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Design relevant properties of hardened Ultra High Performance Concrete

Summary

Ultra High Performance Concrete (UHPC) offers a great spectrum of favourable material properties. The structural behaviour of UHPC differs from normal- or high-strength concrete, particularly for a supplement of fibres. In most countries valid design rules for this new material do not yet exit. In Germany a work group of the German Commission on Reinforced Concrete (Deutsche Ausschuss für Stahlbeton DAfStb) has presented a state of the art report on UHPC [1]. Chapter 6 of this report describes the knowledge about the properties of hardened UHPC. This paper summarises some of the main aspects dealt with there.

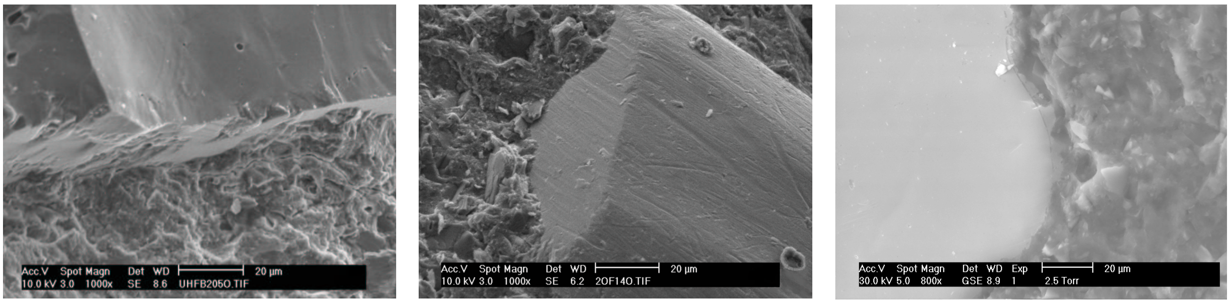
Keywords: *material properties, shrinkage, creep, fatigue behaviour, bond, fire resistance*

1 Introduction

The properties of hardened Ultra High Performance Concrete (UHPC) [2] are determined by the very dense structure of this material. The microstructure of UHPC differs significantly from normal- and high-strength concrete. With respect to the mechanical behaviour, UHPC with fibres shows, depending on the type and quantity of fibres contained in the mix, ductile behaviour under compression as well as in tension. In contrast to this, UHPC without fibres behaves brittle, if no additional measure such as confinement is chosen. Since the pre-peak behaviour does not show significant differences, the elastic properties of UHPC with and without fibres can be described in common whereas the influence of fibres has to be described separately.

As one consequence of the dense structure of UHPC, the porosity of UHPC is much lower than for normal- and even for high-strength concrete. Another consequence is the improvement of

the contact zones between the cement matrix and the aggregates as well as the fibre reinforcement which allows a short length of fibres.
This is illustrated by Figure 1 showing the good bond between the different components (a and b). Figure 1c shows a situation which can often be found in normal-strength concrete. The dense structure is also responsible for the very low permeability for gases and fluids and hence superior durability of this material. The low permeability has an adverse effect with respect to fire resistance. This, however, can be compensated as shown in chapter 8.



a) good bond between cement matrix and quartz sand particles (left)
b) exceptional bond between matrix and steel fibre
c) less satisfactory bond between matrix and quartz sand particle (right)

Figure 1: Contact zones in UHPC between matrix and aggregates or fibres

2 Behaviour under Compression

The typical compressive strength of UHPC is in the range of 150 to 220 MPa. Until about 70 to 80 % of the compressive strength, UHPC shows a linear elastic behaviour (Figure 2). According to experimental evidence as obtained until now, this holds true for UHPC regardless of the maximum aggregate size. The failure of UHPC without fibres is of explosive nature. No descending branch in the stress-strain-diagram does exist. This, however, can also be observed for HSC with f_c > 90 MPa.

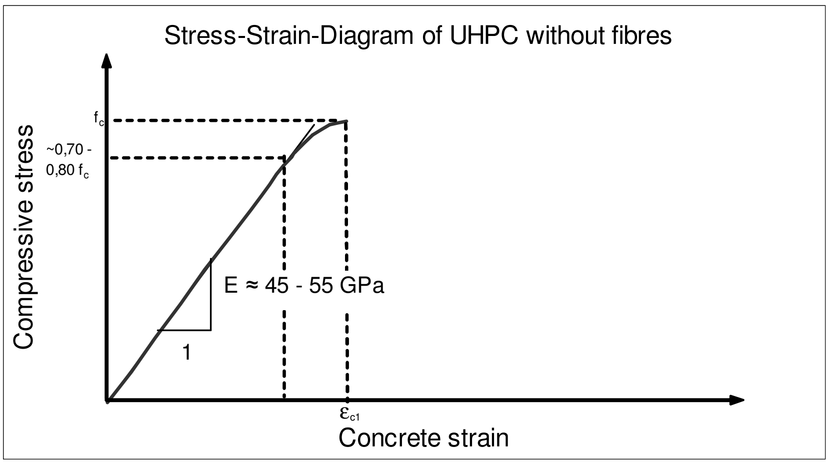


Figure 2: Stress-strain-diagram of UHPC without fibres

Due to the dense structure, the elastic modulus of UHPC is higher than for normal- and high-strength concrete when using identical aggregate types. Figure 3 shows typical results as obtained at Leipzig University [1].

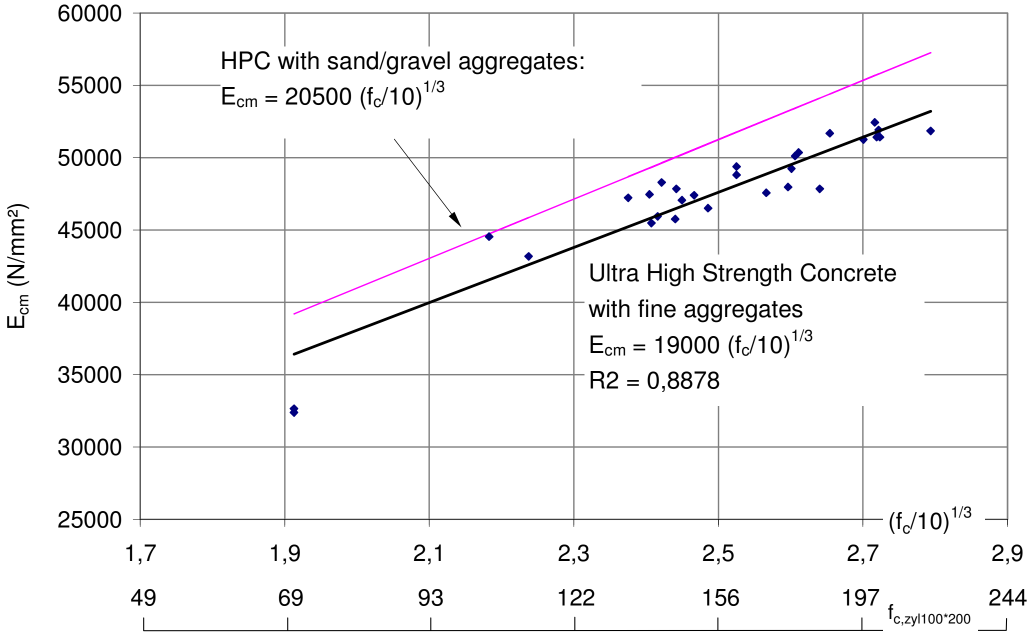


Figure 3: Elastic modulus versus compressive strength

The Poisson ratio in general has been determined to be about 0.2 in the linear elastic range.The strain at peak stress for UHPC with fine aggregates amounts to approximately 4.4 ‰. For basaltic aggregates or e. g. DENSIT-UHPC using bauxite, lower values have to be expected.
For UHPC with fibres (UHPFRC), a pronounced descending branch can be developed by the effect of the fibres (Figure 4). The slope of the descending branch depends on

- fibre content,
- fibre geometry (length, diameter),
- fibre length in relation to maximum aggregate size,
- fibre stiffness (in case of fibre cocktails) and
- fibre orientation.

Although in general the influence of fibres on the compression strength is low. Due to 2.5 vol.-% of fibres, an increase of the compressive strength of about 15 % has been noted [3].
For UHPC, the geometry of test specimens seems to have less influence on the compressive strength. However, contradictory results from different sources exist with respect to this question.
Heat treatment can speed up the development of the compressive strength. At 250 °C, a significant increase of the strength can be obtained, since the high temperature does not only accelerate the chemical reaction but also leads to an improvement of the microstructure. According to [1 ,3], even at 90°C heat treatment lasting 48 hours will enable higher compressive strength values than for the case of curing 28 days in water.

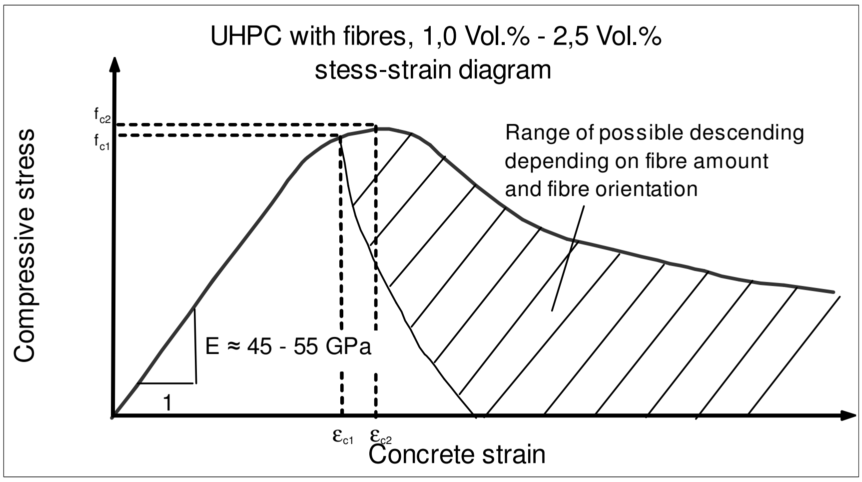


Figure 4: Typical stress-strain-diagrams of UHPFRC

3 Behaviour in Tension

The tensile strength can be determined experimentally using prismatic or cylindrical specimens. It may be advantageous to use probes sawn out of plates. In principle, it is possible to use specimens with or without notches.

Direct tension tests on UHPC without fibres have delivered tensile strength values between 7 and 10 MPa. According to results obtained at the Universities of Kassel and Leipzig, there are only small differences between UHPC with fine or coarse aggregates. The failure is rather brittle, hence without a significant descending branch.

Depending on the amount, type and orientation of fibres, the tensile strength of UHPFRC can be increased beyond the matrix strength. Values in the range between 7 and 15 MPa [3] have been recorded. Due to the effect of fibres, the behaviour becomes ductile. After onset of cracking, the material may be characterised by the stress-crack-opening-diagram. The typical behaviour is depicted in Figure 5. It should be noted, that the slope of the descending branch can be very different, depending on the fibre orientation and the content and type of fibres.

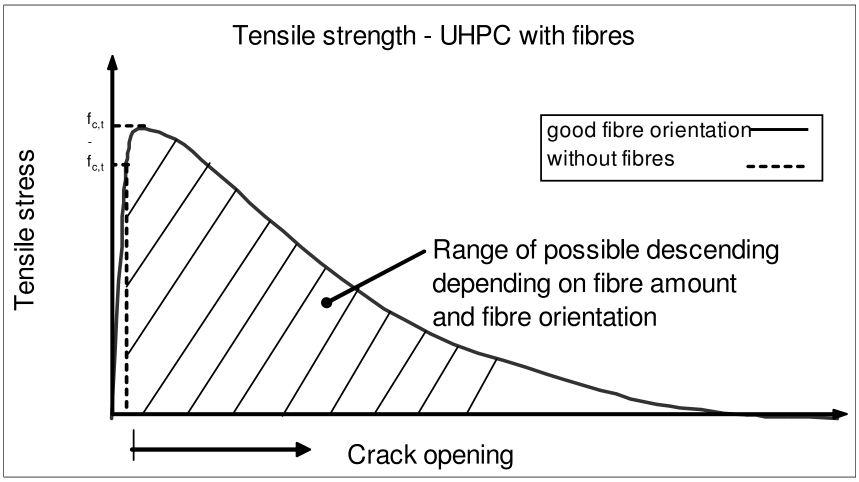


Figure 5: Typical stress-crack-opening-curve for UHPC

In [1], a formula for the estimation of the splitting tensile strength in dependency on the compressive strength is given. Furthermore, the axial tensile strength may be derived from the bending tensile strength considering the size effect.

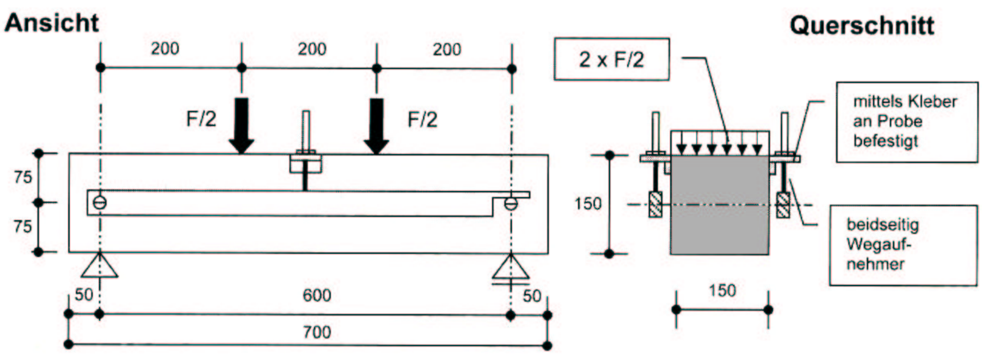


Figure 6: Standard bending test according to DAfStb-Guideline on Steel-Fibre Concrete [4]

In order to simplify the testing procedure for tensile properties, the DAfStb-Guideline on Steel-Fibre Concrete [4] defines a test setup which allows the determination of the tensile strength as well as a stress-crack-opening-relationship. This is possible, since in general only one crack opens significantly so that the bending deformation is concentrated there and the crack opening is almost proportional to the deflection. Furthermore, a method to transform the stress-crack-opening-relationship into a stress-strain-relationship is presented in these guidelines. Figure 7 shows the typical result as obtained from bending tests, see [1].

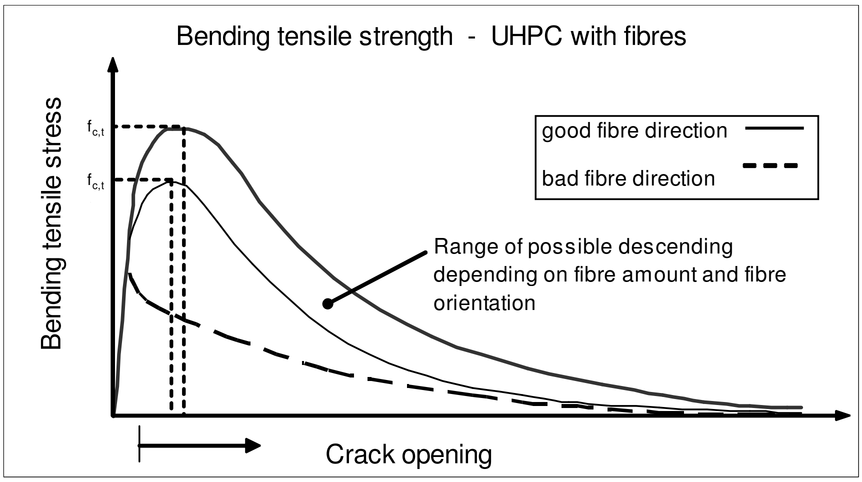


Figure 7: Typical results from bending tensile tests

The influence of the fibre orientation has been studied by Bernier und Behloul [1], see Figure 8. The influence of the fibre orientation is also picted in Table 1, where different types of specimens with vertical and horizontal pouring direction are compared.

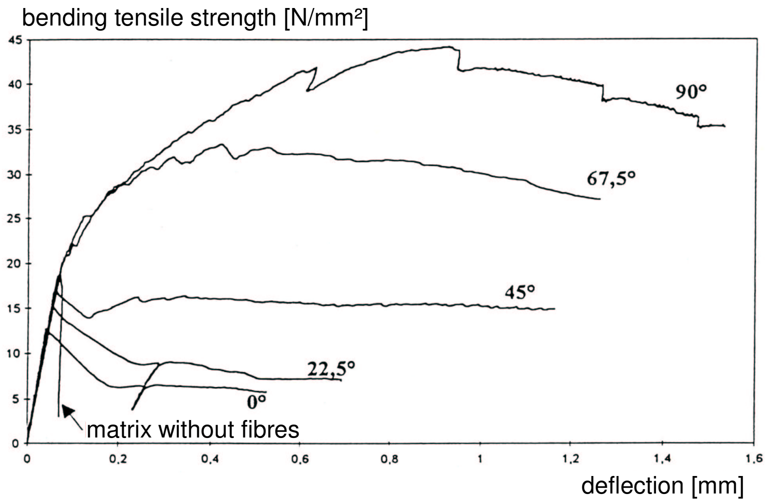
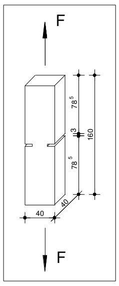
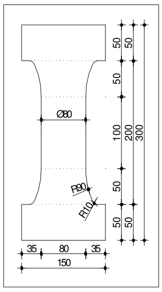
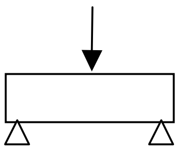
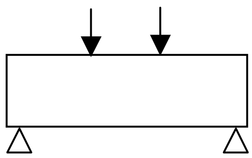


Figure 8: Influence of the fibre orientation on the bending behaviour

Table 1: Influence of casting direction on tensile strength and fracture energy

Test specimens	Age	Axial tension			Bending tension						
					Prism 160 * 40 *40 		Beam 700 * 150 * 150 				
Concrete		M1Q		B3Q	M1Q		M1Q			B3Q	
Curring		90°		90°	90°		WL	90°		WL	90°
Pouring direction		hori-zontal	vertical	horizontal	hori-zontal	vertical	horizontal		vertical	horizontal	
Fracture energy $G_{F,10\%}$[N/m]	7d	16757	9993	-	20100	15097	-	20355	14543	-	-
	28d	14555	-	12932	18052	-	-	19892	-	-	-
	28d*	17014	-	-	19820	-	-	-	-	-	-
Tensile strength f_{ct} [N/mm²]	7d	14,2	7,9	-	34,0	22,5	11,1	22,1	17,6	18,3	18,0
	28d	13,3	-	7,0	35,7	-	13,3	22,2	-	20,4	17,9
	56d	17,7	-	-	36,3	-	16,2	22,1	-	24,2	18,1

Tests at TU Delft show, that especially the flow direction during the casting process affects the fibre orientation highly and thus, the tensile strength and ductility properties. The fracture energy of UHPC without fibres has been investigated e. g. at Leipzig University. Results are shown in Table 2. Figure 9 shows the decrease of the characteristic length with the compressive strength for NSC, HSC and UHPC.

Table 2: Fracture parameters of UHPC for different mix designs

	Mortar 1	Mortar 2	Mortar 3	selfcompacting fine-grained concrete	compacted fine-grained concrete	UHPC with basalt grain
Cylinder compressive strength [N/mm²]	40	81,2	106,6	149,1	196,3	145,0
Fracture energy G_F [(N/m]	53,7	65,1	66,5	62,8	54,7	95,0
Tensile strength [N/mm²], f_{ct}=0,9$f_{ct,sp}$	3,2	6,1	8,0	9,4	11,9	8,3
Characteristic length l_{ch} [mm]	133,5	61,3	44,7	32,6	20,1	80,6
Softening function	bilinear	bilinear	Linear	linear	linear	bilinear
Limit crack width [µm]	79,2	65,6	15,1	13,2	9,8	127,2

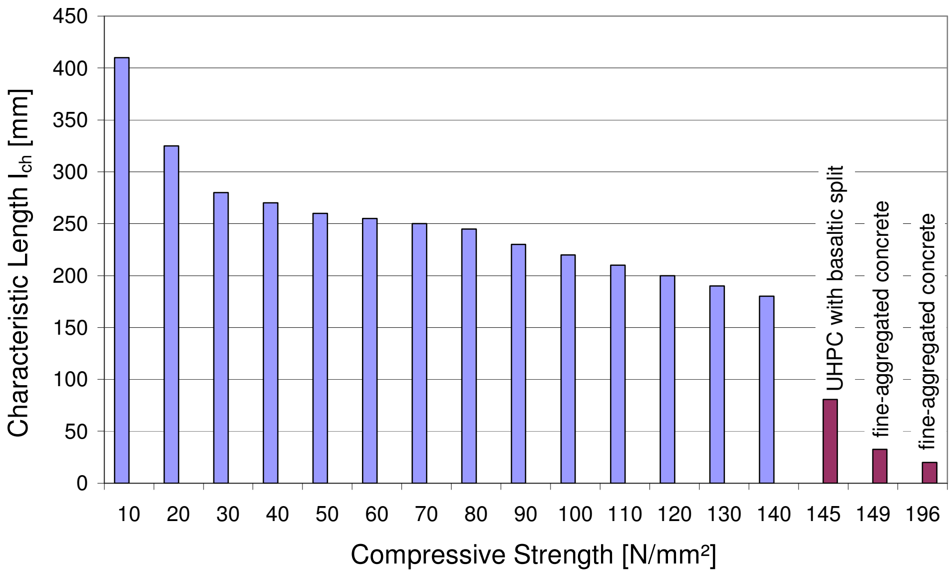


Figure 9: Characteristic length l_{ch} versus compressive strength

4 Time dependant Properties

4.1 Shrinkage

According to data from Kassel and Leipzig [1, 3], the total shrinkage of sealed UHPC with fine aggregates amounts to 0.7 mm/m under isothermal conditions in the first seven days after pouring. Until an age of 28 days, the total shrinkage increases to about 0.9 mm/m. The influence of steel fibres on the autogenous shrinkage is of minor importance. Figure 10a and b give examples for the development of shrinkage versus time.

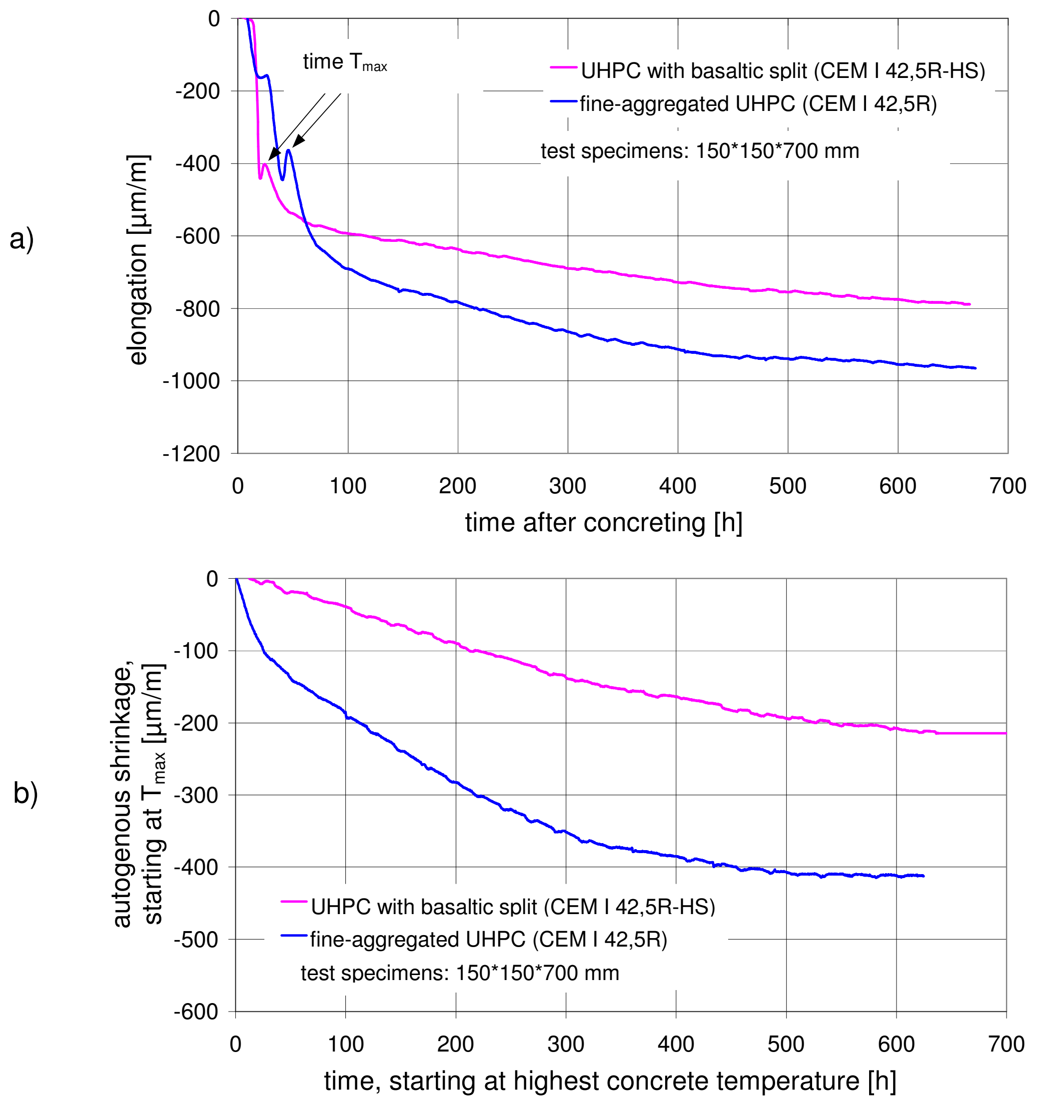


Figure 10: Development of shrinkage versus time

The development of drying shrinkage of UHPC is similar as of HPC. Due to the high density of the matrix structure, however, the amount of drying shrinkage is reduced in comparison to HPC. For heat treated UHPC, drying shrinkage can practically be neglected after the end of the heat treatment.

4.2 Creep

Creep of UHPC is generally less than for concrete with lower strength. Table 3 shows the results according to [5] and [1]. A strong dependency on the concrete age at the start of loading becomes evident.

Table 3: Results of investigations on creep of fine-aggregated-UHPC [6]

Age at Start of Loading [days]	Amount of Creep (10^{-6}/MPa)	Creep-Number ϕ (-)
1	46,9	2,27
4	37,2	1,80
7	32,5	1,57
28	22,2	1,08

(Age at Start of Loading = 7 d, Loading Duration = 135 d)

Degree of Utilisation	Amount of Creep (10^{-6}/MPa)	Creep-Number ϕ (-)
45%, sealed	37,2	1,613
45%, free	42,1	1,787
53%, sealed	34,0	1,378

5 Coefficient of thermal expansion

As for NSC, the coefficient of thermal expansion is age-related. For UHPC with fine aggregates, 12 µm/mK have been recorded in [7]. This value is in the same range as for NSC (about 11,0 µm/mK). For very young UHPC (less than 3 days), further research is necessary.

6 Fatigue Resistance

For fatigue loading under compression, tests performed at the University of Kassel for UHPFRC have shown a rather good-natured behaviour. S-N-curves for UHPC and NSC are compared in Figure 11. The (relative) stress range of UHPFRC for a large number of load reversals (> 2 million) is similar 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 fibres does not lead to disadvantages with regard to fatigue.

Currently, fatigue tests in bending are conducted at Delft University of Technology. Since a paper on this topic is given to the conference, the subject is not to be discussed here.

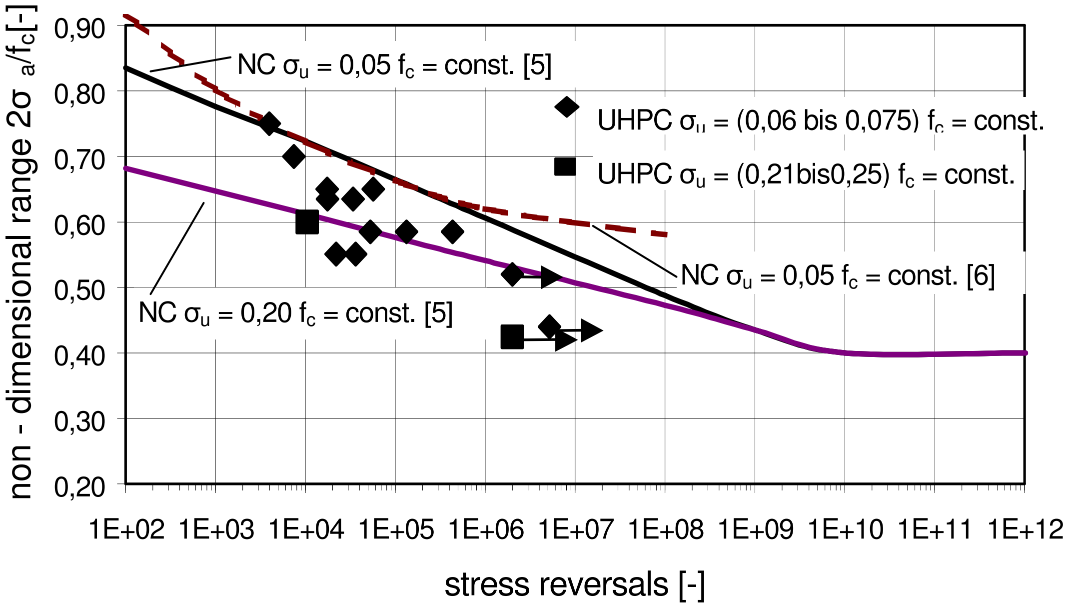


Figure 11: S-N-curves for UHPC in comparison to NSC

7 Bond of Reinforcement

Due to the high compressive strength and the high density, UHPC enables very high bond stresses. For smooth fibres (l = 13 mm, Ø = 0.15/0.2 mm), Behloul [1] 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 12)

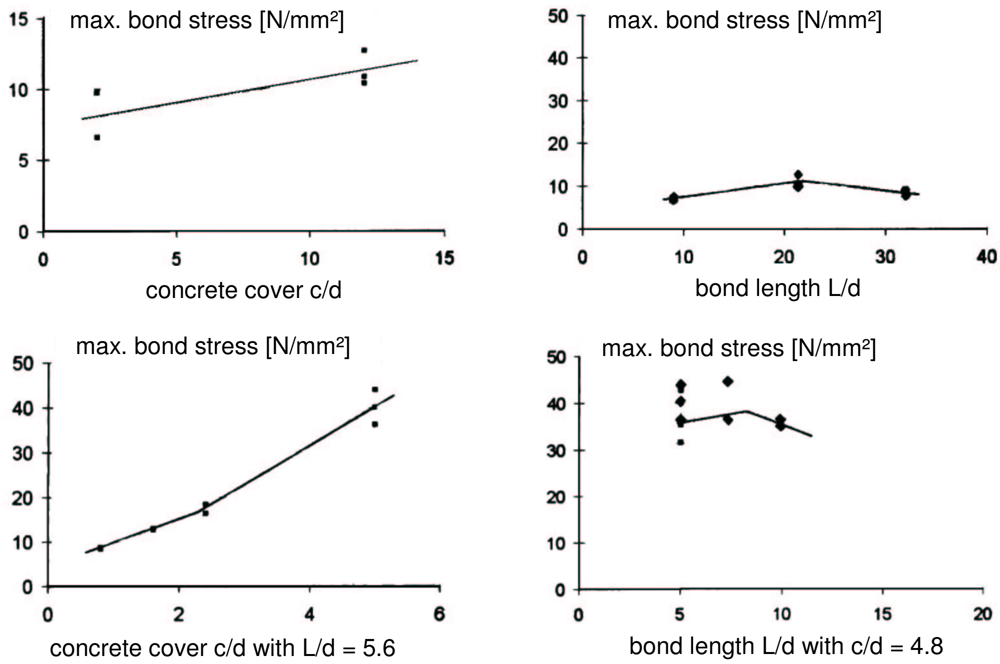


Figure 12: Bond strength for prestressing strands (∅ 12,5 mm) depending on contact length to diameter according to [Cheyrezy, Roux, Behloul, Ressicaud and Demonte (1998)]

For ribbed reinforcing bars, test results are available from Weiße in Leipzig and Greiner/Reineck (University of Stuttgart, Figure 13). Very high bond stresses in the range of 40 to 70 MPa have been reported. In tests on rebars with 10 mm diameter, Weiße observed splitting failure in the concrete cover 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 ∅ instead of 5 ∅ (see Figure 14). Otherwise, no pull-out would be feasible before the yielding of steel. Weiße used 1.5 ∅ for his tests.

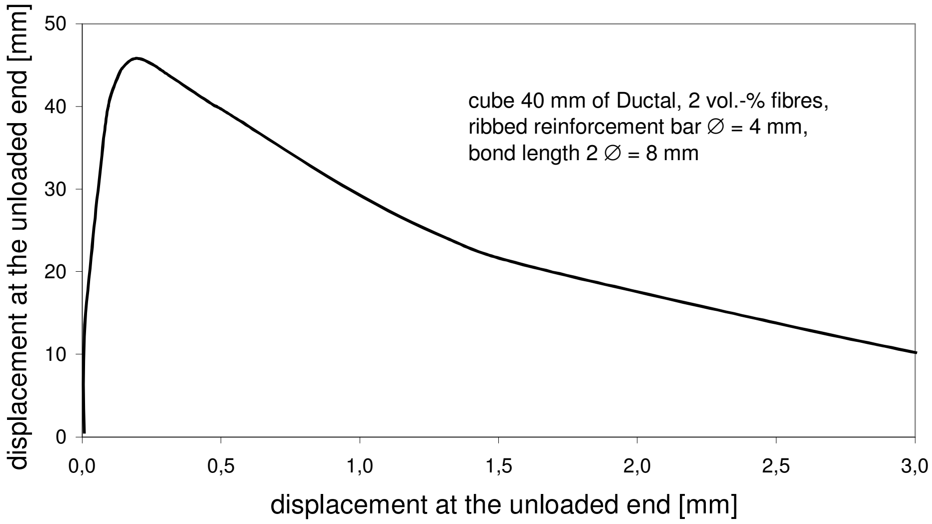


Figure 13: Bond-stress-slip-relationship of UHPC according to Reineck and Greiner [1]

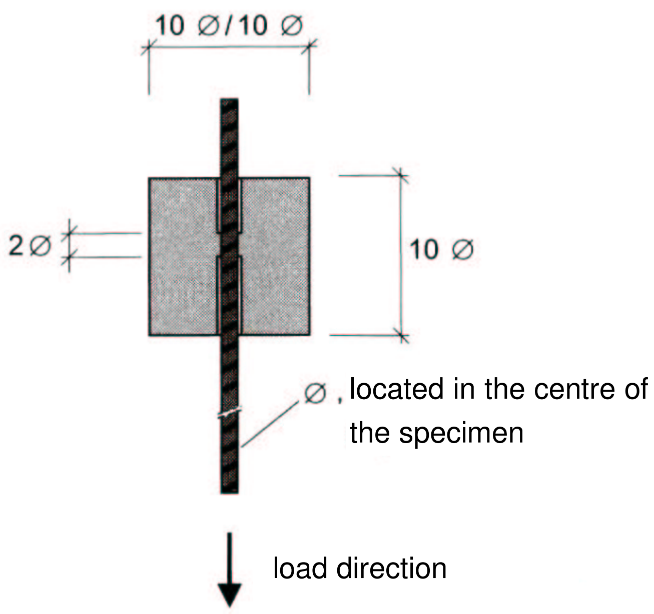


Figure 14: Modified RILEM pull-out test

8 Fire Resistance

Due to the extremely high density of UHPC, high water pressure can arise when UHPC is exhibited to fire. This can lead to deterioration of the concrete structure. The problem can be overcome by the use of fibres, e. g. polypropylene fibres. One effect of the fibres is that they create capillary pores due to melting and burning. Furthermore, around the fibres 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 effectivity of adding polypropylene fibres [8, 9, 10, 11].

Another problem is associated with the anomaly of quartzitic compounds with respect to the volumetric expansion occurring at 573 °C due to the change of crystal phases (α-quartz to β-quartz). Good results could be obtained by replacing quartz by basalt [12].

9 References

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