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Dynamic Increase Factor of High Strength Concrete with Silica Fume at High Strain Rate Loading

Koh Sin Long[1, a] Mudiono Kasmuri[1,b] Abu Sufian Zia Hasan[2,c] and Roszilah Hamid[1,d]

[1]Department of Civil and Structural Engineering,
Faculty of Engineering and Built Environment,
Universiti Kebangsaan Malaysia, 43600, UKM Bangi, Selangor DE, Malaysia

[2]Department of Civil Engineering,
Rajshahi University of Engineering and Technology, Rajshahi-6204, Bangladesh

[b]mudionoakasmuri@yahoo.com, [c]hasanzia2003@yahoo.co.uk, [d]roszilah@ukm.edu.my

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Abstract. The dynamic mechanical properties (stress-strain diagram, ultimate stress, ultimate strain and strain rate) and of high strength concrete (HSC) with 5% and 10% silica fume (SF) addition at high strain rate of 10 s^{-1} to 10^2 s^{-1} (3.8 MPa, 4.1 MPa and 4.8 MPa) are determined using Split Hopkinson Pressure Bar equipment. The compressive strength of the HSC at design strength of 80 and 90 MPa is also determined. Results show that the compressive strength of the 5%SF and 10%SF HSC are 83 MPa and 92 MPa, respectively. The dynamic stress-strain diagrams show that the higher the pressure load, the higher the values of ultimate dynamic stress, σ_u and the ultimate strain rate, $\dot{\varepsilon}_u$ for both percentages of SF addition concrete. The ultimate dynamic stress, σ_u are between 200 – 250 Mpa and the ultimate strain rate, $\dot{\varepsilon}_u$ is in the range of 95 s^{-1} and 160 s^{-1}. The ultimate dynamic strain, ε_u between 0.005-0.008 mm/mm. The dynamic increase factors (DIF) of the HSC are more than 2 compare to normal strength concrete.

Introduction

Dynamic axial compressive test with low lateral load at strain rate of 10 s^{-1} to 10^2 s^{-1} can be carried out using Split Hopkinson pressure bar (SHPB) system. The strain rate effect of concrete is an important factor in material structural design of structures when impact loadings are concerned. Because structures constructed using high strength HSC have become more common in recent years, additional studies are needed to establish the effect of strain rates on the performance of HPC [1].

In the past, the behaviour of concrete under static loading, creep, and shrinkage have been investigated. Similarly, structural dynamics methodologies are well understood, but are often difficult to apply to new materials and devices. Most of the material parameters of concrete are strain rate sensitive; therefore, a common strategy is to simply multiply their static values with an amplification factor. This factor is the ratio of dynamic value of a mechanical parameter over its static value, which is known as DIF. Therefore, DIF is the most significant parameter to measure the effect of strain rate on the strength of concrete.The CEB [2] formulation expresses the DIF as:

$$\mathrm{DIF} = \frac{f_d}{f_s} = \left[\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right]^{1.026\alpha}, \quad \text{for } \dot{\varepsilon} \le 30 \text{ s}^{-1} \tag{1}$$

$$\mathrm{DIF} = \gamma_s\left[\frac{\dot{\varepsilon}}{\dot{\varepsilon}_s}\right]^{\frac{1}{3}}, \quad \text{for } \dot{\varepsilon} > 30 \text{ s}^{-1} \tag{2}$$

where f_s and f_d are the static and dynamic compressive strength respectively, $\gamma_s = 10^{(6.15\alpha - 2.0)}$, $\alpha = 1/(5 + 9(f_s/f_o))$, $\dot{\varepsilon}_s = 30 \times 10^{-6}$ s^{-1} and $f_o = 10$ MPa. This formulation provides the DIF as a bilinear function of the strain rate on a logarithmic scale and presents a slope variation at 30 s^{-1}.

The following Tedesco & Ross [3] formulation expressed the DIF by considering the influence of different concrete strengths and moistures contents for a strain rate of around 10^2 s^{-1}. It shows the transition point (slope variation) from low rate sensitivity to high rate sensitivity at 63.1 s^{-1} as:

$$\mathrm{DIF} = 0.00965\log\dot{\varepsilon} + 1.058 \geq 1.0, \qquad \text{for } \dot{\varepsilon} \leq 63.1 \text{ s}^{-1} \tag{3}$$

$$\mathrm{DIF} = 0.758\log\dot{\varepsilon} - 0.289 \leq 2.5, \qquad \text{for } \dot{\varepsilon} > 63.1 \text{ s}^{-1} \tag{4}$$

Tang et al. [4] presented a formulation of DIF based on data from SHPB tests on high-strength concrete, which is expressed as:

$$\mathrm{DIF} = 1.155\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{0.12}, \qquad \text{for } 5 \leq \dot{\varepsilon} \leq 230 \text{ s}^{-1} \tag{5}$$

where the value of $\dot{\varepsilon}_0$ is 1 s^{-1}.

The enhancement of concrete stress under dynamic loads has directed great interest in the field of structural design and analysis. Significant numbers of investigations have been conducted to determine the dependency of DIF on strain rate using a variety of test methods, including drop impact, plate impact, SHPB, Gas gun, and explosive field tests. The results of these tests are scattered, in that they have all found different magnitudes of stress enhancement as a function of increased loading rate. These discrepancies primarily exist due to the large number of variables that affect the results, such as (i) the nature of experimental technique; (ii) the specimen size; (iii) the specimen geometry; (iv) the method of analysis; (v) material differences, such as concrete quality, concrete grade, curing, moisture condition, and age etc.; (vi) the end or boundary conditions [5-10]. Hence, the method of measurement significantly influences the strain rate sensitivity, particularly in the stress-strain relationship of concrete. Thus, the objective of the present study is to determine the stress-strain properties of HSC and its DIF under the application of high strain rate loads ranging from 95 s^{-1} and 160 s^{-1}.

Materials and experimental procedure

Materials

Cement. The ordinary Portland cement type I (OPC) from Tenggara Cement Manufacturing Co., Malaysia was used in this study.

Silica Fume. SF with brand name Force 10,000D is employed as addition of cement (5 and 10%) of OPC by mass of cement.

Aggregate. The local natural sand has a maximum aggregate size of 4.75 mm, and a fineness modulus of 2.89. The maximum size of the local coarse aggregate (crushed granite) is 20 mm; its specific gravity is 2.64 and water absorption is 0.48%. The fine aggregate has specific gravity of 2.61 and water absorption of 0.72%.

Details of mix proportions and preparation of specimens

The concrete composition of each cubic meter of concrete (used as basis) is given in Table 1. Silica fume was used as addition to Portland cement at 5% and 10% by mass of cement. The water to binder (W/B) ratio was kept at 0.5. A rotating pan mixer was used to mix the constituent materials for an overall mixing time of approximately 5 min in accordance with ASTM C192-2002. The mixtures were cast as specimens using 150 mm^3 standard cube moulds for compressive strength and 50 mm × 50 mm cylinders for dynamic compression strength. Then, the mixtures were compacted using a vibrating table in three layers and full compaction was made sure by observing the air bubbles on the surface. After casting, the moulded specimens were covered and left in the casting room at 26 C for 24 h until demoulding. Thereafter, all specimens were cured in a water tank and then tested at room temperature for 28 days of curing.

Table 1 Mix design proportion

Type of HSC	Coarse Aggregate (kg/m^3)	Fine Aggregate (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Silica Fume (kg/m^3)	w/c ratio
5%SF	918.51	751.50	466.66	233.33	0.4	0.5
10%SF	918.51	751.50	466.66	233.33	0.7	0.5

Testing

Static compressive strength. The compressive strength of the concrete was determined by crushing three 150 mm^3 sized cubes at ages of 28 days for each mix. The test was conducted according to BS EN 12390-3 using a compressive machine with a load capacity of 5000 kN.

Dynamic Properties. The dynamic stress-strain of each specimen was determined based on ASTM C-39 using SHPB technique. The split Hopkinson pressure bar (SHPB) system consists of a launch tube, a striker bar, a transmission bar, and the energy-absorbing parts. The energy source system contains air compressor and pressure vessel. The measurement system comprises velocity and dynamic strain indicator. The Young's modulus of the projectile, incident and transmission bar, is 210.0 GPa and the wave velocity of 5190 m/s. The schematic arrangement of SHPB system is shown in Figure 1 (all measurements are in mm).

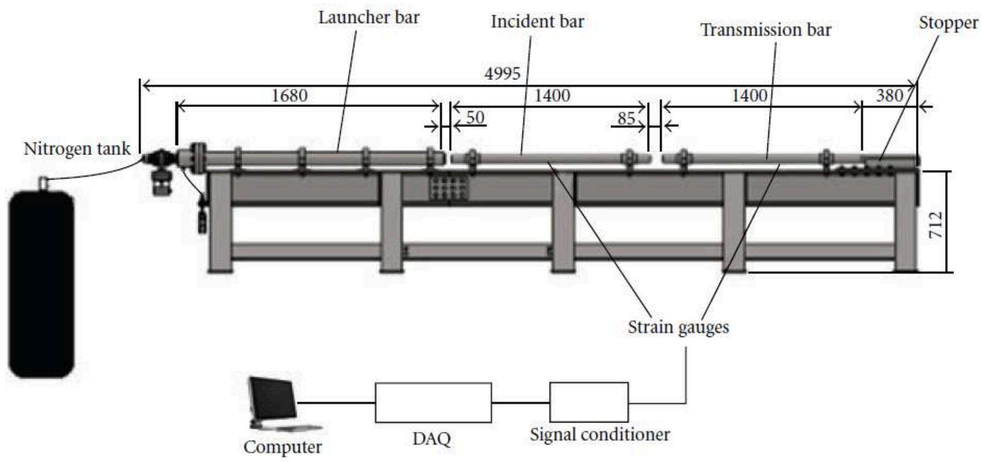


Figure 1 Schematic diagram of split Hopkinson pressure bar system (all measured distance in mm) [11].

Results and Discussion

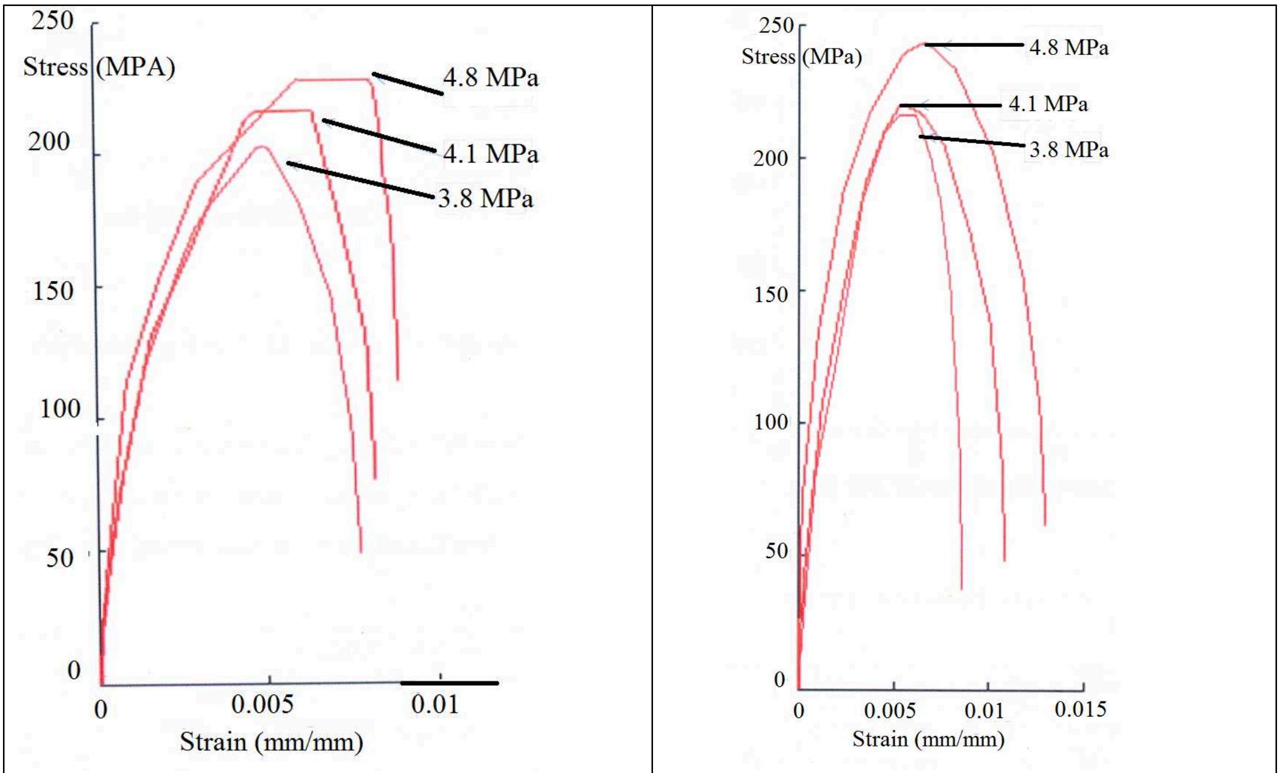
Static compressive strength

The static compressive strength of the 5%SF and 10%SF HSC at 28 days are 83 MPa and 92 MPa, respectively. The increase of silica fume content from 5% to 10% had only increase the strength to about 10 MPa. This is in line with previous research where addition/replacement of 5% SF is the limiting value to achieve twofold increase in strength, but addition beyond this limit only increase the strength minimally [12].

Dynamic Properties

Stress-strain diagram. The dynamic stress-strain diagrams of the HSC are as shown in Figure 2a) and c). Figure 2b) and d) show the strain rates in the specimens. Figure 2a) and c) show that the specimen were tested at three different pressure load i.e. 3.8 MPa (550 psi), 4.1 MPa (600 psi) and 4.8 MPa (700 psi). The ultimate dynamic stress, σ_u and the ultimate strain rate, $\dot{\varepsilon}_u$ are shown in Table 2. Figure 1 and Table 2 show that the higher the pressure load, the higher the values of ultimate dynamic stress, σ_u, ultimate dynamic strain, ε_u and the ultimate strain rate, $\dot{\varepsilon}_u$ for both percentages of SF addition concrete. The ultimate dynamic stress, σ_u are between 200 – 250 MPa, the ultimate dynamic strain, ε_u between 0.005-0.008 mm/mm and the ultimate strain rate, $\dot{\varepsilon}_u$ is in the range of 95 s^{-1} and 160 s^{-1}. The dynamic stress increases with increase in strain rate. At strength 100 MPa [13] and lower, the dynamic stress is sensitive to strain rate, but if strength achieved more than 100 MPa, it is less sensitive to high strain rate loading [13].

Dynamic Increase Factor (DIF). Both compressive strength and strain increase with increasing strain rates. Table 3 shows the DIF of all specimens. The higher the strain rate, the higher the DIF values. The maximum dynamic axial stress is 247.5 MPa for HSC with static compressive strength of 92 MPa. This increase in stress is caused by the loading rate. It can be seen that the DIF increase with increase in strain rate at the same static strength, which also agree with results from Riisgaard et al, 2007 [13].



a) b)

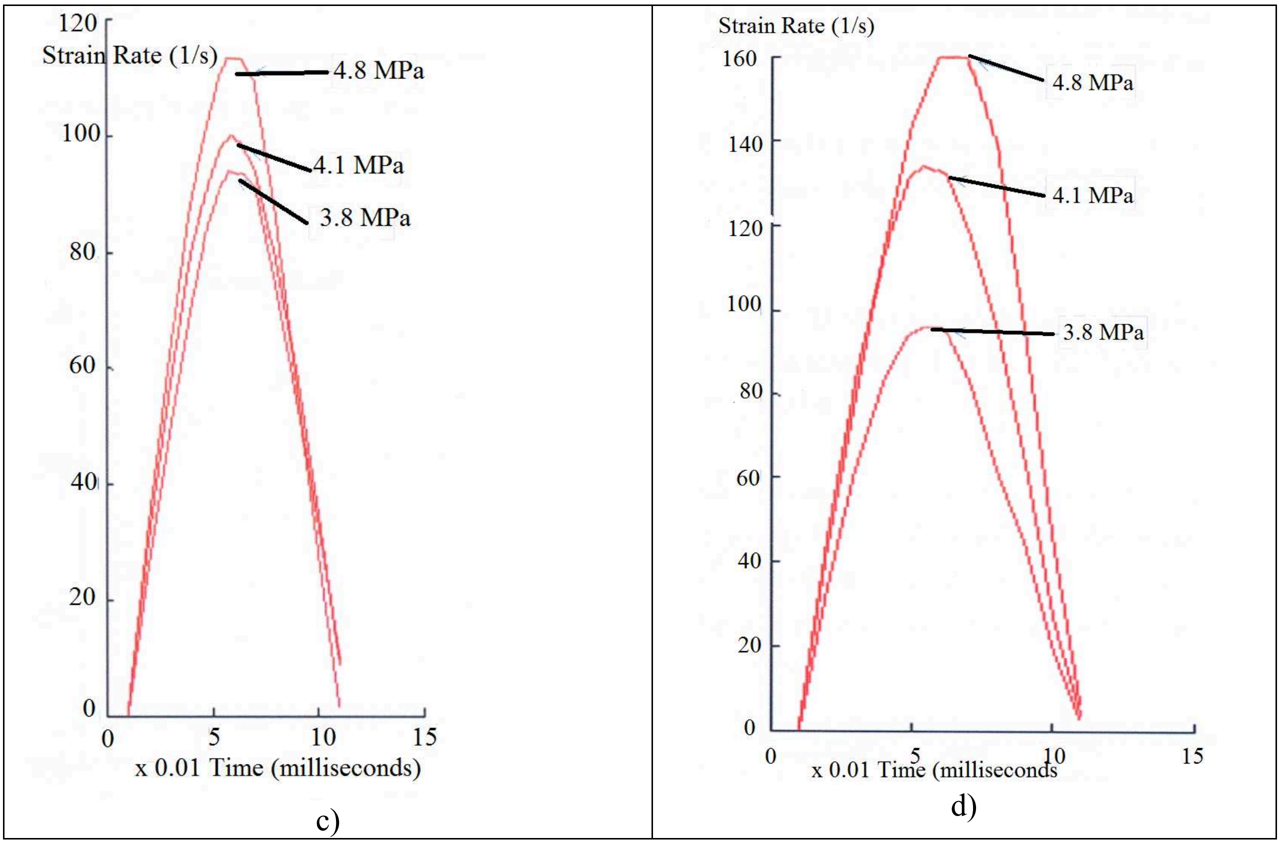


Figure 2 Stress-strain diagram of HSC a) 5%SF and b) 10%SF and strain rate in the specimen c) 5%SF and d) 10%SF

Table 2 The ultimate dynamic stress, σ_u, dynamic strain, ε_u and strain rate, $\dot{\varepsilon}_u$

Type of HSC		Loaded Pressure (MPa) (psi)		
		3.8 (550)	4.1 (600)	4.8 (700)
5%SF	ultimate dynamic stress, σ_u (MPa)	206.8	216.9	227.7
	ultimate dynamic strain, ε_u (mm/mm)	0.005	0.006	0.008
	ultimate strain rate, $\dot{\varepsilon}_u$ (s^{-1})	95.2	101.8	115.2
10%SF	ultimate dynamic stress, σ_u (MPa)	215.9	221.9	247.5
	ultimate dynamic strain, ε_u (mm/mm)	0.006	0.006	0.007
	ultimate strain rate, $\dot{\varepsilon}_u$ (s^{-1})	96.4	135.0	159.7

Table 3 Dynamic increase factor (DIF)

Static compressive strength (MPa)	**Dynamic stress (MPa)**	**Strain rate (s-1)**	**Dynamic increase factor (DIF)**
83	206.8	95.2	2.5
	216.9	101.8	2.6
	227.7	115.2	2.7
92	215.9	96.4	2.3
	221.9	135.0	2.4
	247.5	159.7	2.7
Riisgaard et al., (2007) [13] 100	184	102	1.84
	188	145	1.88
	211	197	2.11

Conclusion

The trend of the stress-strain indicates that HSC failure was primarily accelerated by large deformations. The dynamic stress increases with increase in strain rate. In addition, the behaviour of HSC under high rates of loading is more brittle in nature. At this rate of loading, the stress corresponding to compressive strength was found to be up to 2.7 times higher than the static loading.

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