BetonKalender

Ultra-High Performance Concrete UHPC

Fundamentals – Design – Examples

Ekkehard Fehling, Michael Schmidt, Joost Walraven,
Torsten Leutbecher, Susanne Fröhlich

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Contents

Editorial

The *Concrete Yearbook* is a very important source of information for engineers involved in the planning, design, analysis and construction of concrete structures. It is published on a yearly basis and offers chapters devoted to various, highly topical subjects. Every chapter provides extensive, up-to-date information written by renowned experts in the areas concerned. The subjects change every year and may return in later years for an updated treatment. This publication strategy guarantees that not only is the latest knowledge presented, but that the choice of topics itself meets readers' demands for up-to-date news.

For decades, the themes chosen have been treated in such a way that, on the one hand, the reader gets background information and, on the other, becomes familiar with the practical experience, methods and rules needed to put this knowledge into practice. For practising engineers, this is an optimum combination. In order to find adequate solutions for the wide scope of everyday or special problems, engineering practice requires knowledge of the rules and recommendations as well as an understanding of the theories or assumptions behind them.

During the history of the *Concrete Yearbook*, an interesting development has taken place. In the early editions, themes of interest were chosen on an ad hoc basis. Meanwhile, however, the building industry has gone through a remarkable evolution. Whereas in the past attention focused predominantly on matters concerning structural safety and serviceability, nowadays there is an increasing awareness of our responsibility with regard to society in a broader sense. This is reflected, for example, in the wish to avoid problems related to the limited durability of structures. Expensive repairs to structures have been, and unfortunately still are, necessary because in the past our awareness of the deterioration processes affecting concrete and reinforcing steel was inadequate. Therefore, structural design should now focus on building structures with sufficient reliability and serviceability for a specified period of time, without substantial maintenance costs. Moreover, we are confronted by a legacy of older structures that must be assessed with regard to their suitability to carry safely the increased loads often applied to them today. In this respect, several aspects of structural engineering have to be considered in an interrelated way, such as risk, functionality, serviceability, deterioration processes, strengthening techniques, monitoring, dismantlement, adaptability and recycling of structures and structural materials plus the introduction of modern high-performance materials. The significance of sustainability has also been recognized. This must be added to the awareness that design should focus not just on individual structures and their service lives, but on their function in a wider context as well, i.e. harmony with their environment, acceptance by society, responsible use of resources, low energy consumption and economy. Construction processes must also become cleaner, cause less environmental impact and pollution.

The editors of the *Concrete Yearbook* have clearly recognized these and other trends and now offer a selection of coherent subjects that reside under the common "umbrella" of a broader societal development of great relevance. In order to be able to cope with the corresponding challenges, the reader can find information on progress in technology, theoretical methods, new research findings, new ideas on design and construction, developments in production and assessment and conservation strategies. The current selection of topics and the way they are treated makes the *Concrete Yearbook* a splendid opportunity for engineers to find out about and stay abreast of developments in engineering knowledge, practical experience and concepts in the field of the design of concrete structures on an international level.

Prof. Dr. Ir. Dr.-Ing. h. c. *Joost Walraven*, TU Delft
Honorary president of the international concrete federation *fib*

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.

2 Principles for the production of UHPC

2.1 Development

Concrete technology has made remarkable advances in recent decades. Whereas the compressive strength classes for concrete in the 1988 edition of DIN 1045 ended at B55, the current edition of DIN EN 206/DIN 1045-2 includes the strength classes C55/C67 to C100/115, the ‘high-strength concretes’. Over the past 15 years, many working in this field have developed ultra-high performance concretes (UHPC) up to a level where they are ready for application – and with compressive strengths from about 150 to 200 $\mathrm{N/mm^2}$, which are almost the same as those of steel. Reinforced with fine steel fibres with a high tensile strength, such concretes become ductile and reach tensile strengths exceeding 15 $\mathrm{N/mm^2}$ (really exceptional for concrete) and flexural tensile strengths of up to 50 $\mathrm{N/mm^2}$ [11]. So this type of concrete can for the first time be designed to accommodate tension, and by using new design principles suited to this material, with or without traditional reinforcement, the result is forms of concrete construction that save materials and are thus especially sustainable. It is not only the strength of UHPC that is high. Compared with conventional normal- and high-strength concretes with their capillary porosity, UHPC exhibits a much denser microstructure. It has virtually no capillary pores and is therefore so impervious to liquids and gases that its corrosion is practically zero; it can serve as the wearing course of a bridge deck without any additional protection against chlorides, alkalis or de-icing salts [12]. Owing to UHPCs good durability, its materials-saving composition and the low maintenance requirement, structures made from UHPC, when properly designed, are also considerably more cost-effective than comparable structures made from normal-strength concrete when the, predictably, longer design life is considered, despite the fact that the concrete itself is more expensive [13, 14].

The basic idea of producing a concrete with a very high strength and especially dense microstructure had already been put forward in the 1980s [3]. But the practical breakthrough came with the development of an especially efficient superplasticizer that enabled the production of concrete with a high proportion of optimally tightly packed ultrafine particles and at the same time an extremely low water/binder ratio of only about 0.20 in an easy-flowing consistency. The optimum combination of these two principles is what gives UHPC its special properties. Originally produced in the majority of cases as a fine-grained concrete with a maximum particle size of 1 mm and an easy-flowing consistency, in the meantime mixes have been developed with up to 60% by vol. 8 or 16 mm coarse aggregate in a mouldable and no-slump consistency with the same hardened concrete properties. Therefore, a wide range of applications can now be covered very economically [16–20].

Key new findings about the special material properties of UHPC and the proper design and construction of components and structures made from this new material were supplied by a programme of research into sustainable building with UHPC (priority programme SPP 1182) funded by the DFG (German Research Foundation) [21], which was concluded in 2012. This book takes into account the results of about 30 research projects in that programme. Besides representing the most extensive practical

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experience with a diverse range of UHPC structures in Germany and abroad, the results of the research programme also form the basis for a first set of technical rules currently being drawn up by the German Committee for Reinforced Concrete (DAfStB) which follows on from the state of the art report dating from 2008 [22].

The research programme covered virtually all the issues relevant to the raw materials, production, processing, design, construction details and durability of UHPC and structures made with UHPC.

2.2 Basic material concepts

2.2.1 Microstructure properties

The excellent performance of UHPC – when compared with normal-strength or even high-strength concretes – is predominantly due to its much denser hardened cement matrix with virtually no capillaries. Furthermore, 'classic' easy-flowing UHPC is a fine-grained mix, with a maximum particle size of 1 mm. Therefore, its internal microstructure is much more homogeneous than customary, coarse-grained concretes and it is essentially more uniformly stressed by external actions. Together, these two aspects result in the compressive strengths of about 150–200 N/mm^2 so typical of UHPC. Even in the case of the coarse-grained UHPC that has been developed in the meantime for various applications, the differences in the strengths and deformation behaviours of the matrix and the aggregate are so small that any cracks that do form propagate in a straight line through the matrix and the aggregate. That in turn means that UHPC has a distinctly brittle failure behaviour. Whereas normal-strength concrete exhibits an increasingly (quasi-)ductile behaviour as compressive stresses rise due to changes to the internal microstructure and still retains a loadbearing capacity even after its strength is reached, unreinforced UHPC fails abruptly. Nevertheless, UHPC can still be used to build safe structures provided it is reinforced with fine high-strength steel fibres (and conventional or prestressed reinforcement if required). With a sufficiently high fibre content, the tensile strength of UHPC can be improved and ensured to such an extent that structural components in tension are possible without any further reinforcement [23].

The very dense microstructure and high strength so typical of UHPC are due to its very low water/binder ratio (cement, silica fume and further reactive substances if required) of only about 0.20. The matrix therefore has practically no capillaries and is thus diffusion-resistant. Another factor contributing to the high strength is the fact that the ultrafine particles (grain size <125 μm) consist of various components (cement, quartz powder, silica fume plus further inert or reactive fine fillers if required) that are combined in such a specific way that the ultrafine particles are packed very tightly together. Figure 2.1 compares the composition (by volume) of normal-strength concrete, high-strength concrete, self-compacting concrete (SCC) and fine- and coarse-grained UHPC for various applications.

The use of grading-optimized admixtures made up of several different components leads to a wider concrete technology approach that goes beyond conventional thinking in mass-based water/binder ratios as the key variable determining the strength. The

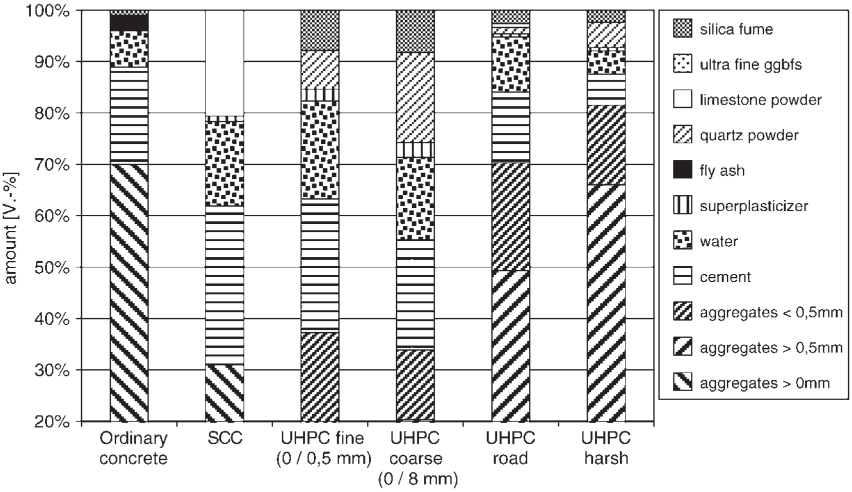

Fig. 2.1 Comparison of mix compositions for normal-strength, high-strength and various UHPCs (see also [24])

volume-based water/ultrafine particles ratio (w/F_v) was therefore introduced in [25] because – as shown schematically in Figure 2.2 – it enables the strength-increasing physical effect of grading-optimized ultrafine particle combinations to be taken into account when predicting the concrete strength and hence when designing UHPC mixes (extended k^+ value).

$$\frac{w}{F_v} = \frac{w}{\sum (c + ultrafine\ particles)_{vol}} \tag{2.1}$$

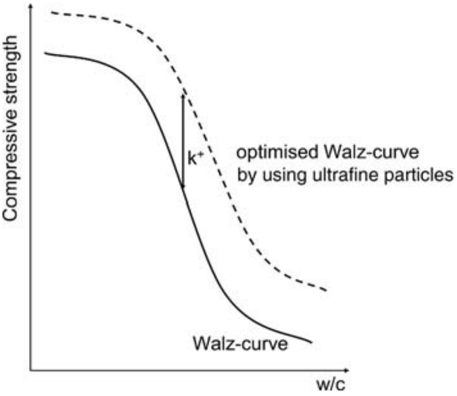

Fig. 2.2 Granulometric coefficient k^+ for assessing how packing-optimized ultrafine particle combinations with various densities influence the compressive strength (optimized *Walz* curve)

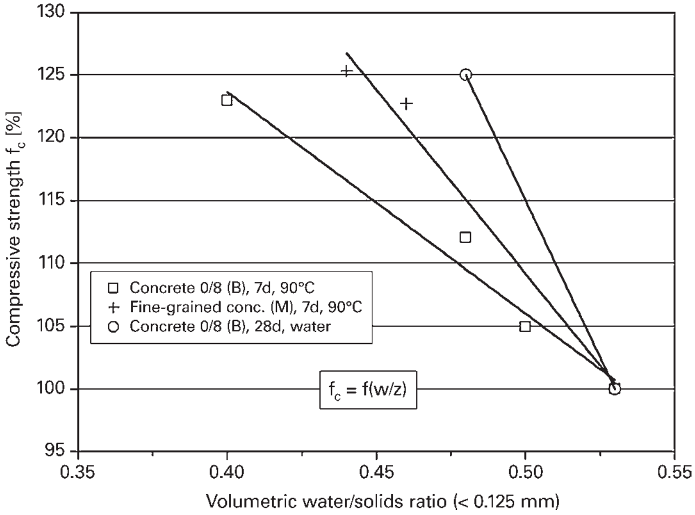

Fig. 2.3 How the volumetric water/solids ratio, as a measure of the packing density, influences the compressive strength of UHPC

Being based on volume, the w/F_V value is also a measure of the quality of the grading of the various ultrafine particles (<125 µm grain size) and the residual pores between the particles, which must be filled by water, and hence the packing density of the ultrafine particles. It forms the actual basis for optimizing UHPC [26].

As an example, Figure 2.3 shows that the 28-day compressive strengths of the fine- and coarse-grained UHPCs investigated in [11] increased by up to about 30% – for practically the same w/c ratio – when the packing density (and hence the water/ultrafine particles ratio of the mixture of cement, various fine quartz powders and silica fume) was improved by about 3% by vol [27]. Incidentally, optimizing the proportion of ultrafine particles even improves the strength of normal-strength concrete significantly – albeit on a much lower basic level of strength, as is reported in [26, 27].

2.2.2 Grading optimization

One way of achieving optimum packing of the fine particles is through experimentation. Another way is to use numerical modelling to optimize the packing density on the basis of the characteristics of the raw materials measured beforehand.

In experiments it is possible to approach the optimum packing of the grains iteratively, e.g. using the *Puntke* method [28]. However, without exact knowledge of the grading, and possibly the forms of all the particles, and without a numerical model in advance, this method is usually costly and often tedious.

The numerical grading optimization of fine particle combinations for UHPC and their principles have been described in detail in [29] and [30–32]. Most models are based on circular discs, some on spheres. A spheres-based model was used in [33], for example, in order to find a grading curve that enables optimum utilization of the space