Chapter 3
New Types of High Performance Concretes – Potentials for Innovations in Concrete Construction

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Abstract Among the new types of high performance concretes this paper deals with self-compacting concrete (SCC) and ultra high strength concrete (UHPC). Both types of self-compacting concrete, the powder type SCC and the stabilizer type SCC, are presented. Differences in the mix design and composition as well as the properties in the fresh and in the hardened state are indicated. While most of the properties of SCC are roughly similar to normal concrete (NC) – apart from the self-compacting property – this holds by far not true for UHPC. Not only the mechanical properties but also the durability of UHPC deviates significantly from normal concrete. In addition, it is shown that UHPC is more sustainable than normal concrete if the ecological impact is considered in relation to the performance of the concrete.

3.1 Introduction

In the last two decades considerable progress in concrete technology has taken place. New types of concrete, such as self-compacting concrete (SCC) and high strength concrete (HSC), are produced and applied in practice on a routine basis. Today even ultra high strength concrete (UHPC), reaching compressive strength values above 200 MPa, may be produced and applied for precast concrete elements. Further, promising trends towards the development of ultra ductile concrete, ecological concrete (green concrete) and textile concrete are under way. Besides, also the strengthening of concrete by the use of carbon nanotubes reveals a remarkable potential for the improvement of concrete performance.

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It is not possible to treat the above mentioned special concretes in detail here. Hence, this paper concentrates on self-compacting concrete and ultra high strength concrete. These two types of concrete may be roughly characterized as follows:

- *self-compacting concrete (SCC)*: a type of structural concrete which strongly deviates from normal concrete (NC) in the fresh state, as it de-aerates and flows without the application of additional compaction energy;
- *ultra high strength concrete (UHPC)*: a type of structural concrete with a compressive strength above 120 MPa and a very high durability, achieved by an optimized packing density of all granular raw materials.

As the very high strength of UHPC is always associated with a very high durability, i.e. excellent performance characteristics, this type of concrete is usually termed as ultra high performance concrete.

Mix design, composition and properties in the fresh and the hardened state of these special concretes deviate considerably from those of conventional structural concrete, as will be shown in the subsequent sections. Moreover, the related governing parameters and effects are dealt with in the following.

3.2 Self-Compacting Concrete

3.2.1 General

Self-compacting concrete (SCC) is a concrete that de-aerates and flows without the application of compaction energy, while staying homogenous during the whole placing process until hardening. To understand the underlying mechanisms, one has to focus on the rheological behaviour of concrete at the fresh state. Hereby it has to be kept in mind that concrete, i.e. the cement paste as the governing component, is a non-Newtonian material where the viscosity depends strongly on the shear rate. This is indicated in Fig. 3.1 where the viscosity of normal concrete and of self-compacting concrete is shown as a function of the shear rate.

For very low shear rates, or when it is at rest, concrete shows a very high dynamic viscosity, which continuously reduces with increasing shear rate and approaches a final value, the so-called plastic viscosity (Fig. 3.1). In order to compact a concrete after placing, it is subjected to high shear rates using a vibrator-poker. This reduces the viscosity of the concrete and minimizes the viscous flow resistance, allowing air bubbles to escape. At rest, however, the viscosity instantly regains its previous high value, preventing segregation effects (Haist 2009).

In order to facilitate the concrete to de-aerate properly without any additional compaction work during the placing process, i.e. by flowing in the formwork at moderate shear rates, the dynamic viscosity of the mixture at these shear rates must be low enough to enable the entrapped air bubbles to rise to the concrete surface. Today, two procedures are available to achieve this, i.e. to produce self-compacting concrete, as described subsequently.

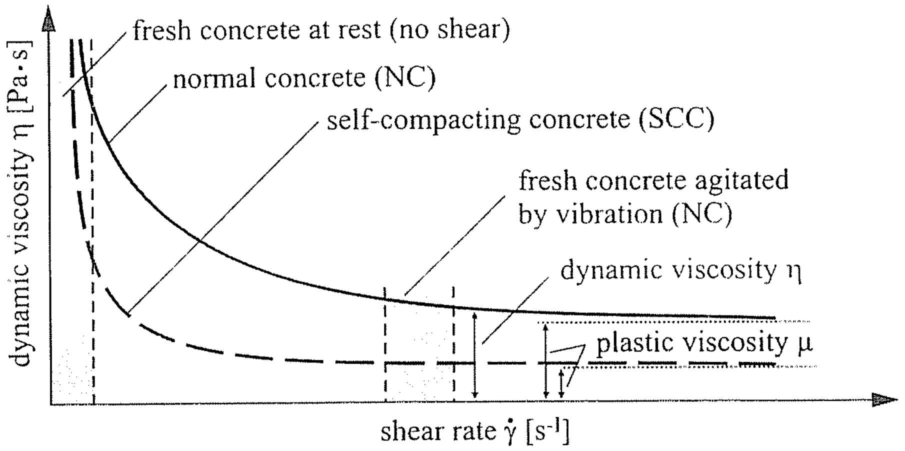


Fig. 3.1 Rheological behaviour of fresh normal (conventional) concrete and self-compacting concrete as a function of the shear rate during placing

The so-called *powder type self-compacting concretes* are characterized by an approximately 30% higher paste content compared to conventional concrete. This ensures a high fluidity of the mix. The paste itself consists of cement, large amounts of mineral additives such as fly ash or limestone powder, water and chemical admixtures (above all superplasticizers). In order to prevent segregation, the water/cement ratio and the water/binder ratio are kept very low, leading to high strength values at the hardened state. Due to the high paste content, powder type SCC generally exhibits a reduced modulus of elasticity in comparison to conventional concretes of equal strength.

In contrast to powder type SCC, *stabilizer type self-compacting concretes* have lower paste content (approximately 10% higher than conventional concrete) but a significantly higher water/binder ratio. By adding superplasticizer, the viscosity of the mixes, especially at low shear rates, is markedly reduced, hence allowing the entrapped air to leave the concrete. At rest, however, strong segregation would occur unless this is prevented by adding stabilizing admixtures, so-called viscosity modifying agents (VMA). At the hardened state stabilizer type SCC has only insignificant differences from conventional concrete of equal strength. The increased water/binder ratio allows for the production of low and normal strength concretes with self-compacting properties.

3.2.2 Mix Design

The mix design process of SCC is still exclusively focused on ensuring self-compacting properties while neglecting other important mix design criteria, such as the compressive strength or the durability. Usually this disadvantage is accepted, as the most commonly used powder type SCC normally results in compressive strength values above 60 MPa at very low water/binder-ratios, ensuring a high durability. However, it should be considered that exceeding the strength class projected by the designer might be associated with significant changes in the concrete's modulus of elasticity and its long-time deformation behaviour, i.e. creep and shrinkage.

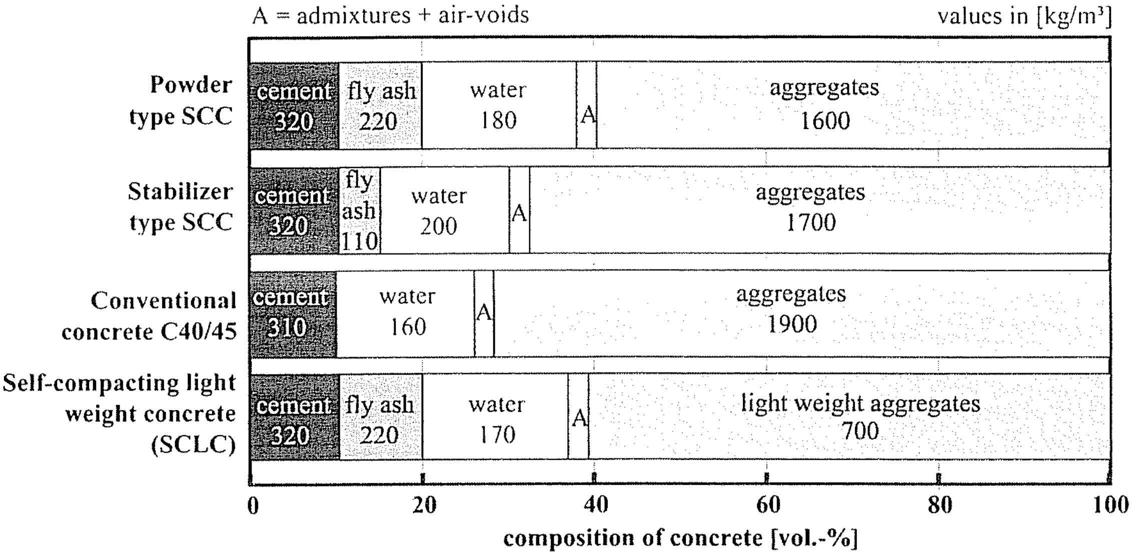


Fig. 3.2 Composition of a powder type SCC, a stabilizer type SCC and a conventional vibrated concrete C40/45, as well as of a self-compacting light weight concrete (*SCLC*)

3.2.2.1 Powder Type SCC

As has already been pointed out, by increasing the powder and thus the paste content in the concrete, its workability can be significantly improved. However, this measure alone is not sufficient to achieve the desired self-compactability. In order for the paste to flow properly and to be able to transport coarse aggregate grains, it must have a sufficient viscosity at high shear rates. On the other hand, at low shear rates the viscosity should not be too high, in order to enable sufficient de-aering and to flow in common placing conditions. This behaviour is usually ensured by using modern superplasticizers, which allow for a targeted adjustment of the paste's viscosity at low shear rates, without significantly influencing the flow behaviour at high shear rates. Prerequisite for such a systematic adjustment of the fresh paste properties is that the water/binder ratio of the paste is kept at a minimum value, the so-called water demand level. In order to prevent segregation of the concrete – i.e. sedimentation of the coarse aggregates in the fresh concrete – the grading curve of the aggregates should be adjusted to have a high fines or sand content. The sand grains hinder the coarser aggregates from sinking and thus prevent sedimentation.

Based on these principles, Okamura and Ozawa (1995) developed a mix design procedure for powder type SCC. Further details on this subject may also be found in (Müller and Haist 2010). A typical composition of a powder type SCC is shown in Fig. 3.2.

3.2.2.2 Stabilizer Type SCC

Today, no standardized mix design procedure for stabilizer type SCC exists. This is due to the fact that the stabilizers and superplasticizers available on the market have a highly diverse working regime, which makes it very difficult to follow standardized approaches.

Stabilizer type SCC normally has a paste content of approximately 32–36% by volume, to be contrasted with 27–32% in conventional concrete. In contrast to powder type SCC, the paste usually contains a much higher water content. This leads to a pronounced reduction of the viscosity of the mix at the fresh state over the full range of shear rates (cf. Fig. 3.1). In order to prevent segregation at rest and to avoid blockage of coarse aggregates in confined reinforcement layouts, stabilizing admixtures are added. These stabilizers significantly influence the viscosity of the concrete at low and medium shear rates.

Similar to the powder type SCC, the grain size distribution of stabilizer type SCC is characterized by a comparatively high sand content, which helps to prevent segregation phenomena. A typical composition of a stabilizer type SCC is also shown in Fig. 3.2.

3.2.3 Composition and Fresh Concrete Properties

As can be seen in Fig. 3.2, mixes based on the powder type formulation are characterized by volumetric powder contents approximately twice as high as those of a conventional structural concrete. When using fly ash as a filler, it should be noted, many national codes allow regarding only parts of this amount as cement replacement (e.g. maximum of 33% by mass in Germany) and hence taking it into account in the equivalent water/cement ratio (e.g., a *k*-value of 0.4 applying in Germany). The rest of the fly ash is normally considered as pure filler, even though it reacts in the same manner as the fly ash considered as a cement replacement. This explains why powder type self-compacting concretes containing fly ash usually show very high strengths and have hardened concrete properties corresponding to a high strength concrete rather than to a conventional concrete.

When using limestone or other inert mineral powders, it should be noted that for the contents considered here, these fillers do not contribute actively to the hydration process. The increased paste content of the concrete might therefore have adverse effects on the hardened state properties and especially on the durability of the concrete. With respect to the use of limestone powders, it is recommended to use powders with low total organic contents (TOC) and high fineness, i.e. powders of LL-quality according to European standard EN 197-1:2004.

The maximum aggregate size for the production of self-compacting concrete should be limited to approximately 16–20 mm. In order to prevent segregation at rest and blocking behaviour during flow, the grading curve of the aggregates should be characterized by a high content in fines. It is possible to produce self-compacting concrete with rounded or crushed aggregates. In the latter case, normally higher paste contents might be required in order to get equivalent flow properties. When using aggregates sensitive to alkali silica reaction, it should be borne in mind that the high paste content of SCC, as well as the high superplasticizer content – which may provide large amounts of alkalis – form unfavourable conditions for such a concrete.

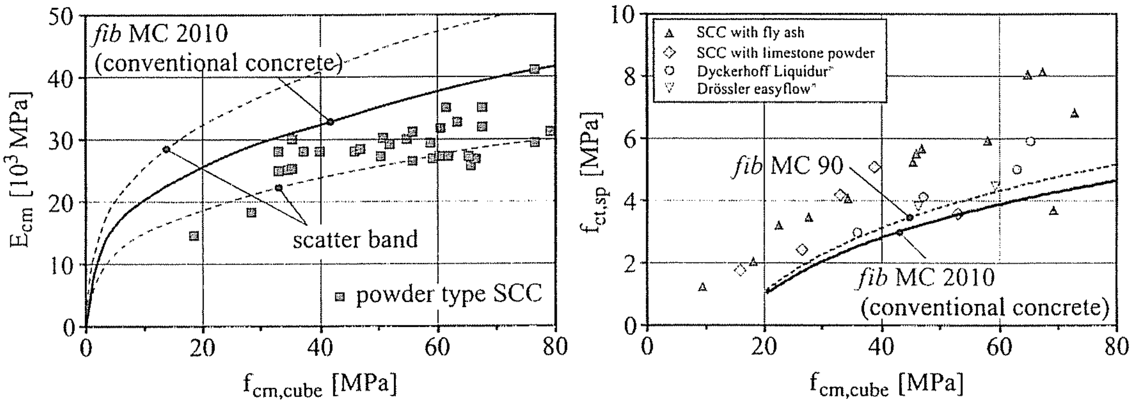


Fig. 3.3 Modulus of elasticity E_{cm} (*left*) and splitting tensile strength $f_{ct,sp}$ (*right*) as a function of the mean concrete compressive (*cube*) strength $f_{cm,cube}$ for various self-compacting concretes; experimental data and *fib* MC 2010 predictions

Testing of the fresh concrete properties of SCC is, among others, covered by the European standard EN 206-9:2008. In contrast to conventional concrete, the complex fresh concrete behaviour of SCC required the introduction of several new test methods, such as the slump flow test (see European standards EN 12350-8:2009 and EN 12350-12:2008 with or without J-Ring), the V-funnel test (see European standard EN 12350-9:2008-01) or the sedimentation test (see EN 12350-11:2008).

The primary goals of the test procedures are to guarantee that the concrete de-aerates properly, stays homogenous during flow and rest until hardening and has suitable flow behaviour in order to fill a given formwork. The last requirement mentioned clarifies that the required flow behaviour is a function of the formwork geometry. On this background the flow properties must vary, depending, e.g., on whether a long wall element with extensive flow passages is cast or whether a slender column is filled with SCC.

3.2.4 *Properties at the Hardened State*

The differences in the composition of self-compacting concrete in comparison to conventional (vibrated) concrete may lead to deviations in the hardened state behaviour. Especially for powder type SCC, the increased paste content normally results in a reduced modulus of elasticity E_{cm}. From experimental results, this deviation can be estimated to be between 10% and 20% below the prediction of e.g. *fib* MC 2010 for a conventionally compacted concrete of equal compressive strength. However, as can be seen from Fig. 3.3 (left), this deviation is still within the scatter band known from conventional concretes. When using pozzolanic additives, like fly ash, the reduced modulus of elasticity at the age of 28 days is outweighed to some extent by an increased gain in stiffness due to the pozzolanic reaction of the fly ash at higher concrete age. The designer should, however, keep in mind that for structures sensitive to the deformation behaviour of the concrete, additional testing of the self-compacting concrete to be used is highly recommended.

Regarding the tensile strength, the increased binder content of SCC may lead to higher values, depending on the type of filler used (see Fig. 3.3, right). Note in this context that *fib* MC 2010 predicts a slightly lower splitting tensile strength $f_{ct,sp}$ for concretes of equal mean compressive strength f_{cm} than the CEB/FIP MC 90. This is due to the fact that, in *fib* MC 2010 the conversion factor to calculate the tensile strength from the splitting tensile strength was changed from 0.9 to 1.0. For structures sensitive to cracking, further attention should be paid to the development of the tensile strength beyond the design age of 28 days. Especially when using large amounts of pozzolanic additives, like fly ash or silica fume, a pronounced growth of the tensile strength at higher concrete ages might be observed.

Similarly to the modulus of elasticity, the creep and shrinkage behaviour of powder type SCC is also affected by the high paste content of such concretes. The limited data regarding the shrinkage behaviour of powder type SCC suggest that the ultimate shrinkage deformation can be expected to be approximately 20% higher than for a conventional concrete of equal strength. The same tendency holds true for the creep behaviour of such concretes. Powder type SCC in general exhibits an increase of approximately 10–20% in creep deformations.

Both creep and shrinkage deformations of SCC are well within the scatter band e.g. of *fib* MC 2010 predictions, which is defined to be ±30%. It should be noted, however, that for structures which are sensitive to variations in the modulus of elasticity as well as the creep and shrinkage behaviour, the deviations mentioned above for SCC occur systematically. In case of doubt it is therefore highly recommended to measure the actual short- and long-time deformation behaviour.

The bond behaviour of SCC, being comparable to NC, is less dependent on the position of the reinforcing bar, i.e. whether the bar is embedded at the top or the bottom of a formwork.

The durability of SCC is characterized by an identical or improved behaviour than conventional concrete of equal strength regarding the carbonation and chloride diffusion behaviour. The freeze-thaw resistance of powder type SCC strongly depends on the type of filler used. For SCC containing fly-ash, an equivalent or even higher freeze-thaw resistance has been observed. However, concretes containing limestone powder have shown increased weathering in the freeze-thaw test. Further, it should be taken into account that SCC has higher paste content, which in general has an adverse effect on the freeze-thaw behaviour.

3.3 Ultra High Strength Concrete

3.3.1 Introduction

Ultra high strength concrete is usually defined as a concrete having a characteristic compressive strength above the strength grade C100/115. One may distinguish between two types:

- the reactive powder concrete (RPC), characterised by a maximum aggregate size of approximately 0.5 mm and
- the ultra high performance concrete (UHPC), with coarse aggregates normally up to an aggregate size of 8 mm.

The water/cement ratios of such concretes are usually below 0.25 and highly reactive additions, such as silica fume, have to be added to the mix. The workability of the concrete can only be ensured by applying large amounts of superplasticizer. Thus a compressive strength of approximately 200 MPa may be achieved. Depending on the type of curing, e.g. with additional heat treatment without or with mechanical pressure, this concrete may reach a compressive strength of up to 800 MPa, provided a proper selection of the aggregates is carried out.

No standard has been adopted yet for this type of concrete, which significantly exceeds the strength range specified in EN 206-1:2001. Nevertheless UHPC might become interesting for a broader application in practice. The reason is that the very high strength allows a significant reduction of the cross-section of members, while retaining a high load bearing capacity. This is accompanied by a significant mass reduction, allowing in principle much longer spans compared to those realized when ordinary structural concrete is used. Mass reduction also decreases the loads on the foundation, as well as inertia and seismic forces in earthquake-resistant construction. In addition, savings in materials affect positively sustainability and make UHPC superior to ordinary structural concrete, despite the significantly higher cement content of UHPC, see below and e.g. (Müller and Scheydt 2009).

Considering the practical application of UHPC, major problems result from the fact that this concrete shows a significant autogenous shrinkage during the early hardening process. As a consequence, construction with UHPC in practice is realised mostly by precasting. However, research is under way to overcome this deficiency, e.g. through addition of super-absorbent polymers.

3.3.2 Mix Design

UHPC is composed of aggregates, cement, water, additives and admixtures. Aggregates that may be used include the materials referred to as "aggregates for concrete" in EN 12620:2008. The particle strength should be sufficiently high and the grain size distribution should guarantee a high packing density.

Regarding the cement type used in UHPC, Portland cements with a low C_3A content are recommendable, as these cements have a low water demand. This is also advantageous in view of the risk of a secondary ettringite formation in case of curing at high temperatures. The strength classes of the cements applied is 42.5 or 52.5. Blast furnace slag cement of strength class 52.5 has also been successfully used. The cement contents in UHPC are normally very high and range from 600 to 1,000 kg/m^3. The fineness of the cement should be between 3,000 and 4,500 cm^2/g.

In order to produce UHPC, it is important to achieve the maximum possible packing density of all granular constituents. The voids between the cement particles (diameter from 1 to 20 μm) are filled by silica fume (SF) particles (0.1–0.3 μm). For this purpose, the required silica fume quantity is between 10 and 30% of the cement by mass.

The second major effect expected from the addition of silica fume, beyond the increase in packing density, is a reduction of the amount of calcium hydroxide in the interfacial transition zone between the aggregate grains and the cement paste matrix. The almost pure SiO_2 of silica fume consumes $Ca(OH)_2$, which is created during the hydration of cement clinker, and forms calcium silicate hydrates (CSH). This means that the $Ca(OH)_2$, which has lower strength, is replaced by CSH of much higher strength. The porosity decreases in the bulk and in particular in the interfacial zone. All these effects result in a significant increase in strength.

Quartz powder with particle sizes similar to cement is predominantly used in heat-treated UHPC. The quartz particles are inert at room temperature but, together with $Ca(OH)_2$, they react at high temperatures to form CSH phases.

Fresh UHPC is not workable without the addition of large quantities of high performance plasticizers (up to 5% of the cement by mass). Only third generation plasticizers (polycarboxylate ethers, PCE) allow saving a sufficient amount of water while making UHPC workable. Their mechanism of action relies on the adsorption of the PCE molecules to the surface of the clinker phases and of hydration products, which results in a steric repulsion. This leads to a dispersion of the cement particles, which creates in turn the plasticizing effect.

Like dense natural stone, UHPC shows an elastic and brittle behaviour. Fibres are added to the concrete to compensate for this disadvantage in construction practice. It has been proven that approximately 2.5% of steel fibres by volume, at an aspect ratio l/d between 40 and 60, lead to best results, both in view of fresh and hardened concrete properties. The fibre length should be adjusted to the maximum aggregate diameter. For powder type UHPC (i.e. with limited maximum grain size), the fibre length should be at least ten times the maximum aggregate diameter.

The water content of the mix is the crucial parameter to ensure optimal properties. Water/binder ratios from 0.15 to 0.25 seem to ensure a reasonable balance between the flow properties of the fresh concrete and the strength of the hardened concrete.

3.3.3 Properties of the Fresh Concrete

UHPC is characterized by high powder content, in excess of 1,000 kg/m^3, in combination with high dosages of superplasticizers. Its properties at the fresh state are thus comparable to self-compacting concrete of the powder type. For this reason, the workability of this type of concrete should rather be measured with the test set-up used for SCC, i.e. slump flow and V-funnel flow test. The slump flow of UHPC normally ranges from 650 to 800 mm and the V-funnel flow time from 15 to 40 s. Superplasticizers strongly reduce the flow resistance of the concrete and lead to a normalization of the dynamic viscosity over the whole range of shear rates (Fig. 3.4).

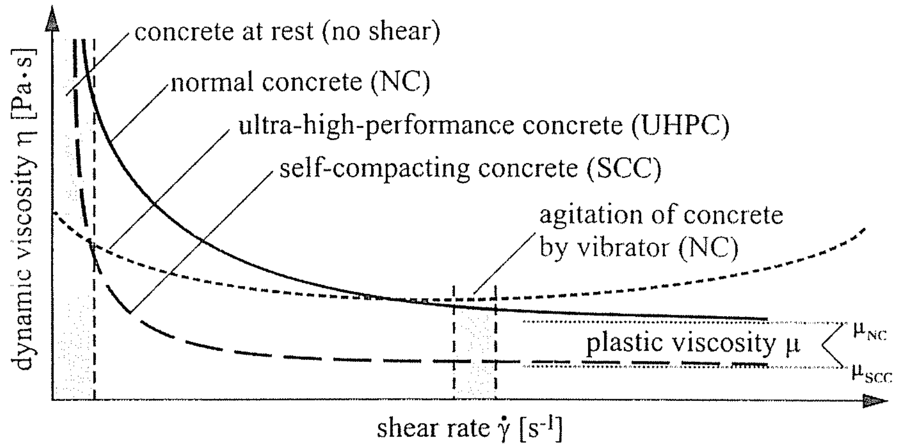


Fig. 3.4 Dynamic viscosity of fresh UHPC, conventional concrete (*NC*) and self-compacting concrete (*SCC*), as a function of the externally applied shear rate

As can be seen from Fig. 3.4, the dynamic viscosity of UHPC remains nearly constant – even though at a very high level – no matter whether the concrete is at rest or it is agitated, for example by a vibrator. For UHPC, the de-airing process therefore cannot be enhanced significantly by vibrating the concrete. At rest, however, for concretes with a very low dynamic viscosity, sedimentation may be observed, which must be prevented in UHPC by optimizing the grain size distribution of the aggregates, thus ensuring an interlocking of the particles. At high shear rates, UHPC normally shows a dilatant material behaviour, i.e. an increase of the dynamic viscosity.

The air content in UHPC ranges from 1% to 5% by volume, with the lower ratios observed in low viscosity mixes. In addition, there is a trend towards an air ratio increase that occurs in line with the increasing length of the steel fibres used.

Plastic (capillary) shrinkage and autogenous deformation are promoted by high cement paste content and a low water/cement ratio. For this reason, the immediate curing of UHPC is basically very important.

3.3.4 Properties of Hardened Concrete

3.3.4.1 Strength Characteristics

The compressive and the tensile strength which may be achieved by UHPC depend strongly on the concrete composition, in particular with regard to the type and amount of binders and the fine aggregates (micro- fillers) as well as the type and duration of curing. If ordinary curing, at room temperature of 20°C, is applied a maximum compressive strength of UHPC of approximately 200 MPa can be achieved. If the curing temperature is increased to 100°C, the strength will reach approximately 250 MPa. A further increase of the curing temperature to 250°C is accompanied by a strength gain to almost 400 MPa. A compressive strength value of approximately 800 MPa may be achieved, if mechanical pressure is applied in addition.

Similarly to ordinary fibre reinforced concrete, the addition of fibres (mostly steel fibres) causes a small improvement of the compressive strength of UHPC, but may significantly affect the strain capacity of the concrete. The investigations on the effect of the volume content of fibres of up to 6% by volume, point to an optimum fibre content of approximately 2.5%.

The uniaxial tensile strength and the flexural tensile strength of UHPC reach values ranging approximately from 10 to 60 MPa. When special binders and techniques are applied, a tensile strength of 150 MPa may be attained. It should be noted that, unlike the compression characteristics, the tensile strength of UHPC may be doubled when fibres (1.5–3.0% by volume) are added to the mix. This may be attributed to a large extent to the reduction of the brittleness of non-reinforced UHPC, where minor flaws and cracks may tremendously reduce the tensile strength.

Concerning the fracture energy and the characteristic length of UHPC, the available knowledge is still very insufficient. It appears that for UHPC made without fibres these values are somewhat lower than for high strength concrete. Of course, the addition of fibres may increase the fracture energy up to a factor of approximately 100.

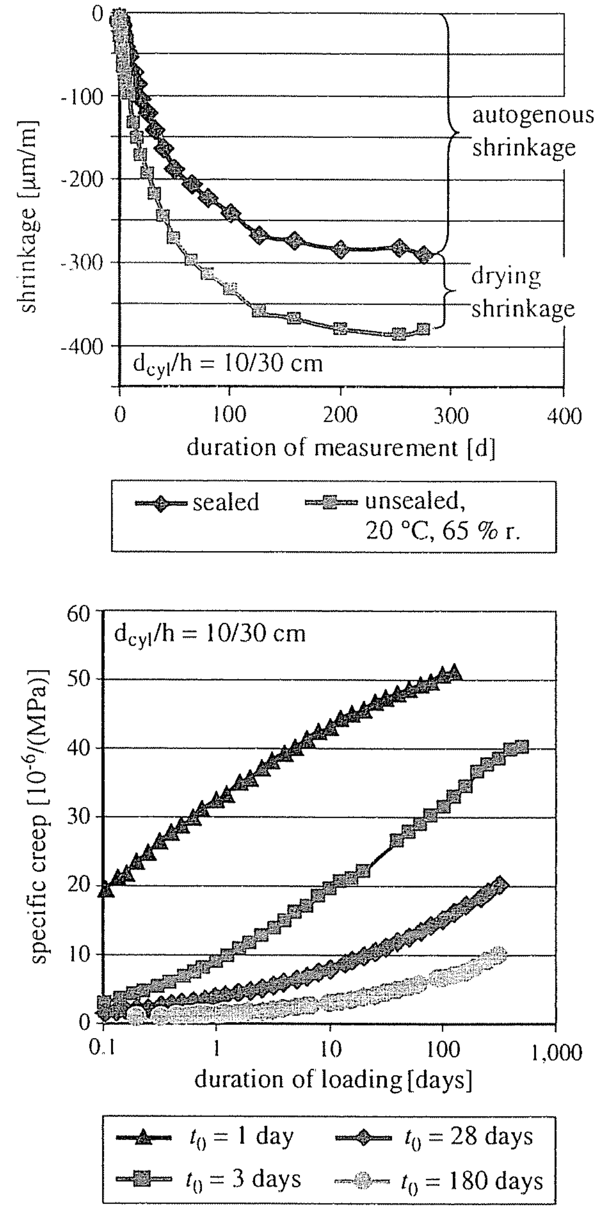
3.3.4.2 Deformation Behaviour

The stress-strain behaviour of non-reinforced UHPC shows a linearly elastic pattern almost up to the ultimate load level. Most of the commonly used testing equipment and specimen sizes do not allow the determination of a descending branch in the stress-strain diagram. An explosive failure occurs, causing a strong impact on the testing equipment. In a fibre reinforced UHPC, the fibres prevent macro-cracking, because they hold the crack edges together already at the micro-cracking stage and thus hinder the cracking progress. As a result, a significant additional strain capacity is obtained while the increase in strength is minor. Similar to ordinary fibre reinforced concrete, the fibre content determines whether this strain results in strain softening or in strain consolidation.

The modulus of elasticity of UHPC reaches approximately 50–60 GPa when the compressive strength is 200 MPa. If reactive powder concrete (RPC) is produced, having a compressive strength of up to 800 MPa, the modulus of elasticity may approach 75 GPa. As it holds for conventional structural concrete, the modulus of elasticity of UHPC also strongly depends on the paste content and the type of aggregates.

The autogenous shrinkage of UHPC is very pronounced and may reach values beyond 0.0012 (1.2 μm/mm). Often much lower values are reported in the literature. However, this is mostly due to the applied measurement technique, in connection with the age of concrete when the measurement starts. When it starts too late, e.g. at a concrete age of one day, most of the autogenous shrinkage, which develops mainly between an age of 8–24 h, has already taken place and is consequently not recorded. As may be seen from Fig. 3.5 (top), autogenous shrinkage observed after a concrete age of one day reaches strain values of approximately 0.3 μm/mm for an UHPC with a compressive strength of 170 MPa (C170).

Fig. 3.5 Shrinkage of UHPC under different storage condition (*top*), and creep of UHPC for different ages at loading (*bottom*)



Drying shrinkage of UHPC, obtained from the difference of total shrinkage and autogenous shrinkage, is much lower, even when compared to that in high strength concrete. This may be traced back to the extremely low porosity of UHPC. In studies on autogenous and drying shrinkage of different UHPC starting at the concrete age of 1 day, an autogenous shrinkage of 0.3 µm/mm and a drying shrinkage of 0.1 µm/mm (at a maximum) have been observed (see Fig. 3.5, top). The test results shown in Fig. 3.5 have been obtained on concrete cylinders (with diameter 100 mm and height 300 mm) stored at an ambient temperature of 20 °C, where the specimens were either sealed (water loss prevented) or remained unsealed in an ambient environment of 65% relative humidity.

Figure 3.5 (bottom) exemplarily shows the influence of different concrete ages at loading on the specific creep (creep per unit stress) of an UHPC (C170). The stress level was 30% of strength and the specimens were stored unsealed in a climate of 20°C and 65% relative humidity. As already observed in experiments on normal strength and high-strength concretes, the magnitude of creep is significantly decreasing with increasing concrete age. However, this effect is much more pronounced for UHPC than for high strength concrete or normal strength concrete. If creep coefficients are calculated from the results shown, for an age at loading of $t_0 = 1$ day or $t_0 = 3$ days, final creep coefficients between approximately $\varphi = 3$ and $\varphi = 2$, respectively, are obtained. Even for an age at loading of $t_0 = 28$ days the final creep coefficient reaches approximately $\varphi = 1.5$. This means that the pronounced decrease of the creep capacity of concrete with the increase in strength of the hardened cement paste is no longer true for UHPC.

The application of high sustained loads showed no significant difference in the sustained load strength of UHPC compared to normal strength concrete.

3.3.4.3 Physical Characteristics

The physical characteristics of concrete are mainly determined by its capillary porosity. Whereas conventional concrete (C35) and high strength concrete (C100) show marked peaks in the pore size distribution between 0.01 and 0.1 μm, these peaks are nearly eliminated in the case of UHPC (C200) and disappear completely in RPC (C500). Absolute porosities then become so low, that transport processes almost come to a halt.

As a consequence carbonation depths measured on UHPC are almost negligible. Chloride penetration was investigated in migration tests where a diffusion coefficient of $0.02 \cdot 10^{12}$ m^2/s was measured, which is about 100 times lower than the value for a C30 concrete.

The nitrogen permeability of UHPC decreases to a level that is ten times lower than in a high performance C100 concrete and 100 times lower than in a C30 concrete. The water permeability of a C190 UHPC was found to be in a range between 4 and $5 \cdot 10^{-15}$ m^2/s, which corresponds to the permeability of dense natural stone. The same behaviour was found for capillary water absorption.

3.3.4.4 Durability

Structural concrete usually containing capillary pores is often destroyed by mechanisms triggered by frost or by freeze-thaw cycles. If no capillary pores are present, or if only a minimal amount of such pores exist, only a small quantity of water can be absorbed and no saturation will occur. Correspondingly, the concrete shows a very good behaviour when exposed to frost or freeze-thaw cycles.

Tests in sodium sulphate solution have demonstrated a very high chemical resistance. No conclusive findings have been established yet with regard to alkali silica reaction. However, the tightness of the material appears to be one of the crucial factors that determine resistance.

Even though UHPC is exposed to a strong acid attack (pH = 1 and 3) it shows a significantly better performance than ordinary structural concrete. Of course, also

UHPC will be destroyed by a long-term attack of strong acids, as the CSH component of the hydrated cement paste is principally dissolved by acids as a consequence of its chemical nature. However, due to the extreme low porosity of UHPC compared to ordinary structural concrete and even high strength concrete, the rate of damage is much slower, leading to a significant higher durability or life time, respectively (Müller and Scheydt 2009).

Initially UHPC had not been fire-resistant: the tested concrete bursted and the fibres in the fibre reinforced concrete oxidised under heat exposure. Fire resistant UHPC could be successfully produced by adding 0.3–0.6% of polypropylene fibres by volume. It is also helpful to replace quartz with basalt aggregate, which prevents occurrence of the deleterious quartz conversion.

3.3.4.5 Sustainability

Compared to normal strength concrete, ultra high performance concrete is up to three times more expensive, owing to the high binder and fibre content. But beyond cost efficiency, also the mechanical and durability properties of the concretes, as well as their sustainability, should be compared.

For the evaluation of the environmental impact and thus the sustainability, various impact categories are considered, see e.g. (Stengel and Schießl 2008). When entering the values of the material's impact categories in a radar chart, a closed polygon can be drawn. The closer the polygon lines approach the point of origin, the more favourable is the environmental impact of the considered material.

In a direct comparison, i.e. when a volume-based analysis is made, the UHPC (C190) has a significantly more adverse impact than the normal strength concrete NPC (C30), see Fig. 3.6. This is caused in particular by its higher cement, steel fibre and superplasticizer content, compared to NPC. When, by contrast, these environmental impact parameters are related to durability values, e.g. to the permeability, the UHPC demonstrates a clear superiority (Fig. 3.7). Analogous diagrams result if the impact categories are related to other performance parameters, such as the resistance against chemical attack, or also to the concrete strength.

3.4 Summary and Outlook

This paper deals with self-compacting concrete (SCC) and ultra high strength concrete (UHPC). Mix design, composition and properties in the fresh and in the hardened state of these concretes are shown. While practical experience with self-compacting concrete already exists, which is produced as ready mixed concrete, for ultra high strength concrete only a few applications, primarily its use in precast elements, are known so far. In view of the promising properties of these both new types of concrete, a broader application in practice seems to be very likely in the future. Still remaining technical problems, such as the high sensitivity of SCC to minor

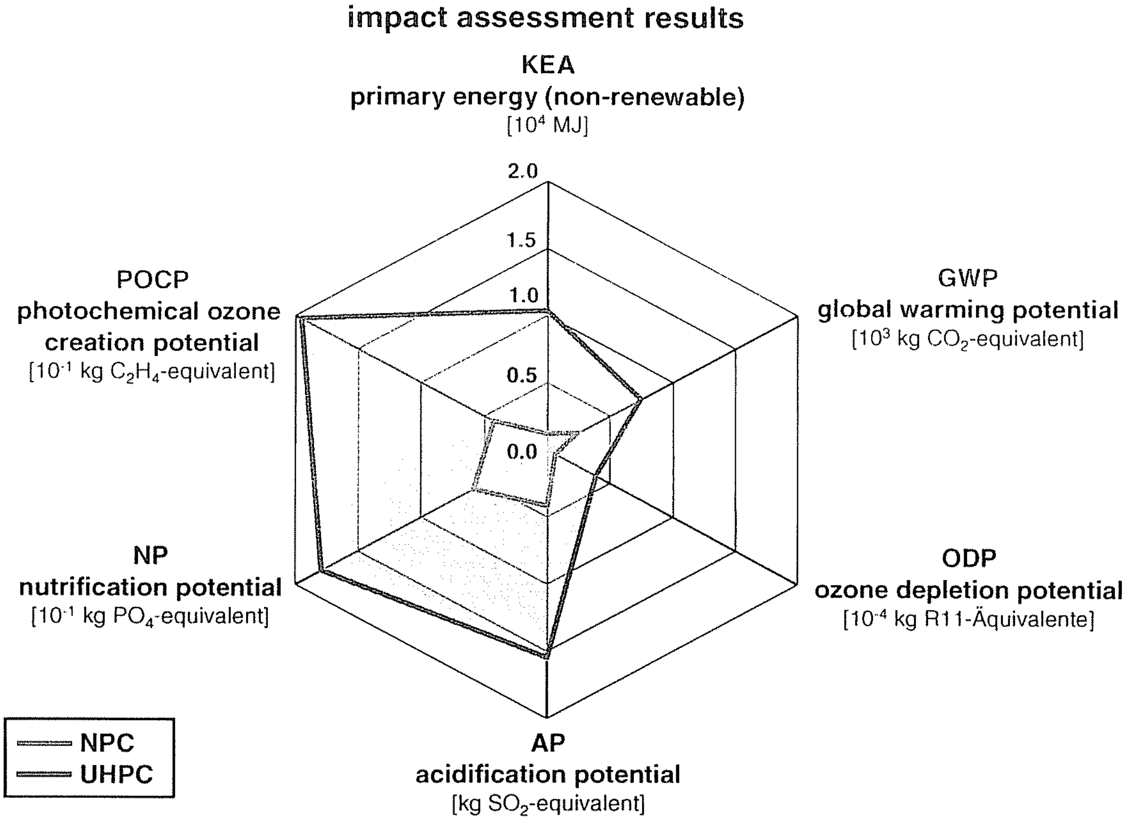


Fig. 3.6 Impact assessment results for 1 m³ of concrete when normal strength concrete (*NPC*) and ultra high performance concrete (*UHPC*) are compared

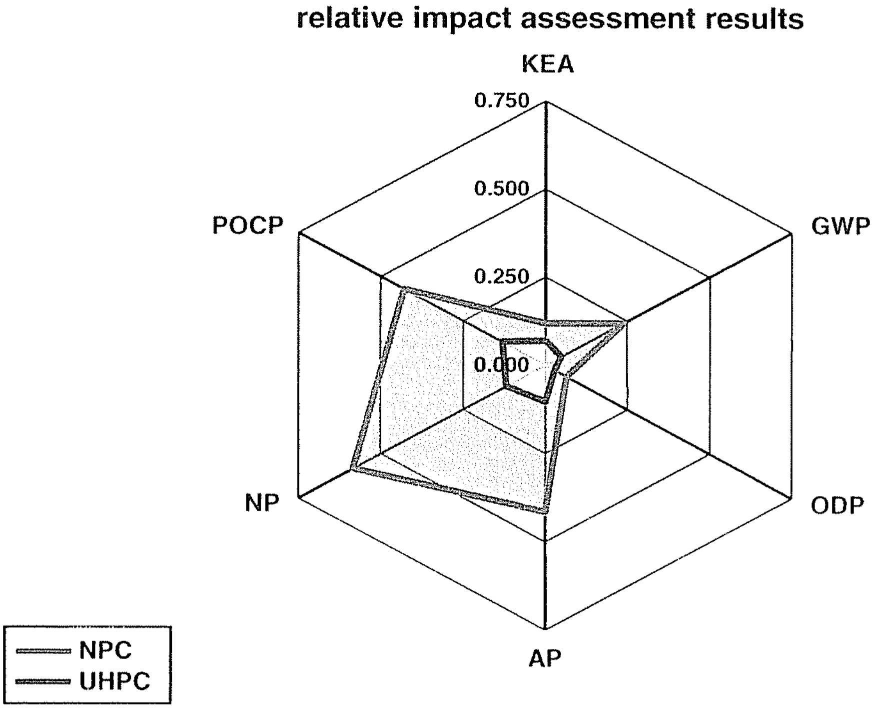


Fig. 3.7 Relative impact assessment results for 1 m³ of normal strength concrete (*NPC*), when NPC and UHPC are compared, referring to the individual values of the permeability

variations in composition and concrete temperature, or the very high autogenous shrinkage of UHPC, have to be solved by continuing research.

Further, promising trends towards the development of ultra ductile concrete, ecological concrete (green concrete) and textile concrete are under way, revealing remarkable potentials for the improvement of the concrete performance. Having a time scale in mind and looking to the recent developments in concrete technology, it becomes clear that the end of innovations may not be seen in the future.

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