Fibres in ultra-high-performance concrete

***Peter Buitelaar** of **Peter Buitelaar Consultancy** and **Stephan Müller** of **KrampeHarex** discuss the use of fibres in ultra-high-performance concrete (UHPC) and look at some European project examples.*

After the initial development of UHPC in 1978 (by Hans Henrik Bache), it soon became very clear that the ultra-high-strength binder (cement plus ultra-fine fillers) was brittle like glass and more brittle than traditional cement paste.

As with traditional cement paste, the ultra-high-strength cement paste needs to be combined with sand, aggregate and reinforcement. The effect of aggregates on the fracture energy is, compared with traditional concrete, reduced in UHPC unless very strong aggregates are used.

In general, the greater the volume and dimensions of strong aggregates used, the less brittle the UHPC. However, such a UHPC will only be useful for certain applications and not for most precast and applications where a certain rheology is needed. The first tests on such UHPC showed that the mechanical fixation of very fine fibres was greatly increased (four to five times higher than in traditional concrete mortar) in the very dense micro-structure of the ultra-high-strength binder (Figure 1) and that high volumes could be added due to the properties of the ultra-high-strength binder. The only way to give the UHPC a high degree of ductility is thus to incorporate high-energy-absorbing reinforcement (bars, fibres and combinations of both).

The addition of high-strength steel fibres will thus make a brittle material much more ductile. This is influenced by the following parameters: fibre content; fibre geometry (length, diameter in relation to maximum particle size UHPC); fibre orientation; bond between fibre and matrix; and stiffness of the fibres.

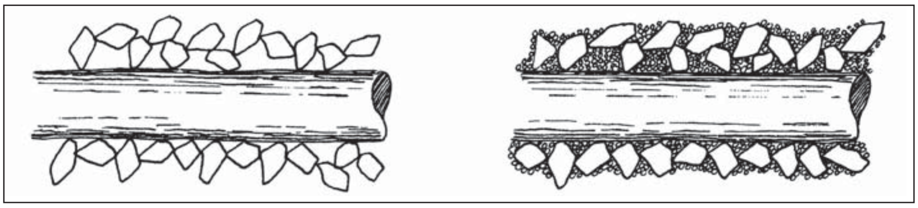


Figure 1: Fine fibre embedded in cement paste (left) and UHPC paste (right). The mechanical fixation of the short and thin fibre is greatly increased by incorporating the ultra-fine particles in the spaces between the cement particles (Hans Henrik Bache 1978).

Types of fibres used in UHPC

The selection of fibres is very important for the design of the UHPC, as it has a strong influence on the composition, strength, ductility and price of the concrete and the final product. Although there are many types of fibres – including carbon, basalt and many synthetic fibres – three types of fibres are mainly used in UHPC: polyvinyl alcohol (PVA), polypropylene and steel. Different kinds of fibres result in different properties of the fresh and hardened UHPC. Fibre lengths for UHPC are in the range of 6–20mm, while fibre diameters are 0.009–0.5mm.

In the main, steel fibres are used in UHPC since they are the best choice economically and contribute most to the properties of the fresh and final concrete product. Polypropylene fibres are used for non-structural applications to control plastic shrinkage, such as in UHPC sprayed concrete and toppings, and in combination with steel fibres to obtain a certain degree of fire resistance. PVA fibres are mainly used for smaller elements and when very high flexural strengths are demanded.

Steel fibres for UHPC are straight and cold-drawn. The carbon steel fibres mostly have a brass coating, which indicates that the fibre is made from wire that was initially produced for tyre cord. The quantity of steel fibres in the UHPC for short fibres and micro-fibres is 81,000–675,000 per kg.

Cocktails and hybrids

It is thus also possible to make a fibre blend/cocktail. This can be a mix of different types of fibres, for example, steel and polypropylene fibres to improve fire resistance, but also steel fibres of different lengths and diameters. Buitelaar *et al* carried out research in 1986[1] with UHPC and combinations of steel fibre blends of short and long fibres. While short fibres are very efficient to bridge micro-cracks, longer fibres are very efficient to bridge macro-cracks (Figure 2). This positively influences the strain hardening but also impacts the strength and toughness of the UHPC.

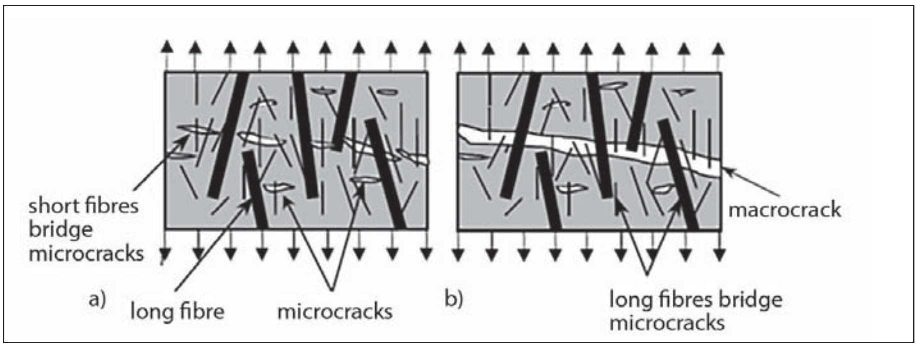
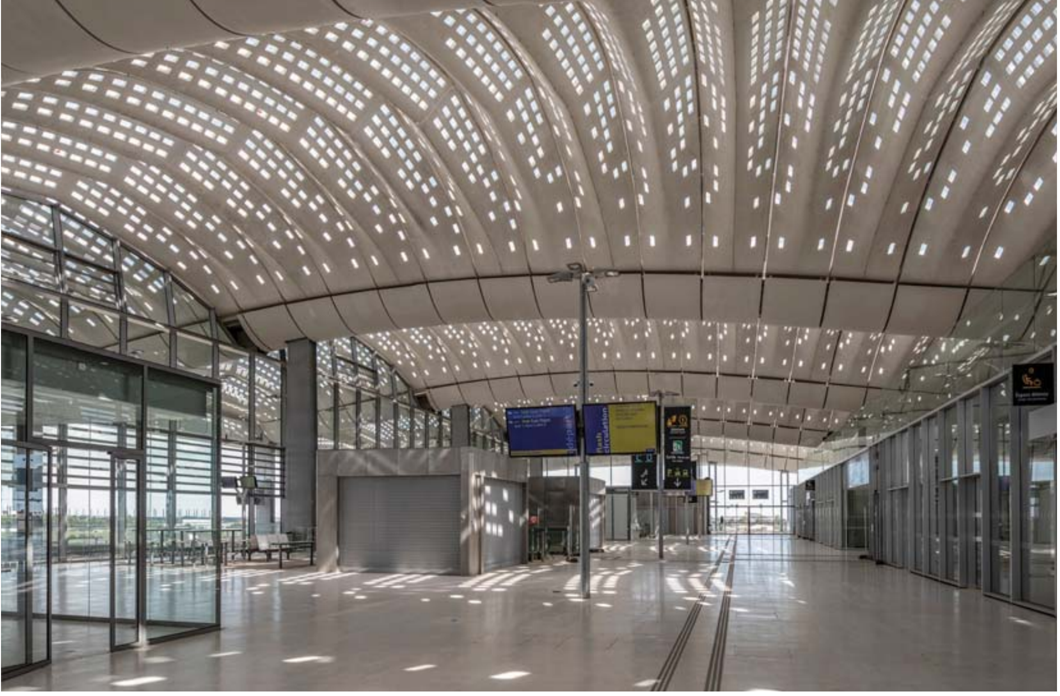


Figure 2: The main principle of hybrid fibre concrete: a) The influence of short thin fibres on the bridging of micro-cracks and the increase of tensile strength; b) the influence of long thick fibres on the bridging of macro-cracks and the increase of ductility (Markovic 2006).



Figures 3 and 4: TGV station, Montpellier, France.
(Photo: Ductal/Hisao Suzuki.)

Table 1 – Properties of three types of fibres used in UHPC

	PVA	Polypropylene	Steel
Tensile strength (MPa)	880–1600	600–1200	1200–3000
Elongation at break (%)	6	25	3–4
Young's modulus (GPa)	25–41	2–9	200
Density (g/cm³)	1.30	0.91	7.80

In addition, combining traditional reinforcement and steel fibres in a UHPC element or structure is a very interesting option. This hybrid reinforced UHPC is mainly known as compact reinforced composite (CRC) and was invented by Hans Henrik Bache in 1986. This combination of UHPC, very short, thin and strong steel fibres, and reinforcement bars (steel, high-strength steel, carbon, etc) results in an extremely high compressive strength, flexural strength and ductility.

Selection of fibres
The selection and percentage of fibres is very important, since the addition of fibres will influence the rheology and final properties of the UHPC. When aesthetics are important – but also absolutely necessary in the case of exposure to high and very high temperatures such as in applications of special refractory UHPC – stainless steel fibres are a good but expensive alternative. Special fibre shapes – such as hooked, crimped, corrugated, paddled, etc – are not only difficult and thus expensive to produce as short and thin micro-fibres but also will change the rheological properties of the UHPC. Special fibres will thus have much influence on the maximum dosage of steel fibres and on the composition and the packing model of cement, ultra-fine fillers and aggregates. The typical percentages of steel fibres in UHPC are 1–3% (V/V); in special applications higher dosages are used.

Typical applications
The use of different fibre types performing in various UHPCs with varying requirements is described below in a few applications.

TGV station, Montpellier, France
The Montpellier train station's striking 10,000m^2 roof structure has drawn inspiration from the Mediterranean surroundings with its organic double-curved UHPC shells and glass panes embedded directly into the UHPC and looking like super-sized palm tree leaves. Each unit (115 in total) is 18m long, 2.7m wide and has a 3m depth, with a wall thickness of 50mm. The separate units are joined together by post-tensioning. The units are cast in a white Ductal UHPC with stainless steel fibres type KrampeHarex DG 14/0.2 E316 to avoid corrosion of exposed fibres during its expected lifespan.

University of Southern Denmark
The façade of the new building for the Faculty of Engineering at the University of Southern Denmark (SDU) in Odense is based on the idea of a glasshouse placed within a shroud made up of prefabricated as-struck UHPC elements. The perforated façade is created from 292 elements, each sized 5 × 3m and with a thickness of 65mm. The façade around the building is reducing direct sunlight by up to 50%. Differently sized circular openings with a maximum diameter of approximately 2m in the white concrete façade provide the building with natural ventilation and glare protection, while lending it a feeling of airiness and elegance. The façade's prefabricated panels are made of white CRC concrete reinforced with 140kg/m^3 KrampeHarex DG 12.5/0.3 E304 stainless steel fibres. Additional reinforcement bars have been placed at critical locations around the circular openings.

Figure 5: University of Southern Denmark, Odense.
(Photo: Hi-Con.)

Figure 6: University of Southern Denmark, Odense. *(Photo: Hi-Con.)*

Figure 7: A4 Küsstnacht–Brunnen, Switzerland. *(Photo: ASTRA Federal Roads Office/KrampeHarex.)*

Figure 8: Grand Pont Bridge, Thouaré Sur Loire, France. *(Photo: Vicat.)*

Figure 9: Lubina River footbridge, Czech Republic. *(Photo: KŠ PREFA - Štětí, Marek Blank.)*

A4 Küsstnacht–Brunnen, Switzerland

This project saw the overhaul of a 5km stretch of national road and sections of road with several large bridge structures, renovation of two tunnels and expansion of two tunnel control centres. Several deteriorated bridges needed strengthening and rehabilitation to increase the maximum loads and to extend their lifespan. The construction period was significantly shortened when the weather-dependent work – such as sealing and waterproofing with a membrane – was replaced with the use of a UHPC overlay.

In comparison with similar older projects in The Netherlands, where only a thin wearing course or porous asphalt has been applied, two additional layers of gussasphalt on the UHPC are used as a wearing course.

Deteriorated concrete girders were repaired and strengthened with an additional UHPC layer. A total area of 14,000m^2 was resurfaced with UHPC, with the use of a slipform paver. A 45mm-thick layer was applied in the field area and a 100mm-thick layer in the support section of the bridges. The UHPC was mixed on-site in a mobile batching plant to reduce transport time. The UHPC was reinforced with 250kg/m^3 KrampeHarex DM 12.5/0.175 steel fibres, which were automatically weighed and added in the batching plant.

Bridge, Thouaré Sur Loire, France

The 394m-long steel through-truss 'Grand Pont' bridge crossing the Loire River was erected in 1882 and was damaged during World War II. Leaking rainwater, traffic loads and corrosion had damaged the existing concrete deck, masonry arches and steel girders, resulting in restricted traffic. Initially suggested renovation resulted in a too high dead weight, couldn't cope with Eurocodes and would take longer than 12 months. A lightweight UHPC deck consisting of 218 prefabricated slabs of 624 × 158mm and 70mm thick at the edge and 120mm at the axis has been placed on additional girders with Nelson studs on top of the existing girders. Prefabricated panels and girders are joined together using the integrated transversal reinforcement bars and Nelson studs in a small wet joint with UHPC grout. A thin wearing course was applied on the UHPC. A new pedestrian and bicycle lane as overhanging structures will be realised later; the prefabricated UHPC panels here are only 40mm thick. Dead weight has been reduced by 43%, with a shorter closure of the bridge (total duration of six months) and the project has remained within budget. The prefabricated slabs were cast in Vicat's SMARTUP UHPC with 200kg/m^3 KrampeHarex DM 12.5/0.175 steel fibres.

Lubina River bridge, Czech Republic

This 36m-long footbridge has been built from five prefabricated elements (each section 7.2 × 2.5 × 0.8m) made from UHPC. To create the support-free bridge with a slenderness ratio of 1:44, the designer used a post-tensioning concept with a unique multiple system of cable protection. To achieve a lightweight structure, the bridge elements are recessed with polystyrene blocks, reducing the amount of UHPC. KS Prefa, a mid-size precast company, has developed its own UHPC, achieving a compressive strength of ≥120MPa and the post-cracking strength of ≥7MPa. The concrete has a binder content of more than 700kg/m^3 and a water:cement ratio from 0.18. To achieve the necessary ductility, the UHPC is reinforced with 120kg/m^3 KrampeHarex DG 12.5/0.175 steel fibres. ■

Figure 10: Lubina River footbridge, Czech Republic. *(Photo: KŠ PREFA - Štětí, Marek Blank.)*

Reference:

1. BUITELAAR, P., BAALBERGEN, J. and VAN DEN HEUVEL, E.A. *Failure behavior of notched specimens made from Densit concrete reinforced with steel fibers*. Ultra-High-Strength Concrete Task Force, Aannemingsbedrijf J.G. Nelis, 1986–1987, Haarlem, The Netherlands.