Ultra-High-Performance Concrete: Research, Development and Application in Europe

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Synopsis: One of the breakthroughs in concrete technology is ultra-high-performance concrete with a steel like compressive strength of up to 250 N/mm² and a remarkable increase in durability compared even with high-performance concrete. In combination with steel fibres it is now possible to design sustainable filigree, lightweight concrete constructions with or even without additional reinforcement. Wide span girders, bridges, shells and high rise towers are ideal applications widening the range of concrete applications by far. In addition e.g. to some pedestrian bridges heavily trafficked road bridges has been build in France and in the Netherlands. Bridges are already under construction in Germany as well. A wide range of new concrete formulations has been developed to cover an increasing number of applications. Technical recommendations have recently been published in France and in Germany covering material as well as design aspects.

The paper will report on the state of research and application of UHPC in Europe, on material and design aspects of UHPC and will present the state-of-the-art based on an International Symposium on UHPC held in Kassel in 2004.

Keywords: ultra high performance concrete; raw materials; durability; design aspects
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INTRODUCTION

Within the last two decades amazing progress has been made in concrete technology. One of the breakthroughs is the development of ultra-high-performance concrete with a steel like compressive strength of up to 250 N/mm² and a remarkable increase in durability compared even with high-performance concrete. In combination with a sufficiently high amount of steel fibers it is now possible to design sustainable filigree, lightweight concrete constructions without any additional reinforcement. In prestressed construction elements the prestressing forces may be increased significantly especially if high-strength steel is used. Long span girders, bridges and shells are ideal applications widening the range of concrete applications by far. First practical steps into the future of concrete constructions have already been done. In addition to the well known pedestrian bridge in Sherbrooke in Canada and in South Korea heavily used road bridges has been build or reconstructed in France and in the Netherlands. A long span footbridge is under construction in Germany and the construction of a road bridge used by traffic under severe climatic conditions with intensive salt attacks in winter will start this year to gain more practical experiences with the durability of UHPC.

The growing store of knowledge about the material itself and about the adequate design of constructions with UHPC enabled a technical working groups in France to draw up first technical recommendations primarily focussing on the design (Resplendino 2004, SETRA-AFGC 2002). In Germany a state-of-the-art report has recently been published covering all material and design aspects (DAfStB UHPC 2003). That means that the concrete itself is steadily optimized and a wide range of new formulations are developed to cover the individual needs of an increasing number of different applications. This paper will report on the state of research and development on UHPC in Europe and about recent applications either already realized, under construction or under development.
HISTORY OF DEVELOPMENT AND APPLICATIONS

In the 1960s concretes with an compressive strength of up to 800 N/mm² has been developed and produced under specific laboratory conditions. They were compacted under high pressure and thermally treated. In the early 1980s the idea was born to develop fine grained concretes with a very dense and homogeneous cement matrix preventing the development of microcracks within the structure when being loaded. Because of the restricted grain size of less than 1 mm and of the high packing density due to the use of different inert or reactive mineral additions they were called “Reactive Powder Concretes (RPC)” (Bache 1981; Richard and Cheyrezy 1995). Meanwhile there existed a wider range of formulations and the term “Ultra-High-Performance Concrete” or – in short – UHPC was established worldwide for concretes with a minimum compressive strength of 150 N/mm².

The first commercial applications started around 1980, based on the development of so called D.S.P. mortars in Denmark (Buitelaar 2004). It was primarily used for special applications in the security industry – like vaults, strong rooms and protective defense constructions.

First research and developments aiming at an application of UHPC in constructions started in about 1985. Since then different technical solutions were developed one after the other or parallelly: Heavily (conventionally) reinforced UHPC precast elements for bridge decks; in situ applications for the rehabilitation of deteriorated concrete bridges and industrial floors (Buitelaar 2004) ductile fiber reinforced fine grained “Reactive Powder Concrete” (RPC) like “Ductal” produced by Lafarge in France or Densit produced in Denmark (Acker and Behloul 2004). With or without additional “passive” reinforcement it is used for precast elements and other applications like offshore bunched foundations. In addition, coarse grained UHPC with artificial or natural high strength aggregates were developed e.g. for highly loaded columns and for extremely high-rise buildings (Schmidt et al. 2003). Nowadays an increasing range of formulations is available and can be adjusted to meet the specific requirements of an individual design, construction or architectural approach.

Breakthroughs in application were the very first prestressed hybride pedestrian bridge at Sherbrooke in Canada in 1997, the replacement of steel parts of the cooling tower at Cattenom and two 20.50 and 22.50 m long road bridges used by cars and trucks at Bourg-lès-Valence in France build in 2001 (Hajar et al. 2004), see fig. 1.

For these projects the UHPC was reinforced with about 2.5 to 3 Vol.-% of steel fibers of different shape. The bridges in Bourg-lès-Valence consists of five precast beams which are pre-tensioned. They were placed on site and then joined together with in-situ UHPC.

Other footbridges with decks and/or other load bearing components made of fine grained, fiber reinforced UHPC exist in Seoul and in Japan (Acker and Behloul 2004).

A spectacular example of architectural taking advantage of the special benefits of UHPC is the toll-gate of the Millau Viaduct in France, currently under construction. Fig. 2 shows the elegant roof “looking like an enormous twisted sheet of paper”, 98 m long and 28 m wide with a maximum thickness of 85 cm at the center (Resplendino 2004). The structure remembers an aircraft wing. It will be made of match-cast prefabricated 2 m wide segments connected by an internal longitudinal prestressing.
In other European countries UHPC is gaining increasing interest as well. In Germany, as a result of an extensive research project financed by the government, technical criteria and measures have been already developed to use regionally available raw materials for fine or coarse grained UHPC, to reduce the cement content and to use fiber mixtures and noncorrosive high strength plastic fibers to control the strength and the ductility depending on the requirements given by an individual design and construction (Fehling et al. 2003; Bornemann et al. 2001; Schmidt et al. 2003; Bornemann and Faber 2004). As a first application, a hybrid bridge is under construction (Fehling et al. 2004) for pedestrian and bicycles with a length of about 135 m and a maximum span of 40 m consisting of precast prestessed chords and precast bridge deck elements made of UHPC with a maximum grain size of 2 mm using local materials. Fig. 3 shows an animation of the bridge, fig. 4 its cross section. The 4.50 x 2.00 x 0.08 m wide bridge deck elements are prestessed transversely. As an additional step of innovation, the load bearing UHPC-elements are glued together without any additional mechanical connection. This means a further step towards an economic material adequate construction technique for UHPC.

Inspired by first applications in Canada, South Korea and Europe and by intensive research and development efforts at different universities and of the cement- and construction industry, the DAfStB draw up a state-of-the-art-report on Ultra-High-Performance Concrete (DAfStB UHPC 2003). The DAfStB is part of the German Standardization Organization DIN being responsible for all standards and technical requirements related to the production and application of concrete and giving the rules for the design of concrete structures.

The German state-of-the-art-report covers the technical know-how and the experience with UHPC worldwide published. It covers nearly all applications that exist hitherto – primarily based on commercially available UHPC mixtures – the main principles and the characteristic behavior criteria, durability aspects and the resistance against fire. A second part report refers to the adequate design and construction of structures using UHPC. The report traditionally is a first step towards a reliable technical guideline and a latter standard for UHPC.

In the following some of the material and design aspects covered by the German state-of-the-art-report and by the French design recommendations are presented in more detail.

**MATERIALS**

**Raw materials and material structure**

Both the high compressive strength and the improved durability of UHPC are based upon the same four principles

- a very low water-cement-ratio of about 0.20 to 0.25 resulting in a very dense and strong structure of the hydration products and minimizing the capillary pores, which are ductile to prevent brittle failure and to be able to use more or less traditional design approaches against the transport of harmful gases and liquids into and through the concrete,
- a high packing density especially of the fine grains in the binder matrix reducing the water demand of the fresh mix and increasing the compressive strength – as well as the brittleness of the concrete,
- the use of higher amounts of effective superplastizisers to adjust the workability and – if needed –
- the use of steel or other fibers to increase the tension, the bending tension and the shear strength and to make the concrete sufficiently ductile.

Fig. 5 shows the packing effect schematically. As a simplified example, fig. 6 shows how the packing density develops when two quartz powders of different fineness (Q 1 and Q 2) are mixed together in different amounts (Geisenhanslüke and Schmidt 2004a). Up to a ratio of about 30 % of the fine and 70% of the “coarse” powder the packing density – defined by the part by volume of particles per unit volume - increases from 48 to 54 Vol.-%. The finer particles by and by fill up the hollow space in between the coarser grains. At the same time, the viscosity of a lime prepared with the powder-mixes at a constant water/fines-ratio of 0.26 decreased from 7500 to less than 5000 mPa s. If the amount of fine particles is further increased beyond the maximum packing density, the rheology of the mix becomes suboptimal again.

To optimize the packing density of UHPC, usually specified quartz powders are used. Table 1 shows typical compositions of fine and course grained UHPC developed and used in Germany, fig. 7 the optimized grain size distribution of mix M1Q in table 1 consisting of four different fines. The correlation between the packing density – characterized by the water/fines-ratio of the matrix w/Fv – and the compressive strength of heat treated (90°C) and water cured Cylinders (150/300 mm) is shown in fig.8. It is obvious that the packing density not only affects the rheology but also the strength of UHPC as well: at nearly the same water-cement ratio of 0.20 the compressive strength increased by about 25 % when the w/Fv-value decreased from 0.53 to 0.40 by adding an pre-calculated amount of another quartz filler with a specified fineness. And table 1 a fig. 8 show that the use of coarser grains help to reduce the cement content and contributes to the compressive strength as well. Further tests showed that autogenous shrinkage and creeping were significantly reduced. The effectiveness of the fibers was reduced as well. This disadvantage could be partly compensated for using longer and stiffer fibers with a length of 17 mm and a diameter of 0.25 mm (Bornemann and Faber 2004).

Due to an European Directive, quartz fillers containing particles with a diameter of less than 5 micron are suspected to cause health problems. This led to intensive efforts to replace those particles by other mineral powders. Positive experiences have been gained with finely ground granulated blast furnace slag, the fine and glassy parts of ground or assorted fly ashes from stone coal power plants and with some high quality stone dusts e.g. produced from basalt. Ultra fine slag particles are even adequate to partly replace microsilica. Common limestone fillers are – as a rule – less beneficial. Research is done to further improve the rheological and the strength performance of UHPC by adding nanotubes (Kowald 2004).

The optimization process can be based on both a theoretical and experimental approaches. Usually the procedure of Okamura (Okamura 1995) is used. In Germany the actual packing density of cements or other powders is tested using the fast and easy Puntke-test (Puntke 2002). A specimen of about 100 g of the powder is filled into a container and slightly compacted. Than water or – for tests on powder mixes containing
cement - a non-reactive liquid of known density is added until the surface is just wet. The amount of liquid added is a measure for the hollow space and – indirectly – for the packing density.

Testing is time consuming and expensive, especially if the existing information about the powders is lacking and the grain size optimization needs several steps of iteration. Therefore some mathematically based, computer aided calculation procedures have been developed to pre-calculate the best fitting powders and the amounts of each being adequate to reach a maximum packing density (Geisenhanslüke and Schmidt 2004a). Experiences have shown that the results of the existing calculation procedures do not reflect sufficiently the reality when powders of different grain size, grain size distribution, shape and roughness of the surface are mixed in different proportions. In an active research project these procedures are developed further considering the 3-dimensionality of the structure, the shape, the friction of the grains and the so called “particle handicap” schematically shown in figure 9. These effects hinder the individual grains to really reach their theoretical optimum position within the structure of the powder mix.

**Strength and deformation behavior**

Basis of an adequate, economic and safe design of structures fully or even partly consisting of UHPC elements are reliable reference values characterizing the strength and the deformation behavior under static and dynamic loads. Fiber free fine or coarsely grained UHPC mixtures as shown in table 1 are characterized by both, a high compressive strength in between 150 and 250 N/mm² primarily depending on the water-cement ratio, the volumetric water-to-fines ratio \( \frac{w}{\Sigma \text{Vol}(cement+silica+fillers)} \) of the matrix and the grain size of the aggregates as well as a linear elastic deformation up to about 95% of the fracture load. That means UHPC without fibers is a glass like brittle material with a comparatively high modulus of elasticity of 50.000 to 70.000 N/mm². The typical tension strength of the pure matrix is about 8 N/mm².

Using steel or other adequate fibers with a sufficiently high modulus of elasticity of more than about 45.000 N/mm², the compressive strength keeps constant or increases slightly while the tension, the bending tension and the shear strength as well as the ductility are significantly improved. As an example, table 2 (Bornemann et al. 2001; Fehling and Bunje 2004) shows that the bending tension strength of concrete prisms 40/40/160 mm made of fine grained UHPC (Mix M1Q) with 2.5 Vol-% of short steel fibers (length 6 to 9 mm, diameter 0.15 mm) was up to 36 N/mm², that of beams 150/150/700 mm made from the same concrete but without steel fibers was 22 N/mm² only.

That means if the bending strength of fibered UHPC is introduced into the design of structures it has to be considered that the bending strength primarily depends on the kind and the amount of fibers used, but the orientation and the distribution of the fibers within the matrix and the shape of the specimen used and of the structural element produced with the specific concrete may have a significant influence as well. As a rule, the spread of test results of a specific mixture exceeds that of UHPC mixtures without fibers significantly. Therefore the number of tests done to characterize one specific mix has to be increased to allow a calculation based on the standard deviation („Characteristic Strength“, 5% fractile). In some active research projects these aspects are further
investigated. Until sufficient knowledge has been gathered and measures have been developed in order to influence e.g. the fiber orientation by the production process, elements of the designed shape should be placed and tested to validate the theoretically assumed design criteria.

The same aspects have to be considered regarding the ductility of UHPC. The “amount” of ductility being necessary to fit the needs depends on the individual design and construction approach: if the UHPC is assigned for bearing the full tension and bending tension loads without any additional active or passive reinforcement – like in some of the applications e.g. of Ductal – the fiber content has to be sufficiently high to prevent sudden failure even if cracks due to uncalculating stresses and strains appearing locally. In those cases a fiber content of about 2.5 to 3 Vol.-% may give a satisfying compromise regarding workability of the fresh concrete, bending strength and ductility. For other applications, a reduced amount of e.g. 1 Vol.-% of fibers may satisfy the needs, e.g. if slabs, girders or other elements made from UHPC are fully pre-stressed and/or have a passive reinforcement. The fibers are some kind of “transportation reinforcement” and/or allow to utilize the high compressive strength more efficiently due to a higher safety margin to failure. As explained later a combination of passive reinforcement and fibers allow the shear reinforcement of beams to be omitted under bending loads. And in some cases UHPC may be applied even without fibers, e.g. for highly loaded columns or framework constructions consisting of ductile steel pipes filled with UHPC (Tue, Schneider, and Schenk 2004).

In Fig. 10 the effectiveness of steel fibers, high strength non-corrosive Polyvinyl fibers and a mixture of both, a so called “fiber cocktail” is shown (Bornemann and Faber 2004). Mixes consisting of steel and other suitable fibers of different kind, length and diameter may fulfill the individual needs of a construction more effective by and more economically than fibers of one uniform type.

**Durability**

The improved resistance of UHPC to all kinds of harmful gases and liquids, to chloride and frost or freezing and thawing attacks is related to the improved density both of the grain structure of the matrix and the much denser contact zone between the matrix and the (coarser) aggregates as well as by the denser structure of the hydration products. Fig. 11 gives an impression of the dense structure.

The porosity of UHPC is characterized by the absence of capillary pores, as one can see from the pore size distribution shown in fig. 12 tested by mercury intrusion. As a result, the extremely high resistance e.g. to chloride diffusion is shown in fig. 13. The resistance to attacks by freezing and salting are significantly improved even when compared with High Performance Concrete, see fig. 14.

In table 3 some characteristic durability indicators are given based on different sources (Schmidt et al. 2003, Teichmann and Schmidt 2004; Resplendino 2004;
DESIGN ASPECTS

As a rule, the design of concrete structures has to be based on reliable but simplified material reference values, e.g. for the strength and the deformation behavior. For ordinary concrete those approaches are given in the relevant standards. For UHPC two similar approaches have been developed, one established by AFGC/SETRA in France in 2002 (SETRA-AFCG 2002) and one as part of the state-of-the-art report of the DAfStB in Germany in 2003 (DAfStB UHPC 2003). They both consider the fact, that as a rule the material properties of fiber reinforced UHPC show a significant higher deviation due to an inhomogenious distribution and orientation of the fibres in the matrix (Bernier and Behloul 1996).

The French recommendations consist of three parts:

– the first part gives specifications on the mechanical performance to be obtained and recommendations for characterizing UHPC including checks of finished products and of the concrete being produced,
– the second part deals with the design and analysis of structures made with fibre reinforced, non-prestressed and/or non-reinforced UHPC-elements and
– a third part dealing with the durability of UHPC.

An important part deals with the behavior of fiber containing UHPC under tensile loading. As fig. 15 (Resplendino 2004; SETRA-AFCG) shows, the stress-strain relation is characterized by an elastic stage limited by the tensile strength of the cement matrix $f_t$ and a post cracking stage characterized by the tensile strength of the composite material reached by fiber action.

Using characterization tests depending on the type of structure studied (thin or thick slabs, beams, shells) and on the kind of load (direct or flexural tensile) the recommendations give the transfer factors to come from the test results to an “intrinsic” curve for tensile behavior independent of the size of the specimen and the kind of test used. In addition, a reduction factor is given to take into account the effect placement methods has on the real strength values to be obtained in a specific structural element.

The French design methods proposed are in accordance with the French codes for prestressed or reinforced concrete BAE 91 and BPEL 91 based on semi-probabilistic limit state values. Supplementary to the design codes the recommendations contain specificities concerning UHPC like the strength provided by fibers which allows the design of structures without any conventional reinforcement.

For normal stress verification, the French recommendations use the AFREM-BFM method which concerns fiber concrete, and use a stress-crack width constitutive law $\sigma = f(w)$. Moreover the characteristic length $l_c$ is introduced, to go from crack width $w$ to strain $\varepsilon$:

$$\varepsilon = f_t / E_{ij} + w / l_c,$$

The value of $l_c$ depends on the sections area. The analysis for standard sections is based on the assumptions that plane sections remain plane and the concrete behavior law follows fig. 16. The limit stresses at the SLS are the same as for a reinforced or
prestressed structure: 0.3 mm for normal cracking, 0.2 mm for detrimental and 0.1 mm for highly detrimental cracking.

For calculation of the Serviceability Limit State (SLS), a somewhat more simplified stress strain relationship as shown in Fig. 17 may be used according to the recommendations given by (DAFStb UHPC 2003).

The German report describes a standard test procedure as shown in Fig. 18 to evaluate the load-deformation behavior of UHPC under bending loads in order to determine a stress strain relationship.

Fig. 19 shows the result of such a test. To transform it into a stress-strain relation, the stresses at a crack width of 0.5 and 3.5 mm are being considered.

Fig. 20 shows the stress-strain curves calculated according to this proposal. The stresses at the significant points of the curve are determined from the equations

\[ \sigma_{2.0-3.5}\% = f_{ctk} \cdot 0.37 \]
\[ \sigma_{25}\% = \beta \cdot f_{ctk3.5} \]

The factor \( \beta \) as well as the factor 0.37 have been established by recalculating test results. As for ordinary concrete, the factor \( \beta \) depends on the relation \( f_{ctk,3.5} / f_{ctk,0.5} \). It can be taken from Fig. 21.

Normally a strain limit of 25\% is adequate. But re-calculations of test results already showed that for a ratio \( f_{3.5} / f_{0.5} < 0.5 \) the design may fall short of the necessary safety margin. In Fig. 21 the reduced strain for \( f_{3.5}/f_{0.5} < 0.5 \) is characterized by the marked curve.

For the design in the Ultimate Limit State, the stress strain law according to DIN 1045-1 is proposed. It is defined by the following equation (1):

\[ \sigma_e = -f_{cd} \cdot \left[ 1 - \left( 1 - \frac{\varepsilon_c}{\varepsilon_{c2}} \right)^n \right] \quad \text{for} \quad 0 \geq \varepsilon_c \geq \varepsilon_{c2} \quad (1) \]

\( \varepsilon_{c2} \) strain at maximum stress

\( \varepsilon_{c2u} \) ultimate strain for design purposes

The exponent \( n \) in Eq. 1 can be taken from Table 4. This enables a transition to the rules for High Strength Concrete (HSC/HPC). For UHPC 210 and higher strength classes, hence, a linear relationship results. Furthermore, for UHPC without fibers or insufficient confinement, \( \varepsilon_{c2} = \varepsilon_{c2u} \) shall be assumed in order to account for the brittleness in such cases.

The design value of the compressive strength follows Eq. 2.

\[ f_{cd} = 0.85 \cdot \frac{f_{ck}}{\gamma_e \cdot \gamma_c} \quad (2) \]

with
\( \gamma_c \) partial safety coefficient according to table 2 in DIN 1045-1
\( \gamma_c \) additional partial safety factor taking into account the sensibility for deviations during the production process and brittle failure of high strength concrete

\[
1,00 \leq \gamma_c = \frac{1}{1,1 - f_{ck}/500} \leq 1,25
\]

The strain at the maximum stress can be assumed to be 2,2‰ starting with strength class C 100/115 acc. to EN 206. For the special permit required in Germany for structures built of new materials, different values may be proposed by the obligatory expertise.

For UHPC with fibers or sufficient confinement, a plastic branch until the strain \( \varepsilon_{c2u} \) can be used in order to account for the improved ductility. The value of \( \varepsilon_{c2u} \) can be determined in such a way that the capacity in bending is adjusted to the bending capacity obtained from a stress strain law with a descending branch and assuming yielding of steel in the tension zone. However, since the influence of the descending branch of the stress strain relationship is of minor importance, the additional strain (length of the horizontal branch in the stress strain diagram) can be assumed to be quasi linear.

**Shear and Torsion**

In order to determine the reinforcement possibly required for shear loading, the resistance due to the concrete, the shear reinforcement (e.g. stirrups) and the fibers can be added according to the SETRA–AFGC regulations:

\[
V_u = V_{Rb} + V_a + V_f \quad (3)
\]

with:
- \( V_{Rb} \) = shear resistance of concrete section
- \( V_a \) = shear resistance to discrete reinforcement
- \( V_f \) = shear resistance due to fibers

The resistance due to the fibers can be determined as follows:

\[
V_f = \frac{S \cdot \sigma_p}{\gamma_{bf} \cdot \tan \beta_u} \quad (4)
\]

with:
- \( \sigma_p \) = residual tensile strength: \( \sigma_p = \frac{1}{K \cdot w_{lim}} \int_0^{w_{lim}} \sigma(w)dw \)
- \( K \) = orientation coefficient for the fibers
- \( w_{lim} \) = max\((w_u; 0,3 \text{ mm})\), where \( w_u = l_c \cdot \varepsilon_u \) and \( l_c \) ... characteristic length
- \( \sigma(w) \) = characteristic post cracking tensile resistance for crack width \( w \) (according to tests)
- \( S \) = area of fiber action:
  - \( S = 0,9 \cdot b_0 \cdot d \) bzw. \( b_0 \cdot z \) for rectangular and T-shape sections
  - \( S = 0,8 \cdot (0,9 \cdot d)^2 \) bzw. \( 0,8 \cdot z^2 \) for circular sections
- \( \gamma_{bf} \) = particular safety coefficient for fiber concrete in tension
- \( \beta_u \) = angle of compression struts
Similar concepts have been proposed in the German design guidelines for steel fiber concrete of DAfStb. Experimental results obtained in Germany (Fehling and Bunje 2003) lead to similar results. However, additional research is required for the behavior of UHPC subject to shear and torsion loads.

**Bond of Reinforcement**

Due to the high compressive strength and the high density, UHPC enables very high bond stresses. For smooth fibers (l = 13 mm, Ø = 0.15/0.2 mm), Behloul (1996) reports a value of $f_b = 11.5$ MPa for BPR (DUCTAL). For prestressing wires and strands, the maximum bond stress depends on the concrete cover (see Figure 24). For ribbed reinforcing bars, very high bond stresses in the range of 40 to 70 MPa have been reported. (Weiße 2003, Reineck and Greiner 2004), see fig. 25. In tests on rebars with 10 mm diameter splitting failure in the concrete cover was observed for a cover less than 25 mm. Due to the high bond stresses, the bond length in the standard RILEM pull-out specimen has to be reduced to $2\,\varnothing$ instead of $5\,\varnothing$ (see Figure 26). Otherwise, no pull-out would be feasible before the yielding of steel.

**Fatigue Resistance**

For fatigue loading under compression, tests performed at the University of Kassel for UHPC have shown a rather good behavior. S-N-curves for UHPC and NSC are compared in Figure 27. The (relative) stress range of UHPFRC for a large number of load reversals (> 2 million) is similarly high as for NSC, while the absolute stress level is much higher than for NSC. Thus, it can be said, that in contrast to other high strength materials, the high strength of UHPC with fibers does not lead to disadvantages with regard to fatigue (Fehling et al. 2003; Schmidt et al. 2003) Currently, fatigue tests in bending are conducted at Delft University of Technology.

**Fire Resistance**

Due to the extremely high density of UHPC, high water pressure can arise when UHPC is exposed to fire. This can lead to deterioration of the concrete structure. The problem can be overcome by the use of fibers, e. g. polypropylene fibers. One effect of the fibers is that they create capillary pores due to melting and burning. Furthermore, around the fibers transition zones to the cement matrix are formed. By this, the existing transition zones between aggregates and matrix are interlinked so that the permeability increases and the steam pressure is reduced. Experiments have shown the effectiveness of adding polypropylene fibers (Diederichs 1999; Dehn and König 2002; Bornemann, Schmidt, and Vellmer 2002). Another problem is associated with the anomaly of quartziferous compounds with respect to the volumetric expansion occurring at 573 °C due to the change of crystal phases. Good results could be obtained by replacing quartz with basalt.
SUMMARY AND CONCLUSIONS

Within the last two decades amazing progress has been made in concrete technology. One of the breakthroughs is the development of ultra-high-performance concrete with its steel-like compressive strength and a remarkable increase in durability. UHPC is a high-tech material following new technological rules regarding its composition, its production, the mechanical behaviour as well as regarding design and construction of structures. Meanwhile a great store of knowledge about the material and about the adequate design and construction of structures with UHPC exist. Provisional Technical Recommendations have been published in France and in Germany. Some first spectacular applications in Canada, Europe and Asia have proven the assumed benefits of the new technology regarding costs, sustainability and service life. A wide range of different formulations are developed worldwide to meet the individual needs of the increasing number of different applications. Nevertheless there is a need for further research and development to close existing gaps of knowledge and to come to a widespread “regular” application based on comprehensive technical regulations.
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German Standards and Guidelines


Figure 1--Roadbridge at Bourg-lès-Valence, France. (Hajar et al. 2004)

Figure 2--Roof of the Millau toll-gate (Resplendino 2004).

Figure 3--Hybrid bridge in Kassel (Fehling et al. 2004)
Figure 4--Cross section of the Gaertnerplatzbruecke in Kassel

Figure 5--Packing effect schematical
Figure 6--Influence of the packing density on the rheology of UHPC (Geisenhanslüke and Schmidt 2004a)

Figure 7--Grain size distribution for maximum packing density (Mix M1Q) in table 1.
Figure 8--Compressive strength vs. water/fines- ratio of the cement matrix.

Figure 9--“Particle handicap” influencing the packing density (Geisenhanslüke and Schmidt 2004b)
Figure 10--Effectiveness of Steel and Polyvinyl fibers (PVA) on the ductility of UHPC (Mix M1Q in table 1)

Figure 11--Structure of HPC100 and UHPC200 matrix (SEM, width of picture: left: 3.6 µm; right: 3.0 µm)
Figure 12--Pore size distribution of UHPC, HPC and Normal Strength Concrete

Figure 13--Chloride diffusion values of UHPC, HPC and Normal Strength Concrete
Figure 14--Scaling of UHPC under freeze-salt attack compared with air entrained concretes.

Figure 15--Example of a UHPC tensile constitutive law
Figure 16--Assumed concrete behavior law for serviceability limit states (SETRA-AFGC 2002).

Figure 17--Simplified Stress – Strain - Relationship for SLS
Figure 18--Standard- Bending Prism Test according to DAfStb-Guideline Steel-Fiber Concrete

Figure 19--Crack-opening vs. bending tension stress curve for a test specimen made of fine grained UHPC according to Fig. 18.
Figure 20--Simplified stress-strain relation to characterize the tension zone.

Figure 21--Determination of factor $\beta$
Figure 22--Stress Strain relationship for design in ULS

Figure 23--Idealized post-cracking behavior of fiber reinforced UHPC (DAfStB UHPC 2003); $K_e = 2.0$. 
Figure 24--Bond strength for prestressing stands (\(\varnothing\) 12.5 mm) depending on contact length to diameter according to (Cheyrezy et al.1998)

cube 40 mm of Ductal, 2 vol.-% fibers, ribbed reinforcement bar \(\varnothing = 4\) mm, bond length \(2\varnothing = 8\) mm

Figure 25--Bond-stress-slip-relationship of UHPC according to (Reineck and Greiner 2004)
Figure 26--Modified RILEM pull-out test

Figure 27--S-N-curves for UHPC in comparison to NSC
Table 1--Typical composition of fine and coarse UHPC mixtures (Schmidt et al. 2003)

<table>
<thead>
<tr>
<th>UHPC</th>
<th>M 1</th>
<th>M 1Q</th>
<th>M 2Q</th>
<th>B 1</th>
<th>B 1Q</th>
<th>B 2Q</th>
<th>B 3Q</th>
</tr>
</thead>
<tbody>
<tr>
<td>cement</td>
<td>kg/m³</td>
<td>900</td>
<td>733</td>
<td>832</td>
<td>800</td>
<td>630</td>
<td>723</td>
</tr>
<tr>
<td>Sand 0/1 mm</td>
<td>kg/m³</td>
<td>1016</td>
<td>1008</td>
<td>975</td>
<td>440</td>
<td>433</td>
<td>425</td>
</tr>
<tr>
<td>basalt 2/8</td>
<td>kg/m³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>870</td>
<td>867</td>
<td>850</td>
</tr>
<tr>
<td>microsilica</td>
<td>kg/m³</td>
<td>225</td>
<td>230</td>
<td>135</td>
<td>200</td>
<td>197</td>
<td>118</td>
</tr>
<tr>
<td>steel fibers 2,5 Vol.-%</td>
<td>kg/m³</td>
<td>192</td>
<td>192</td>
<td>192</td>
<td>192</td>
<td>192</td>
<td>192</td>
</tr>
<tr>
<td>quartz powder I</td>
<td>kg/m³</td>
<td>-</td>
<td>183</td>
<td>207</td>
<td>-</td>
<td>158</td>
<td>181</td>
</tr>
<tr>
<td>quartz powder II</td>
<td>kg/m³</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>superplastizicer</td>
<td>kg/m³</td>
<td>28,2</td>
<td>28,6</td>
<td>29,4</td>
<td>25,0</td>
<td>24,7</td>
<td>25,6</td>
</tr>
<tr>
<td>water</td>
<td>l/m³</td>
<td>185</td>
<td>161</td>
<td>166</td>
<td>165</td>
<td>151</td>
<td>157</td>
</tr>
<tr>
<td>(w/c)</td>
<td></td>
<td>(0,23)</td>
<td></td>
<td>(0,24)</td>
<td>(0,22)</td>
<td>(0,23)</td>
<td>(0,27)</td>
</tr>
<tr>
<td>w/Fv</td>
<td></td>
<td>0,18</td>
<td></td>
<td>0,19</td>
<td></td>
<td>0,18</td>
<td></td>
</tr>
<tr>
<td>slump</td>
<td>cm</td>
<td>55</td>
<td>55</td>
<td>65</td>
<td>55</td>
<td>55</td>
<td>65</td>
</tr>
</tbody>
</table>
Table 2--Influence of the casting direction and the geometry of the specimen on tensile strength and fracture energy (Fehling and Bunje 2004).

<table>
<thead>
<tr>
<th>Test specimens</th>
<th>Age</th>
<th>Axial tension</th>
<th>Bending tension</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Prism 160 * 40 *40</td>
<td>Beam 700 * 150 * 150</td>
</tr>
<tr>
<td>Concrete</td>
<td>M1Q</td>
<td>B3Q</td>
<td>M1Q</td>
</tr>
<tr>
<td>Curing</td>
<td>90°</td>
<td>90°</td>
<td>90°</td>
</tr>
<tr>
<td>Pouring direction</td>
<td>horizontal</td>
<td>vertical</td>
<td>horizontal</td>
</tr>
<tr>
<td>Fracture energy</td>
<td>7d</td>
<td>16757</td>
<td>9993</td>
</tr>
<tr>
<td></td>
<td>28d</td>
<td>14555</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>28d*</td>
<td>17014</td>
<td>-</td>
</tr>
<tr>
<td>Strength</td>
<td>7d</td>
<td>14,2</td>
<td>7,9</td>
</tr>
<tr>
<td></td>
<td>28d</td>
<td>13,3</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>56d</td>
<td>17,7</td>
<td>-</td>
</tr>
</tbody>
</table>

WL: Stored under water at 20°C.
### Table 3--Characteristic durability values for UHPC, HPC and Normal Strength Concrete

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Ordinary Concrete C 35 EN 206</th>
<th>High Performance Concrete C 100/115 EN 206</th>
<th>Ultra High Perf. Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total porosity [%]</td>
<td>app. 15</td>
<td>app. 8</td>
<td>4-6</td>
</tr>
<tr>
<td>Capillary pores [%]</td>
<td>app. 8</td>
<td>app. 5</td>
<td>1.5-2.0</td>
</tr>
<tr>
<td>Nitrogen permeability [m²]</td>
<td>10⁻¹⁶</td>
<td>10⁻¹⁷</td>
<td>&lt;10⁻¹⁸</td>
</tr>
<tr>
<td>Chloride-ion diffusion (6h quick-migration test)</td>
<td>23</td>
<td>8</td>
<td>1</td>
</tr>
<tr>
<td>Depths of intrusion [mm]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Carbonation depth (after 3 years) in mm (20°C, 65% r. humidity)</td>
<td>7</td>
<td>4</td>
<td>1.5</td>
</tr>
<tr>
<td>Freeze-salt-resistance (scaling in [g/m²])¹</td>
<td>&lt; 1500 (air entrained)</td>
<td>150 (air entrained)</td>
<td>20…50 water … heat cured</td>
</tr>
<tr>
<td>Water absorption factor³</td>
<td>60</td>
<td>11</td>
<td>1</td>
</tr>
</tbody>
</table>

1) CDF- test, 28 cycles, limit 1500 g/m²  2) (Tang and Nielsson 1992)  3) DIN 52617

### Table 4--Proposal for the exponent n in Eq. 1

<table>
<thead>
<tr>
<th>$f_{ck}[N/mm^2]$</th>
<th>110</th>
<th>120</th>
<th>130</th>
<th>140</th>
<th>150</th>
<th>160</th>
<th>170</th>
<th>180</th>
<th>190</th>
<th>200</th>
<th>210</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N$</td>
<td>1.50</td>
<td>1.45</td>
<td>1.40</td>
<td>1.35</td>
<td>1.30</td>
<td>1.25</td>
<td>1.20</td>
<td>1.15</td>
<td>1.10</td>
<td>1.05</td>
<td>1.00</td>
</tr>
</tbody>
</table>