Dynamic increase factors for High-Performance Concrete in compression using Split Hopkinson Pressure Bar

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ABSTRACT: This paper provides dynamic increase factors (DIF) in compression for two different High Performance Concretes (HPC), 100 MPa and 160 MPa, respectively. In the experimental investigation 2 different Split Hopkinson Pressure Bars are used in order to test over a wide range of strain rates, 100 sec^{1} to 700 sec^{-1}. The results are compared with the CEB Model Code and the Spilt Hopkinson Pressure Bar technique is briefly described.

1 INTRODUCTION

1.1 *Strain rate dependency*

It is today well-known and accepted that the dynamic behavior of concrete and concrete like materials are strain-rate dependent. (Grote and Park, 2001)

Compared with statically behavior, increases in strength, strain capacity and fracture energy are observed when such materials are exposed to impact loads (Lok and Zhao, 2004). The term DIF (Dynamic Increase Factor) is used to describe the relative strength enhancement.

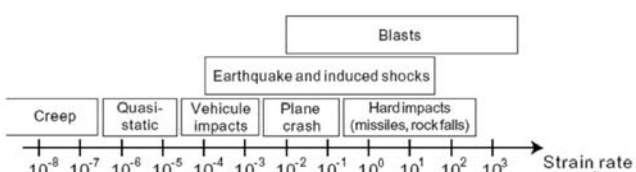

Figure 1. Various strain rate regions.

1.2 *Split Hopkinson Pressure Bar*

The dynamic strength enhancement for concrete was first observed by Abrams in 1917 (Bischoff and Perry, 1991) and it has been generally accepted that concrete and concrete like materials are strain rate sensitive and the constitutive model of such materials under dynamic loading should include strain-rate effects.

Split Hopkinson pressure bar (SHPB) technique has been widely used to measure the dynamic strength enhancement at high strain-rates in the range of 10^{1}sec^{-1} to 10^{3} sec^{-1}.

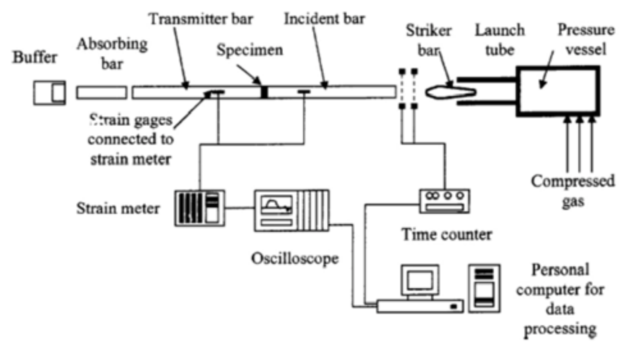

Figure 2. Typical setup for a SHPB device.

1.3 *CEB Model Code*

The most comprehensive model for predicting the strain rate enhancement of concrete is presented by the CEB Model Code (Comite Euro-International du Beton - Federation Internationale de la Precontrainte, 1990)

$$DIF = f_{cd} / f_{cs} = \left(\frac{\dot{\varepsilon}}{\varepsilon_s}\right)^{1.026\alpha} \qquad \text{for } \dot{\varepsilon} \le 30 \text{ s}^{-1} \qquad (1)$$

$$DIF = f_{cd} / f_{cs} = \gamma\left(\frac{\dot{\varepsilon}}{\varepsilon_s}\right)^{1/3} \qquad \text{for } \dot{\varepsilon} \ge 30 \text{ s}^{-1} \qquad (2)$$

The CEB DIF formulation for concrete has been accepted by most researchers as an accurate representation of the strength enhancement. The formulation takes a bilinear relation between DIF and log($\dot{\varepsilon}$) with a change in slope at strain-rate of 30 s^{-1}. (Malvar and Ross, 1998)

2 SPLIT HOPKINSON PRESSURE BAR

2.1 *How the SHPB works*

The principle of a SHPB device is shown in Figure 2. The axial compression impact is caused by the striker bar impinging the incident bar. When this occurs, an incident stress pulse is developed. The pulse propagates along the incident bar to the interface between the bar and the specimen. At this point, the pulse is both reflected and transmitted. The reflected wave propagates back along the incident bar and the transmitted wave attenuates in the specimen and into the transmitter bar. Both the incident and the reflected waves are measured by a strain gauge mounted on the surface at mid-length of the incident bar. Similarly, the transmitted wave is measured by a strain gauge on the surface at mid-length of the transmitter bar. (Li and Meng, 2003)

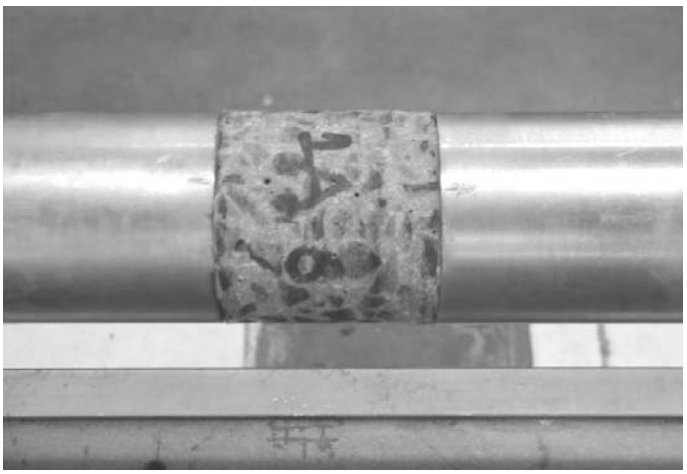

Figure 3. Interfaces between pressure bars and specimen.

The circular specimens are placed between the two long horizontally aligned pressure bars which serve as the medium for the propagation of elastic pulses as well as for measuring the stress-time history. Figure 3 and Figure 4.

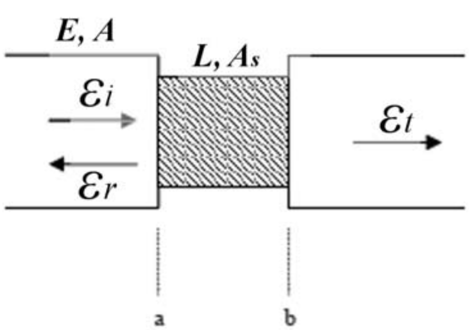

Figure 4. Strain gauge measured wave initiated strains in the SHPB setup. Interfaces at location a and b. Incident, reflected and transmitted, respectively.

2.2 *How to read the data*

A typical output from a SHPB test is shown in Figure 5.

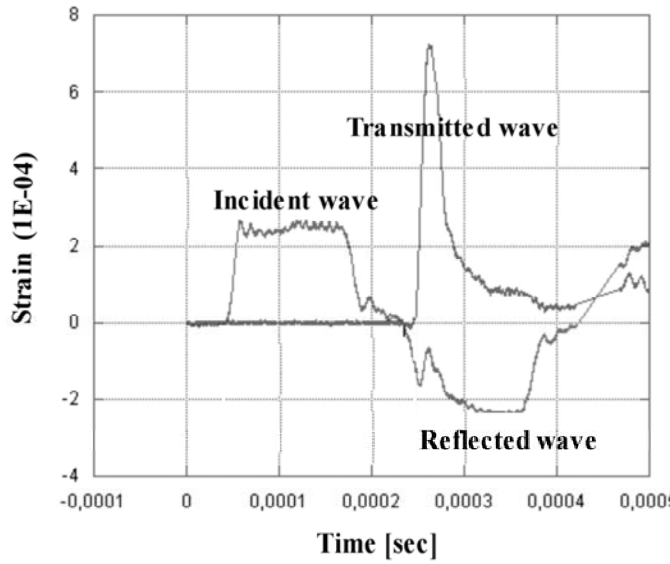

Figure 5. Output from SHPB test.

All three waves, $\varepsilon_i(t)$, $\varepsilon_r(t)$ and $\varepsilon_t(t)$, are measured at the gauge locations, situated at some distance away from the interface. Therefore, an appropriate time-shifting procedure must be undertaken to transfer the strain histories from the gauge locations to the interfaces Figure 6.

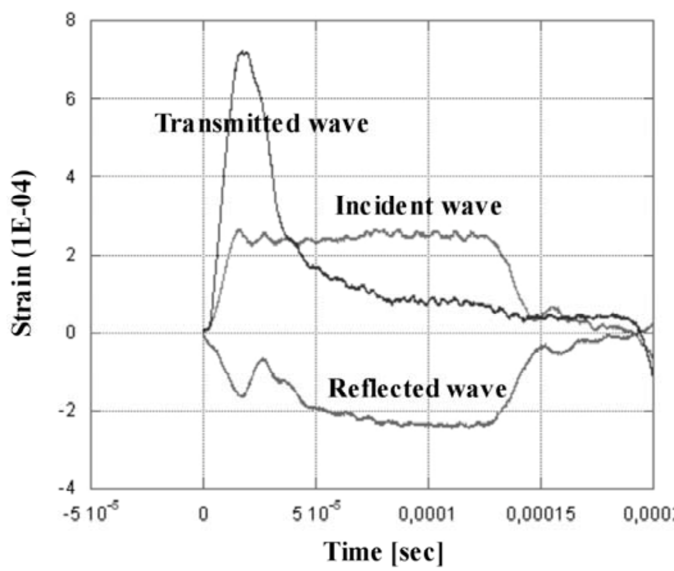

Figure 6. Time-shifted output from SHPB test.

To calculate the specimen stress and the dynamic increase factor, Hooke's law is used to determine the stress of the pressure bars from the measured strain values. Based on (Linholm and Bunshah, 1971) summery of SHPB technique following strain rate, strain and stress history with respect to time, can be calculated, respectively, as

$$\dot{\varepsilon}(t)=\frac{c_0}{L}\left[\varepsilon_i(t)-\varepsilon_r(t)-\varepsilon_t(t)\right] \quad (3)$$

$$\varepsilon(t)=\frac{c_0}{L}\int_0^t\left[\varepsilon_i(t)-\varepsilon_r(t)-\varepsilon_t(t)\right]dt \quad (4)$$

$$\sigma(t)=\frac{AE}{2A_s}\left[\varepsilon_i(t)+\varepsilon_r(t)+\varepsilon_t(t)\right] \quad (5)$$

2.3 *Experimental program*

For obtaining dynamic increase factors (DIF) for HPC in a wide range of strain rates, two different Split Hopkinson Pressure Bars has been used in this test. A 50 mm SHPB for strain rates in the range of 100 sec^{-1} to 300 sec^{-1} and a 22 mm SHPB for strain rates in the range of 600 sec^{-1} to 700 sec^{-1}. Dimensions of specimen are shown in Table 1.

Table 1. Specimen dimension.

Test ID #	*Specimen diameter, D [mm]*	*Specimen length, L [mm]*	*L/D*	*Pressure bar diameter [mm]*
22	15	10	0.67	22
50	50	50	1.00	50

HPC specimens of two different strengths and 4 different mix proportions have been prepared for this test. The 50mm specimens for the 50mm SHPB were cored out of a 500 x 500 x 150mm slab. The 15 mm specimen for the 22 mm SHPB were cast in cylinders. All specimens were cured in water for 28 days at a temperature of 20^o C. The mix proportions for all tested HPC are shown in Table 2 and Table 3.

Table 2. Mix proportions for 15mm specimen (kg/m^3).

f_{cs} [MPa]	*Binder**	*Water*	*Bauxite [1-3mm]*	*Sand [1-3mm]*
100	1139	201	433	867
160	1163	193	1300	0

* Densit Binder (ready mix)

Table 3. Mix proportions for 50mm specimen (kg/m^3).

f_{cs} [MPa]	*Cement*	*Silica Fume*	*Silica Flower*	*Aggregate [8mm]*
100	500	50	0	1270
160	657	202	202	0

f_{cs} [MPa]	*Sand [1-3mm]*	*Water*	*Super plasticiser*
100	630	135	20
160	965	130	43

3 RESULTS

Results from the experimental investigation are presented in Table 4 and Figure 8. DIF indicates the dynamic increase factors in compression for the tested HPC.

Table 4. Experimental results.

Test ID	*f_{cs} [MPa]*	*Strain rate [1/sec]*	*f_{cd} [MPa]*	*DIF*
01-22	100	710*	336	3.36*
02-22	100	777*	322	3.22*
03-22	100	856*	335	3.35*
04-22	100	722*	340	3.40*
05-22	100	749*	340	3.40*
06-22	160	679*	354	2.36*
07-22	160	674*	338	2.25*
08-22	160	544*	408	2.33*
09-22	160	611*	409	2.34*
10-22	160	516*	433	2.47*
01-50	100	102	184	1.84
02-50	100	145	188	1.88
03-50	100	197	211	2.11
04-50	100	298	240	2.40
05-50	160	81	187	1.17
06-50	160	187	226	1.41
07-50	160	267	241	1.50

* Indicates an average has been used in the plot in Figure 8.

It can be seen that the compressive strength for the 100 MPa HPC increases to 340 MPa at a strain rate of approximately 700 sec^{-1} and the compressive strength for 160 MPa HPC increases to approximately 400 MPa at a strain rate of approximately 600 sec^{-1}.

Also in Figure 8 the dynamic increase factors from the constitutive CEB Model Code are presented for 100 MPa and 160 MPa, respectively. It can be observed that the CEB Model Code give matching results for the 100 MPa HPC but overestimates the dynamic strength enhancement for the 160 MPa HPC.

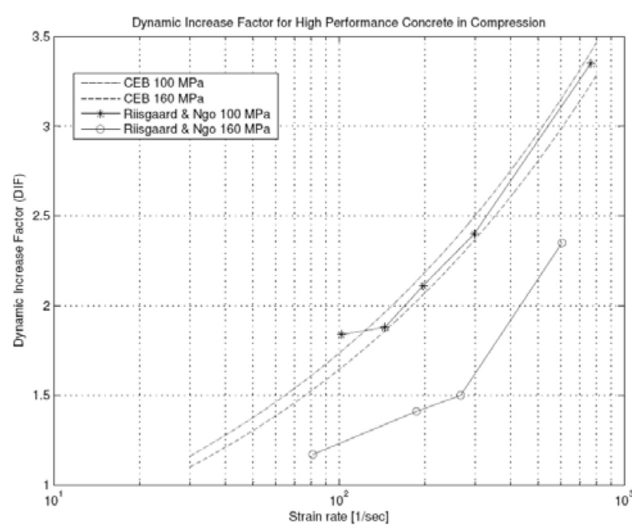

Figure 8. Plot of experimental results of the dynamic increase factors (DIF) compared with dynamic increase factors (DIF) derived from the CEB concrete model.

4 DISCUSSION

The physical mechanisms about the strength enhancement for concrete have yet not been fully understood. At least two factors, the viscoelastic character of the hardened concrete and the time-dependent micro-crack growth, may contribute to macroscopic strain rate dependent strength enhancement.

The fact that concrete and concrete like materials are hydrostatic dependent could also cause the dynamic strength enhancement seen using the SHPB device. In the SHPB test lateral confinement could wrongly be initiated from both the contact surface and the lateral inertia during the impact and because of hydrostatic dependency lead to incorrect dynamic increase factors.

As expected the dynamic strength increases with increase in strain rate. Also, as expected, the 160 MPa HPC is less sensitive to high strain rate loading than the 100 MPa HPC. A literature study revealed that no SHPB tests had earlier been conducted on concrete with strength over 100 MPa. Also revealed by that study, is that no constitutive models had been proposed for deriving the dynamic increase factor for concrete over 100 MPa. The presented results was compared with an existing constitutive model for dynamic strength enhancement, and indicates that existing constitutive models only are usable for compressive strengths up to 100 MPa.

Although this programme is based on a limited number of tests only, it is recommended that new constitutive models for deriving dynamic strength enhancement for HPC are developed. In addition extra SHPB tests and special setup will be required to determine the dynamic tensile strength of HPC.

5 CONCLUSION

An experimental investigation of the dynamic behaviour of High Performance Concretes (HPC) has been conducted using two different Split Hopkinson Pressure Bar devices. The statically compressive strengths of the tested HPC are 100 MPa and 160 MPa, respectively. The specimen has been tested at strain rates in the range of 100 sec^{-1} to 700 sec^{-1}.

The dynamic increase factor (DIF) for compressive strength due to strain rate effects is between 1.84 and 3.40 for 100 MPa HPC, and between 1.17 and 2.47 for 160 MPa HPC, respectively.

Comparing the results with the constitutive CEB Model Code shows accordance for the 100 MPa HPC but only accordance in a very slight extent for the 160 MPa HPC.

It is recommended that new and more accurate constitutive models for deriving dynamic strength enhancement for HPC are developed.

6 NOTATION AND REFERENCES

The following symbols and equations are used in this paper:

A = cross-section area of pressure bar
A_s = cross-section area of specimen
D = specimen diameter
E = Young's modulus of pressure bar
L = length of specimen
c_0 = wave velocity in pressure bar
f_{cd} = dynamic compressive strength
f_{cs} = static compressive strength
f_{ts} = static tensile strength
f_{cd}/ f_{cs} = compressive DIF
f_{td}/ f_{ts} = tensile DIF
f'_{co} = 10 MPa
t = time
ε = strain
$\dot{\varepsilon}$ = strain rate (dynamic)
$\dot{\varepsilon}_s$ = strain rate (static)
$\log \gamma = 6.156\,\alpha - 2$
$\alpha = 1/(5+9\, f_{cs} / f'_{co})$

REFERENCES

Bischoff, P. H. and Perry, S. H. Compression behaviour of concrete at high strain-rates. Materials and Structures [24], 425-450. 1991.

Comite Euro-International du Beton - Federation Internationale de la Precontrainte. CEB-FIP Model Code 90 Redwood Books, Trowbridge, Wiltshire, Great Britain. 1990.

Grote, D. L., Park, S. W., and Zhou, M. Dynamic behavior of concrete at high strain rates and pressures: I. experimental characterization. International Journal of Impact Engineering 25[9], 869-886. 2001.

Li, Q. M. and Meng, H. About the dynamic strength enhancement of concrete-like materials in a split Hopkinson pressure bar test. International Journal of Solids and Structures 40[2], 343-360. 2003.

Linholm, U. S. and Bunshah, R. F. High strain rate tests - Measurement of mechanical properties. Interscience, New York 5, 199-216. 1971.

Lok, T. S. and Zhao, P. J., 2004, Impact response of steel fiber-reinforced concrete using a split Hopkinson pressure bar: Journal of Materials in Civil Engineering, v. 16, p. 54-59.

Malvar, L. J. and Ross, C. A., 1998, Review of strain rate effects for concrete in tension: Aci Materials Journal, v. 95, p. 735-739.