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Dynamic Characterization of Concrete using Split Hopkinson Pressure Bar

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Abstract

Concrete exhibits brittle behaviour and is weak under tensile and flexural loading. The response of concrete to dynamic loading is of interest in a variety of civilian and military applications. Understanding the response of concrete to impact or explosive loading is important for effective protection of defence and civil structures. The split Hopkinson pressure bar (SHPB) technique has been used widely to measure the dynamic strength enhancement of materials at high strain rates. Although, SHPB technique has been verified for metallic materials, but validity and accuracy of SHPB results for non-metallic, e.g. concrete materials have not been thoroughly studied so far. The present study examines the application of SHPB to determine the dynamic strength of concrete under compressive loading. The aim of this study is to understand the strain rate effect on the ultimate uniaxial compressive strength of concrete in SHPB tests for two different grades of concrete. The behaviour of concrete at strain rates of the order of 200 - 600 per second and pressures up to 0.38 MPa are studied experimentally. The strength of concrete is found to be increased with the increase in strain rates. Further, it is observed that due to the composite microstructure of concrete, deformation and stresses are non-uniform in the concrete specimens.

Keywords: SHPB, Plain cement concrete, dynamic increase factor

1. Introduction

In the present scenario, extreme loading conditions such as impact, projectile penetration, blast events have been so frequent that there is an urgent need to understand the behavior of the construction materials such as concrete under such circumstances. Some of these scenarios are (i) tunnel lining subjected to vehicular accident or blast, (ii) any possible projectile attack on nuclear power plant, (iii) airport concrete runways undergoing impact loading due to aircraft landing (iv) other military and important structures subjected to impact or blast load.

The impact mechanical properties of different structural materials such as concrete, rocks, metals, and rubber are experimentally investigated within range of strain rate of order 10^2 /s to 10^4 /s using SHPB setup. The fundamental principles behind this experimental analysis are one-dimensional stress wave propagation and stress equilibrium during the SHPB experiment. SHPB was first developed by Hopkinson (1914) and later on modified by Herbert Kolsky (1949) and it is then further extended with recent advances by Chen and Song [1].

In the literature, the impact properties of concrete under split Hopkinson pressure bar has been calculated [2]. It is found that concrete properties are varying with respect to strain rate effect. Enrichment in the compressive strength of the concrete was noticed. Bischoff and Perry [2] studied the effect of strain rate and reported a detailed description of brittle fractures in concrete under static as well as impact loading. A definite increase in compressive strength and elastic modulus was observed when the strain rate increased from 10^{-4} /s to 10^2 /s. It was reported that critical strain (strain at peak stress) may have negative or positive correlation with the rate of loading. Malvern et al. [3] carried out experiments with strain rate range of 80 /s to 500 /s for mortar and 5 /s to 120 /s for concrete specimens using SHPB. SHPB of larger diameter of 75 mm was used to take into account the effect of aggregate size on the dynamic strength of the concrete. Ahmad and shah [4] investigated the compressive behavior of hoop confined concrete under high strain rate of loading. Different parameters such as compressive strength of concrete mix, amount of lateral confinement, type of aggregates were varied in order to investigate their effect on its constitutive relation. Based on the experimental data, empirical equations were proposed to assess the strain rate effect on maximum compressive strength, critical strain and secant modulus of material.

Tedesco and Ross [5] conducted split tensile test on concrete specimens using 50.8 mm diameter SHPB with strain rate of order 10^2 /s. A high-speed camera was used to

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acquire the deformation and cracking information while fracturing in SHPB test. Finite element (FE) analysis was carried out and crack patterns were compared with those obtained from the experiments. Forquin et al. [6] carried out experiments using 80 mm diameter SHPB to investigate compressive behavior of MB50 grade of concrete confined with metal ring at three different strain rates of 80 /s, 141 /s, and 221 /s. A methodology was proposed to predict the hydrostatic and deviatoric behavior of the material. Li and Meng [7] investigated the effect of hydrostatic stress on dynamic compressive strength of concrete by simulating SHPB test using FE methods and concrete material by rate independent Drucker-Prager material model. Georgin and Reynouard [8] numerically simulated SHPB using FE model and concrete using viscoplastic hydrostatic pressure dependent material model to investigate structural effect, inertia effect and rate effect on the enhanced compressive strength of the concrete subjected to high strain rate conditions. It was found that decoupling of inertia effect from the rate effect was not feasible with the above-said material model. Zhou and Hao [9] investigated the effect of lateral inertia on *DIF* along with the material strain rate effect by considering two different numerical models. Both homogeneous macroscale model and heterogeneous mesoscale model were developed to compare the result with those obtained from the experiments. It was observed that lateral inertia effect was not pronounced up to the strain rate of 200 /s and it becomes substantially high for strain rate greater than 1000 /s. The results from mesoscale model demonstrated that the crack initiates always from the interfacial transition zone (ITZ). Hao and Hao [10] studied the effect of aggregate and ITZ on compressive strength at three strain rates 10 /s, 100 /s, and 1000 /s. Different volume fractions as 20 %, 30 % and 40 % of aggregate were considered in the mesoscale model of the concrete. It was noted that ITZ affects both static and dynamic strength of the concrete. It plays vital role in concrete failure at lower strain rates only and has negligible effect on DIF.

Lee and Meng [7] performed SHPB test on concrete and proposed that the the visco-elastic characteristics of the hardened cement matrix and time-dependent microcrack growth are the possible mechanisms behind the increase in compressive strength. Along with these material phenomenon, there are other structural effects associated with the SHPB experiments which also contribute in improvement of the compressive strength. Factors affecting structural effects include specimen geometry (diameter, slenderness ratio) and material parameters, such as density, strength, hydrostatic dependence, and dilation [11]. Along with these parameters, non-uniform distribution of stress and strain along the specimen length at the time of testing, stress wave propagation effects and limitation of one-dimensional wave propagation theory make the prediction of the dynamic behavior of the concrete much complex [2]. Lee et al. [12] proposed dynamic increase factor (*DIF*) due to pure strain rate effect excluding inertia effects by taking into account the strain acceleration and geometry of the specimens by conducting SHPB experiments and finite element analysis.

Thus, it may be revealed from the literature that the strength and energy absorbing capacity of the concrete during impact loading gets affected by its initial strength [13]. Thus, in order to predict the response of the structure to such a dynamic loading scenario, it becomes indispensable to understand the behavior of different grades of concrete at varying strain rate and it requires prediction of appropriate constitutive relation of the material at these high strain rates.

The basic aim of this study is to investigate the high strain rate characterization of two grade of concrete in terms of stress-strain curves. In the present work, dynamic increase factor which is defined as the ratio of dynamic strength of concrete to its static strength has been calculated. Based on the determined *DIF* values empirical correlation equations are proposed corresponding to strain rate produced.

2. Experimental Setup

Figure 1 shows the schematic diagram of the SHPB set up at the Geo-dyn laboratory, IIT Delhi. Split Hopkinson pressure bar or Kolsky apparatus comprises of three parts namely loading device, bar components and data acquisition and recording system. Loading device includes gas gun filled with air pressure, used for accelerating the striker bar. Striker bar is propelled through the gas gun at varying pressure to get different striker velocity. Bar components of SHPB includes incident bar, transmission bar and striker bar having diameter of 76 mm each. The length of incident and transmission bars is 3048 mm and made up of maraging steel with density 8244 kg/m3. In the compressive split Hopkinson pressure bar set up, the specimen is positioned between the incident and transmission bar. As the striker bar impacts on the incident bar with some velocity, compressive stress pulse is produced in the incident bar which travels through it and impinges on the specimen bar interface. At this interface some part of the stress pulse is reflected back into the incident bar known as reflected pulse and remaining part of the pulse travels through the specimen and transmitted into the transmission bar as transmission pulse. The incident and reflected pulse is measures by strain gage installed at the centre of the incident bar whereas transmitted stress pulse is measured by strain gage installed on the transmission bar. In the current study, copper pulse shaper is used at the impact end of the incident bar to increase the rise time of the incident pulse so as to attain stress equilibrium and constant strain rate deformation.

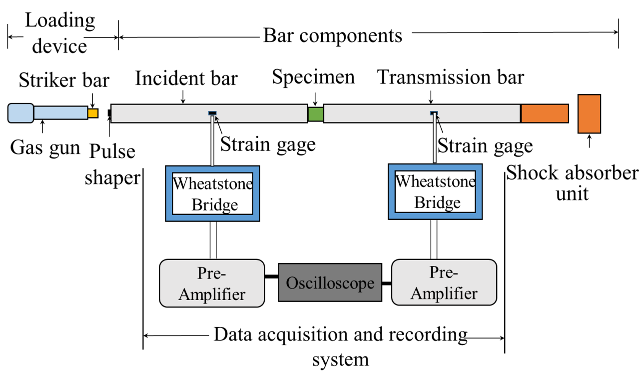

Fig. 1. Schematic diagram of split Hopkinson pressure bar

In the SHPB experiment based on one dimensional stress wave propagation and assumption of the stress equilibrium in the sample i. e. $\varepsilon_t = \varepsilon_i + \varepsilon_r$, strain, stress and strain rate history for the specimen can be determined from the following equations,

$$\varepsilon(t) = \frac{-2c_{bar}}{L_s} \int_0^t \varepsilon_r dt \qquad (1)$$

$$\sigma = \frac{A_{bar} E_{bar} \varepsilon_t}{A_{sp}} \qquad (2)$$

$$\dot{\varepsilon}(t) = \frac{2c_{bar}\varepsilon_r}{L} \qquad (3)$$

Where, ε_i, ε_r, and ε_t represent incident, reflected and transmitted strains, respectively.,
c_{bar} is the wave velocity which can be calculated using one dimension stress wave theory as, $c_{bar} = (E_{bar}/\rho_{bar})^{0.5}$. A_{bar} and A_{sp} are the cross-sectional areas of the bar and specimen, respectively.
E_{bar} is the elastic Young's modulus of the bar and $\dot{\varepsilon}$ is the loading strain rate of the tested specimen of length L.

3. Preparation of Concrete Specimens

In the present work, mix design for the characteristics compressive strength of 25 MPa and 30 MPa plain cement concrete are prepared as per IS 10262:2009 [14] which is summarised in Table 1. 43 grade Ordinary Portland cement, zone II sand and 10 mm aggregate are used in the preparation of the concrete mix. Table 1 shows the proportion of the ingredients used in the design mix of the concrete, slump and quasi-static compressive strength of the concrete. For quasi-static compressive test, cubes of 150 mm size are casted and for dynamic test, cylindrical specimen with 70 mm diameter and 140 mm length are casted. All cubical and cylindrical specimens are taken out of the moulds after 24 hours of casting and then placed in a water tank for 28 days curing. For SHPB test cylindrical specimens are further cut, ground and polished to obtain the slenderness ratio (L/D) of 0.5.

4. Dynamic Study

In the SHPB test, concrete specimens of M25 and M30 grades are prepared with 70 mm diameter and 0.5 slenderness ratio. Specimens are polished till the edges are perfectly parallel to each other. While fixing the specimen between the incident and transmission bar, high vacuum grease is applied on the both faces of the specimen which acts as a lubricant and helps to eliminate frictional effects. In the current experimental program striker velocity of 12 m/s - 19 m/s are applied on the incident bar and strain rate are observed in the range of 383 /s to 583 /s.
Figure 2 shows the waveform for M25 grade concrete obtained from SHPB test corresponding to 583 /s strain rate of the sample. This waveform is recorded by strain gages installed on the incident and transmission bar. Table 2 demonstrates the SHPB test results of the concrete samples in terms of strain rate, peak stress, strain at peak stress and dynamic increase factor.

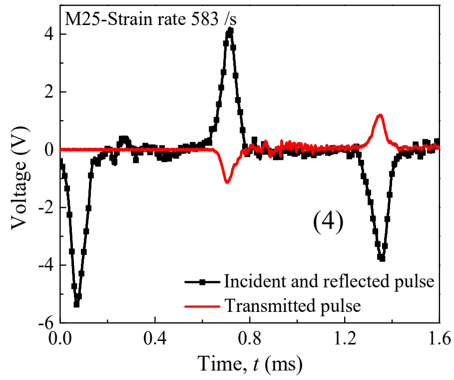

Fig. 2. Waveform for M25 grade concrete obtained from SHPB test.

Table - 1. Mix design and slump for M25 and M30 grades of concrete

Design mix	M25	M30
Design compressive strength f_{ck} (MPa)	31.60	38.25
Cement (% by weight)	25.26	27.85
Sand (% by weight)	29.34	24.39
Aggregate (% by weight)	34.04	36.62
Water (% by weight)	11.37	11.14
Slump (mm)	65	64
Average uniaxial compressive strength (MPa)	31.10	37.35

Table - 2. Dynamic properties of M25 and M30 grade concrete

Grade of concrete	V (m/s)	$\dot{\varepsilon}$ (/s)	σ_{dc} (MPa)	ε	*DIF*
M25	13.62	431	88.53	0.028	2.85
	14.73	467	91.08	0.02	2.93
	14.32	500	96.92	0.026	3.12
	19.41	583	97.99	0.025	3.15
	15.66	633	97.5	0.029	3.14
M30	12.45	383	83.4	0.027	2.23
	13.91	397	85.8	0.02	2.3
	15.29	423	108.07	0.023	2.89
	17.17	483	126.47	0.02	3.39

*V = Striker bar velocity, * $\dot{\varepsilon}$ = Maximum strain rate, *σ_{dc}= peak stress, *ε = Strain at peak stress, **DIF* = Dynamic increase factor.

Figure 3 represent constitutive relations for M25 grade concrete with slenderness ratios 0.5. The strain rate obtained for M25 grade concrete specimens is in the range of 431 /s – 633 /s and peak stress is noted for each strain rate in the range of 88 MPa – 97 MPa. The corresponding *DIF* is calculated and it ranges from 2.85 to 3.15.

For M30 grade concrete, stress-strain relations are depicted in Figure 4. The strain rate and peak stress ranges from 383 /s to 483 /s and 83 MPa – 126 MPa respectively. Here, corresponding *DIF* is calculated which ranges from 2.23 to 3.39.

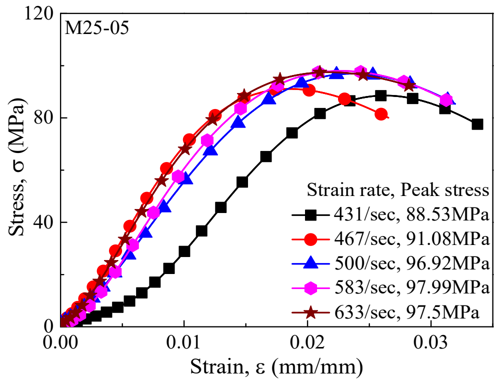

Fig. 3. Stress-strain response of M25 grade concrete

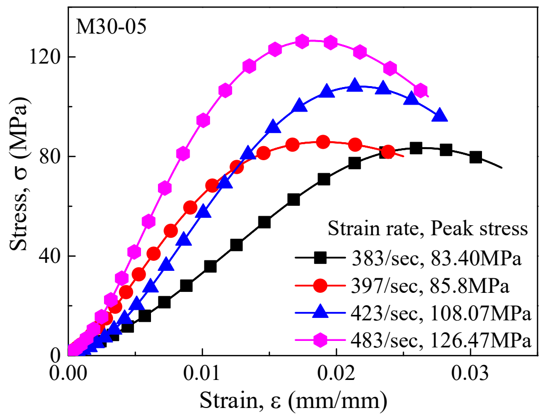

Fig. 4. Stress-strain response of M30 grade concrete

Figure 3 and Figure 4 emphasizes that peak stress of the concrete increases with increase in strain rate. Concrete is a strain rate sensitive material, however, the strain at peak stress does not follow any particular pattern.

From Table 2, it is also observed that striker bar velocity, strain rate and peak stress are showing dependent behaviour, as striker bar velocity increases, strain rate and corresponding peak stress of the concrete increases.

It is observed that for M25 concrete there is an increase in strength of concrete by 10 % for strain rate varying from 431 /s to 583 /s. Further no increase in peak stress of the concrete in noted for strain rate varying from 583 /s to 633 /s. Similarly, for M30 grade of concrete when strain rate ranges from 383 /s to 483 /s, dynamic compressive strength of the concrete increases by 51.64 %.

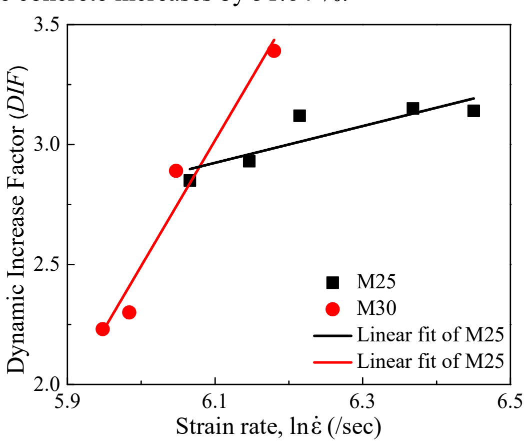

Fig. 5. Comparison of maximum dynamic increase factor corresponding to strain rate for different grades of concrete

In the present experimental study, the correlation equation has been recommended for M25 and M30 grade of concrete as shown in equations (4) and (5). These correlation equations have been fixed by the best fit of the curves obtained through the *DIF* values and logarithmic of strain rate for the strain rate range achieved through the experiments studies as shown in Figure 5.

$$(DIF)_{M25} = 0.76\ln\dot{\varepsilon} - 1.75 \quad \text{for } 431/\text{s} \le \dot{\varepsilon} \le 633/\text{s} \quad (4)$$

$$(DIF)_{M30} = 5.23\ln\dot{\varepsilon} - 28.91 \quad \text{for } 383/\text{s} \le \dot{\varepsilon} \le 483/\text{s} \quad (5)$$

5. Conclusions

In the present study, static and dynamic properties of plain cement concrete are investigated by using SHPB tests and a comparative analysis is performed for two different grades with slenderness ratios (L/D) of 0.5.

Based on this experimental investigation, following conclusions are arrived.

- The strain rate is in the range of 383 /s – 633 /s.
- The peak stress of the concrete increases with increase in strain rate for both grades of concrete.
- Dynamic increase factor (DIF) is also varies from 2.23 to 3.39 irrespectively to the grade of concrete.
- The dynamic properties of plain cement concrete like peak stress, strain at peak stress, etc. are increases with respect to the grade of concrete.
- The new correlation equation for the dynamic increase factor has been proposed for M25 and M30 grade of concrete with respect to the logarithmic of strain rates obtained in the present experimental study, which can be useful in the design of concrete structures subjected to impact load.

Disclosures

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