STRUCTURAL BEHAVIOUR OF HIGH PERFORMANCE CONCRETE

STRUKTURELLES VERHALTEN VON HOCHLEISTUNGSBETON

COMPORTEMENT STRUCTURAL DU BETON A HAUTE PERFORMANCE

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SUMMARY

The paper describes the general mechanical behaviour of high strength concrete (HSC) compared with normal strength concrete (NSC). Uniaxial, biaxial, and triaxial tests are presented.

ZUSAMMENFASSUNG

Der Beitrag beschreibt das allgemeine mechanische Verhalten von Hochfestem Beton im Vergleich zu Normalfestem Beton. Einachsige, zweiachsige und dreiachsige Versuche werden dargestellt.

RESUME

La contribution décrit le comportement structural general du béton à haute résistance comparé avec le béton à résistance normale. Des essais uniaxiales, biaxiales et triaxiales sont présentés.

KEYWORDS: high strength concrete, uniaxial loading, stress-strain curve

1. INTRODUCTION

High performance can be related to any property of concrete. It can mean excellent workability in the fresh state like self-levelling concrete, or low heat of hydration in case of mass concrete, or very rigid setting and hardening of concrete in case of sprayed concrete or quick repair of roads and airfields, or very low imperviousness of storage vessels, or very low leakage rates of encapsulation containments for contaminating material. However, when „high performance“ is linked to „structural behaviour“ one understands usually that high performance is synonymous with high strength. According to the new European standard EN 206 high strength concrete ranges from C55/67 to C100/115 for normalweight concrete and from LC55/60 to LC80/88 for lightweight aggregate concrete. These are large ranges and the relevant concretes are not alike. The lower strength classes can be designed similarly to normal strength concrete with a little lower a water-cement ratio whereas the higher strength classes require some extra additions like silica fume and additives like high performance water reducers. The question is how these high strength concretes differ from normal strength concrete with respect to the structural behaviour of concrete components. In the following, some aspects like ultimate load, cracking and deformation will be presented and discussed.

2. STRESS-STRAIN BEHAVIOUR OF HIGH STRENGTH CONCRETE

If the structure of normal strength concrete (NSC) is compared with high strength concrete (HSC) one realizes several differences: first, the matrix stiffness of HSC is larger than the one of NSC and approaches the stiffness of the aggregate, second, the bond strength between matrix and aggregate becomes higher with HSC, third, the matrix tensile strength becomes higher and, forth, internal cracking is reduced in terms of number of cracks and size of intrinsic cracks before loading. These aspects together mean that HSC behaves more elastic and more brittle than NSC. Fig. 1 shows a schematic of the stress-strain curve from a uniaxial test together with the simplified crack pattern.

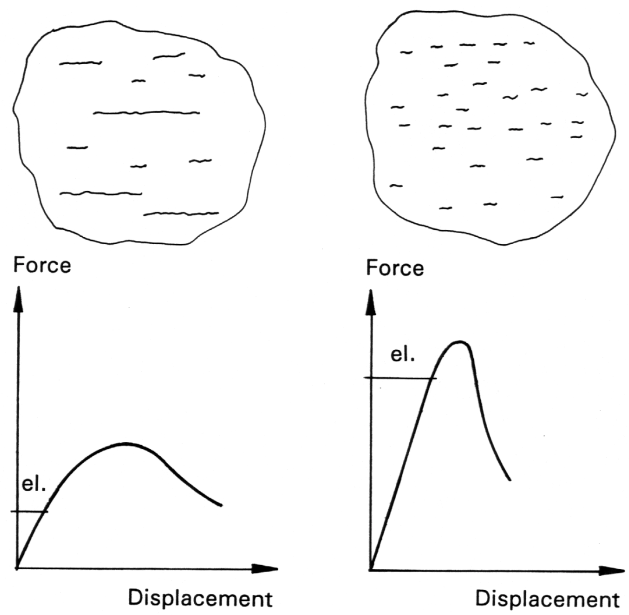

Fig. 1. Schematic of stress-strain curve and cracking pattern in NSC (left) and HSC (right)

NSC shows a diversity of crack lengths which means on a fracture mechanics basis that larger cracks reach a critical state earlier than smaller cracks, i. e. there is a subsequent and continuous crack extension which causes a non-linear stress-strain curve from the beginning. Opposite to this behaviour, HSC has shorter cracks which become active only at a higher load, but when they extend they extend at once and lead to almost immediate failure. Such a behaviour is usually called brittle. It is not only the uniform or non-uniform crack size which makes the difference it is also the crack-arrest effect of aggregate-matrix interfaces in NSC which are weak and delaminate. Delamination consumes energy and causes a crack to deviate from the initial direction. In HSC, a crack will run straight through the aggregate grain which leads to brittle failure again. Compressive strain in the loading direction is accompanied by tensile strain in the lateral direction. When the specimen is confined in the lateral direction either by active loading or by passive constraint in a tube the ultimate load is increased the more the larger the constraining force is. Since the main effect of lateral constraint is that cracks are suppressed from opening and extension it is anticipated that lower strength concrete benefits more from lateral constraint than higher strength concrete does. This expectation has been confirmed in triaxial confined tests [Setunge et al. 1993]. Table 1 shows a summary of the results. It can be seen that the influence of a confining pressure on the triaxial compressive strength is almost the same for concretes with uniaxial compressive strength between 96 and 118 MPa and that it is much larger for a concrete of medium strength.

Table 1. Strength ratio between strength with confined to unconfined loading [Setunge et al. 1993]

Confining stress [MPa]	Uniaxial compressive strength [MPa]								
	age 28 days				age 90 days				
	96	96	102	108	58	98	100	110	118
0	1	1	1	1	1	1	1	1	1
5	1.22	1.30	1.42	1.33	1.69	1.21	1.28	1.39	1.30
10	1.50	1.53	1.55	1.59	2.10	1.49	1.53	1.49	1.49
15	1.57	1.70	1.72	1.80	2.48	1.59	1.70	1.68	1.69

Evaluating this and additional results a failure criterion has been proposed as by [Newman 1979]:

$$\frac{f_c}{f_{c0}} = \left(A \frac{\sigma_{conf}}{f_{c0}} + 1 \right)^B \quad (1)$$

with f_c = triaxial strength, f_{c0} = uniaxial strength, σ_{conf} = confining pressure and A, B empirical constants. For high strength concrete (90 to 130 MPa) B = 0.45, for lower strength (20 to 50 MPa) B = 0.63, i. e. the relative strength increase is smaller for HSC than for NSC.

For practical purposes, a simplified relation can be used which is similar to the classical one by [Richart et al. 1929]:

$$\frac{f_c}{f_{c0}} = 1 + 3 \frac{\sigma_{conf}}{f_{c0}} \quad (2)$$

This linear relationship is a lower bound of results of numerous tests.

Biaxial testing with brush loading platens has been reported by [Hussein and Marzouk 2000]. Three concrete grades have been tested in the compression-compression, compression-tension, and tension-tension range. The strength envelopes are shown in Fig. 2.

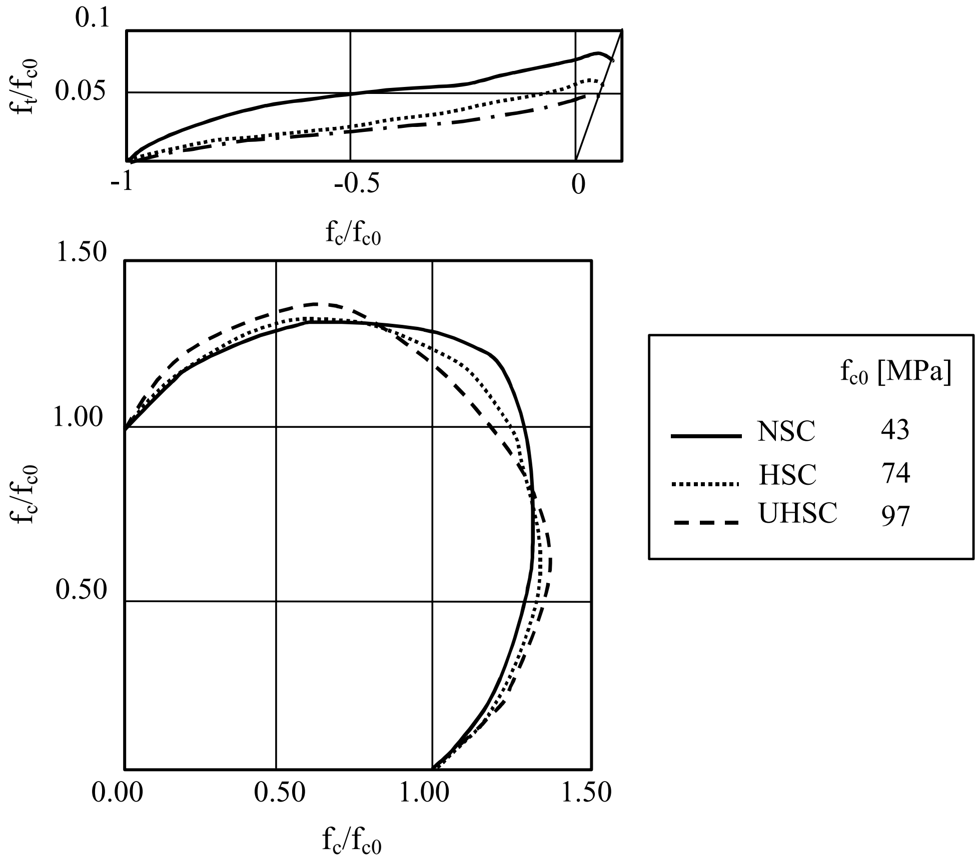

Fig. 2. Biaxial strength envelopes for three types of concrete [Hussein and Marzouk 2000]

a) Compression-tension and tension-tension
b) Compression-compression

The upper figure applies to pure tensile or combined tension-compression loading. There are two important aspects to be seen: the tensile strength decreases with respect to the compressive strength with higher concrete grade and the decay of compressive strength due to a simultaneous lateral tensile stress is larger for high strength concrete. The lower figure depicts the compression-compression regime with an increase of strength by about 32 to 35% for a stress ratio of 0.5. For a stress ratio of 1.0, NSC shows an increase of 20%, the very high strength concrete (UHSC) only 10%. This means again that a confining stress is less effective the higher the concrete strength is as has already be seen with triaxial compression.

HSC has a larger Young's modulus than NSC and the post-peak softening branch is steeper. Fig. 3 shows the results of displacement controlled tests on concrete with peak stresses between 23 and 106 MPa.

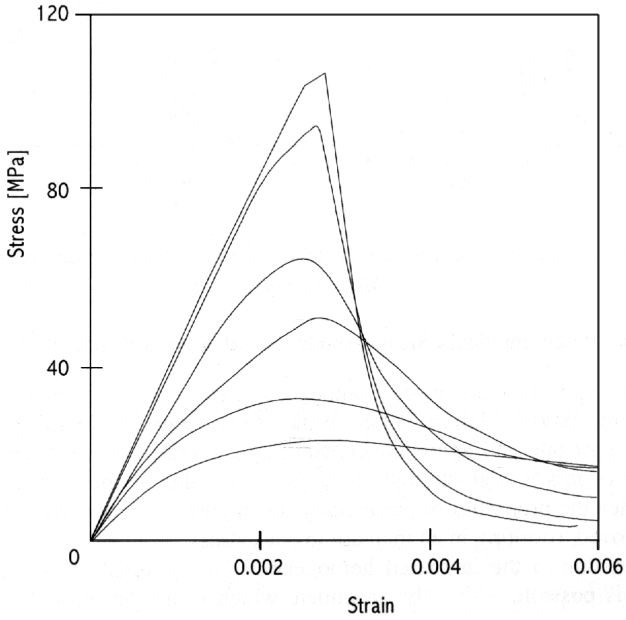

Fig. 3. Stress-strain curves of concrete with various strength grades [Dahl 1992]

The linear part of the ascending branch stretches to more than 90% of the peak stress of HSC whereas lower strength concrete shows almost no linear part at all. When the peak stress has been reached the stress decays very fast on HSC. Brittleness can be described by fracture energy compared to elastic energy stored in a stressed member. Considering a structural member under tension [Hillerborg 1976] has defined his so-called characteristic length such that the elastic energy stored in a bar equals the specific fracture energy G_F. If the same idea where applied to a member under compression the length of a column would be calculated which would collapse in a stable manner under a stress equal to the compressive strength. The column length would be

$$l_{col} = \frac{2EV \int_0^{\varepsilon_o} \sigma \, d\varepsilon}{A f_c^2} \tag{3}$$

with E = Young's modulus, ε_0 = strain at complete failure, f_c = compressive strength, A = cross-section, and V = failure volume. If a fracture plane under 30° to the vertical is assumed and a crushed zone of d_u = 20 mm is supposed one can calculate the column length l_{col}. Evaluating this approximative relation with the results of Fig. 3 the values in Table 2 are obtained. Although the analysis is very rough it becomes obvious that usual column sizes become more brittle with a higher concrete strength.

Table 2. Approximate column length for stable failure

f_c, MPa	23	32	50	64	94	106
l_{col}, mm	245	230	170	160	120	115

When HSC is confined by lateral compressive stresses the material becomes some ductile. Tests on a HSC with cube compressive strength of 80 MPa have been loaded in a triaxial test with brush loading platens either with two equal lateral stresses or in a plane-strain condition, i. e. the strain in one lateral direction is kept zero. Fig. 4 shows the stress difference σ_1-σ_3 and the displacement of a 100 mm cube in three directions. Compared to the dashed line which represents a uniaxial experiment the displacements increase by two orders of magnitude with lateral stress equal to 100 MPa.

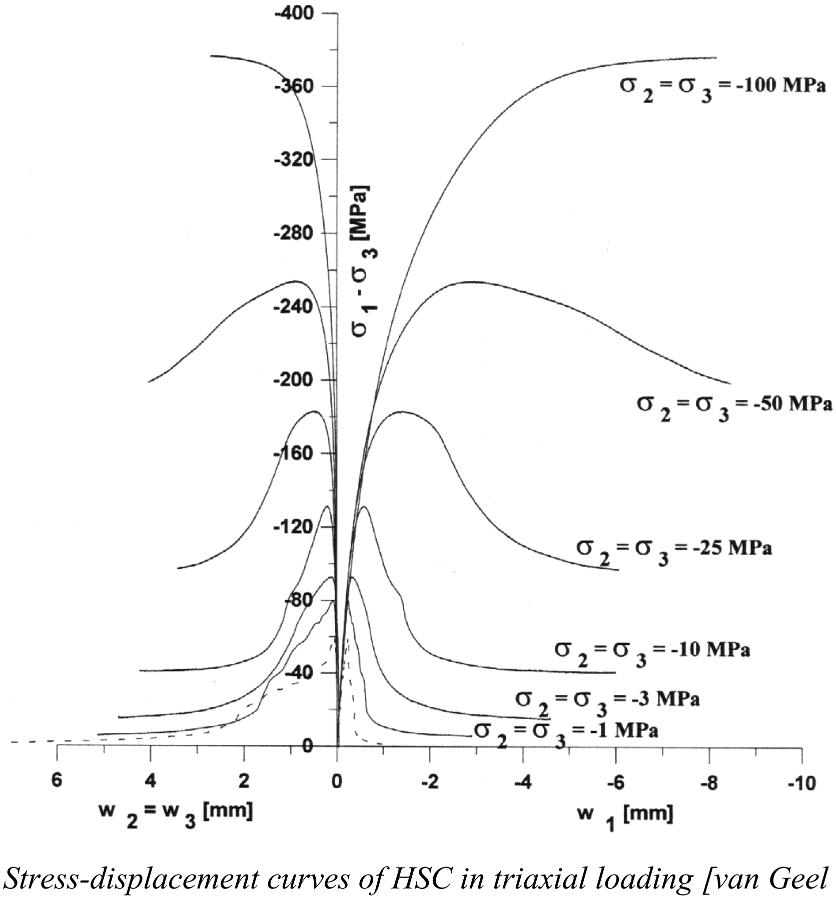

Fig. 4. Stress-displacement curves of HSC in triaxial loading [van Geel 1998], dashed line for σ_2 = σ_3 = 0

The stresses in the main axis σ_1 reaches 460 MPa and the deformation resembles plastic behaviour up to about 8%.

In plain strain experiments when σ_2 is controlled such that the displacement in the 2-axis is zero the strength increase in the main direction is almost the same as in hydrostatic loading, however the displacements are different.

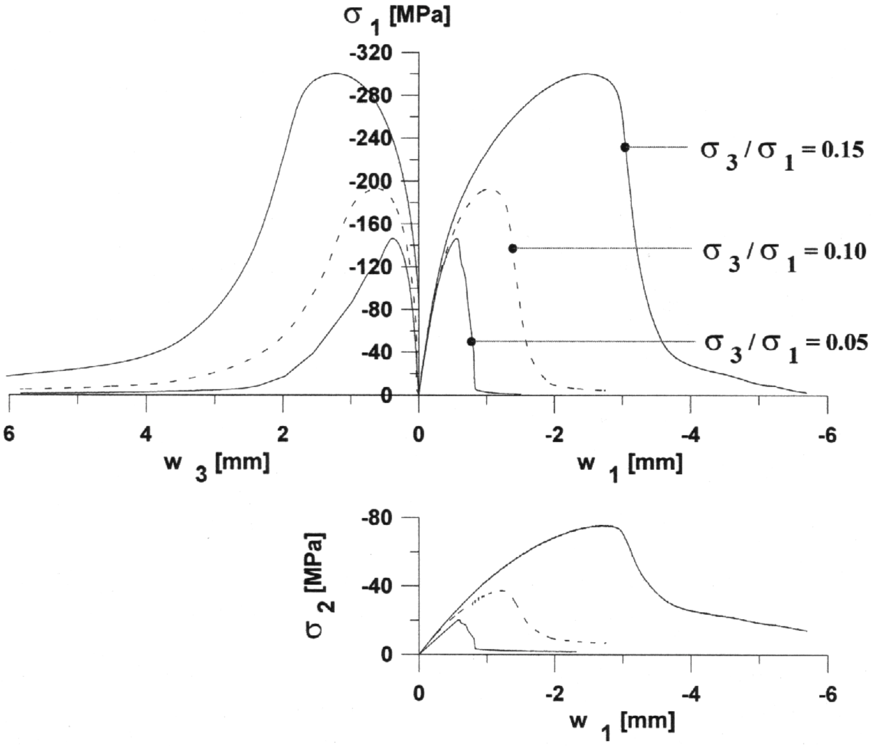

Fig. 5. Stress-displacement curve of HSC in plain strain [van Geel 1998]

After having reached the peak stress there is a rapid decay of stresses. This is due to crack formation in planes which are inclined to the 1- and 3 axis and run in the direction of the 2-axis. It is worth to note that the softening branch reaches almost immediately zero stress.

Summarizing the stress-strain behaviour of HSC one can state that HSC is more brittle in the uniaxial state of stress but it has also a great potential of ductility when it is loaded in triaxial compression. However, in tension-compression loading it behaves more brittle than NSC.

3. CONCLUSION

High strength concrete (HSC) is more homogeneous than normal strength concrete (NSC). Initial flaws like pores, cracks, and interfacial delaminations in HSC are smaller and less numerous than in NSC which makes HSC stiffer and more elastic than NSC. The nonlinear part in the ascending branch of the stress-strain diagramme and the post-peak softening part are reduced which is a token of brittleness. However, if HSC is confined by lateral compression or reinforcement it becomes rather ductile.

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