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Technical Note

Characterization of three Himalayan rocks using a split Hopkinson pressure bar

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1. Introduction

The design of the civil infrastructure in mountainous regions involves many complexities related to the diverse geological and geomorphological features of the region – the Chenab river bridge in the Himalayas and the Gotthard Base tunnel in the Alps, for example. The young mountain ranges of the Himalayas and the Alps contain joint planes, shear seams, active folds and fault zones. Moreover, high in-situ stresses and high levels of seismicity in these regions pose severe challenges to the construction of infrastructure. In addition to this, unanticipated loads caused by natural hazards, e.g., landslides and earthquakes, and by manmade hazards, e.g., blasts and projectile penetration, add to the difficulties already existing therein. It may be noted that the loads caused by hazardous events such as an earthquake or a blast are highly transient in nature, generating high strain rates in the rock, and the strain rate caused by a blast may reach up to 10^4/sec[1,2], which in turn affects both the stiffness and the strength properties of the rocks. Thus, to ensure sustainable design of civil infrastructure in the mountains, it is necessary to characterize the rocks under both static and dynamic loading conditions.

In the present work, the dynamic compression response of the rocks has been discussed and reported. Dynamic compression tests of rocks at different strain rates have been performed by several researchers using the split Hopkinson pressure bar (SHPB) and dynamic triaxial tests.[3–18] Dynamic uniaxial compression tests were performed on three rocks by[3] using SHPB at strain rates from 10^{-4}/sec to 10^4/sec at varying temperatures and the SHPB test data for rocks were reported for the first time in the literature. They observed that the rocks exhibited increased stiffness and higher stress with increasing strain rate and decreasing temperature. Energy absorption in SHPB test in two different rocks, Bohus granite and Solenhofen limestone was reported in.[6] It was observed that the energy absorbed by the rocks increased significantly when the applied load reached the critical value of 1.8 and 1.3 times the static compressive strength for Bohus granite and Solenhofen limestone, respectively. SHPB tests on tuff, which is a hard igneous rock of volcanic origin, was performed in[9] for strain rates varying from 10^{-6}/sec to 10^3/sec. It was observed from the results that the strength of the rock was a weak function of the strain rate for strain rates varying from 10^{-6}/sec to 76/sec; however, for the strain rate above 76/sec, the rate of increase in strength was proportional to the cube root of the strain rate. Dynamic uniaxial compression tests were conducted by[11] on Bukit Timah granite in Singapore at four different loading rates (10^0 MPa/sec, 10^1 MPa/sec, 10^3 MPa/sec and 10^5 MPa/sec). It was concluded from the tests that, for each log scale increase in loading rate, the compressive strength of the rock increased by 15%. They also observed that there were small changes in the elastic modulus and Poisson's ratio values with an increase in loading rate. Uniaxial compressive SHPB tests on limestone was conducted by[12] by using a copper disk at the impact end of the incident bar as a pulse

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shaper, which resulted in dynamic stress equilibrium of the samples and maintained constant strain rates over the test duration. An improved experimental approach for eliminating oscillation that exists in the dynamic stress–strain response of rocks and other brittle materials obtained from SHPB tests was reported in[13]. The tests were conducted on granite, sandstone and limestone and was concluded that the improved method eliminates oscillation in the tests, provides better stability of strain rate and more representative results than those obtained from the conventional rectangular loading waveform shape. The dynamic stress–strain response of Bukit Timah granite loaded at a medium strain rate of 20–60/sec. using SHPB testing was reported by.[15] It was observed from the results that the dynamic fracture strength of the granite was directly proportional to the cube root of the strain rate, whereas the elastic modulus remained unchanged with increasing strain rate. At higher strain rates, the rocks showed a higher amount of energy absorption and the particle size of the fragments at the end of the test became smaller. Uniaxial compression tests on Thai sandstones were reported in[17] and they found an increase in strength and elastic modulus with an increase in strain rate. It was observed that both the strength and the elastic modulus tended to increase exponentially, with the loading rates ranging from 0.001 MPa/sec to 10 MPa/sec. A maximum of 71% increase in the modulus of elasticity was observed for sandstone with the increase in loading rate from 0.001 MPa/sec to 10 MPa/sec. It may be summarized from the literature review that dynamic compressive strength testing on rocks using SHPB has been carried out on different rock types, e.g., granite, Barre granite, basalt, volcanic tuff, Kawazu tuff, red sandstone, Indiana limestone, porphyritic tonalite, oil shale, granodiorite, coal, kidney stone, Tennessee marble and Akyoshi marble at up to a 2000/sec strain rate[19] and that strain rate had a significant effect on the mechanical behavior of the rocks.

In the Indian sub-continent, the young and diverse rock formations of the Himalayas are often devastated by high intensity earthquakes, blast loads due to cross-border insurgency and blasting activities necessary for roadway construction, which creates high loading rates in the rocks. The objectives of the present work are to characterize three Himalayan rocks, i.e., quartzite, limestone and dolomite, under strain rate dependent loading at different levels of strain rates, i.e., low strain rates varying from 49/sec to 94/sec depending on rock type, medium strain rates varying from 91/sec to 135/sec depending on rock type and high strain rates varying from 174/sec to 316/sec depending on rock type. The quartzite and limestone rocks collected herein are of unweathered nature and the dolomite is slightly weathered. The rock blocks are collected from a hydropower project site in Vilaspur, India. In the present work, blocks of the three rock types, quartzite, limestone and dolomite, are collected from the site. The rock samples have been tested for both physical and mechanical properties. The physical properties, e.g., dry density, saturated density and specific gravity; and the static mechanical properties, e.g., uniaxial compressive strength, static elastic modulus and static tensile strength of the rocks, are determined. The strain rate dependent tests are carried out using the SHPB. The stress–strain response of the rocks under dynamic loading, force equilibrium at the incident and transmission bar ends of the rock sample and peak stress and dynamic elastic modulus are studied. The dynamic increase factor (*DIF*), i.e., the ratio of dynamic to static peak stress, is calculated for each test at different strain rates. The rock tested by using SHPB device should fail under the upper limit of strain rate. The stress–strain response of the rock if tested above the upper limit of strain rate would give erroneous result which can be explained by non-achievement of force equilibrium due to inertia effect. It has been reported in[20] that the upper limit of the strain rate for a material to fail should be

$$\dot{\varepsilon}_1 = \frac{\varepsilon_f c}{\alpha L} \tag{1}$$

where c is the elastic wave speed of the specimen, L is the length of the specimen and α is a non-dimensional parameter which depends on the shape of the incident pulse. Further, suitable correlation equations are proposed herein for changes in *DIF* with strain rate for all three rocks.

2. Laboratory tests performed on rocks

In the present work, three rock types, i.e., quartzite, limestone and dolomite, are collected from the Vilaspur site for testing. The rock samples are prepared with a diamond bit core cutter of 38 mm. For all three rocks, the physical properties, e.g., both dry and saturated densities and specific gravity have been obtained. Static uniaxial compressive strength tests on dry and saturated rock samples have been carried out using the CONTROLS uniaxial compression and splitting test device for rock samples with aspect ratio $(L/D)=2{:}1$. Brazilian and point load tests on dry and saturated rock samples have been carried out to determine the tensile strength values of the rocks. For the Brazilian test, $L/D=0.5{:}1$ and for the point load test, $L/D=1{:}1$ have been used. All static tests have been carried out following the specifications given in[21,22].

The dynamic tests are performed using a 38-mm diameter SHPB for all three rocks at different strain rate levels. For this test, the rock samples are prepared with a diameter of 38 mm and aspect ratio of 0.5:1. The results obtained from the static tests are presented in Table 1 and those from the dynamic tests are presented in Tables 2, 3 and 4 for quartzite, limestone and dolomite, respectively. The striker bar is propelled using a compressed air gas gun. The strain rate in the dynamic tests is controlled by varying the striker bar length and the striking velocity. The sample number, sample length, length of the striker bar used and the striking velocity applied for a particular strain rate are also reported in the above-mentioned tables.

3. SHPB test setup

Fig. 1 shows the schematic diagram of the compression SHPB test setup in the RelInc laboratory, Calumet, Michigan, USA. The setup is composed of an incident bar, a transmission bar and striker bars of different sizes. The bars are made of C300 maraging steel. The incident bar length is 2.59 m and the diameter is 38.1 mm. The transmission bar length is 2.43 m and the diameter is 38.1 mm. The dimensions of the incident and transmission bars

Table 1
Physical and static properties.

Rocks	Dry density, ρ_d (kg/m^3)	Saturated density, ρ_{sat} (kg/m^3)	Specific gravity, G	Uniaxial compressive strength, σ_c(MPa)	Modulus of elasticity, E_t (GPa)
Quartzite	2585.841	2605.577	2.80	108.18	11.65
Limestone	2630.601	2664.206	2.71	51.21	2.62
Dolomite	2731.820	2723.202	2.70	38.59	3.75