Compressive Behaviour of Plain Concrete at Higher Strain-Rates

George Solomos[1], and Mario Berra[2]

[1]*European Commission, Joint Research Centre, Ispra (VA), 21020 Italy*
email: george.solomos@jrc.it
[2]*CESI, Via Rubattino 54, Milan, 20134 Italy*

1. SUMMARY

The compressive dynamic behaviour of normal concrete has been experimentally investigated. Two concrete grades (C25/30, C50/60) have been examined using 100mm cubic specimens with a maximum aggregate size of 16mm. Three testing conditions, i.e., static, intermediate strain-rate and higher strain-rate, have been implemented. For the faster velocities of deformation, Hopkinson bar techniques have been employed. The entire stress-strain curve, including its softening branch, is being constructed. The results clearly show that concrete exhibits strong sensitivity to strain-rate.

2. INTRODUCTION

The knowledge of the influence of increased loading rate on the true stress-strain diagram of concrete and steel is of fundamental importance for assessing the resistance of reinforced concrete structures to accidental loadings, such as those occurring in impacts, explosions, blasts or near field effects of strong earthquakes. Attention in this paper is focused on concrete.

Reviews of the properties of concrete in both tension and compression under dynamic loading can be found in /1-3/. The effect of strain rate on the concrete compressive and tensile strengths is customarily reported as a dynamic increase factor (DIF) – i.e. the ratio of dynamic to static strength – versus strain rate. Such a graph is usually presented on a semi-log or log-log scale. This is a convenient format for implementation into numerical models, as it can provide for failure criteria.

For high loading rates the Hopkinson bar technique is widely used to determine the mechanical properties of structural materials. Standard Hopkinson bars with a diameter in the range of 10mm to 20mm are sufficient for dynamic testing of fine-grained materials, such as steel. However, much bigger bars are needed to load representative volumes of plain concrete specimens with real size aggregates, which can exceed the size of 25mm. An in-house made big Hopkinson bar apparatus is described below.

Thus the objective of this investigation is to test under dynamic compression plain concrete with real size aggregates, and apart from determining the DIF, to capture and construct the entire stress-strain curve under these conditions. Some results on tensile properties under dynamic testing have been reported elsewhere /4/.

The strain-rate ranges envisaged in this work are as follows: quasi-static testing $10^{-7}/s < \dot{\varepsilon} < 10^{-3}/s$, dynamic testing at intermediate strain rates $10^{-3}/s < \dot{\varepsilon} \le 10^{0}/s$, and dynamic testing at higher strain rates $10^{0}/s \le \dot{\varepsilon} < 10^{2}/s$.

3. SPECIMEN PREPARATION AND TESTING

Two concrete grades have been used: C25/30 and C50/60. A maximum aggregate size of 16mm has been chosen, and cubic specimens of size 100mm have been selected. In this manner the specimen dimensions are at least five times the aggregate maximum dimension, which is the accepted rule for obtaining homogenized straining conditions during testing.

The detailed specifications for the construction of the specimens are reported in Table 1 below, and the main properties of the 28-day hardened concretes, as resulted from the quality control procedure based on 70

Table 1

Concrete compositions.

Components	**C25/30**		**C50/60**	
	kg/m³		*kg/m³*	
Cement CEM II/A-L 42.5 R	**300**		**450**	
Limestone aggregate of Zandobbio	**1910**		**1830**	
0-1 mm	30%	573	30%	549
1-3 mm	10%	191	10%	183
2-5 mm	10%	191	10%	183
3-8 mm	10%	191	10%	183
6-12 mm	15%	286.5	15%	274.5
8-16 mm	25%	477.5	25%	457.5
Water	**195**		**171**	
Water/cement ratio	0.65		0.38	
Superplasticizer (Mapefluid X404)	**1.50**		**6.75**	
Theoretical concrete density	**2406.5**		**2457.75**	

specimens, are summarised in Table 2. The specifications further included: minimum 7-day wet cure; minimum 4-week/ maximum 6-week dry time to testing (dryness condition).

The static compressive tests were carried out on the 10cm cubic specimens, under displacement control. The applied rate was of 0.1 μm/s in the ascending branch of the stress-strain curve and of 0.5 μm/s in the descending branch. The strain rates obtained were of the order of 10^{-6}/sec. The test was controlled through the displacements recorded by inductive transducers, while the data given by the strain gauges, mounted to the specimen, were used to better reproduce the ascending branch of the curve and to calculate the Poisson Coefficient.

The higher strain rate tests were carried out with the same type of specimens. The strain rates achieved were approximately 10^{-3}/sec and 10/sec. The softening branch was also captured and included in the curves. All tests were performed on a single machine, which can be operated in a quasi-static fashion or as a modified split Hopkinson bar for real dynamic testing.

The principle of operation of the modified Hopkinson bar version of the device is shown schematically in Figure 1. The machine consists of two half-bars, the incident and transmitter bar respectively, with the specimen introduced in between. Elastic energy is stored in a pre-tensioned bar, which is the solid continuation of the incident bar. By releasing this energy (rupturing the brittle intermediate piece at the far left), a rectangular compressive wave with small rise-time is generated and transmitted along the incident bar loading the specimen to failure. This is a uniaxial elastic plane stress wave, as the wave-length of the pulse is long compared to the bar transverse dimensions, and the pulse amplitude does not exceed the yield strength of the bar.

Table 2

Some quality control data of hardened concrete at 28 days.

Properties	C25/30	C50/60
Density	2421 ± 6 kg/m^3	2491 ± 8 kg/m^3
Cube Compressive Strength (10cm)	36 ± 1 MPa	68 ± 1 MPa
Cylinder Compr. Strength (∅10-H 20cm)	30 ± 2 MPa	60 ± 1 MPa
Elastic Modulus E (∅10-H20cm cylinders)	31820 ± 2070 MPa	35290 ± 1560 MPa

The average values of the hardened concretes are based on 3÷4 specimens.

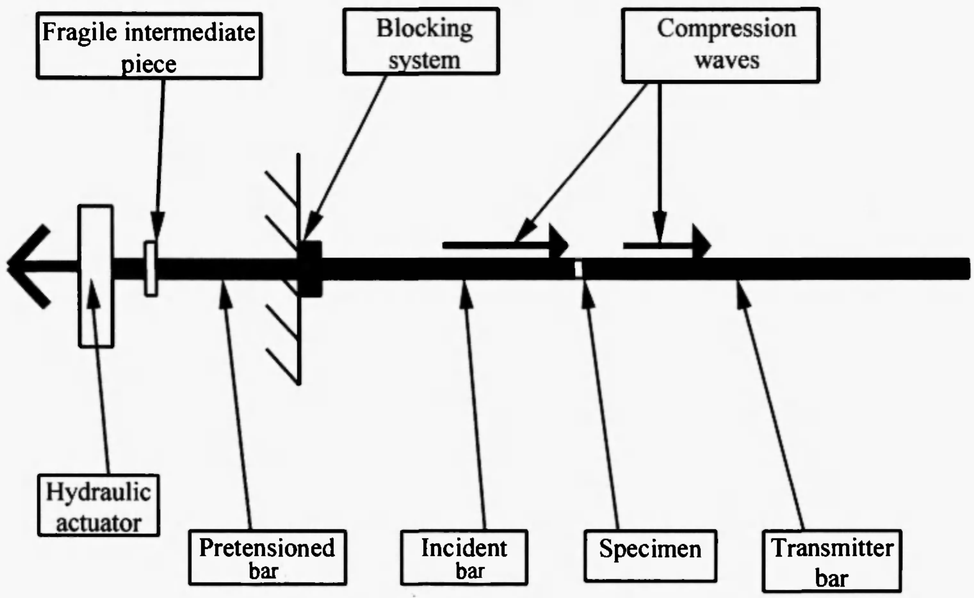

Fig. 1: The JRC-Ispra modified compression Hopkinson bar.

Fig. 2: Picture with details of the experimental set-up; the 10cm-cube specimen is in this case equipped with 6cm-long strain-gauge; a thin layer of grease is applied on the contact surfaces between concrete and aluminium.

The pulse propagates along the incident bar with the velocity C_o of the elastic wave with its shape remaining constant /5/. When the incident pulse (ε_I) reaches the specimen, part of it (ε_R) is reflected by the specimen whereas another part (ε_T) passes through the specimen propagating into the transmitter bar. The relative amplitudes of the incident, reflected and transmitted pulses, depend on the mechanical properties of the specimen. Strain gauges mounted on the incident and transmitter bars of the device are used for the measurement of the elastic deformation (as a function of time) created on both half-bars by the incident/reflected and transmitted pulses, respectively. Using the theory of elastic wave propagation in bars, and the well substantiated assumption of specimen equilibrium attainment, the engineering stress σ_E, strain rate $\dot{\varepsilon}_E$, and strain ε_E of the specimen can be calculated:

$$\sigma_E(t) = E_b\, \varepsilon_T(t)\, \frac{A_b}{A_o}\ , \qquad \dot{\varepsilon}_E(t) = \frac{2C_o}{L_c}\varepsilon_R(t)\ , \qquad \varepsilon_E(t) = \frac{2C_o}{L_c}\int_0^t \varepsilon_R(z)dz \tag{1}$$

where, L_c = length of the specimen, A_b = cross-sectional area of output and input bars, A_o = initial cross-sectional area of the specimen, E_b = elastic modulus of the bars, $C_o = (E_b/\rho)^{1/2}$ the bar elastic wave speed, ρ = bar density. Stress-strain diagrams obtained with the different dynamic experimental set-ups are re-adjusted by imposing a correct Young modulus /5/, which in the current case is the static Young modulus value.

This prototype machine has a total length of approximately 7m. The concrete specimen, instrumented or not with strain gauges, is sandwiched between the incident and transmitter bars, which are prismatic, made of aluminium and of dimensions 20x20x200cm, as shown in Figure 2. Aluminium is chosen because in this way the acoustical impedance ρCA of the bars (ρ = density, C = bar elastic wave speed, A = cross-sectional area) can be brought closer to that of the concrete specimen.

4. TEST RESULTS

The detailed results of the static compression tests of Normal Concretes at all strain rates are reported in the final report of the ANCHR project. For each test a suit of curves are included: Stress-time and strain rate-time, Load-displacement, and Stress-strain. From these curves some basic parameters have also been calculated, such as: Compressive strength, Strain at the maximum stress, Elastic modulus, Poisson Coefficient.

Table 3

Dynamic strength test results for several strain rates and computed D.I.F

COMPRESSIVE STRENGTH (MPa)						
Concrete type	**C25/30**	**C50/60**	**C25/30**	**C50/60**	**C25/30**	**C50/60**
Strain rate (/sec)	1.0E-06	1.0E-06	1.0E-03	1.0E-03	10	10
Mean cube strength	35.0	61.0	52.7	95.7	71.7	119.9
Computed **D.I.F.**	1.00	1.00	1.51	1.57	2.05	1.97

Reduced values of test compressive strength are shown in Table 3. The strain rates are average values of the test series. In the same Table an experimental dynamic increase factor is calculated - the ratio between average experimental material strengths corresponding to dynamic and quasi-static loadings.

The stress-strain curves from the dynamic testing together with a typical static curve are shown in Figures 3 and 4. It is clarified that for the dynamic tests the sampling-rate in the data acquisition system has been set to 10^6 points per second. This has allowed for the softening branch of the stress-strain diagram to be fully captured and included in the curves. However, this has not been the case for the medium strain-rate tests, where a much lower sampling-rate has been used, and thus the softening branch of the curves is abruptly terminated. The results of Table 3 are plotted in Figure 5 on a logarithmic scale showing the increase of compressive strength as a function of the strain rates applied.

5. CONCLUDING REMARKS

As clearly observed in Figure 5, the velocity of deformation during testing has a significant effect on the compressive strength of the concrete grades examined. The values of this strength are almost doubled at strain rates of ~10/sec with respect to the corresponding values at strain rates of 10^{-6}/sec. The relationship between the DIF and the logarithm of the applied strain rate is close to linear in this range. Lower grade concretes seem to exhibit a higher sensitivity to the increasing strain rate. Further, the ductility and energy absorption capacity of these concretes show improved behaviour under dynamic monotonic loading.

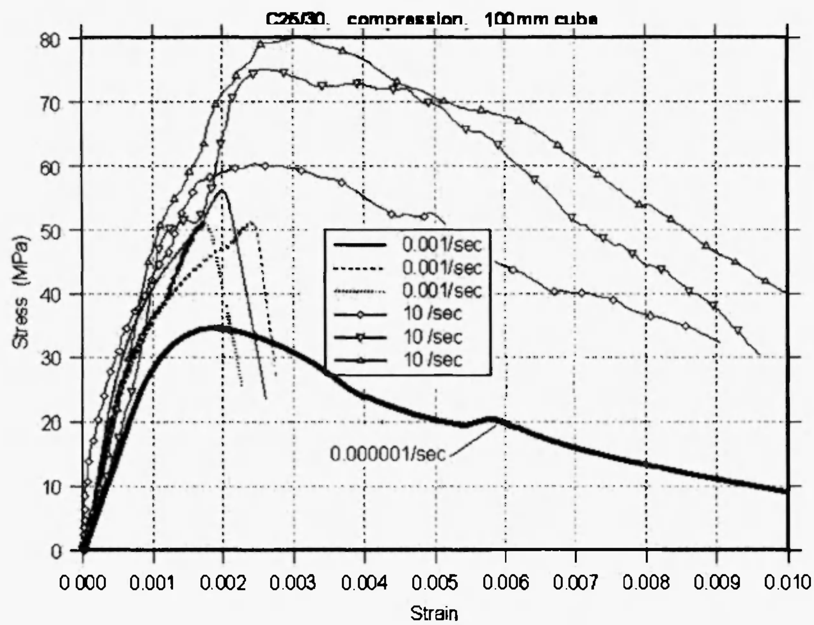

Fig. 3: Compression stress-strain curves of C25/30 under static and dynamic loading conditions.

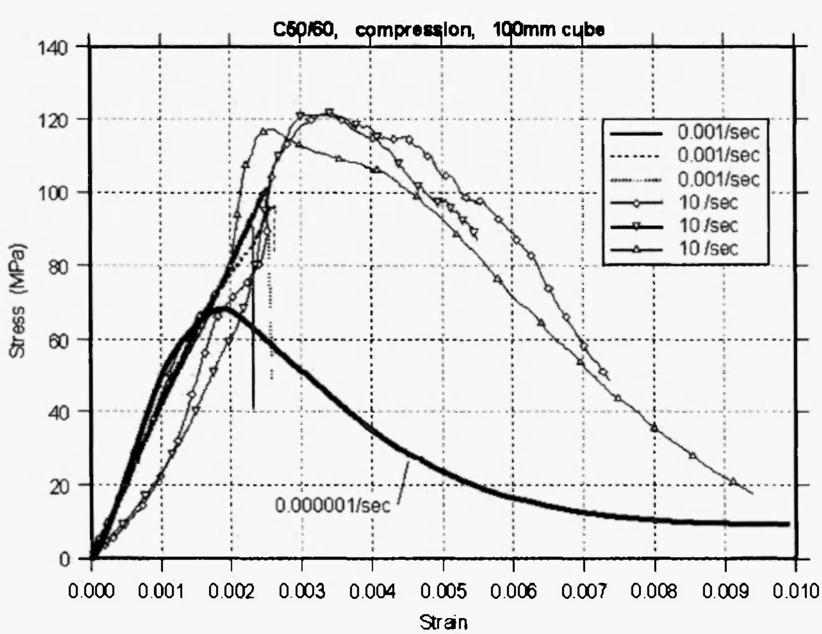

Fig. 4: Compression stress-strain curves of C50/60 under static and dynamic loading conditions.

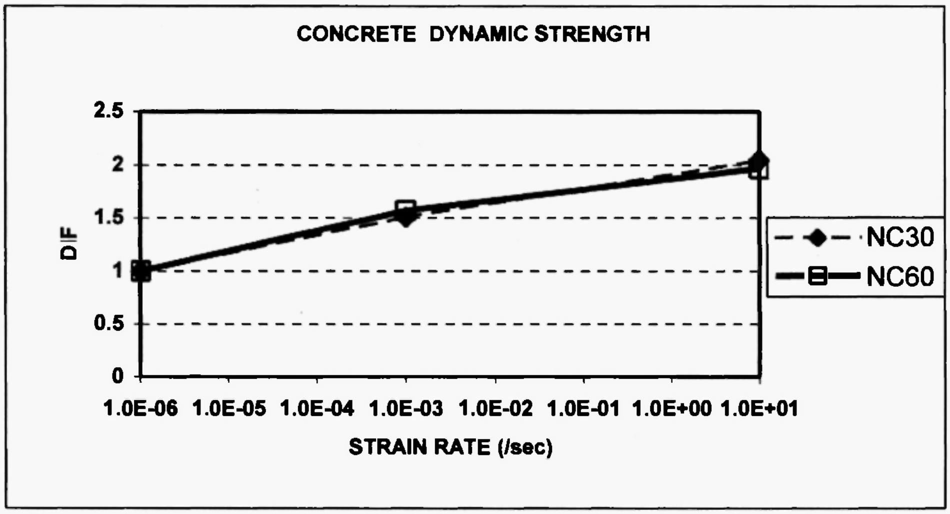

Fig. 5: Experimentally determined dynamic increase factor vs. Logarithm of strain rate for normal concrete under compression (100mm cubes).

These results confirm other investigations and extend their validity to the case of more realistic concrete cases, i.e. of maximum aggregate size of 16mm and testing with 100mm cubic specimens. This latter ensures that the strong size effects on concrete strength are minimized. Additional experimental work would help for a better quantification of the trends observed. However, the present investigation has shown that reliable and reproducible results concerning the dynamic compressive behavior of concrete can be obtained by properly employing Hopkinson bar testing techniques

ACKNOWLEDGEMENTS:

This activity has been performed within the EU funded Brite-EuRam project ANCHR (BRPR-CT97-0549) "Anchorages in normal and high performance concretes subjected to medium and high strain rates". The partners of the consortium were: DENSIT a/s (DK), HILTI (LI), JRC/ISIS, ENEL-CRIS (IT), Politecnico di Milano (IT), University of Patras (GR), Bekaert (BE).

6. REFERENCES

1. D.L. Grote, S.W. Park and M. Zhou, "Dynamic behavior of concrete at high strain rates and pressures: I, experimental characterization", *Int. J. Impact Engng*, **25**, 869-886 (2001).
2. P.H. Bischoff and S.H. Perry, "Compressive behavior of concrete at high strain rates," *Materials and*

Structures, **24**, 425-450 (1991).

3. L.J. Malvar and J.E. Crawford, "Dynamic increase factors for concrete", *Proceedings 28th DDESB Seminar*, Orlando FL, August 1998.
4. E. Cadoni, C. Albertini, K. Labibes and G. Solomos, "Behavior of plain concrete subjected to tensile loading at high strain-rate", *Proceedings FraMCos-4*, Paris, May 28-June 1, 2001.
5. U.S. Lindholm, "High strain rate tests", in: *Techniques of Metals Research*, Vol. V, Part 1, R.F. Bunsmah (Ed.), J. Wiley & Sons, 1971.