MICROSTRUCTURAL AND PERFORMANCE BASED CRITERIA FOR UHPC WITH IMPROVED DURABILITY – OUTCOME OF A COORDINATED RESEARCH PROGRAM IN GERMANY.

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Abstract

In Germany, a 12 Mio. € Research Program on UHPC was performed since 2005, covering a wide range of topics related to UHPC. The program was funded by the German Research Foundation (DFG) and coordinated by the University of Kassel. More than 20 research institutes were involved. Its purpose was to elaborate the basic knowledge necessary to draft reliable technical standards covering materials, material-adequate design principles and innovative construction and fitting technologies to make UHPC a commonly available and regularly applied material. Based on the results of several projects dealing with the microstructure, the time depending early age behaviour und the resistance of hardened UHPC to chemical and physical attacks adequate limits for the composition of highly durable UHPC are presented for discussion.

Résumé

En 2005, l'Allemagne a débuté son programme de recherche sur les bétons à ultra-hautes performances (BUHP). Le programme a mis en œuvre plusieurs domaines de recherche lié aux BUHP. Le programme, financé par la Deutsche Forschungsgemeinschaft (DFG, fondation allemande pour la recherche) et coordonné par l'Université de Kassel, comptait plus de 20 instituts de recherche. Le but du programme était d'améliorer les connaissances fondamentales pour formuler des normes techniques renforçant la fiabilité des matériaux, les principes de la conception adaptés au matériau et les technologies de la construction innovante et des procédés adaptés pour faire des BUHP un matériau disponible partout et utilisé régulièrement. Sur la base des résultats des nombreux projets concernant la microstructure, le comportement du béton frais dépendant du temps et la résistance du BUHP durci à l'égard des attaques chimiques et physiques, les cadres adéquats pour la formulation de BUHP extrêmement durables sont présentés et livrés à discussion.

1. INTRODUCTION

In Germany, a comprehensive 12 Mio. € Research Program on UHPC has recently reached its end. The program was funded by the German Research Foundation (DFG) and coordinated by the University of Kassel. More than 20 research institutes were involved, striving to elaborate the basic knowledge necessary to draft reliable technical standards covering both materials and design principles to make UHPC a regularly applied material based individual mixes consisting of regionally available raw materials. The fields of interest covered by the individual research projects have included the suitability and performance of the raw materials including cements, inert or reactive mineral fillers, artificial nanoparticles, and improved taylor-made superplasticizers. Basic research on the rheology of UHPC and on appropriate mix designs for different applications, the rheological specifics of the fresh concrete and its hydration have been evaluated as well as the time dependent strength and deformation behavior of young and hardened UHPC with and without fibers. Also covered were material-adequate design and construction procedures including new appropriate technologies to build high performance slender and therefore sustainable structures.

The paper refers to about 10 projects which have directly or indirectly been concerned with durability aspects of UHPC. The knowledge gained from these projects together with the essential basics of former investigations form a solid foundation to propose technical criteria to be considered in the mix design of Ultra-High Performance Concretes with improved durability and thus a significantly prolonged service–life.

2. OBJECTIVES AND TECHNICAL BACKGROUND

The most notable characteristic of Ultra-High Performance Concrete (UHPC) is its extremely dense micro-structure, resulting in both a steel-like compressive strength of about 180 to 250 MPa, combined with a significantly improved durability. The structural density is primarily due to the high packing density accomplished with an optimum grading curve comprising fine and ultra-fine particles ≤ 125 μm in the cement matrix, and a comparatively low effective w/c-ratio of about just 0.18 to 0.25.

Undoubtedly, UHPC represents a milestone in concrete technology due to the new challenges for both civil engineering and architecture and the opportunity to develop material and energy conserving slim and slender concrete structures significantly reducing the energy and material related impact on the environment by up to 40% as has been proven for the Gärtnerplatz-Bridge in Kassel [1, 2], the first wide span Hybrid-Bridge in Germany built with UHPC made of regional materials in 2007.

The technical and scientific basics of this innovative concrete technology were primarily laid by Bache [3] and Richard and Cheyrezy [4] in the 1980th and 1990th of the last century. The practical application started with the Sheerbrooke Bridge in Canada built in 1997. Meanwhile a broad range of expertise of both scientific and practical nature has been gathered, recently presented e.g. in the Proceedings of three International Symposia on UHPC performed in Kassel from 2004 to 2012 [5, 6].

In Germany apart from a small number of pilot projects and the Gärtnerplatz-Bridge, the application of UHPC has up to now been restricted due to the fact that neither the material itself nor the material-specific design of the structures had already been sufficiently explored to draft technical guidelines or standards comparable e.g. to the European Standards for concrete materials and the corresponding design codes being accepted by the traditionally quite conservative building authorities. Without them one is obliged to pass through a comprehensive time consuming and costly certification process for each single project hindering a common application.

To support the idea of promoting UHPC as a commonly available and standardized material based on individual regionally available raw materials, the German Research Foundation initiated an extensive research program in 2005. The projects presented in Table 1 in an abbreviated form cover fundamental research, e.g. on the interaction of fine particles due to surface forces, or the morphology of the cement phases in a dense micro-structures, as well as more application-oriented problems, e.g. developing the appropriate mixing technology, or fitting slender UHPC elements by gluing or by small steel implants. It would break the mould by far to report on all the theoretical and experimental re-search and the information that has already been gathered. A more extensive survey covering most of the findings already gathered is given in the Proceedings of the Second and the Third International Symposiums on UHPC, held in Kassel in 2008 and 2012 [5, 6]. A compendium covering all projects and their results will be available at the end of the year. The volume will be published by Kassel University Press.

About half of the projects dealt with the strength and deformation behaviour of fine and coarse graded UHPC mixes with and without fibres and with the material adequate design and construction of structures made of UHPC. In combination with the knowledge and practical expertise gathered worldwide and presented in design codes as e.g. published in France and Japan the mechanical aspects of UHPC are widely covered and sufficiently worked up for a wide range of practical applications.

This is not the case regarding the second big advantage UHPC affords: the significantly improved durability and thus the prolonged service life of buildings made of it. Thus a number of projects were directly or indirectly concerned with durability aspects aiming at material adequate limits for the composition of long lasting UHPC mixes being unaffectable by potentially harmful chemical or physical attacks. The idea is to define application oriented limitations for the composition and the w/c-ratio to extend the Exposition Classes already given in EN 206 for Ordinary Concrete.

The improved strength and durability of UHPC are both caused by the dense and impermeable micro- and nanostructure of the cement matrix.

3. MICROSTRUCTURE

The most notable characteristic of Ultra-High Performance Concrete (UHPC) is its extremely dense micro-structure of the matrix based on the high amount of fines with an optimum packing density and a low w/c-ratio. Numerous investigations have already been performed on this topic [e.g. 7, see 4, 5]. The following refers to relevant SPP-projects and to some related research projects performed together with industrial partners at the University of Kassel funded by other parties. Depending on the application and especially on the aggregate content and maximum grain size, UHPC contains between 450 and 1000 kg cement per m^3, between 50 and 250 kg/m^3 of microsilica and a significant amount of other mineral fillers (primarily fine ground quartz or basalt). Table 2 shows some quite different mixture compositions with different fresh concrete consistencies developed at the University of Kassel and already practically realized: Self compacting UHPC for precast elements and floor layers (e.g. M2Q, B5Q in Table 2), UHPC with plastic consistency for concrete pavement layers to be placed by slipform pavers (UHPC-PV) [8] or even UHPC of no-slump consistency for sewer system pipes with an increased mechanical and chemical resistance (UHPC-NS) [9]. All of these quite individual mixtures were made of individual regionally available raw material and have already been practically applied.

Table 1. Working groups inside the priority program and their individual research topics.

Working group	**# of projects 2005-2013**	**Topics of the individual projects**
Raw materials, rheology, processing, sustainability	4	- Influence of shape and texture of fine grains and of interparticle forces on packing density and rheology - Life cycle inventory on UHPC - UHPC with low-energy binders - Optimization of the mixing process
Hydration and microstructure	2	- Characterization of the microstructure - Micro- and nanostructure of UHPC with nanotubes and pyrogenous SiO_2
Time-dependent behavior (shrinkage, creep, cracking)	6	- Early age behavior of UHPC - Reduction of crack formation by internal curing - Shrinkage-reducing chemical admixtures - Time-dependent stress-strain behaviour - Early age cracking and durability - Autogenous shrinkage and microstructure
Fiber efficiency and interaction with conventional reinforcement	3	- Load-bearing capacity of elements reinforced with fibers and bars under tension and bending - Ductility of UHPC with fibers and nanoparticles - Self-compacting UHPC with fiber meshes
Strength and deformation	2	- Fatigue under uni- or multiaxial loads - Modeling of multiaxial strength
Durability	4	- Resistance to freezing and deicing agents - Resistance to chemical attacks (acid, sulfates) - Fire safety of UHPC under load - Corrosion of steel fibers and influence on the microstructure
Design, construction, and application	11	- Prestressed beams - Performance of steel fitting elements for hybrid structures (UHPC/steel) - Loadbearing of extensively loaded columns - Fitting of elements by gluing - Thin fiber-reinforced UHPC layers on conventional concrete structures - UHPC under transverse (biaxial) forces - Anchorage and overlapping joints of reinforcing bars - UHPC/steel pipes for truss structures - Thin-walled pipes - Structural connection of precast elements - Miniaturized fitting devices for slender slabs
Testing	2	- Adjusted test procedures for rheology and strength - Fiber distribution and orientation

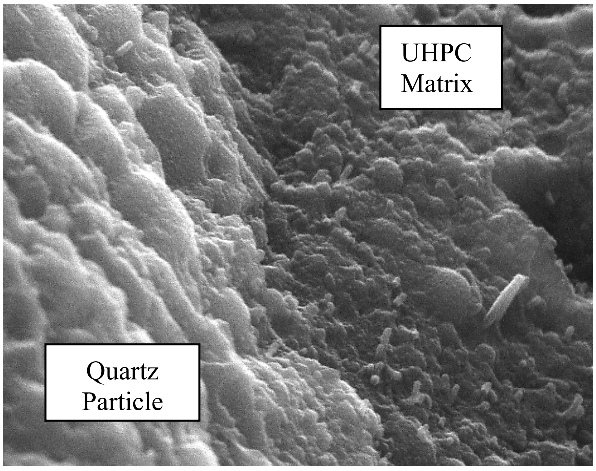
The w/c-ratio of the UHPC mixtures ranged from 0.22 to 0.29, and the effective w/(c+m) ratio considering microsilica as full-value part of the reactive binder (k-value 1.0) was between 0.19 and 0.25. In all cases the packing density was optimized in accordance with [11, 12] by means of differently fine quartz powders and microsilica. Independent of the w/c-ratio, the average 28-days compressive strength of all mixtures in Table 2 was about 150-165 MPa when the concrete specimens were stored at 20°C under water. It was about 190 MPa when the same concrete was heat treated at 90 °C for app. 48h.

Table 2. Application oriented UHPC compositions

	UHPC fine M2Q (0/0,5)	UHPC coarse B5Q (0/8)	UHPC-PV Pavements [8,9]	UHPC-NS Pipes [9]
Water w	166	158	107	49
Cement c	832	650	404	186
Silica fume m	135	177	54	51
Superplastiziser [mass%]	1,1	1,2	0,6	1,2
Quartz powder 12000 m^2/g	207	325	-	93
Quartz powder 3600 m^2/g	-	131	32	38
Sand 0.125/0.5	975	354	541	101
Sand 0/2	-	-	-	616
Sand 0.6/2	-	-	283	-
Gravel 2/8	-	-	-	821
Gravel 8/16	-	-	-	616
Basalt 2/8	-	597	1123	-
w/c-ratio (w+60%SP)	0.22	0.26	0.28	0.29
w/c+m	0.19	0.21	0.25	0.23
28d Compressive strength (150/300) Water 20°C	165	160	150	150
Heat 90°C, 48h	195	185	-	-

As stated before the dense microstructure is the key factor that is determining the outstanding performance of UHPC. Electron microscopy investigations e.g. by Möser [12] using a NanoSEM microscope confirmed that the hydrate phases in UHPC are significantly shorter as a result of the high packing density and the low w/c ratio. Figure 1 [13] shows a SEM micrograph of unhydrated microsilica particles surrounded by dense C-S-H phases in UHPC (left) compared to the long and instable phases and the rather porous structure of ordinary concrete. The presence of nearly unhydrated microsilica particles give reason to presume that the contribution of the microsilica to the structural density of UHPC is primarily of physical nature. It acts as an ultra-fine filler. Due to the restricted amount of water and the rapid hardening of UHPC the chemical reaction seems to be limited to the very surface.

The ability of concrete to withstand physical and chemical attacks is usually attributed to the amount of capillary pores in the cementitious matrix. Capillary pores arise during the hardening period when excess water evaporates, which is the part of the total amount of water that is not chemically or physically bound in hydration phases or in the pores of the microstructure (gel pores).



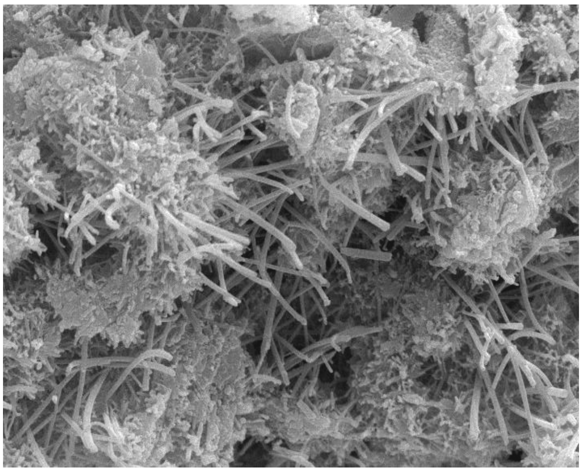


Figure 1. Matrix of UHPC, (left) compared to ordinary concrete (right) [13].

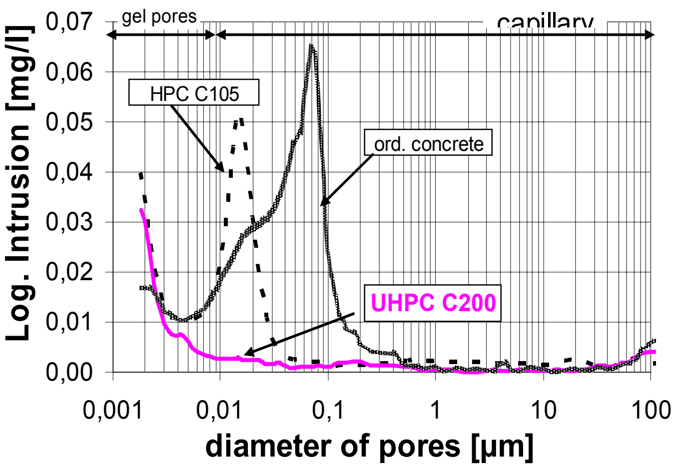


Figure 2. Typical pore size distributions of Ordinary Concrete C 45/55, High Performance Concrete and UHPC M2Q acc. to Table 2 (mercury intrusion) [13].

Thus, the amount of capillary pores is a quite reliable benchmark to classify the durability of a specific concrete. E.g., Figure 2 [13] shows the characteristic pore size distributions of an ordinary concrete C45/55 with a w/c-ratio of about 0.48, a High Performance concrete C105 with a w/c-ratio of 0.35, and UHPC M2Q acc. to Table 2 with a w/c-ratio of only 0.22 being virtually free of capillary pores with diameters between 0.01 and 1 µm. This accounts for its extremely high resistance to the ingress of harmful liquid or gaseous agents, e.g. chloride and alkaline ions or to frost attacks with and without deicing agents.

As an example, Figure 3 shows the results of chloride diffusion tests on the three concretes already mentioned in Figure 2. When tested in an accelerated test [14], both the depths of the chloride intrusion and the transmitted charge fairly correlated with the amount of capillary pores shown in Figure 2 and thus with the w/c-ratio of the concretes. The UHPC M2Q was practically impermeable to chloride ions.

Another indicator for the resistance of the microstructure is the relative absorption of water or other liquids in relation to the total pore volume. Figure 4 shows the relative amount of water or of 3%-NaCl-solution respectively being absorbed by capillary suction and during freeze-thaw-cycles of UHPC when tested acc. to the CIF (water)- or the CDF (NaCl)-procedure respectively [15]. The maximum uptake of water of about 0.25 % b. m. is significantly smaller than for ordinary concrete indicating an extremely high resistance to both frost attacks as well as to harmful liquids.

Due to the low w/(c+m)-ratio of only 0.19 (w/c-ratio 0.22 acc. to table 2), the heat treatment seems to be of minor influence on the porosity of the matrix.

4. MATERIAL-ADEQUATE LIMITS WITH REGARD TO STRENGTH AND DURABILITY

Based on the strength classification system of the European Standard EN 206, the design strength of UHPC is commonly characterized by a minimum characteristic strength of 150 MPa after 28 days when tested on cylinders d/h = 150/300 mm. As can be seen from Table 2, this minimum strength can be achieved even at a w/c-ratio of up to 0.30. This is due to the increase in strength gained by the physical optimization of the packing density of the fine particles of the matrix.

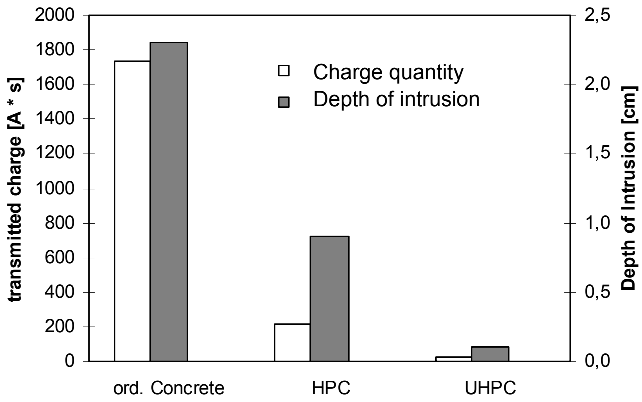


Figure 3: Resistance to chloride diffusion of heat treated UHPC M2Q (table 2), HPC C105 and OPC C45/55. Porosity as shown in Figure 2.

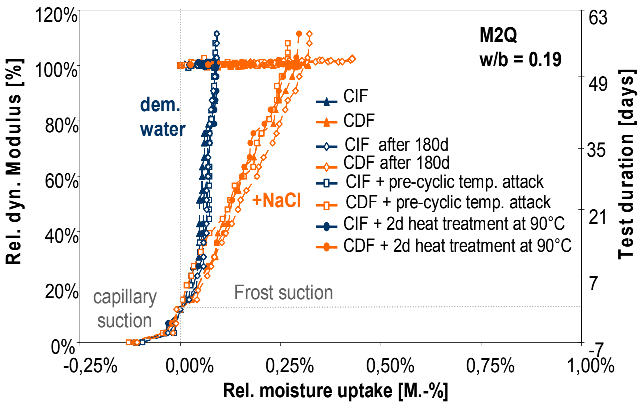


Figure 4. Absorption of water/NaCl-solution during freezing and thawing cycles. UHPC M2Q acc. to Table 2 [15].

But as for ordinary concrete, the compressive strength does not comprehensively describe the durability properties. A general boundary value for the appropriate w/c-ratio assuring an optimum water tightness of the microstructure can be derived from the shrinkage behaviour of the two compositions M2Q and B5Q consistently used in all research projects given in Table 1 and already practically applied.

The amount of drying shrinkage fairly corresponds to the amount of free water evaporated during hydration and thus to the w/c-ratio. No drying shrinkage means that the water added to the fresh concrete is fully bound in the cement hydrates and/or in the gel pores. Figure 5a (left) shows the shrinkage-related contraction of the UHPC mixture M2Q with a w/c-ratio of 0.22 when stored at 20°C/65% r. h., measured in a shrinkage rim with and without water-proof plastic sealing [16]. In both cases, the same contraction could be measured. This leads to the conclusion that the total deformation was caused by autogenous shrinkage only. As no free water evaporated, capillary pores were not formed as can be seen from the pore size distribution of the M2Q mixture presented in Figure 2. The w/c-ratio of the UHPC mix B5Q in Figure 5b (right) was 0.26. In this case, the unsealed specimen showed a small but significant amount of drying shrinkage due to evaporation of unbound water and thus capillary pores arose weakening the microstructure.

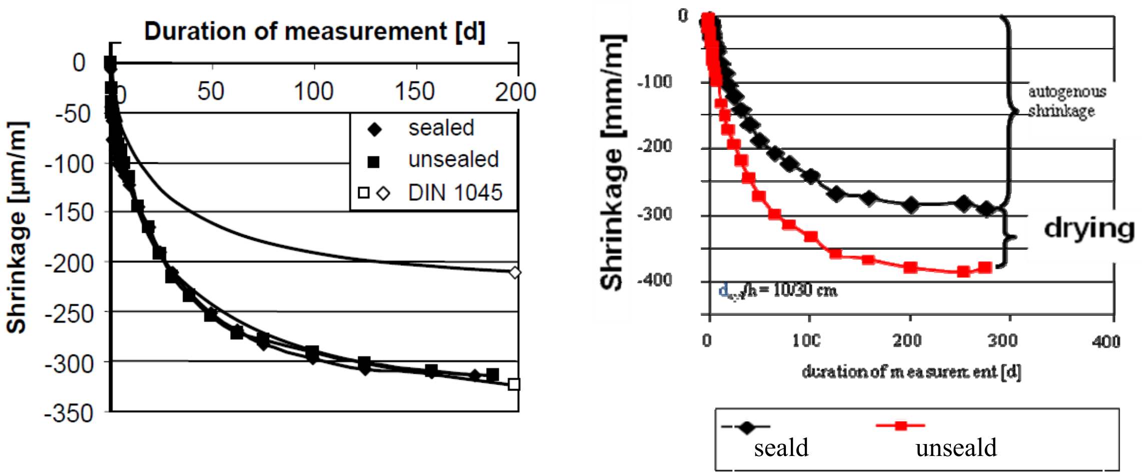


Figure 5. Shrinkage of UHPC with an w/c-ratio of 0.22 (left) and 0.26 (right) both tested at 20°C/65% r.h. sealed and unsealed respectively [16].

Based on these and also on further research results gained in other projects of the Coordinated Research Program dealing with the durability of UHPC (see Table 1), a boundary value for a cement based w/c-ratio assuring both high strength and a virtually negligible permeability and thus optimum durability is proposed to be 0.22, if the concrete hardens under ambient conditions and is not heat treated. In this case, silica fume primarily acts as a physical filler improving the packing density and thus partly contributing to the higher strength of UHPC. Primarily due to the low water content and the rapid hardening without an intensive heat treatment only a small share of silica fume will react with the cement components to form additional C-S-H phases [17]. Therefore it is not a reliable factor with regard to durability. If one will consider silica fume to be part of the reactive binder content the mix has to be heat treated.

If the hydration is accelerated and improved by heating the young concrete e.g. for 24 to 48 h at 80 to 90 °C a maximum value for the cement based w/c-ratio of 0.26 corresponding to an effective w/c+m-ratio of about 0.22 may be acceptable to assure a sufficient water tightness.

5. CONCLUSIONS

In a comprehensive Coordinated Research Project performed in Germany a wide range of open scientific and technical questions of UHPC were clarified. The research results provide a safe foundation to develop technical regulations for UHPC based on regionally available raw material. One of the outcomes was that an appropriate compressive strength of at least 150 MPa can be achieved even at a w/c-ratio of up to 0.30, if the packing density of the matrix is sufficiently improved by means of calculated amounts of various micro-fine fillers of different fineness. This could be a sufficient definition for “Ultra-High Strength Concrete” aiming at a high compressive design strength only. To make the microstructure of UHPC practically impermeable to harmful gases and liquids and thus to achieve a significantly improved resistance to concrete corrosion and its high ability to protect the steel reinforcement from corrosion as well UHPC must be practically free of capillary pores. Thus in addition to the optimized packing density the cement based w/c ratio of UHPC hardening under ambient conditions shall be limited to no more than 0.22, if the kind of application calls for an improved durability (“Ultra-High Performance Concrete”). Without heat treatment, Silica fume should not be considered to be part of the binder. If the concrete is heat treated e.g. at temperatures of 80-90 °C the silica fume is activated and a maximum w/c-ratio of 0.26 (w/c+m about 0.22) seems to be adequate.

These scientifically based limit values form the basis for further discussions in the working group being responsible to draft a German Technical Guideline for UHPC. They correspond with the previous practical experiences gained with the UHPC elements of the bridges already built in Germany. Within 7 years no carbonation and no degradation of the surface have been determined up to now. Understandably they are not finally validated by long term experiences.

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