  - hardened concrete properties, e.g. compressive and tensile strength, modulus of elasticity, fracture characteristic (brittleness)
- properties of the reinforcement
  - rebar diameter
  - rib geometry and its arrangement, e.g. high- or deep-ribbed, orientation and number of rows of the ribs
  - relative rib area
- loading regime
  - short or long term monotonic (static) loading, e.g. loading rate
  - dynamic loading, e.g. frequency, amplitude, load history
- system parameter
  - concrete cover, confinement (e.g. due to transverse reinforcement, fibers)
  - transverse pressure or tension in the anchorage/splice zone
  - position of the rebar during casting (good and poor bond conditions)
  - orientation of the rebar (horizontal or vertical orientation during the casting process)
  - method of concreting (pouring, shotcrete, sliding formwork method)

For these reasons it becomes apparent how complex the bond between reinforcement and concrete is. The spectrum of possible bond characteristics can be extremely wide because of the influencing variables, the boundary conditions and their interaction. In the following only such parameters and their possible effects will be discussed, so the compressive and tensile strength as well as changes in the mix design of UHSC.

UHSC - PARTICULARITIES FOR THE BOND

Ultra high strength concrete is mainly characterized by its high compressive strength, but also the tensile strength is raised. In this context two points have to be assessed critically: first the tendency of splitting of the concrete cover (the risk of longitudinal cracking), because the concrete tensile strength does not increase proportionally with its compressive strength (13), and second the minimum required reinforcement for the crack width control.

The modulus of elasticity of concrete increases less than proportionally with the increase in concrete strength. This will have an influence on the ascending branch (Figure 1) in the bond stress-slip relationship as well as on the bond stiffness.

Furthermore, great importance must be attached to the increasing brittleness of the material. Under impact and impulse loading, high loading rates could change the bond properties.

Finally, the modified mix design may affect the bond behavior. For ultra high strength concrete, the matrix is more homogeneous due to smaller maximum aggregate sizes, higher binder contents and micro fillers. The reinforcement is therefore better enclosed in the matrix. However, the aggregate interlock may be lower because of the reduction in the maximum aggregate size.

STATE OF THE ART

Only a few investigations can be found in the literature about “bond in ultra high strength concrete“. Hansen (6) reported on bond tests using Densit Joint Cast® with different rebar diameters. The main series was carried out with Ø 16 mm, whereby the bond length was 170 mm. It should be mentioned that Densit Joint Cast® is a fiber reinforced ultra high strength concrete with a fiber content of 6% by volume (about 480 kg/m³), and therefore splitting failure is nearly impossible. Furthermore the bond length was chosen quite high, so that the descending branch of the bond stress-slip relationship (pull-out of the rebar) could not be measured. For the pull-out specimens, steel failure was observed.

Lubbers (7) reported on the “bond performance between ultra-high performance concrete and prestressing strands”. Different strand diameters were used with normal strength concrete and different UHSC mixes. For the same embedment length, the transferable bond stresses increased, but less than proportional with the compressive strength. The depth of the embedment required to anchor the strands could be decreased to about 50 - 66% of those values required for normal strength concrete.

For lack of sufficient experimental investigations, the test program was carried out to gather basic knowledge about the bond behavior in UHSC. In the following the results of this experimental investigation and the conclusions will be presented.

TEST PROGRAM

Materials

Three different mix designs were used for ultra high strength concrete, which varied in the composition as well as in the basic concept. Whereas the principle of a “classic“ reactive powder concrete (RPC) was chosen for the UHSC 2 (Table 1), crushed aggregates with a maximum grain size of 5 mm were used for the two other UHSC mixes. In order to compare the results with UHSC, two reference concretes with natural round and crushed aggregates were produced. For all mixes, a Portland cement CEM I 42,5 R was chosen, with fly ash and/or silica fume as reactive filler in order to ensure a similar strength development. The mix designs of the concretes are presented in Table 1.

Within the test program the fresh concrete properties for each mix were determined in order to ensure similar workability. In the hardened state the mechanical properties (concrete compressive and splitting tensile strength, modulus of elasticity) were measured at the concrete age of 3, 7, 28 and 56 days for evaluating the bond tests. An overview on the test program is given in Table 2 - Table 4.

Pull-out Specimen

The bond properties were determined with pull-out tests using the RILEM-specimen (8). Within the test program rebars with $d_s = 10$ mm were used primarily (Table 3), but in some test series rebars of 8 mm diameter were also used (Table 2). Because of the two different rebar diameters, the dimensions of the pull-out specimens were also varied. Figure 4 (rebar in vertical orientation) shows the specimen size for Ø 10 mm. The rebar was placed in the concrete in two different directions that means horizontal (at a right angle to the casting direction) and vertical (parallel to the casting direction). The vertical rebar orientation can be distinguished between loading in and against concrete placing direction (Figure 5 and Table 3).

Besides the rebar diameter the concrete cover is also a crucial parameter. According to the RILEM-recommendation (8) for a rebar Ø 10 mm the size of the concrete cover results in 4.5 cm (Figure 4). This is required only for extreme exposures (sulphate or chloride attack) and for abrasion. Therefore, for one test series, the cover thickness was gradually decreased in order to have a lower cover (common in the construction practice) and to provoke splitting failure of the cover (Table 4). This failure type occurred at covers of 2.5 cm and less, so that 2.5 cm was selected for the test series (Figure 4).

The bond length between concrete and reinforcement measures 5-times the reinforcing bar diameter d_S according to the RILEM-recommendation (8). This recommendation was admittedly intended for normal strength concrete. Since the bond strength increases with the compressive strength, the bond length must be reduced for high and ultra high strength concrete (9). This change is necessary because of the high transferable bond stresses, otherwise the rebar would yield beyond the bond length. After some preliminary tests, the bond length was chosen as 1.5-times the rebar diameter d_S for ultra high strength concrete, i.e. 1.5 cm for Ø 10 mm.

Except for one series (Table 4 - see also last section in RESULTS) the pull-out specimens were loaded by displacement-control with a loading rate of 0.005 mm/s by means of a servo-hydraulic testing machine. The specimens were placed in an apparatus in the testing machine (Figure 6). The slip between rebar and concrete was measured at the unloaded end of the specimen with three LVDT's around the rebar spaced 120° apart (Figure 7).

TEST RESULTS

Hardened Concrete Properties

All test specimens for the hardened concrete properties were cured under water until the time of the test (concrete ages of 3, 7, 28 and 56 days). The cylinder compressive strength and the E-modulus were determined on cylinders (Ø 100 mm/h = 200 mm). The cube compressive and the splitting tensile strength were obtained from cubes measuring 100 × 100 × 100 mm according to DIN EN 12390 (12). The smaller dimensions of the specimens compared to those used in DIN 1045-2 (10) (cylinders Ø 150 mm/h = 300 mm and 150 mm cubes) to classify the concrete were necessary because of the limited capacity of available testing machines. In Table 6 the hardened concrete properties determined after 28 days are shown each as the average of 3 values.

The time development for all hardened properties was also measured in order to evaluate the bond properties. Typically for UHSC, not only the high compressive strengths after 28 days, but also high early age strengths are achieved. So it is easily possible to achieve 85 - 95 N/mm² after 3 days (see Table 5 and Figure 8). Therefore this type of concrete should be of interest for prestressed concrete members, because the pretensioning can be applied earlier. Furthermore, the construction progress can be accelerated so that the time of construction may be diminished. Figure 8 indicates the time development of the cylinder compressive strength; the curves for the other properties are summarized in (13).

Bond of Reinforcement in UHSC

The bond stress-slip relationships for the different concrete types were determined on RILEM-specimens (8). At each test age three pull-out specimens per rebar orientation were experimentally analyzed, so that the curves shown represent the mean of three corresponding pull-out tests. Altogether 201 bond tests were performed, including 183 tests for rebar Ø 10 mm and 18 tests for Ø 8 mm.

Time Development of the Bond Properties — The time development of the mean bond stress-slip relationships is illustrated separately for three of the concretes in Figure 9 - 12. It is clearly visible that the bond strength as well as the bond stiffness at an age of 3 days is quite high for UHSC. The further increase of the maximum reachable bond stress at 28 days was 50% for the UHSC 1 and nearly 100% for the UHSC 2. However, the increase after 28 days is rather small for UHSC 2 (Figure 10), but the increment for UHSC 1 is still remarkable. The reason for this fact is the effect of the fly ash, which reacts definitely later than silica fume and therefore it contributes later to the strength. The bond stiffness increases over the time too. It is worthwhile to mention the ductile bond behavior of UHSC and Reference concrete 2, characterized by the level descending branch of each curve. Despite of the reached high bond stresses (for UHSC) only in a few cases splitting failure occurred. In comparison to Reference concrete 2, higher values of the bond stresses relative to the compressive strength were achieved (Figure 12). In this figure, the different bond stiffnesses for the different concrete types are also visible.

Influence of the Concrete Cover Size — In order to determine the necessary size of the concrete cover, two main basic principles must be considered:

- a sufficient mechanical anchorage of the rebar as well as
- the protection of the reinforcement against environmental attacks like chlorides, acids or carbon dioxide in order to prevent corrosion.

The splitting of the cover and/or the bond degradation due to corrosion and, for both cases, the associated loss of bond strength must be avoided. The effect of concrete cover and corrosion level on splitting and bond strength of corroded rebars has been examined previously, e.g. (14) - (17). In addition, the permeability of ultra high strength concrete has also been investigated. It has been shown that the resistance against ingress of ions like chloride and sulfate is very high (18). From this point of view it may be possible to reduce the required cover size, so possibly the standard values stated in DIN 1045-1 (10) for the different exposures.

Nevertheless the mechanical anchorage plays the major role in UHSC, because the changed relations of the hardened concrete properties (see paragraph: Hardened Concrete Properties) may dominate the general bond behavior. Engström et al. presented results about the influence of confinement and cover on bond in high strength concrete (19). A reduction of the concrete cover to 16 mm (same as rebar diameter) resulted in a drop of the maximum bond stress of about 25 – 30% in comparison to well confined concrete. When using stirrups or a cover increase to 32 mm, the same load level as for well confined concrete could be reached. However, the post-peak behavior was brittle due to longitudinal cracking.

In the present study, the cover size was reduced from 4.5 cm to 2.5 cm (see Figure 4). At the concrete age of 3 days, there is no effect: the maximum bond stresses were at the same level and no splitting occurred for UHSC 2. Beginning at 7 days splitting failure occurred for the smaller cover. The measured results at an age of 28 days differed for the concretes used. Whereas both UHSC-mixes with a maximum grain size of 5 mm (UHSC 1 and 3) showed no negative effect due to the reduction of the cover in terms of splitting or bond stress, the splitting risk increased for UHSC 2. One third and two thirds of the specimens cracked by longitudinal splitting after 28 days and 56 days, respectively. With the large cover size, this failure mode was less significant. It should be mentioned that UHSC 2 showed high shrinkage rates, and some specimens had small surface cracks, so they were predamaged.

<u>Influence of the Type of Reinforcement</u> — As mentioned earlier, in addition to rebar of diameter 10 mm, also rebars with Ø 8 mm diameter were also tested for Reference concrete 2 and UHSC 3 (Table 2). Both reinforcing bars and reinforcing mesh bars were used, the latter one with a conventional ribbed surface and a fairly new "deep-ribbed" surface (Figure 13). The different bond behavior and bond characteristic is clearly displayed in Figure 14 and Figure 15. With both concretes the deep-ribbed mesh bar shows the most ductile behavior whereas the reinforcing bar reached the highest bond stresses. The relative bond stress-slip curves for the reinforcing bar are quite similar for both concrete mixes. However, the difference between reinforcing bar and mesh bars is lower for UHSC 3. Furthermore, the stiffness is increased for the reinforcing mesh bars comparing UHSC 3 with Reference concrete 2.

<u>Influence of the Loading Rate</u> — Within a small test series the influence of the loading rate was investigated. Five different loading rate levels (1/1000, 5/1000, 10/1000, 50/1000 and 100/1000 mm/sec loading rate) were applied using displacement-control. It is shown in Figure 16, that the loading rate influences the shape of the bond stress-slip curves. At the lowest loading rate (1/1000 mm/sec) the descending branch is flatter than that of the other curves. Other interesting points are the maximum bond stress and the slip values at maximum bond stress. The faster the loading rate (especially 50/1000 and 100/1000 mm/sec), the higher the bond stress values as well as the larger the displacement at maximum bond stress (Figure 16). The third significant aspect is the ascending branch of the bond stress-slip relationship. The lower the loading rate the steeper the ascending branch of the corresponding pull-out test, so the higher the bond stiffness.

CONCLUSIONS

Based on this test program, it is concluded that the bond behavior of reinforcement in ultra high strength concrete is not negatively affected by the high brittleness of the material. The bond stiffness is increased due to the high compressive strength and modulus of elasticity; the bond stresses relative to the compressive strength are in the same range as the Reference mixes. Regarding the time development of the bond stresses, the mix design has a major influence on UHSC. In future studies, lapped splices will be investigated.

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Table 1 — Mix designs

	content of cement (mass-%)				
	Reference 1	Reference 2	UHSC 1	UHSC 2	UHSC 3
Sand 0/2 mm	1.86	2.42	0.92	-	-
Gravel 2/8, 8/16 mm	3.46		-		-
Crushed aggregates 2/5 mm	-	0.49	1.68	2.06	2.06
Crushed aggregates 5/8 mm	-	2.15	-	-	-
Cement CEM I 42,5 R	1.00	1.00	1.00	1.00	1.00
Fly ash	0.21	0.27	0.20	-	-
Silica-slurry 50/50			0.13 (solids)	-	-
Silica fume		-	-	0.30	0.18
Quartz sand 0.3/0.8 mm		-	0.30	1.53	0.88
Quartz powder		-	-	0.43	0.54
Water	0.53	0.52	0.30	0.25	0.27
Superplasticizer	0.01	0.02	0.04	0.03	0.04

Table 2 — Overview about the pull-out tests with 8 mm rebar

Age at testing	Reference 2	UHSC 3
	rebar diameter 8 mm, bond length 15 mm, cover size 3.6 cm rebar orientation - variant 1: vertical, loaded in casting direction; variant 2: horizontal; variant 3: vertical, loaded against casting direction	
28 days	variants: 2 reinforcing bars and reinforcing mesh bars: conventional-ribbed surface and deep-ribbed surface	variants: 2 reinforcing bars and reinforcing mesh bars: conventional-ribbed surface and deep-ribbed surface

Table 3 — Overview about the pull-out tests with 10 mm rebar

Age at testing	Reference 1	Reference 2	UHSC1	UHSC 2	UHSC 3
	rebar diameter 10 mm, bond length 15 mm, cover size 4.5 or 2.5 cm rebar orientation - variant 1: vertical, loaded in casting direction; variant 2: horizontal; variant 3: vertical, loaded against casting direction				
3 days	-	-	cover 4.5 cm, variants: 1, 2, 3	cover 4.5 cm, variants: 1, 2, 3	-
7 days	cover 4.5 cm, variants: 2	cover 4.5 cm, variants: 1, 2	cover 4.5 cm, variants: 1, 2, 3	cover 4.5 cm, variants: 1, 2, 3	-
28 days	cover 4.5 cm, variants: 2	cover 4.5 cm, variants: 1, 2	cover 4.5 cm, variants: 1, 2, 3	cover 4.5 cm, variants: 1, 2, 3	cover 4.5 cm, variants: 1, 2, 3
56 days	-	-	cover 4.5 cm, variants: 1, 2, 3	cover 4.5 cm, variants: 1, 2, 3	-
3 days	-	-	-	cover 2.5 cm, variants: 1, 2, 3	-
7 days	cover 2.5 cm, variants: 2	cover 2.5 cm, variants: 1	-	cover 2.5 cm, variants: 1, 2, 3	-
28 days	cover 2.5 cm, variants: 2	cover 2.5 cm, variants: 1	cover 2.5 cm, variants: 1, 2, 3	cover 2.5 cm, variants: 1, 2, 3	cover 2.5 cm, variants: 1, 2, 3
56 days	-	-	-	cover 2.5 cm, variants: 1, 2, 3	-

Table 4 — Additional pull-out tests with 10 mm rebar

Age at testing	UHSC 1	UHSC 2
	rebar diameter 10 mm rebar orientation - variant 1: vertical, loaded in casting direction; variant 2: horizontal; variant 3: vertical, loaded against casting direction	
28 days	cover and bond length variab1e variants: 2	cover 4.5 cm, bond length 15 mm variants: 2

Table 5 — Hardened concrete properties after 3 days

Material property [N/mm²]	Reference 1	Reference 2	UHSC 1	UHSC 2	UHSC 3
Cylinder compressive strength $f_{c,cyl}$	-	-	87	93	-
Cube compressive strength $f_{c,cube}$	-	-	93	94	-
Splitting tensile strength $f_{ct,sp}$	-	-	7.7	7.1	-
Modulus of elasticity E_c	-	-	43,600	40,600	-

Table 6 — Hardened concrete properties after 28 days

Material property [N/mm²]	Reference 1	Reference 2	UHSC 1	UHSC 2	UHSC 3
Cylinder compressive strength $f_{c,cyl}$	53	62	135	147	144
Cube compressive strength $f_{c,cube}$	63	66	133	148	144
Splitting tensile strength $f_{ct,sp}$	4.4	5.1	9.5	12.2	10.9
Modulus of elasticity E_c	33,700	33,300	49,800	47,100	52,900

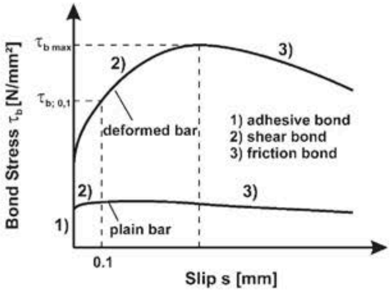

Figure 1—Bond stress-slip relationship for deformed and plain reinforcing bars according to Will (4)

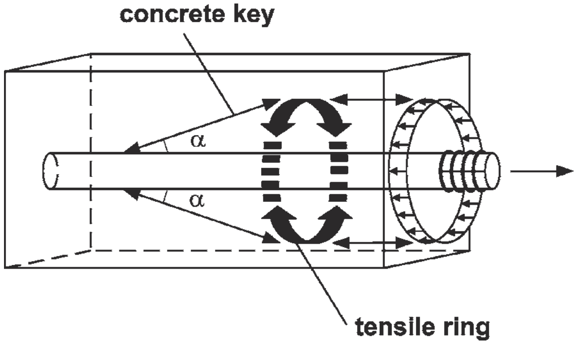

Figure 2—Spatial model of the force transfer at the rebar according to Tepfers (5)

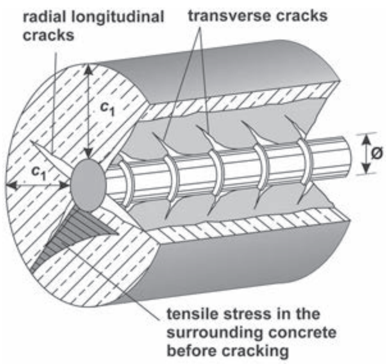

Figure 3—Longitudinal and transverse crack development due to the bond according to Tepfers (5)

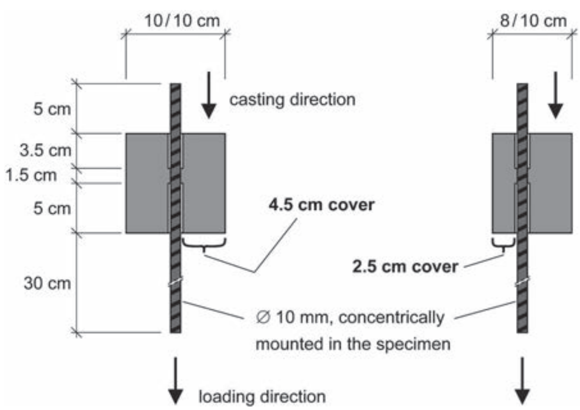

Figure 4—Pull-out specimen with vertical orientated rebar
Left side: concrete cover according to RILEM (8)
Right side: reduced concrete cover