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A Study on the Compressive to Tensile Dynamic Strength Ratio of Synthetic Sandstone Rock under Varying Loading Conditions

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Abstract

Natural rocks are inherently variable in terms of their composition, texture, and mechanical properties due to the geological processes. This variability can make it challenging to obtain consistent and repeatable results, especially in experiments replicating dynamic loading conditions. Synthetic rocks, on the other hand, can be manufactured with controlled properties such as density, strength, and elastic modulus, ensuring more uniform and predictable behavior during testing. Moreover, synthetic rocks provide the ability to produce multiple identical specimens, allowing to perform repeated tests under the same conditions. This reproducibility is important for validating experimental findings and comparing results across different studies. The key objectives of this study include the dynamic mechanical response and failure patterns in synthetic sandstone rock specimens under dynamic compressive and indirect tensile loading conditions using a split Hopkinson pressure bar (SHPB) device. The experimental study uses a cylindrical specimen with a diameter of 48 mm and a slenderness ratio of 0.5 which is subjected to both axial and diametral loading along the bars to replicate dynamic compressive and indirect tensile loading conditions. The SHPB setup in the present study uses a striker bar length (L_{st}) of 300 mm which is propelled at varying gas gun pressures (P_g) of 0.15 MPa, 0.25 MPa, 0.35 MPa and 0.45 MPa which creates varying impact velocities (V_{st}) of 12.74 m/s, 15.33 m/s, 18.92 m/s and 21.23 m/s, respectively. These impact velocities produce a wide range of dynamic increase factors (*DIF*) and strain rates ($\dot{\varepsilon}$) from the synthetic sandstone specimens. The experimental results obtained from the SHPB tests are systematically analyzed, compared, and meticulously reported in this study highlighting the ratio of compressive to tensile dynamic strength of the specific synthetic sandstone rock.

Keywords

Dynamic characterization, Dynamic compressive strength, Dynamic tensile strength, High strain rate loading, SHPB, Synthetic sandstone.

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1 Introduction

Mechanical properties of rocks such as compressive strength and tensile strength, are fundamental parameters in the design, construction, and stability assessment of underground structures namely tunnels, mines, nuclear waste repositories and military bunkers. These properties govern how a rock mass responds to the stresses induced by excavation and external loading, influencing both short-term and long-term stability of a structure. Furthermore, in dynamic scenarios such as blast loads, earthquakes, and high-velocity impacts, the strength parameters of rocks may deviate significantly compared to the static loading due to strain-rate effects, under dynamic loading conditions.

Researchers in the past conducted numerous studies on the dynamic mechanical responses of various rock types such as Dresser basalt, Bohus granite, Bukit Timah granite, Carrara marble, metadolerite, phyllite gneiss to name a few (Lindholm et al. 1974; Lundberg 1976; Zhao and Li 2000; Doan and Billi 2011; Mishra et al. 2018(a), Mishra et al. 2018(b), Mishra et al. 2019, Mishra et al. 2021). The studies revealed that with increasing loading rates or impact velocities, there is an increase in the dynamic strength of the rocks. The studies conducted were mostly carried out under dynamic compressive behaviour of the rocks. A very few studies in the past were conducted focusing on the both dynamic compressive and dynamic tensile strength of natural and synthetic rocks. Wang et al. (2009) studied the effect of varying loading rate on saturated and dry concrete in which it was observed that the strength of both saturated and dry concrete increased with increase in loading rates. Similarly, dynamic compressive and tensile tests on Bukit Timah granite were carried out at moderate strain rates which resulted a slightly higher strength at high loading rates (Li et al. 2011). A numerical approach was carried out by Liao et al. (2016) to investigate the dynamic compressive and dynamic tensile behaviour of rocks using SHPB and split Hopkinson tensile bar (SHTB) which revealed a significant effect of varying impact velocity, specimen size and bar size on the dynamic strength of rocks. Binder et al. (2020) and Shi et al. (2021) studied on the compressive and tensile strength of cementitious material and clay bricks respectively under moderate and high strain rate loading conditions using various testing devices.

Based on the existing literature and experiments conducted, the mechanical properties of various rock types under dynamic compressive loading conditions have widely been covered. However, the dynamic tensile responses and the dynamic compressive to dynamic tensile strength ratio of the rocks have seldom been studied in the literature. Therefore, the present study aims to experimentally investigate the mechanical properties of synthetic rock under dynamic compressive and dynamic indirect tensile loading conditions with effect of varying impact velocities using SHPB device. Additionally, an analysis is carried out with respect to the ratio of dynamic compressive to dynamic tensile strength of the synthetic rocks.

2 Materials and Methods

The dynamic compressive and dynamic indirect tensile tests for the present study are conducted on the synthetic rocks in order to maintain reproducibility in the data under same testing conditions. The synthetic sandstone specimens are prepared by mixing sand, Portland cement and water having a proportion of 1:2:1 (Pu and Cao 2012, Xiong et al. 2018, Wang et al. 2020, Song et al. 2021, Wibisono et al. 2022). The mixture is converted to a slurry, which is casted into the PVC moulds of 50 mm diameter and a slenderness ratio of 0.5 (Fig. 1). Thereafter, the samples are kept for a curing period of 28 days and the casted samples are polished to prepare a finished specimen of 48 mm diameter having a slenderness ratio of 0.5.

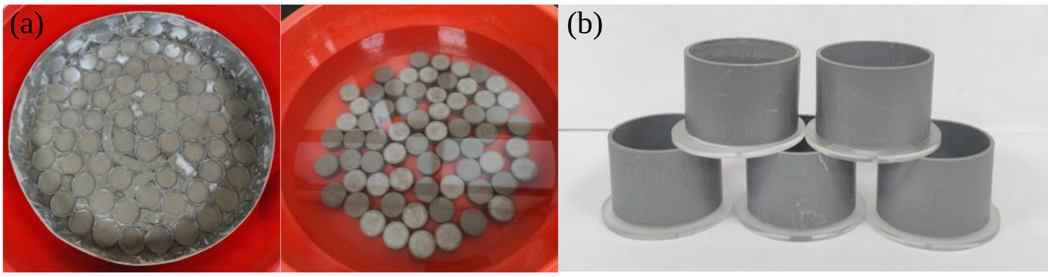

Fig. 1 (a) Casting of synthetic rock samples into moulds and submerged in the water for curing process and (b) PVC moulds used for casting synthetic rock.

Initially, the physical properties such as dry density, porosity, void ratio, P-wave velocity and slake durability index of the synthetic rock is determined and listed in Table 1, after carrying out various standardized tests in the laboratory suggested by IS, ASTM and ISRM (IS:13030, ASTM D4644). Thereafter the static characterization of the synthetic rock is performed using the 3500 kN INSTRON universal testing machine available in the Rock Mechanics Laboratory at the Department of Mining Engineering, Indian Institute of Technology Kharagpur, whereas the Brazilian setup is used in conjunction with the universal testing machine to determine the indirect tensile strength of rock. The mechanical properties namely uniaxial compressive strength (UCS), Young's modulus, Poisson's ratio, uniaxial tensile strength (UTS), cohesion and angle of internal friction are obtained through the static tests conducted following the ASTM, ISRM and IS standards (ASTM D7012-14, ISRM 1978a, IS:9179, IS:10082) and are listed in Table 1.

Table 1 Physical and mechanical properties of synthetic rock.

Rock	ρ (kg/m^3)	n (%)	e	V_P (m/s)	*S.D.* (%)	E (GPa)	ν	σ_c (MPa)	σ_t (MPa)	σ_c/σ_t	c (MPa)	ϕ
Synthetic rock	1831	32	0.47	3557	97.40	7.34	0.25	33.02	4	8.26	10.74	23.55

Note: ρ = Density, n = Porosity, e = Void ratio, V_P = P-wave velocity, *S.D.* = Slake durability, E = Young's modulus, ν = Poisson's ratio, σ_c = Uniaxial compressive strength of rock, σ_t = Uniaxial tensile strength of rock, σ_c/σ_t = Strength ratio, c = Cohesion and ϕ = Angle of internal friction of rock.

The dynamic tests are performed using the SHPB setup installed in the Material Dynamics Laboratory at the Department of Mining Engineering, Indian Institute of Technology Kharagpur Fig. 2. The present study uses a striker bar length (L_{st}) of 300 mm which is impacted on to the incident bar at varying gas gun pressures (P_g) of 0.15 MPa, 0.25 MPa, 0.35 MPa and 0.45 MPa which produces varying impact velocities of 12.74 m/s, 15.33 m/s, 18.92 m/s and 21.23 m/s, respectively. Four specimens each for dynamic compressive tests (CSS9, CSS10, CSS11 and CSS12) and dynamic indirect tensile tests (SS9, SS10, SS11 and SS12) are tested with varying impact velocities to analyse the effect of varying loading conditions on the mechanical behaviour of rock Fig. 3. The specimens are placed axially between the incident and transmission bars to determine the dynamic compressive behaviour of the specimens, however for the dynamic indirect tensile behaviour the specimens are placed diametrically between the incident and transmission bars as shown in Fig. 4.

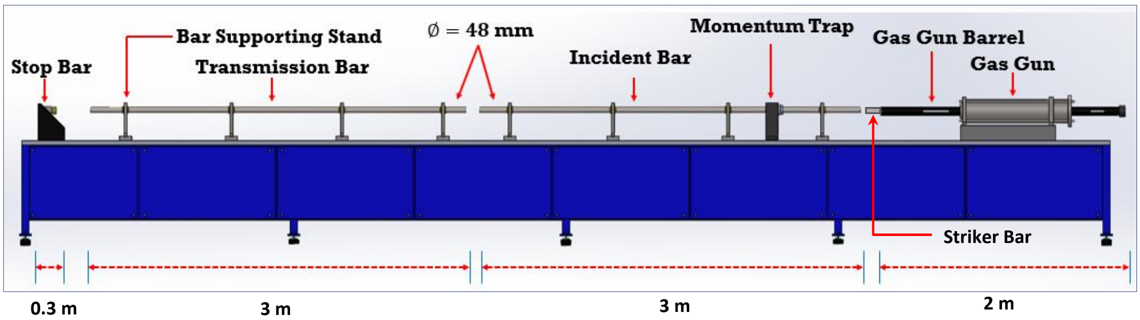

Fig. 2 SHPB setup used in the present study for carrying out the dynamic tests.

Fig. 3 Synthetic rock specimens used for (a) Dynamic compressive tests and (b) Dynamic indirect tensile tests.

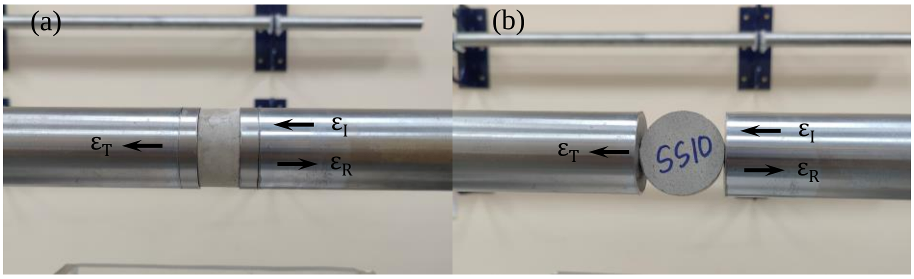

Fig. 4 (a) Axial placement of specimen for dynamic compressive tests and (b) Diametrical placement of specimen for dynamic indirect tensile tests between incident and transmission bars.

The experimental test data are captured from the dynamic compressive and dynamic indirect tensile tests performed on the synthetic rock using the high precision strain gauges attached on the centre of both incident and transmission bars. Thereafter, the responses captured are post-processed using the following equations to obtain the strain rate, strain and stress values respectively:

$$\dot{\varepsilon} = -2\frac{C_B}{L_S}\varepsilon_R \tag{1}$$

$$\varepsilon = -2\frac{C_B}{L_S}\int_0^t \varepsilon_R \, dt \tag{2}$$

$$\sigma = \frac{A_B}{A_S}E_B\varepsilon_T \tag{3}$$

Where $\dot{\varepsilon}$ Strain rate generated from the specimen
ε Strain induced in the specimen
σ Stress induced in the specimen
C_B Wave speed of the bar
L_S Length of the specimen
ε_R Reflected strain pulse
ε_T Transmitted strain pulse
E_B Young's modulus of the bar
A_B Cross-sectional area of the bar
A_S Cross-sectional area of the specimen

3 Results and Discussions

Fig. 5 shows the deformation pattern of synthetic rock tested under dynamic compressive and dynamic indirect tensile loading conditions. It is observed that the specimens are completely crushed and deformed into very small fragments for dynamic compressive test. However, the failure pattern for the dynamic indirect tensile test shows a predominant central splitting with a wedge pattern failure at the specimen periphery. Thereafter, the stress vs strain responses for synthetic rock under both dynamic compressive and dynamic indirect tensile loading are plotted for each varying impact velocities (Fig. 6) and are listed in Table 2. It is observed from Fig. 6 that the highest peak stress achieved is around 112 MPa with a strain rate of 356.77 /s for dynamic compressive tests. However, for dynamic indirect tensile tests, a peak stress of 14.91 MPa is observed with a strain rate of 335.23 /s generated from the synthetic rock.

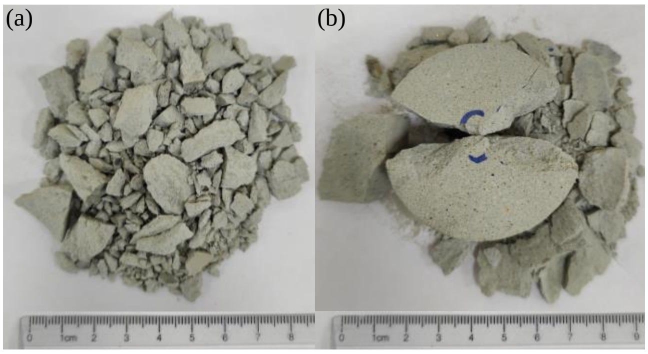

Fig. 5 Failure pattern of synthetic rock under (a) Dynamic compressive loading conditions and (b) Dynamic indirect tensile loading conditions.

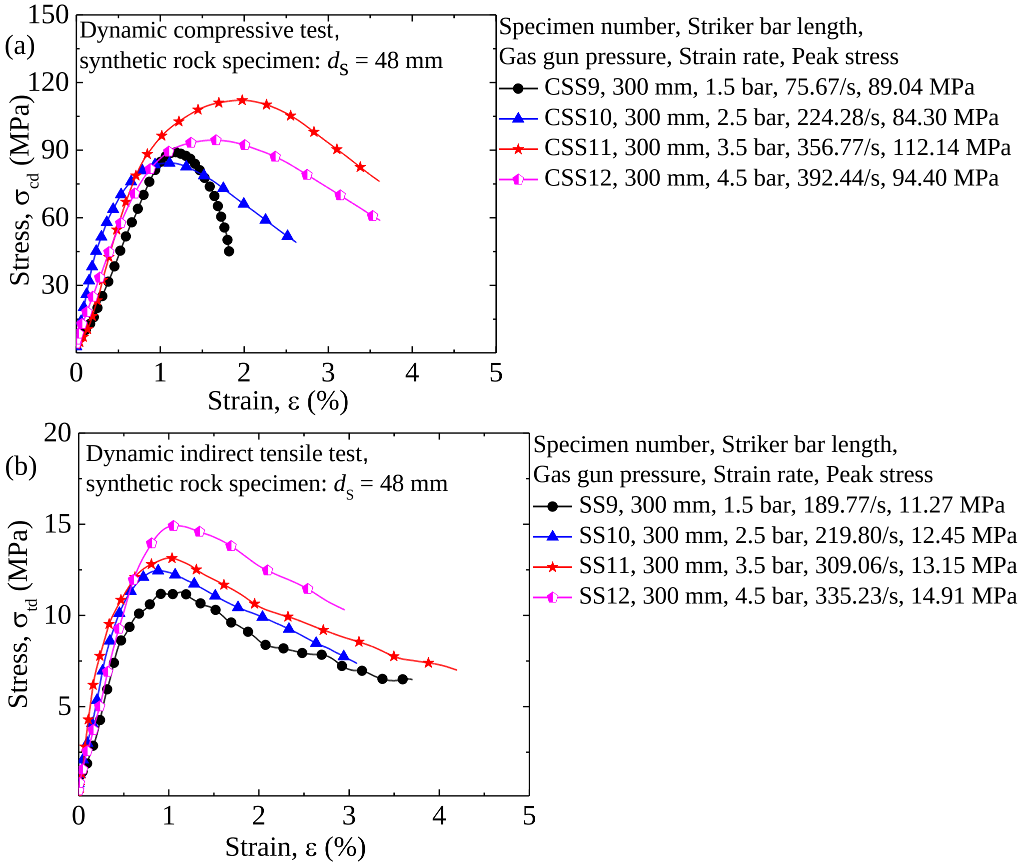

Fig. 6 Stress vs strain responses obtained from (a) Dynamic compressive tests and (b) Dynamic indirect tensile tests on synthetic rock.

Table 2 Dynamic properties of synthetic rock subjected to both compressive indirect tensile loading conditions using 300 mm striker bar length.

Specimen	P_g (bar)	V_{st} (m/s)	E_d (GPa)	σ_d (MPa)	*DIF*	ε (%)	$\dot{\varepsilon}$ (/s)
CSS9	1.5	12.74	8.63	89.04	2.70	1.17	75.67
CSS10	2.5	15.33	19.78	84.30	2.55	1.11	224.28
CSS11	3.5	18.92	11.33	112.14	3.40	1.95	356.77
CSS12	4.5	21.23	11.39	94.40	2.86	1.61	392.44
SS9	1.5	12.74	1.88	11.27	2.82	0.94	189.77
SS10	2.5	15.33	2.63	12.45	3.11	0.89	219.80
SS11	3.5	18.92	3.78	13.15	3.29	0.99	309.06
SS12	4.5	21.23	2.14	14.91	3.73	1.06	335.23

Note: P_g = Gas gun pressure in bar, V_{st} = Striker bar velocity in m/s, E_d = Dynamic Young's modulus in GPa, σ_d = Dynamic strength of the material in MPa, *DIF* = Dynamic increase factor, ε = Strain in %, $\dot{\varepsilon}$ = Strain rate in mm/mm/s.

Thereafter, the dynamic properties of synthetic rock such as strain rate, dynamic peak stress, dynamic increase factor (*DIF*) and dynamic modulus (E_d) obtained from both dynamic compressive and indirect tensile tests are plotted against striker bar velocities and strain rates to analyse the behaviour with varying strain rates. It is observed from Fig. 7 that with increasing striker bar velocities, the strain rate increases for both dynamic compressive and indirect tensile conditions. Thereafter, the peak stress and *DIF* are plotted against the varying strain rates as strain rate is a function of the striker bar velocity. It is observed that both peak stress and *DIF* increases with increasing strain rate for dynamic indirect tensile tests. However, in case of dynamic compressive tests, a continuous increasing and decreasing trend is observed for both *DIF* and peak stress. *DIF* is the ratio of peak stress at dynamic loading conditions to the static loading conditions, and is directly proportional to the peak stress at dynamic loading conditions. Therefore, a similar trend is observed for both DIF and peak stress with varying strain rates (Fig. 7). The dynamic modulus obtained from the dynamic compressive tests lies between a range of 8.63 to 19.78 GPa whereas, a range of 1.88 to 3.78 GPa is obtained for dynamic indirect tensile tests. However, there is no such uniform trend observed for dynamic modulus with varying strain rate with both dynamic compressive and dynamic indirect tensile loading conditions. Fig. 8

illustrates the responses between the dynamic-to-static modulus ratio and varying strain values derived from dynamic compressive and dynamic indirect tensile tests. The results indicate a general decrease in the dynamic-to-static modulus ratio with increasing strain values. It is to be noted that the dynamic experiments are conducted three times for each of the specimens. However, it is analysed from the results that the deviation from the mean value remains within ±5%. Therefore, the error estimates shown in the plots for Figures 7, 8 and 9 represent a variation of up to ±5% of the corresponding data.

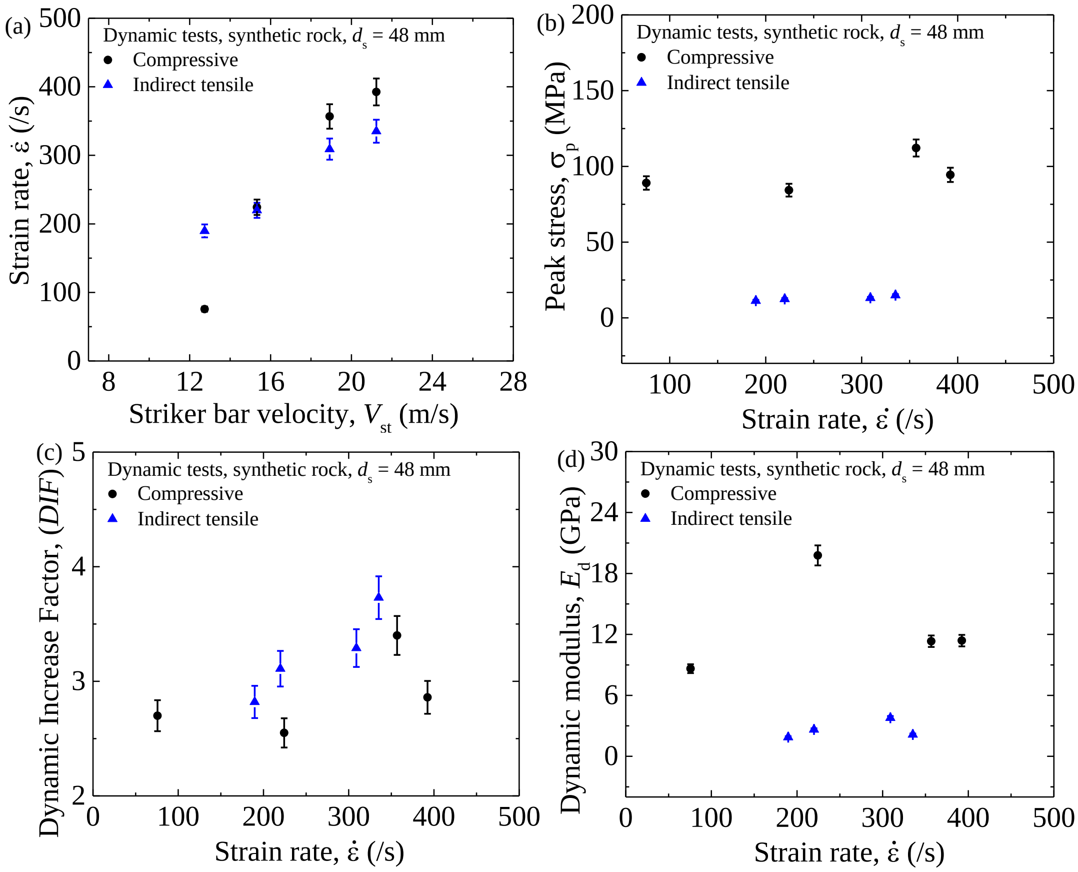

Fig. 7 Plots obtained with dynamic properties of synthetic rock: (a) Strain rate vs striker bar velocity, (b) Peak stress vs strain rate, (c) *DIF* vs strain rate, (d) Dynamic modulus vs strain rate.

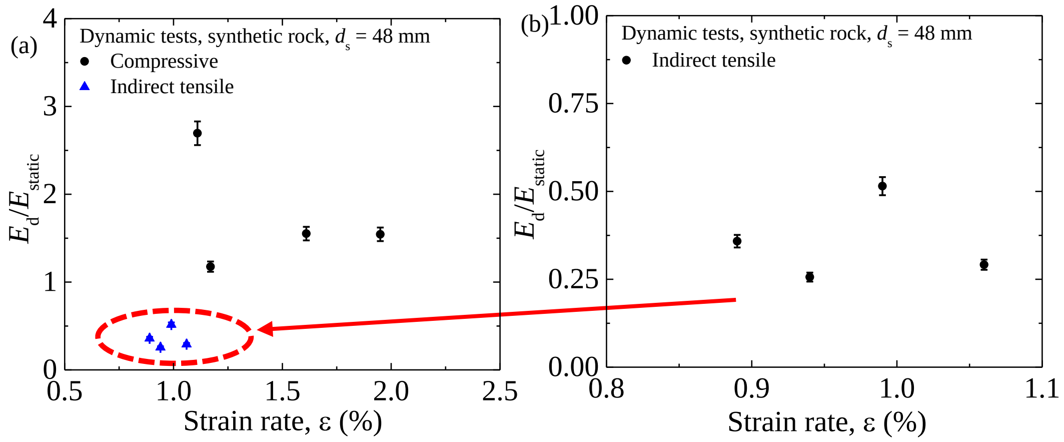

Fig. 8 Plots showing ratio of E_d/E_{static} vs strain for (a) Dynamic compressive tests and (b) Dynamic Indirect tensile tests (enlarged plot) on synthetic rock.

Finally, the dynamic strength ratio (σ_{cd}/σ_{td}) is plotted against the varying strain rates. Dynamic strength ratio is the ratio between the peak stress under dynamic compressive loading conditions to the peak stress under dynamic indirect tensile loading conditions. It is observed from Fig. 9 that the dynamic strength ratio decreases gradually with increase in strain rate values, except in the case where the dynamic strength ratio shows a sudden rise at strain rate value of 356.77 /s. The dynamic strength ratios obtained from the dynamic compressive and dynamic indirect tensile tests shows an overall range between 5.77 - 8.94.

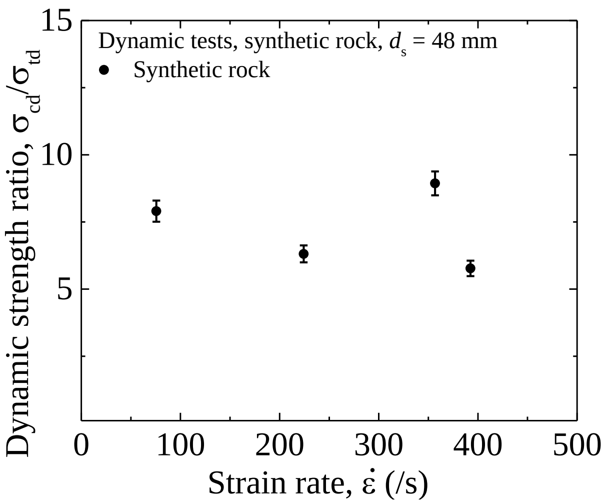

Fig. 9 Plot showing Dynamic strength ratio vs strain rate for synthetic rocks.

4 Conclusions

The present study discussed about the characterization of synthetic rock under both dynamic compressive and dynamic indirect tensile loading conditions highlighting the influence of strain rate on the mechanical behaviour of synthetic rocks under dynamic loading conditions. These findings provide valuable insights into the strain rate-dependent behaviour of rock type materials. The conclusions derived from the study are as follows:

- The dynamic properties obtained from the dynamic tests increases with increase in striker bar velocity and strain rate.
- The experimental investigation of synthetic rock under dynamic compressive and dynamic indirect tensile loading conditions revealed distinct deformation and failure patterns. Dynamic compressive tests resulted in complete fragmentation of specimens, while indirect tensile tests exhibited central splitting with peripheral wedge failures.
- Dynamic properties such as peak stress, *DIF*, and dynamic modulus generally increased with strain rate, however compressive tests exhibited non-uniform trends for peak stress and *DIF*.
- The dynamic modulus ranged from 8.63 to 19.78 GPa for compressive tests and 1.88 to 3.78 GPa for tensile tests, with no consistent trend observed with varying strain rates.
- The dynamic-to-static modulus ratio decreased with increasing strain, and the dynamic strength ratio (σ_{cd}/σ_{td}) generally decreased with strain rate, except for a sudden increase at 356.77 /s. The dynamic strength ratio ranged from 5.77 to 8.94.

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