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TRIAXIAL EXPERIMENTAL STUDY ON CHANGES IN THE MECHANICAL PROPERTIES OF ROCKS UNDER DIFFERENT RATES OF CONFINING PRESSURES UNLOADING

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To determine the relationship between the unloading rate and the rock's mechanical properties, an experimental study on specimens of granite at different unloading rates was conducted. The results of the study show that during unloading, the axial strain increases slowly and the lateral expansion of the rock sample is considerable. The slower the confining pressure unloading rate, the more thoroughly the fissures propagate through the rock and the more complete the stress transfer. The result is that more fracture surfaces are produced and the rock is broken more fully. Conversely, if the confining pressure is unloaded more quickly, the crack propagation and stress transfer are terminated abruptly and the rock specimen can only generate a few rupture surfaces along the initial rupture direction. Rock samples are easier to break when unloaded at a greater rate, and the stress difference at break is smaller. Poisson's ratio increases with decreasing confining pressure. The research results provide a theoretical basis for the prevention and control of geological disasters in deep rock excavations.

Introduction

Deep underground excavations have advantages for effective exploitation of natural resources, expansion of infrastructure capacity, and environmental improvement. This trend has led to the development of deep underground transportation, energy extraction, and underground storage facilities including projects related to water conservation, hydropower, and sewage treatment [1]. Very deep excavations include the Kolar gold mine in India, a gold mine in Witva Garsland, South Africa, with a depth of more than 3000 m, and a maximum depth below the surface of 2500 m for tunnels at the Jinping II hydropower station in China. In China, the GDP of the eastern region accounts for more than 70% of the country's total GDP, and the demand for natural resources is huge. As a result, the shallow resources in this portion of the country have been mined and the mines have been successively deepened. There are coal mines with depths of more than 1,000 m in Shandong Province and the mine at Sun Village in Xinwen has reached 1350 m. The types of geological hazards encountered during construction at these depths differ, but the common factor for the geological problems is the unloading of the deeply buried rocks. The problems, and in some cases disasters, are manifested by rockbursts, water inrushes, coal and gas outbursts, and significant rock deformation.

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Excavation disturbs the stresses in the rock and leads to stress redistribution. Excavation is essentially just unloading the rock, but unloading is not simply loaded rock mechanics in reverse. The deformation and failure of rock masses during unloading are widespread in nature. The rockbursts that occur during or after the excavation of underground caverns where ground stresses are high are a typical type of deformation failure. The excavation increases the resulting stress differences, and the unloading of the rock mass in the elastic zone leads to failure in the strain softening zone [2-5]. Many factors affect the rock's strength, including the lithology, the stresses at the unloading points, the unloading stress paths, and the unloading rates. Many scholars have studied the mechanical properties of rocks during unloading [6-8]. Chen et al. [9] studied the influence of unloading confining compressive stress paths on marble deformation and rock strength. The results showed that different loading paths had little influence on rock strength but the paths changed the trajectory and form of the stress-strain curve. Wu Gang and Sun Wei [10] discussed the effect of the unloading rate on the strength of a fractured rock mass and found that the rock was stronger when the unloading rate was higher. Pettitt and King [11] conducted a uniaxial cyclic loading and unloading test to simulate a rockburst and studied the acoustic emissions before the rockburst. Their research results can guide rockburst prediction at project sites. Cai et al. [12] conducted field tests on the stresses and recorded the acoustic emissions at different depths in an arch excavated for the underground powerhouse at the Kannagawa hydropower station in Japan. They found that the excavation did not start at the initial stress point and when unloading began, σ_1 and σ_3 (the principal and subordinate stresses) changed at the same time. Gong et al. [13] used the discrete element method to simulate the relationship between the development of rock fractures during excavation and the excavation rate. They documented three stages of fracture formation and development. Research by Lu et al. [14] showed that when excavating deeply buried rock under high ground stresses the dynamic effect of excavation unloading cannot be ignored.

The main areas of current rock mechanics research are the fundamental mechanical properties of rock, the mechanics of constitutive relations, models and mechanical equations, mechanical analysis and calculation software, and some nonlinear disciplines. The research methods mainly include laboratory and field tests and stress-strain relations. Mechanical criteria and analytical and computational theories are all based on loading conditions and therefore do not address the deformation and mechanical strength degradation effects of different confining pressure unloading rates.

To study the effects of different unloading rates, this paper uses granite. There are many factors that affect rock strength during unloading, and using only one rock type as a test subject will avoid some of the many factors that can affect the test results. The influence of the confining pressure unloading rate on rock strength is of considerable significance for the evaluation and prediction of rock damage in deep rock excavations.

Experimental Procedures

To explore the influence of different unloading rates on the mechanical properties of rock, both triaxial loading and triaxial unloading tests with different loading and unloading rates were carried out. To ensure accurate control and precise measurements during the tests, a MTS816 pressure testing machine (MTS Systems Corp., Eden Prairie, MN USA) was used for the tests (Fig. 1). The confining pressure uses stress control, and the axial pressure uses displacement control. The system can measure sample axial and hoop strains and can measure and record data collected at a high rate. It is the rock mechanics test equipment with the most complete functions and the highest level of technology. The machine's frame rigidity is 10.5×10^9 N/m, the servo valve sensitivity is 290 Hz, the minimum sampling time is 50 μs, and the maximum axial pressure 4600 kN. A maximum confining pressure 140 MPa can be applied. The command flow of the servo control system is shown in Fig. 2.

The samples tested were dense, equigranular granites acquired from a stone processing plant. The specimens prepared from the samples were cylinders 50 mm in diameter and 100 mm long; the allowable deviation of end face irregularities was ±0.05 mm.

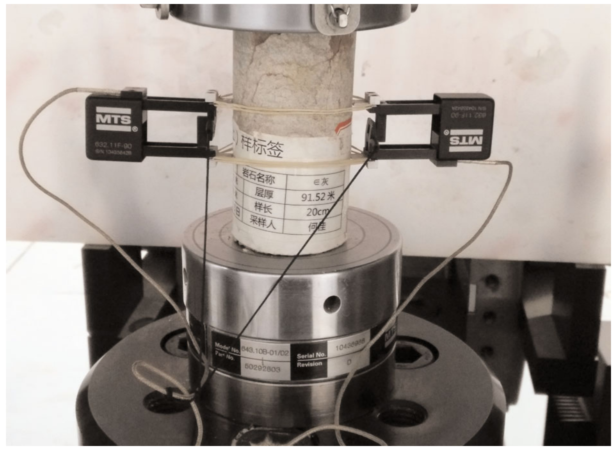

Fig. 1. MTS816 compression platen with a specimen and sensors.

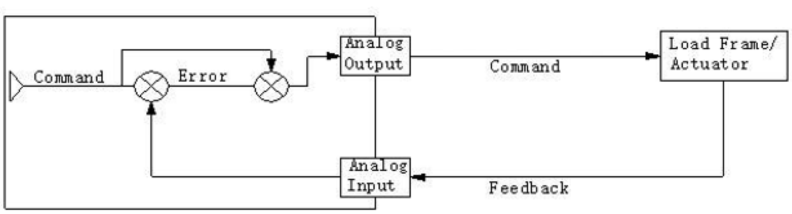

Fig. 2. Command flow of the servo control system.

Testing Program

Conventional uniaxial and triaxial compression tests were performed first to determine the specimen's mechanical parameters and their deformation failure mode. Different stress levels were tested against different confining pressure unloading rates and the results compared. The confining pressures used in these tests were 20, 30, and 40 MPa.

To keep axial pressure changes from influencing the confining pressure unloading test results, the testing procedure used the stress path of the confining pressure of the constant axis pressure relief. The steps for performing a confining pressure unloading test are listed below.

(1) With the specimen in the MTS816 test system, load the confining pressure to the predetermined value at a rate of 0.5 MPa/s.

(2) Keep the confining pressure constant and apply axial pressure at a rate of 0.5 MPa/s to the predetermined value. The predetermined value is 75%-80% of the specimen's peak strength at this confining pressure as determined by the conventional triaxial compression tests. Allow the specimen to equilibrate.

(3) Keeping the axial pressure constant, reduce the confining pressure at the predetermined confining pressure unloading rate until the specimen fails.

As mentioned, the confining pressures used in these tests were 20, 30, and 40 MPa. The three different confining pressure unloading rates tested were 0.01, 0.05, and 0.1 MPa/s.

Stress-Strain Analysis

Table 1 shows the results of the confining pressure unloading tests. To analyze the effect of the unloading rate on the mechanical properties of the granite specimens without having other factors affect the conclusions, we selected the same values for the other factors to be able to compare the tests without loss of generality. Three tests with a confining pressure of 30 MPa were selected, and the stress-strain curves for these tests are shown in Fig. 3. As can be seen, in the early loading stages, the original micro-fissures in the samples have been compacted and the samples are elastic. The rock body is subjected to high strain,

TABLE 1

Confining pressure unloading rates tested (MPa/s)	Sample number	Confining pressure (MPa)	Axial pressure (MPa)	Destruction of confining pressure (MPa)
0.01	X-2-1			15.2
0.05	X-2-2	20	269.85	9.8
0.1	X-2-3			7.7
0.01	X-3-1			23.5
0.05	X-3-2	30	300.24	14.7
0.1	X-3-3			12.3
0.01	X-4-1			31.5
0.05	X-4-2	40	351.27	21.2
0.1	X-4-3			18.9

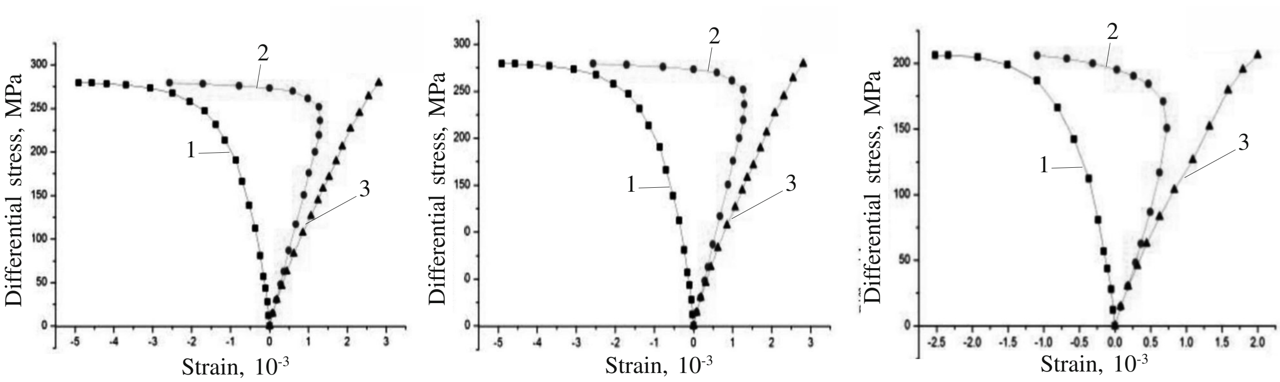

Fig. 3. Stress-strain curves for confining pressure unloading tests on three samples under a confining pressure of 30 MPa: a) 0.01 MPa/s; b) 0.05 MPa/s; c) 0.1 MPa/s; 1) lateral strain, 2) lateral strain, 3) lateral strain.

stress differences, and strains. Approximating a straight line, the rock sample has only a small amount of transverse strain, and the volumetric strain is positive. At this time, the rock sample is in compression. After the confining pressure begins to be unloaded, the lateral strain increases rapidly because of lateral unloading. Significant lateral expansion takes place but the axial strain increases only slightly. This differs from the loading tests. In the loading tests, rock failure is caused by axial compression deformation. In the confining pressure unloading tests, rock failure is caused by expansion in the unloaded directions; the rock's brittleness is more evident and the rock sample's surface displays large tension cracks. The slower the confining pressure unloading rate, the larger the final expansion of the rock sample. The slower the pressure release rate, the more time there is for the cracks in the rock to propagate and the stress transfer to be completed. More fracture surfaces will be generated, and the rock will be broken more fully. When the confining pressure is unloaded at a faster rate, crack propagation and stress transfer are less complete, only a few rupture surfaces are generated in the specimen in the initial rupture directions, and the damage is much more uneven. The faster the unloading is, the smaller the stress difference is when the rock sample breaks, which means that the rock sample breaks more easily when unloading occurs at a greater rate. For projects excavated deep underground, the rate of pressure unloading during excavation has an important influence on the stability of the rock. In an underground mine, reducing the disturbance of the surrounding rock can reduce the degree of roadway deformation and damage.(b) Confining pressure unloading rate 0.05 MPa/s

Effect of Confining Pressure Unloading Rates on Mechanical Parameters

A rock's mechanical parameters, such as elastic modulus E and Poisson's ratio μ, are generally defined by

$$E = d\sigma_1/d\varepsilon_1 \text{ or } E = \sigma_1/\varepsilon_1; \tag{1}$$

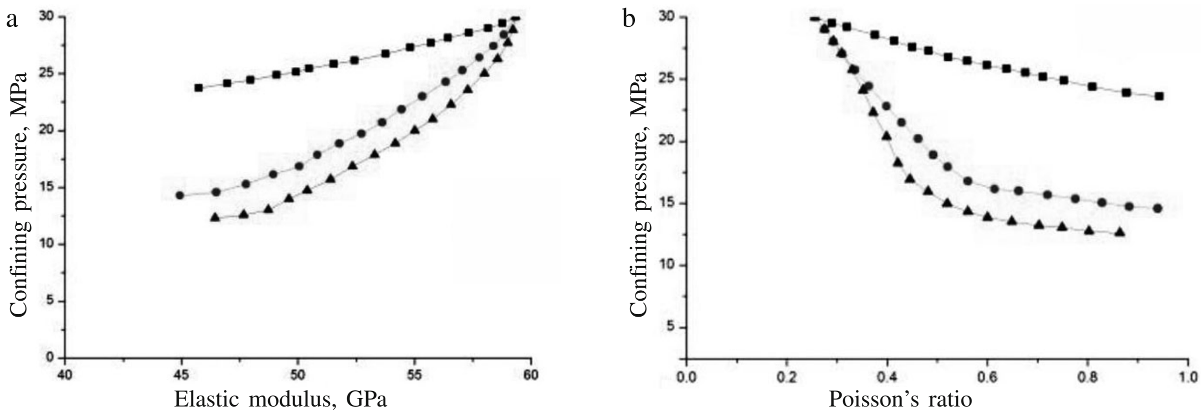

Fig. 5. Graph showing confining pressure vs. elastic modulus (a) and Poisson's ratio (b) for different confining pressure unloading rates: ■) 0.01 MPa/s, ●) 0.05 MPa/s, ▲) 0.1 MPa/s.

$$\mu = d\varepsilon_1/d\varepsilon_3 \text{ or } \mu = \varepsilon_1/\varepsilon_3. \tag{2}$$

In conventional triaxial tests, the axial pressure σ_1 can be replaced by $\sigma_1 - \sigma_3$ because the confining pressure does not change and the axial strain during unloading is very small. However, if conventional triaxial calculations are used to solve for the deformation parameters using the results from the confining pressure unloading tests, the deformation modulus will be very large, which is inconsistent with the actual situation. Therefore, the deformation parameters for the unloading tests should consider the influence of the confining pressure σ_3 and the lateral deformation ε_3:

$$E = (\sigma_1 - 2\mu\sigma_3)/\varepsilon_1; \tag{3}$$

$$\mu = \frac{B\sigma_1 - \sigma_3}{\sigma_3(2B-1) - \sigma_1}; \tag{4}$$

$$B = \varepsilon_3/\varepsilon_1, \tag{5}$$

where σ_1 is the lateral stress and B is the coefficient of lateral expansion.

The elastic modulus represents a material's resistance to being deformed elastically under a certain load and is commonly defined by the slope of the straight section on the material's stress-strain curve. For an ideal elastic material, the stress-strain curve should be completely replicable after repeated loading and unloading within the material's elastic limit. There should be no residual deformation after unloading and no hysteresis loop or lag of unloading deformation. After the loading exceeds the elastic limit and deformation enters the plastic stage, the stress-strain curve during unloading will have changed significantly because of the plastic deformation. For the granite specimens used in these experiments, the confining pressure-elastic modulus curves for different unloading rates are shown in Fig. 5a. As can be seen from the figure, the elastic modulus for the rock sample on each curve decreases as the confining pressure decreases. In addition, when the confining pressure unloading rate is low, the relationship between the two variables is more linear and the elastic modulus decreases rapidly. At faster pressure unloading rates, the elastic modulus' rate of decrease slows and the relationship between the elastic modulus and the confining pressure gradually becomes nonlinear. The faster the confining pressure unloading rate, the more distinct the nonlinear relationship.

The relationship between Poisson's ratio and the confining pressure during the unloading experiments is shown in Fig. 5b. The experimental results show that as the confining pressure decreases, Poisson's ratio increases, and as the confining pressure unloading rate increases, Poisson's ratio increases slowly. The rate of change of Poisson's ratio during the initial loading stages is relatively low, but at the limit of the specimen's strength, the rate of change increases rapidly. After specimen failure, Poisson's ratio is greater than 0.9 (the ultimate Poisson's ratio for an elastic-plastic material is 0.5). The Poisson's ratio at this time is different from that during uniaxial compression. During unloading and recovery, a large number of cracks are developed, and these cracks are almost perpendicular to the unloading directions; this causes the specimen to expand rapidly in a transverse direction.

Conclusion

For any work involving rock excavation, different amounts of damage caused by pressure unloading will occur. The mechanical properties of rock during unloading differ from the properties during loading. To study the mechanical properties and deformation mechanisms of rocks being unloaded, a laboratory testing method was developed. Under hydrostatic pressure, the confining pressure on a specimen was loaded to a predetermined value at a rate of 0.5 MPa/s and then, under different axial pressures, the confining pressure was unloaded at a 0.01 MPa/s rate. The deformation and strength of rock specimens at confining pressures unloading rates of 0.05 and 0.1 MPa/s were also studied. The main conclusions from this study are:

(1) during unloading, the rock specimen undergoes significant lateral expansion and the axial strain increases slowly. The damage to the specimen during loading is caused by the axial compressive deformation, but the rock specimen fails during unloading. Failure is due to expansion in the unloading directions.

(2) the slower the confining pressure release rate during unloading, the larger the final expansion strains in the rock sample. The slower release rate allows sufficient time for the propagation of cracks in the rock and the transfer of stress is completed. More fracture surfaces are produced and the rock is thoroughly fragmented. When the confining pressure is reduced more quickly, the crack propagation and stress transfer are incomplete and only a few rupture surfaces are generated along the initial rupture direction. The fracturing is interrupted when the confining pressure goes to zero. Rock samples are easier to break when unloaded at a greater rate, and the stress difference when the rock breaks is smaller. For deep underground excavations, the excavation rate has a considerable influence on the stability of the rock. Reducing the damage to the surrounding rock can reduce the number or severity of engineering disasters.

(3) during unloading, as the confining pressure decreases, the elastic modulus decreases steadily. When the confining pressure reduction rate is slow, the relationship between pressure reduction and the elastic modulus is approximately linear, but as the rate is increased, the linear relationship gradually becomes nonlinear. The faster the unloading rate, the more nonlinear the relationship becomes and the slower the elastic modulus decreases. In addition, Poisson's ratio increases with decreasing confining pressure. The faster the confining pressure release rate, the slower the increase in Poisson's ratio and the slower the rate of change. However, when the confining pressure goes to zero, the rate of change increases rapidly.

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