# Rock Materials' Behaviour in Terms of Their Dynamic Mechanical Properties

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**Abstract**

*Dynamic rock mechanics is the study of the mechanical behaviour of rock under dynamic loading situations, as well as changes in the mechanical properties of the rock. Loading methods were almost exclusively employed for intermediate and high strain rate testing. Dynamic testing and dynamic mechanical behaviour of rock materials were investigated in this paper. The use of dynamic testing to forecast stress-strain behaviour was explored. The dynamic mechanical characteristics of rock materials were summarised, including uniaxial and triaxial compressive strength, tensile strength, shear strength, and fracture toughness. The influence of pressure, temperature, and water saturation, as well as rock microstructure, size, and form, on the mechanical characteristics of rock materials, was investigated.*

***Keywords:*** *Mechanical behavior, Dynamic, Rock, Strain*

## INTRODUCTION

The effect of dynamic stress on rock is a critical aspect in many rock engineering challenges (1). Rock dynamics has several applications, including earthquakes, mining, energy, the environment, and civil engineering. Environmental characteristics such as confining pressure, temperature, and ground water, as well as rock variables such as microstructure, size, and form, all have a substantial impact on the dynamic mechanical behaviour of rock materials (2-5). In recent years, experimental methodologies for characterising the dynamic mechanical behaviour of materials have been developed (6-8).

Previously, dynamic experimental procedures for rock-like materials such as concrete, mortar, ceramic, and rock materials were investigated (9-12). The dynamic experimental procedures and mechanical behaviour of rock material have been reviewed in this paper. The experimental procedures for intermediate and high strain rate testing, as well as the dynamic mechanical properties of rock materials, were examined.

## LOADING METHODS FOR INVESTIGATION OF DYNAMIC BEHAVIOR

Loading techniques have been used for investigation of dynamic behavior of rock materials. The loading techniques for rock materials are illustrated in Figure 1. In the range of $10^{-8}$-$10^{-5}$ $s^{-1}$ strain rate, the creep behavior is considered and creep laws are used (5). In the range of $10^{-5}$-$10^{-3}$ $s^{-1}$ strain rate, the quasi-static stress–strain curve obtained from constant strain rate (CSR) test has been applied to investigate the mechanical behavior (13). The ordinary hydraulic servo-controlled testing machines and hydraulic oil machines, can load specimens at strain rates up to $10^{-3}$ and $10^{-1}$ $s^{-1}$, respectively. The pneumatic– hydraulic machines and drop-weight machines have been developed to reach strain rates on the order of $10^{0}$ and $10^{1}$ $s^{-1}$, respectively (1). The mechanical behavior of rock materials at strain rates ranging from $10^{-1}$ to $10^{1}$ $s^{-1}$ is defined as intermediate strain rate. The loading techniques in the high strain rate, in the range of $10^{1}$ to $10^{4}$ $s^{-1}$ are the split Hopkinson pressure bar (SHPB). At high strain rates, there is a transition from nominally isothermal condition to quasi-isothermal/adiabatic condition (14).

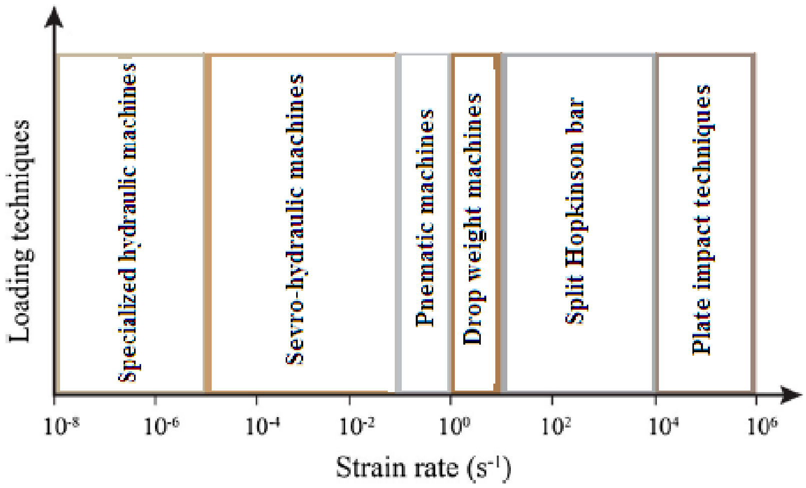


***Figure 1 Loading techniques of rock materials***

 

For exploring the intermediate strain rate behaviour of rock materials under uniaxial compression, pneumatic-hydraulic devices have been created. The load in pneumatic-hydraulic machines is provided by the movement of a light weight piston propelled by the expansion of compressed gas. The strain rate is determined by the connection between the stiffness of the specimen and the stiffness of the machine (15). Drop-weight machines operate on gravitational potential energy by manipulating a hammer of known height and weight. The strain rate of 101 s-1 has been achieved using drop-weight machines. The use of drop-weight machines is limited due to several issues, including: 1) the technique is passive, and testing conditions are determined by trial and error or empirical parameters; 2) the rate and form of the compressive loading depend on both the specimen and machine compliances, as well as the average energy of the falling weight; and 3) the rate and form of the compressive loading depend on both the specimen and machine compliances, as well as the average energy of the falling weight. 3) Because of the coupling effects between machine vibration and wave propagation, great care should be used in interpreting experimental results. 4) The computed displacement may be erroneous; 5) The loading rate cannot be accurately controlled, making multi-axial testing unreliable (16). With the split Hopkinson bar, high strain rate loading techniques have been frequently used. A striker bar, an incident bar, and a transmission bar comprise the structural split Hopkinson bar, with a specimen sandwiched between the incident and transmission bars.

The strain rate ($\dot{\varepsilon}$) is given as follows (17):

$$\dot{\varepsilon} = \frac{(u^{\bullet}_1 - u^{\bullet})_2}{L_s} \qquad (1)$$

Where $u_1$ and $u_2$ are the velocities at the incident bar– specimen and specimen–transmitted bar interfaces, respectively. $L_s$ is the length of strike bar.

For a split Hopkinson bar test, the requirements of constant stress rate and stress equilibrium must be met at the same time. It has been proposed that the equilibrium time should be 5-10 times the transit time in order to achieve the stress equilibrium condition (18). End friction between the specimen and the loading device can result in a complicated stress state of multi-axial compression, and rock materials are extremely sensitive to confining pressure. Although fiction effects may be physically reduced in testing by using sufficient lubrication, they cannot be fully avoided.

Using numerical simulations, different contact states such as lubricated, dry, and bonded with high-strength adhesive might be used to reduce friction (19). Furthermore, in high strain rate experiments, stress wave loading causes inertia to affect observed mechanical characteristics (20).

The extent of the inertial contribution to perceived stress is also affected by the speciem's density and size. Powell (21) explored the effects of radial inertia on rock behaviour. They discovered that after fracture, the radial stress increased towards the core of the specimen, and inferred that failure propagates internally in a progressive way. Three changes were made to the Split Hopkinson bar to increase strain rates.

**These modifications were**

1. decrease of the specimen size, especially the length;
2. direct impact on the specimen; and
3. miniaturization of the entire system (21).

The first approach is typically limited by frictional effects (22). A projectile directly impacts on a specimen placed in front of an elastic bar in the second approach. Several miniaturized versions on the millimeter order in diameter have been developed, and the strain rate can reach up to about $10^5$ $s^{-1}$ in the third approach (22).

## DYNAMIC MECHANICAL PROPERTIES OF ROCK MATERIALS

The mechanical properties of rock materials are sensitive to loading rate, and enhancement in mechanical properties of rock materials. On the other hand, the dynamic mechanical properties and fracture behaviors of rock materials depend on the loading and measurement technique, testing method and influencing environmental factors (23).

### Uniaxial Compression Tests

The uniaxial compression tests were conducted under dynamic loading in different measurement type and different size, shape (e.g. cube, cylinder or prism) and aspect ratio of the specimens. The size and shape of the specimen are normally defined by the same value of the ratio Ls/Ds of 2.5–3.0 for quasi-static tests.

Furthermore, the diameter should be close to 50 mm or at least 10 times the average grain size, with the ratio Ls/Ds taking values of 1:1 and 0.5:1 for small and large specimens, respectively (24).

### Triaxial Compression Tests

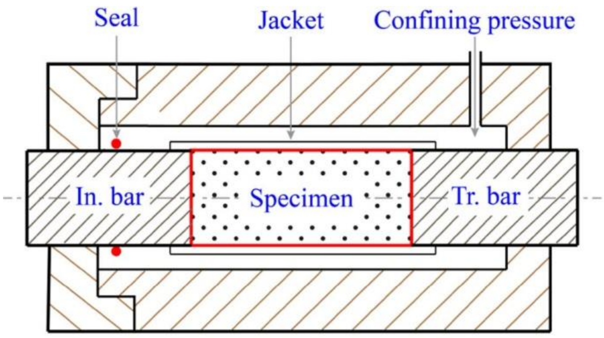


*Figure 2. Schematic of triaxial compression tests design*

The specimen is put within a pressure chamber and isotropically loaded by hydrostatic pressure using various confining fluids in triaxial compression experiments (Figure 2). (16). The confining pressure is determined by the sleeve's thickness and material type. Strain gauges are installed on the sleeve surface to record the specimen's stress status. There are general trends for: increasing triaxial strength with increasing strain rate at all confining pressures; increasing triaxial strength with increasing confining pressure, as demonstrated in quasi-static tests; deformation behaviour to become more ductile at HSR; and a lower confining pressure than in quasi-static tests, especially for sedimentary materials (16, 25).

### Tension tests

Direct tension and indirect tension are the two sorts of conventional procedures. Direct tension testing under quasi-static loads are challenging to execute because even minor misalignments and stress concentrations in the loading system might result in undesired failure modes. Figure 3 depicts the schematics of four different split Hopkinson tension bar methods (26). Direct tension testing include the following limitations: (1) the same constraints as for quasi-static testing; (2) the complexity of the specimen form; and (3) pulse shaping techniques are difficult to use, therefore the stress equilibrium requirement may be broken (27). In order to address these issues, indirect tension techniques have been created. In terms of specimen fabrication, experimental setup, and data reduction, indirect testing procedures provide a practical option for determining tensile strength (28). Figure 4 depicts the schematic of indirect tension techniques.

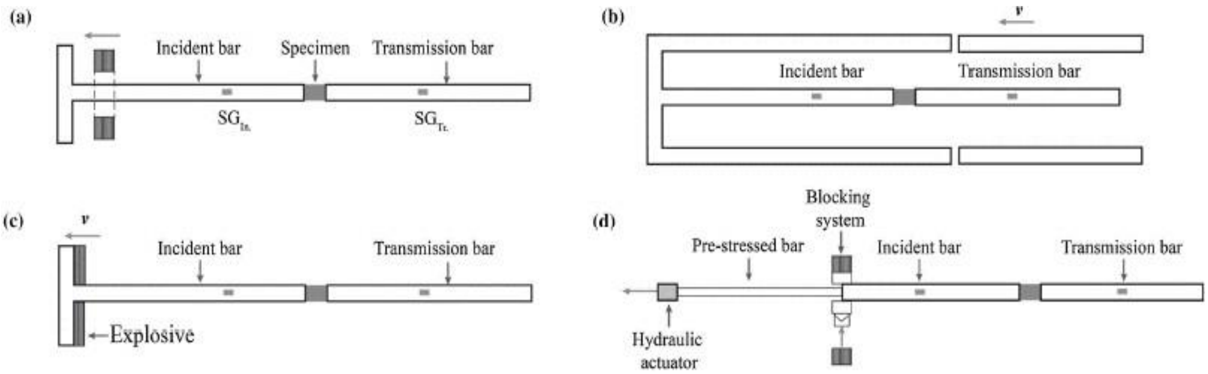


***Figure 3. Schematics of four types of split Hopkinson tension bar techniques: (a) a mass is impacted directly on an anvil attached to the incident bar;***
***(b) an anvil is loaded by a compressive wave transmitted through a hollow tube; (c) a pulse is generated by the detonation of an explosive against the anvil; and (d) a pre-stressed bar is connected to the incident bar to produce the loading pulse***

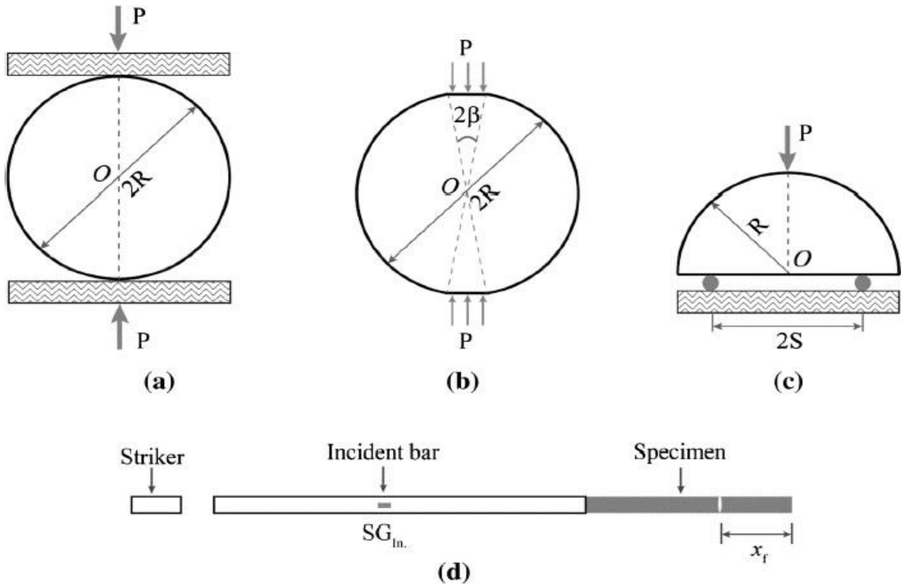


***Figure 4. Schematics of indirect tension testing methods: (a) Brazilian disc, (b) flattened Brazilian disc, (c) semi-circular bending and (d) spalling***

***Shear tests***

For higher strain rates, the torsional split Hopkinson bar technique has been developed, which overcomes the limitations of lateral inertia, friction and wave dispersion effects on the experimental results in the traditional Split Hopkinson pressure bar test (29). The dynamic shear strength of the thin-walled tubular specimen, $\tau_d$, iscalculated from the dynamic torque, $T_d$, as follows (29):

$$\varepsilon^{\bullet} = \frac{(u_1^{\bullet} - u_2^{\bullet})}{L_s} \qquad (2)$$

where $B_{ws}$ is the wall thickness and R is the mean radius ofthe specimen.

***Stress–strain behavior at high strain rate***

The strength, strain to failure, Young's modulus, Poisson's ratio and brittle/ductile behavior can be evaluated from stress–strain curves. The stress–strain curves are almost evaluated by load transducers and on-specimen strain gauges without considering inertia effects. Methods for determining the stress–strain curve at high strain rate are illustrated in Table 1. Among them, the direct estimation method is recommended to determine the stress–strain curve (7).

**Dynamic uniaxial compressive behavior**

Dynamic mechanical parameters are usually obtained from stress–strain curves extracted directly from load transducers. In high strain rate testing, the effects of inertia and wave propagation should be considered (30). The increase or decrease with increasing the strain rate means that the critical strain becomes more brittle or ductile at higher strain rate. Young's modulus decreases slightly and the Poisson's ratio increases slightly with increasing loading rate. The inverse method employed force and particle velocities measured at both sides of the specimen, was successfully used to determine the stress–strain curves of concrete and salt. Therefore, the inverse analysis method produces accurate and repeatable results for rock- like materials at high strain rate. There is a definite increase in the uniaxial compressive strength of rock materials under dynamic loading (31).

***Table 1. Methods for determining the stress–strain curve at high strain rate (7)***

| Method | Strain history $\varepsilon(t)$ | Stress history $\sigma(t)$ |
|---|---|---|
| One-wave analysis | $\varepsilon(t) = -(2C_B/L_s) \cdot \int_0^t \varepsilon_{Re.}(t)dt$ | $\sigma(t) = (A_B E_B/A_s) \cdot \varepsilon_{Tr.}(t)$ |
| Two-wave analysis | $\varepsilon(t) = -(2C_B/L_s) \cdot \int_0^t \varepsilon_{Re.}(t)dt$ | $\sigma(t) = (A_B E_B/A_s) \cdot [\varepsilon_{In.}(t) + \varepsilon_{Re.}(t)]$ |
| Three-wave analysis | $\varepsilon(t) = (C_B/L_s) \cdot \int_0^t [\varepsilon_{In.}(t) - \varepsilon_{Re.}(t) - \varepsilon_{Tr.}(t)]dt$ | $\sigma(t) = (A_B E_B/2A_s) \cdot [\varepsilon_{In.}(t) + \varepsilon_{Re.}(t) + \varepsilon_{Tr.}(t)]$ |
| Direct estimate | $\varepsilon(t) = (C_B/L_s) \cdot \int_0^t [\varepsilon_{In.}(t) - \varepsilon_{Re.}(t) - \varepsilon_{Tr.}(t)]dt$ | $\sigma(t) = (A_B E_B/A_s) \cdot \varepsilon_{Tr.}(t)$ |
| Foot-shifting | $\varepsilon(t) = (C_B/L_s) \cdot \int_0^t [\varepsilon_{In.}(t) - \varepsilon_{Re.}(t) - \varepsilon_{Tr.}(t + t_0)]dt$ | $\sigma(t) = (A_B E_B/A_s) \cdot \varepsilon_{Tr.}(t)$ |
| Hybrid analysis | Direct measurement | One of the above or load transducer |
| Inverse analysis | Combination of FEM simulation and/or direct measurement | Combination of FEM simulation and/or one of the above |

**Dynamic triaxial compressive behavior**

Mechanical loads applied to rock materials are almost not uniaxial (32). The stress–strain curves at high strain rates under 0.1 and 10 MPa confining pressures are approximately consistent with those under 27 and 55 MPa confining pressures in the quasi-static tests, respectively. The used techniques were modified and improved to determine the triaxial compressive strength of rock-like materials precisely. The dynamic strength curve relative to confining pressure is almost parallel to the static one for rock materials. At constant confining pressure, the normalized dynamic triaxial compressive strength increases with increasing strain rate. The dynamic strength curve relative to confining pressure is almost parallel to the static one for rock materials, and the triaxial compressive strength at high strain rate is about 20-100% higher than those obtained in quasi-static tests (33, 34).

**Dynamic tensile behavior**

The tensile strength increases with increasing strain rate, whereas the strain decreases. The increase in the tensile strength and the decrease in the strain to failure, indicate that the material displays more brittle features in higher strain rate tests. The strain rates of the direct tension results are higher than those obtained by indirect tension testing methods, since the specimen sizes are usually smaller in indirect tension tests. Therefore, attempts have been made to determine the tensile stress–strain curve by means of indirect testing methods under quasi-static loads (35).

## CONCLUSION

The dynamic mechanical behaviour of rock materials is examined in this paper. Pneumatic-hydraulic, totally gas-driven, and drop-weight machines are the loading systems utilised for intermediate strain rate testing of rock materials. The split Hopkinson bar is commonly employed at high strain rates, and substantial advancements of this technology for rock materials have occurred.

The strain rate in loading technique testing should be tightly regulated. Mechanical loads applied to engineering constructions are not always uniaxial. Loading procedures for multiaxial stress, such as true-triaxial and compression-shear testing, can be used. The quantitative evaluation of testing methodologies yields dynamic uniaxial and triaxial compressive, tensile, and shear strength of rock materials.

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