These columns of ICJ offer an opportunity to the engineering fraternity to express their views on the current practices in design, construction and management being followed in the industry.

To share your opinion with our readers, you may send in your inputs in about 1500 words via e-mail to editor@icjonline.com

Structural significance of high performance concrete

C.S. Suryawanshi

High performance in a broad manner 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 significant behaviour' high performance is usually synonymous with high strength. The BIS code of practice on plain and reinforced concrete, IS 456 : 2000 or Indian Roads Congress, IRC-21 do not define HPC. According to the new European standard, EN 206 high strength concrete ranges from C55/67 to C100/115 for normal weight 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 water-cement ratio whereas the higher strength classes require some extra additions like silica fume and additives like high performance water reducers. The question remains as to how these high strength concretes differ from nominal strength concrete with respect to the structural behaviour of concrete components. In the succeeding sections some aspects like ultimate load cracking and deformation are presented and discussed.

Stress-strain behaviour

Structures are designed with reference to important parameters such as stress-strain, compression, tension and shear properties of concrete. If the structure of normal strength concrete (NSC) is compared with high performance concrete (HPC) one notes several differences: (i) The matrix stiffness of HPC is larger than NSC and approaches the stiffness of the aggregate (ii) the bond strength between matrix and aggregate is higher for HPC (iii) matrix tensile strength is higher (iv) Reduced internal cracking in terms of number of cracks and size of intrinsic cracks before loading. These aspects show that HPC is more elastic and more brittle than NSC. Figure 1 shows a schematic representation of the stress-strain curve from a uniaxial test along with the simplified crack pattern.

NSC shows a diversity of crack lengths which means as per fracture mechanics 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. Contrary to this behaviour, HPC has shorter cracks which become active only at a higher load, but they extend at once and lead to almost immediate failure. Such behaviour is technically termed as brittle. It is not only the uniform or non-uniform crack size which makes the difference but also the crack-arrest effect of aggregate-matrix

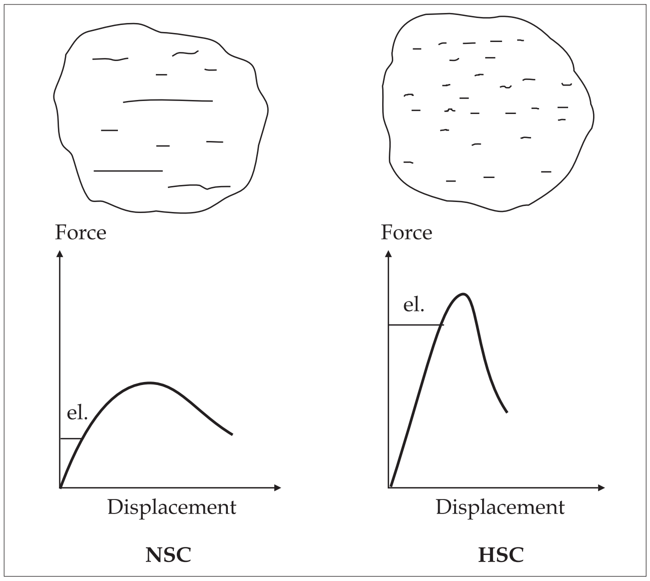


Figure 1. Schematic representation of stress-strain curve and cracking pattern

interfaces. In NSC the interface is relatively weak and delamination occurs. Delamination_consumes energy and causes a crack to deviate from the initial direction. In HPC, a crack runs 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 and larger is the constraining force. Since the main effect of lateral constraint is suppresion of cracks from opening and extending. It is anticipated that lower strength concrete benefits more from lateral constraint than higher strength concrete and has been confirmed in triaxial confined tests[6]. Table 1 shows a summary of the results. It can be seen that the influence of a confining pressure on the triaxial compressive strength of concrete is almost the same as the uniaxial compressive strength between 96 and 118 MPa, and it is much higher for concrete of medium strength.

Table 1. Strength ratio between confined and unconfined loading[6]

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
1	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[4].

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

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

For practical purposes, simplified relation can be used which is similar to the classical one[5]:

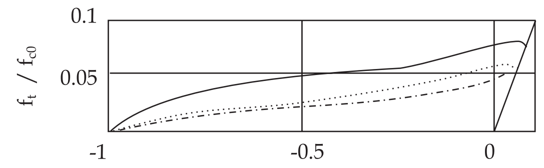
$$\frac{f_c}{f_{c0}} = 1 + 3 \frac{\sigma_{conf}}{f_{c0}} \qquad ......(2)$$

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

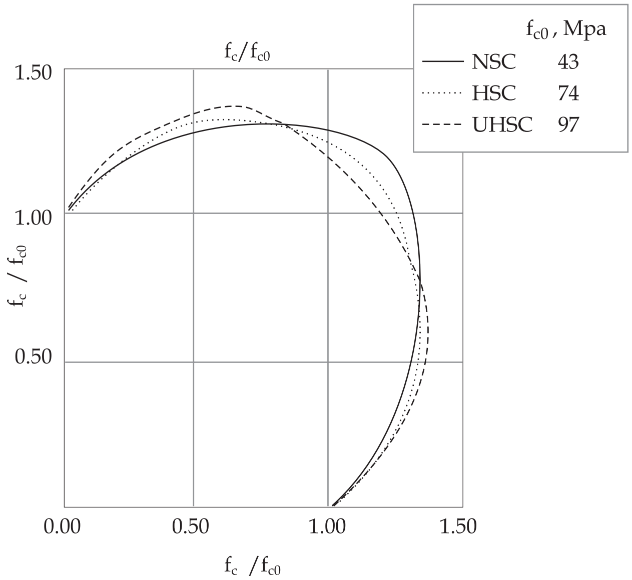
Biaxial testing with brush loading platens has been reported[3]. Three concrete grades have been tested in the compression-compression, compression-tension and tension-tension range. The strength envelopes are shown in Figure 2.

Figure 2 applies to pure tensile or combined tension-compression loading. It may be noted that the tensile strength decreases with respect to compressive strength for higher concrete grade and also the decay of compressive strength due to simultaneous lateral tensile stress is larger for high strength concrete. Therefore, HPC does not show corner cracks normally displayed by NSC. Figure 3 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% and very high strength concrete (VHPC) only 10%. This shows again that higher the concrete strength, lesser is the effectiveness of confining stress as observed for triaxial compression.

HPC has a greater Young's modulus than NSC and the post-peak softening branch is steeper. Figure 3 shows the results of displacement controlled tests on concrete with peak stresses between 23 and 106 MPa. The linear part of the ascending branch stretches to



(a) Compression-tension and tension-tension



(b) Compression-compression

Figure 2. Biaxial strength envelopes for three types of concrete[3]

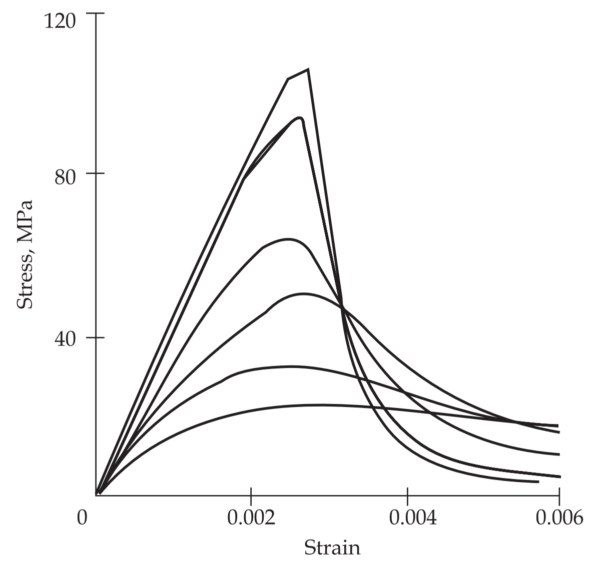


Figure 3. Stress-strain curves of concrete with various strength grades[1]

more than 90% of the peak stress of HPC whereas lower strength concrete shows negligible linear part. The stress decays very fast in HPC after peak stress has been reached. Brittleness can be described by fracture energy compared to elastic energy stored in a stressed member. Considering a structural member under tension has defined characteristic length such that the elastic energy stored in a bar equals the specific fracture energy, GF^2. If the same idea is applied to a member under compression then the length of a column that would collapse in a stable manner under a stress equal to the compressive strength would be:

$$l_{col} = \frac{2EV_0 \int^{\epsilon 0} \sigma \, d' \epsilon}{A f_c^2} \qquad \text{......(3)}$$

where, E = Young's modulus, V = failure volume, ϵ_0 = strain at complete failure, σ = lateral stress, A = cross section and f_c = compressive strength.

If a fracture plane of 30° to the vertical and a crushed zone of du = 20 mm is assumed, one can calculate the column length l_{col} using equation (3). On equating this approximate relation with the results of Figure 3, we get the values mentioned in Table 2. Although the analysis is very rough it is obvious that the usual column sizes become brittle with higher concrete strength.

When HPC is confined by lateral compressive stresses the material becomes relatively ductile. HPC 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 and Figure 4 shows the results of such a test. It shows stress difference $\sigma_1 - \sigma_3$ 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.

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

In plane strain experiments when σ_2 is controlled such that the displacement in the 2-axis is zero, the 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

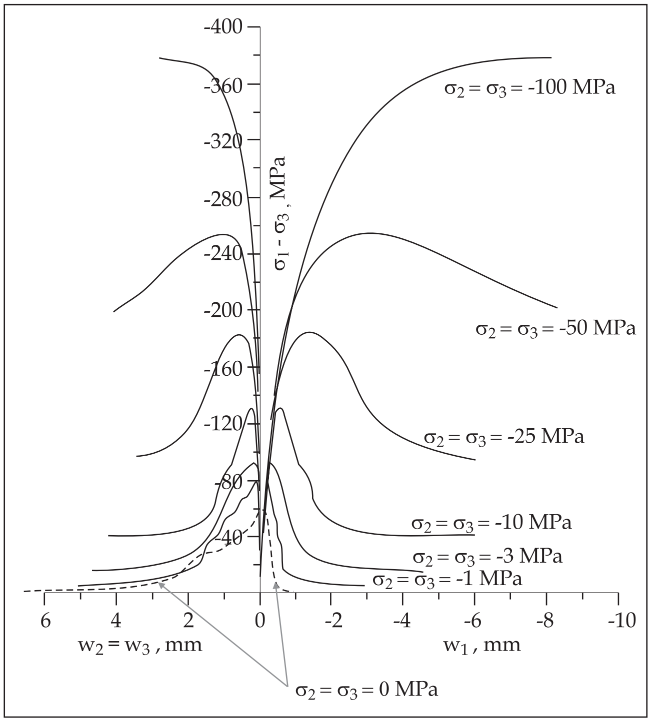


Figure 4. Stress-displacement curves of HSC in triaxial loading[7]

increase in the main direction is almost the same as in hydrostatic loading. However, the displacements are different, Figure 5.

After reaching the peak stress there is a rapid decay of stresses and this is mainly due to crack formation in planes that are inclined to the 1- and 3-axis and run in the direction of the 2-axis. It may be noted that the softening branch reaches almost immediately zero stress.

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

Conclusion

High Strength Concrete (HPC) is more homogeneous than normal strength concrete (NSC). Initial flaws like pores, cracks and interfacial delamination in HPC are smaller and less numerous than in NSC. This makes HPC more stiff and elastic as compared to NSC. The non-linear part in the ascending branch of the stress-strain diagram and the post-peak softening part are reduced which is a sign of brittleness. However, if HPC is confined by lateral compression or reinforcement it becomes ductile.

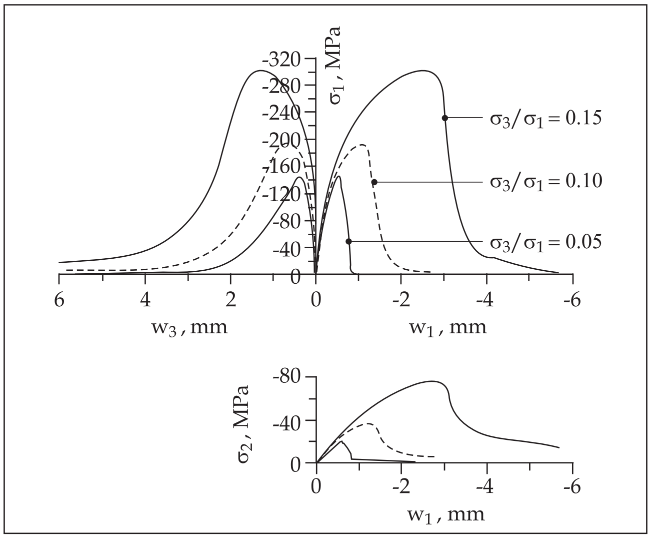


Figure 5. Stress-displacement curve of HSC in plane strain[7]

References

1. Dahl, K.K.B., *A constitutive model for nominal and high-strength concrete,* ABK Report No R 287, 1992, Department of Structural Engineering, TU Denmark, Lyngby, Denmark.
2. Hillerborg, A., Modeer, M., and Petersson, P.E., Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements, *Cement and Concrete Research,* November 1976, Vol. 6, No. 6, pp. 773-782.
3. Hussein, A. and Marzouk, H., Behaviour of high-strength concrete under bi-axial stresses. *ACI Materials Journal*, 2000, Vol. 97, No. 1, pp. 27-36
4. Newman, I.B., Concrete under complex stress, *Developments in Concrete Technology-I,* Edited by F.D. Lydon, 1979, pp. 151-219.
5. Richart, F.E., Brandtzaeg, A. and Brown, R.L., Failure of plain and spirally reinforced concrete in compression, Bulletin 190, 1929, University of Illinois, USA.
6. Setunge, S., Attard, M.M., and Darvall, P.Le P., Ultimate strength of confined very high strength concrete, *ACI Structural Journal*, 1993, Vol. 90, No. 6, pp. 632-641.
7. Van Geel, E., *Concrete behaviour in multiaxial compression*, Experimental research, Doctoral thesis, 1998, TU Eindhoven.

Dr. Suryawanshi, B.E. (civil), M.Tech (structures), M.E. (construction management) and PhD in multidisciplinary subject of analysis and rehabilitation of structures, is a former chief engineer and joint secretary to the government of Maharashtra. Currently, he is a structural consultant and is actively involved in design and execution of concrete structures such as construction of rigid pavement, flyovers/bridges structures & tunnels. ■