hybrid combinations. Park et al. [40] performed similar experiments, also reporting on the benefits of increasing the content of micro fibres in hybrid systems.

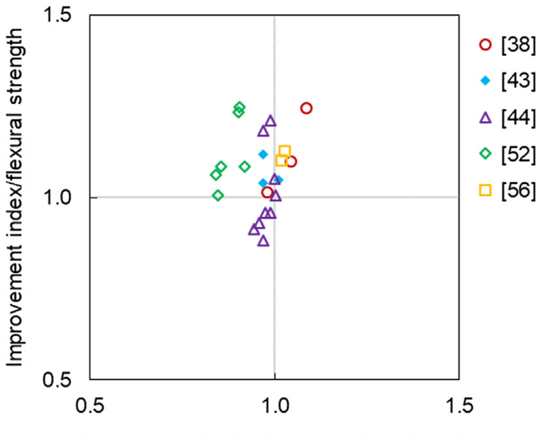


Fig. 8. Improvement index for flexural tensile strength for larger prisms (y-axis) and compressive strength (x-axis) of hybrid fibre reinforced UHPC. The improvement index is calculated by using hybrid fibre combinations relative to only 13 mm straight fibres. The data is obtained from all relevant research papers presented in Table 2. The fibre content is 2–2.5 vol-%.for all datapoints.

5. Conclusions

Through a structured literature search, thirty-seven research papers were analysed considering the influence of fibre content, type and combination on the compressive and tensile strength of UHPC. The results of this review paper show that:

- ASTM C1609 is the most frequently applied standard for testing the effects of fibres on flexural tensile strength of UHPC. This is a standard for fibre reinforced concrete. Standardised procedures for conventional or fibre reinforced concrete is often applied, in spite of the emergence of dedicated UHPC standards. For some tests, e.g. compressive strength, even the dedicated UHPC standards are referring to standards for conventional concrete.
- Different test specimen geometries have been used to measure the effects of fibre reinforcement on compressive and tensile strength of UHPC. This is often a consequence of applying different standards. Differences in geometry are often claimed to influence the test results. From the analysis of the accumulated results from all the included papers in this review, it seems clear that the geometry plays a role both for compressive and tensile strength. However, few of the papers have investigated into this, and the effects of variations in other factors like constituting materials, mix proportion and curing regime seems not to be focused.
- Variations in fibre types have been investigated, spanning from micro to macro fibres, straight or deformed (hooked-end, twisted or corrugated). For all fibre geometries, high strength steel fibres (tensile strength > 2000 MPa) were mostly used. For compressive strength, the accumulated results show little effect of using deformed fibres rather than straight. It seems that deformed fibres can improve the flexural tensile strength for low fibre volumes. In contrast, at higher fibre volumes, straight fibres perform better. Hence, the optimum fibre type seems to be dependent on the fibre volume fraction.
- Fibre reinforcement is necessary in UHPC to avoid explosive behaviour at failure. Several investigations reported that the compressive strength was affected by the inclusion of fibre reinforcement, giving UHPC higher strength. However, the influence of variations in test specimen geometry and other variable factors were hardly discussed. When the accumulated results are differentiated, it seems that inclusion of fibres has little effect on compressive strength when tested on cylinders, though some higher effects 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-%.
- The inclusion of fibre reinforcement profoundly influences the flexural tensile strength of UHPC. In most cases, the flexural tensile strength is improved as a function of increased fibre content. This seems to be valid for both small (l = 160 mm) and large (l > 280 mm) test specimen. At high content, fibres may have the opposite effect by reducing the tensile strength. This might partly be explained by fibre agglomeration and entrapped air.
- Combining different types of fibres might benefit from exploiting the synergetic effect of each type. This is often denoted hybrid fibre combinations. The use of hybrid fibre combinations has the potential to increase the tensile strength of UHPC. Some hybrid combinations seem to improve especially the flexural tensile strength, while others have little effect.

Recommendations for future research

To approach a better accumulated understanding from the collective efforts of the research society, we recommend that future investigations support repeatability and reliability by reporting enough information on all variables and have enough parallel tests to the number of variables tested. Future research should also focus on replication of already reported studies to strengthen the statistical basis of any conclusions.

We believe that it is not advantageous for researchers from different cultural background to agree on the use of only one single set amongst the existing plurality of standards. However, following the emergence of new standards for testing and reporting of UHPC, comparisons of the effects of differences between standards when all other factors are kept constant would benefit the scientific discussions on relating new research towards existing knowledge.

Declaration of Competing Interest

No conflict of interest has been identified.

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