1 Introduction

When *Otto Graf* managed to produce a concrete with a strength of 70 N/mm^2 in the early 1950s, the construction industry showed very little interest in this new product. And this lack of interest didn't change even as in 1966 *Kurt Walz* proved that, using special production methods, it was possible to achieve a strength of 140 N/mm^2. Only after it was realized that adding a limited amount of silica fume plus suitable superplasticizers was a simple way of producing a concrete with high strength and at the same time good workability did the first ideas regarding potential applications begin to materialise.

Not until the late 1980s was it possible to produce concrete in strength classes up to C100/115. The discovery of the effect of silica fume, a fine, reactive material, and the development of efficient superplasticizers proved very important in this development. At the start, high-strength concrete was ascribed only a limited role, primarily because of the much higher production costs compared with conventional concretes. It turned out, however, that it is more realistic to make comparisons on the basis of an entire project. One example was Stichtse Bridge, built near the Dutch city of Amsterdam in 1997. The use of C80/90 concrete enabled the cross-sectional area of this bridge, which spans 160 m, to be reduced by 30%. The smaller cross-sectional area of the box girder resulted in a 26% saving in prestressing steel. Owing to the 60% thinner webs and bottom flange, the length of the individual segments could be increased from 3.50 to 5.00 m, which in turn led to the construction time being shortened by three months. In addition, there were the advantages of the good workability of the concrete, the low creep and shrinkage losses, the high wearing resistance and the excellent durability of the concrete. It became clear that the solution using C80/90 concrete was, on the whole, no more expensive than the alternative with conventional concrete, and at the same time resulted in a structure with a very high quality.

Increasing the strength of the concrete to values beyond about 120 N/mm^2 was regarded as unrealistic because the strength of the aggregate, as the weakest component in the mix and accounting for about 75% of the volume of the concrete, would prevent this.

Another innovation thought of as promising at that time was the development of SIFCON (Slurry Infiltrated Fibre CONcrete). The production of this material involves first introducing steel fibres into the formwork and packing these tightly. The spaces between the fibres are then filled with a cement matrix. This method results in a fibre content of 12–13%, which roughly corresponds to a 10-fold increase over the maximum fibre content of conventional fibre-reinforced concrete. The material is characterized by its very high strain at failure [1]. One disadvantage, however, is that the packing results in an inhomogeneous distribution of the fibres (predominantly 2D). When it comes to the effectiveness and hence the associated costs, this limits the potential applications. A variation on SIFCON is SIMCON (Slurry Infiltrated Mat CONcrete). This material is produced by introducing a mat of discontinuous steel fibres into the formwork and subsequently covering this with an easy-flowing cement mortar [2].

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A new breakthrough came with the development of a new concept for the composition of ultra-high-strength concretes. Based on this concept, it was possible to produce concretes with compressive strengths up to 200 N/mm^2 and fibre contents up to 2.5% by vol. (175 kg/m^3). In order to produce ultra-high-strength concrete with a compressive strength in the region of 150–200 N/mm^2, it is important to observe the following basic rules:

- The maximum grain size should be less than that of traditional concrete mixes because large grains cause stress concentrations that lead to a decrease in strength. These days, the maximum grain size for ultra high performance concrete is usually no larger than 2 mm. However, ultra high performance concretes with a maximum grain size of 8 mm have also been developed.
- An optimum packing density for the aggregate is important. A high packing density can be achieved with the help of fine materials, which reduce the stresses on the contact surfaces and ensure that microcracks do not begin to form until a higher level of stress is reached. The microstructure is, principally, very dense, which expresses itself not only in a high strength, but also in a much higher resistance to all forms of attack that damage concrete or reinforcement (chloride, alkalis, carbonation, de-icing salts).
- The amount of cement used should be such that the water is fully bound. The remaining non-hydrated cement particles then act as fillers.
- Fine steel fibres should be added to the concrete in order to guarantee a ductile behaviour.

The Danish researcher *Hans Hendrik Bache* was the first to recognize and apply these principles. He developed a material with a high fibre content which was also reinforced with a high amount of reinforcing steel. The material was called CRC (Compact Reinforced Concrete) and the first information on this was published in 1981 [3]. This special form of construction is still used frequently today, especially for stairs and balconies and primarily in Denmark.

Bache's ideas were taken up in 1994 by the French contractor Bouygues (*Richard* and *Cheyrezy*) and developed further. Cooperating with Lafarge, a new mix was devised: 'Reactive Powder Concrete', which continues to exist in the form of 'Ductal®'. One early application involved replacing steel beams by ultra high performance concrete ones in the cooling towers of a power station at Cattenom in France. The steel beams had to be replaced because they were corroding in the extremely aggressive environment inside the cooling towers. One important point to note here is that it was not the high strength of the ultra high performance concrete that was decisive in this case, but rather the durability of the material in connection with the anticipated very long service life without maintenance or repairs.

It was the realization that the material can be specified for its other outstanding properties and not just for its high strength that led to the term 'ultra-high-strength concrete' being replaced by 'ultra high performance concrete'. The abbreviation UHPC will be used throughout this book.

As soon as the potential of this new high-performance construction material received more publicity, e.g. through the building of the first footbridge made from this material in Sherbrooke, Canada, in 1997 [4], so architects and engineers began to come forward with a wide range of ideas for new, innovative forms of construction. Current French projects such as MuCEM in Marseille, with tree-like columns and delicate façade elements, or the Jean Bouin Stadium in Paris, which is clad in 3500 prefabricated UHPC elements, show quite aptly the direction in which developments are going. One remarkable structure is the UHPC platform in the open sea which was built for the extension to Haneda Airport in Japan. The slab with an area of 200 000 m^2 is the largest application of UHPC to date. These projects and many others are described in more detail in Chapter 7.

One first pilot project in Germany was Gärtnerplatz Bridge in Kassel [5], which was opened to the public in 2007 and enabled important experience to be gained with UHPC. A national research programme with a budget of €12 million was launched in Germany in 2005.

The first design rules for UHPC were published in France in 2002. As design methods are lacking elsewhere, this pre-standard has often been used since then outside France as well. Japan's first guideline appeared in 2004. Currently, *fib* Task Group TG 8.6 is working on an international standard for UHPC [6].

Until recently, concrete with a very high strength still met with opposition. Comparing the per m^3 cost of producing such a concrete with that of a conventional concrete results in a negative verdict at first sight: up to now, the cost of UHPC per m^3 has been four to five times that of a conventional concrete. However, comparisons should take place on the basis of entire projects. An example of this is Sakata Mirai, a Japanese footbridge (Section 7.1.3). The self-weight of this bridge is only 20% of that of a conventional bridge [7]. Therefore, the costs of the foundations were also much lower. According to information supplied by the initiators, the final cost of the project was 10% lower than that of a comparable bridge in conventional concrete.

In the future, design will be based primarily on the design life, see also [8]. Moreover, sustainability considerations will play an ever greater role. For example, in [9] the Gärtnerplatz Bridge in Kassel, a hybrid design with a steel frame, was compared with a conventional prestressed concrete bridge and a wholly UHPC bridge with the same span and load-carrying capacity within the scope of a life cycle assessment [10]. The result was that the production and upkeep of the wholly UHPC solution causes only 40% of the CO_2 emissions of a normal concrete bridge. What this means is that the new construction material UHPC has a good chance of achieving a breakthrough.