International Journal of Impact Engineering 91 (2016) 183–193

Contents lists available at ScienceDirect

International Journal of Impact Engineering

journal homepage: www.elsevier.com/locate/ijimpeng

Effects of strain rate and confining pressure on the compressive behavior of Kuru granite

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ARTICLE INFO

Article history:
Received 4 August 2015
Received in revised form 22 January 2016
Accepted 24 January 2016
Available online 2 February 2016

Keywords:
Confining pressure
Triaxial loading
High strain rate
Split Hopkinson pressure bar
Granite rock

ABSTRACT

Understanding the influence of hydrostatic pressure and loading rate on the strength and fracture behavior of rocks is very important for the development of deep drilling technology. This paper presents a systematic study on the mechanical properties and behavior of Kuru Gray granite at confining pressures up to 225 MPa and at strain rates of 10^{-6} s^{-1} and 600 s^{-1}. The low strain rate compression tests were carried out with a servo-controlled hydraulic testing machine with a radial confining chamber, and the dynamic tests with a special split Hopkinson pressure bar device with axial and radial confining pressure chambers. The results show that the rock strength increases significantly with strain rate and confining pressure. At confinements below 20 MPa, the strength of the material increases faster at the higher strain rate, but at confinements higher than this, the effect of confining pressure is stronger at the lower strain rate. The strain rate sensitivity increases when even a small confining pressure is applied. However, the rate sensitivity remains rather constant when the confining pressure is increased above 10 MPa. The parameters of the Hoek–Brown model and an alternative power-law model were calibrated for low and high rate data. Also, the fracture behavior of the rock was found to be strongly dependent on strain rate and confining pressure. At the low strain rate, the samples fail by axial splitting in the unconfined tests, whereas the dynamic unconfined tests result in a complete pulverization of the samples. At high confining pressures the fracture behavior is shear fracture for both studied strain rates.

1. Introduction

Hydrostatic or confining pressure has a strong effect on the mechanical behavior of brittle materials, and especially the compressive strength increases when confining pressure is applied. Also the loading rate has a strong effect on the fracture strength and fracture toughness of rocks and other brittle materials [1,2]. One of the most obvious engineering applications where both confinement and loading rate have significant roles is the percussive drilling of hard rocks, where the drill hammer impacts the rock at high speed causing extremely high pressures on the rock under the relatively small cross sectional area of the hammer buttons. The contact pressure causes the rock to fracture and chip between the buttons and the drill hammer can proceed further down in the borehole. Very deep holes are needed when drilling for geothermal energy. In areas away from the tectonic plate boundaries, the required depth of the energy wells can be as deep as 7 km. At these great depths, the rock temperatures can reach 150–200 °C and the hydrostatic pressures can be as high as 100–200 MPa. In any case, the drilling conditions deep in the Earth's crust are extremely hostile combining high pressures, high impact rates, and high temperatures leading to a low rate of penetration and rapid tool wear. Good understanding of rock behavior, strength, fracture, and fragmentation will assist in developing new drilling tools and methods. This includes detailed understanding of the combined effects of strain rate, confinement, and temperature on the rock behavior.

The effect of strain rate on the mechanical behavior of various rocks has been widely studied in compression [3,4], tension [5–9], and bending [1,10]. Liang et al. [11] studied the effects of loading rate on the fracture characteristics in the quasi-static region of granite rock. Macroscopic fracture modes were axial splitting at low strain rates, which slowly changed to shear fracture at higher strain rates. Moreover, microscopy of the fractured samples revealed that the fracture mechanism changes from intergranular to transgranular, and that the samples are fractured to smaller pieces as the strain

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http://dx.doi.org/10.1016/j.ijimpeng.2016.01.010
0734-743X/

rate is increased. Also, Hogan et al. [12] reported smaller fragment sizes with increasing impact energy. The effect of confinement has also been studied in the past. Kawakata et al. [13,14] performed interrupted triaxial compression tests at confining pressures of up to 100 MPa on Westerly granite. The tests were interrupted just after the peak stress and the samples were unloaded and recovered before the complete fracture. According to their results the crack patterns formed at unconfined conditions are more complex than those formed under confined conditions. Also, shear cracks form on the surface of the sample and propagate inwards. The angle of propagation increases when confinement is increased. Li et al. [15] studied the behavior of Bukit Timah granite at quasi-static strain rates and confining pressures up to 170 MPa, and based on their results, the strength of the rock is strongly affected by both strain rate and confinement. They also reported lower rate sensitivity at higher confining pressures. This work was continued by Zhao et al. [16] and further analyzed by Zhao [17], whose main conclusion was that at quasi static strain rates, the effect of confining pressure is not significantly affected by the strain rate. The effect of mineralogy on the strength and fracture behavior of the granite also plays a major role. Hogan et al. [12] found the quartz content to have a strong influence on the fragmentation of granites. The samples with higher quartz content tend to produce larger particles or less fractured rock mass during drop tower impact tests. The rock microstructure poses additional challenges for the mechanical characterization due to its anisotropic nature that can be due to preferred orientation of grains and/or microcracks or segregation of certain minerals along preferred bands or veins. For these reasons, the rocks are among the most challenging materials to study due to their complex and heterogeneous structure.

Experimental research combining both high impact rate and confinement is very challenging, and therefore various modeling approaches have been attempted. However, modeling and simulation require experimental data as input data for building reliable material models. For the low strain rate tests, standard testing methods combining large scale hydraulic materials testing machines and pressure cells for radial confinement are typically used for the characterization of minerals and rock type materials at various loading conditions [18]. However, applying the triaxial confinement at dynamic loading rates is more challenging. The split Hopkinson pressure bar (SHPB) is the typical device for obtaining material data at high strain rates [19,20]. Without special modifications, however, the SHPB devices can only be used for uniaxial loading in compression, tension or shear/torsion. Only few devices have been designed and built for dynamic loading with triaxial confinement, mainly due to the complexity of the test system. Christensen et al. [21] built the first testing devices in the 1970's for the dynamic testing of rock materials at confining pressures. Frew et al. [22] built an improved device based on the work carried out by Christiansen. The improved version of the confined SHPB device replaced the original servo-controlled hydraulic actuator for creating the reaction force needed to hold the bars together with a symmetric tie-rod reaction-plate assembly. These improvements reduced buckling of the stress bars and allowed shaping of the stress pulses. Other methods for imposing radial constraints on the sample include using a metallic sleeve around the sample [23]. However, in these experiments, the confinement is not constant during the test, and the analysis of the results requires additional strain gage measurements and numerical analysis of the whole bar-sample-sleeve assembly.

The development of new and more efficient drilling tools and technology for deep drilling requires reliable experimental data on the rock behavior at extreme conditions. This study brings additional data and understanding on how to break the rock efficiently. This paper presents results of a systematic series of compression tests carried out at quasi-static and dynamic strain rates at confining pressures of up to 225 MPa for Kuru Gray granite. The rock behavior at different conditions is analyzed, and the strain rate and pressure effects are quantified and discussed in detail.

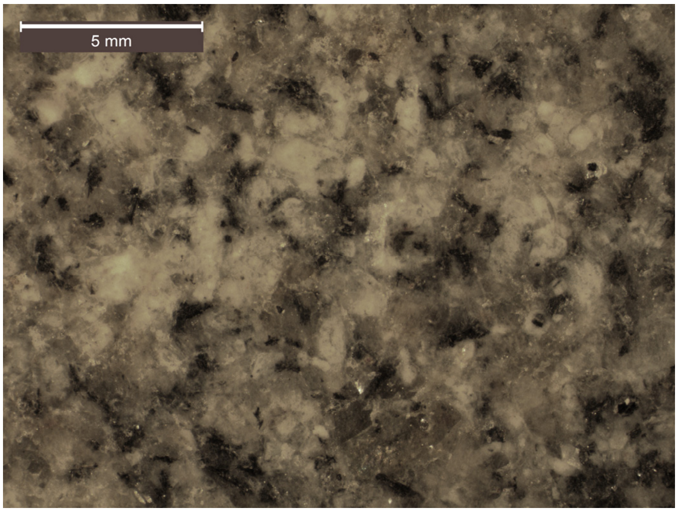

Fig. 1. Microstructure of Kuru Gray granite.

2. Materials and method

The material tested in this work was Kuru Gray granite from the Niemenkylä quarry in Finland. Kuru Gray is a texture free granite with small and equiaxed grains and essentially isotropic mechanical properties. The microstructure of a rock sample is shown in Fig. 1, and the nominal mineral composition is given in Table 1. The white or colorless grains in Fig. 1 are quartz, the gray areas are microline/albite, and the small black spots contain mica. Selected mechanical properties of the Kuru granite are shown in Table 2.

The rock samples were first core drilled from a large piece of Kuru Gray granite. The cores were removed, and the compression samples cut from the cores with a diamond disc cutter. The low rate compression test samples had a diameter of 54 mm and a length of 138 mm, whereas the high rate samples had an 11.8 mm diameter and an 11.6 mm length and a length to diameter ratio just below one. The low rate sample size and dimensions correspond to those suggested by the ISRM. There, however, are no standards for the sample sizes in the dynamic testing, where the sample length is

Table 1
Nominal mineral composition of the Kuru Gray granite [9].

Mineral	wt%
Quartz	35.3
Albite intermediate	30.4
Microcline	28.0
Biotite 1M Mica	2.9
Diopside	2.1
Chlorite IIb	1.3

Table 2
Selected mechanical and physical properties of Kuru Gray granite [8].

Property	Value
Quasi-static tensile strength	13 MPa
Quasi-static compression strength	230 MPa
Young's modulus	60 GPa
Poisson's ratio	0.2
Density	2600 kg/m^3