Impact of confining pressure and orientation of discontinuities on the behaviour of jointed rock mass

P Jarczyk
Silesian University of Technology, Faculty of Mining and Geology, 2 Akademicka Street, 44-100 Gliwice, Poland
E-mail: patrycja.jarczyk@polsl.pl

Abstract. The article deals with issues of rock and rock mass mechanics. The subject of the publication is the behaviour of rock samples with singular discontinuities under three-axial compression conditions, with pressures up to 30 MPa. The effect of confining pressure and orientation of discontinuities in the directions of external loads (30°, 45° and 60°) on the behaviour of discontinuous rock was investigated. It was shown that with the increase of confining pressure, the strength of the samples increases linearly, and higher angles at which the discontinuity is oriented correspond to higher durability.

1. Introduction
Meeting the requirements of economics and safety in the design and implementation of all engineering projects related to mining activities, underground construction and tunnel design is possible only if knowledge of the structure and mechanical properties of the rock mass in the vicinity of the exploitation or construction area is available. There is a huge amount of knowledge about the behaviour of rocks under the conditions of a complex state of stress, but all known theories and endurance conditions refer almost exclusively to unbroken, homogeneous rock masses, with which in practice we deal with extremely rarely. However, knowledge of behavioural properties of fractured rock masses is neither complete nor well-established. In particular, this applies to the behaviour of the rock mass faulted by areas of weakness, fissures or crevices under conditions of great depth. Meanwhile, at the design stage in mining and geo-engineering, numerical models of rocks and rock mass are being used more and more often. To simulate the behaviour of the rock mass in the vicinity of excavations and structures made in a rocky environment, more and more advanced programs and computers with high computing power are used. In this case, the success of numerical analysis is determined more and more by the choice of a proper physical models of the rock mass and reliable determination or estimation of material constant values present in the model. This is particularly important when programs designed for continuous media are used to model the behaviour of a rock mass affected by discontinuities. In such cases, if the values of material constants introduced into the models are determined on the basis of laboratory tests carried out on small samples of undamaged rock material and/or low external loads, this may lead to serious errors in the assessment of rock mass behaviour and stability of excavation and structures made and maintained therein [1, 2].

The research carried out in the last fifty years by scientists around the world has shown the importance of quantity and orientation of discontinuities in the model and how confining pressure affects the strength and deformability of models [3, 4, 5]. The types of destruction as well as the types and shapes of the obtained characteristics have been described [6, 7, 8]. It should be emphasized that, in
majority of cases, models constructed from substitute materials (gypsum, concrete and other mixtures) were used for the research. Few studies have been carried out on the behaviour of real rocks damaged by discontinuities, and those made so far were usually carried out at low confining pressures or normal stresses [9, 10].

2. Program and methodology of research on the behaviour of discontinuous rock mass
The article presents research on conventional tri-axial compression of fine-grained sandstone which frequently accompanies coal seams. For the purpose of the tests, samples were prepared in such way that they contained discontinuities and had smooth walls obtained by cutting an intact rock sample with use of a diamond disk. The discontinuities were oriented at 30°, 45° and 60° to the vertical axis of the sample (figure 1).

![Figure 1. Samples with discontinuities oriented at different angles to the vertical axis.](image)

For the three-axial compression tests, a KTK-60/2 three-axis chamber and a SHM-MG 250/4 servo-controlled hydraulic testing machine were used.

A hydrostatic state of stress was first created \(\sigma_1 = \sigma_2 = \sigma_3 = p\) in the rock samples with singular discontinuities placed in the tri-axial chamber, which corresponded to the desired confining pressure \(p\) (from 5 to 30 MPa). Then, by keeping the pressure at a constant level, the samples were deformed by a constant displacement of the piston of the testing machine (0.002 mm/s).

3. Presentation and discussion of the results of experimental research
As a result of conventional tri-axial compression laboratory tests carried out on rock samples faulted with singular discontinuities, differential stress (\(\sigma_1-\sigma_3\)) and axial displacement (\(\lambda_z\)) characteristics were obtained. Depending on the angle at which the discontinuity was oriented, the test was terminated when a macro-fissure or large axial displacement occurred. In the case of samples with 60° orientation of discontinuities, the test was terminated when a macro-fissure appeared in the rock material. In the case of samples with 30° and 45° inconsistencies, no macro-fissures appeared, so laboratory tests were terminated when the axial displacement reached the length of about 2.5 mm. On the basis of the obtained characteristics, the following values which characterize the behaviour of rock samples were determined:

- linear longitudinal stiffness coefficient (figure 2), i.e. the directional coefficient of the linear parts of the characteristic,
- secant longitudinal stiffness coefficient (figure 3), corresponding to the strength limit, i.e. the directional inclination coefficient connecting the origin of the coordinate system to the top of the curve,
- values of stress and strain at the slip point (i.e. the point where the stress characteristics slope changes – the displacement occurs),
values of stresses for displacements from 0.5 mm to 2.5 mm,
- limit values of stresses in cases when the strength of the rock material was exceeded and the sample was subjected to macro-cracking,
- maximum values of stresses in cases where fissures did not appear.

![Figure 2. The method of determining linear stiffness coefficients from bimodal characteristics.](image)

![Figure 3. The method of determining the linear and secant stiffness coefficients from the characteristics of samples that have cracked.](image)

The conducted tests allowed to obtain information on the effect that the inclination angle between the discontinuity plane and the sample axis and the confining pressure have on the behaviour of simple cracked rock mass models under tri-axial compression.

The deformation of samples with fissures that are oriented to the vertical axis of the sample at 30° and 45° angles is bimodal. A so-called slip point (figure 4a, b) appears in the differential stress ($\sigma_1-\sigma_3$) and axial displacement ($\lambda_z$) characteristics. This is the point where the characteristics slope changes. Below the slip point, the sample has high stiffness due to slight deformation of the rock material. Above this point, one part of the sample slips in relation to the other and that process is intermittent. It is
associated with temporary increases and decreases in differential stress due to the step motion of one part of the sample in relation to the other [6, 11, 8].

Figure 4. Differential stress ($\sigma_1-\sigma_3$) – axial displacement ($\lambda_z$) characteristics for samples cut at a) 30° and b) 45° angles.

Slipping on the cracked plane oriented at an angle of 60° to the vertical axis of the sample is negligible; continuous deformation of rock material dominates the process. Differential stress - axial displacement characteristics of fractured samples with 60° angle orientation are the same as in the case of intact rock samples (figure 5).
Figure 5. Differential stress ($\sigma_1-\sigma_3$) – axial displacement ($\lambda_z$) characteristics for samples cut at 60° angle.

The process of deformation of samples weakened by a 60° angle fracture causes excess of the limit strength of the rock material and the occurrence of the shear macro-cracks, which usually appear in triaxially compressed samples of intact rock material (figure 5).

The strength of the samples increased linearly with the increase of the confining pressure (figure 6).

Figure 6. Effect of discontinuity orientation on strength
The values of the longitudinal stiffness coefficient grow significantly with the increase of the confining pressure. For example, in the case of the samples with a 30° fracture, the longitudinal stiffness coefficient in the pre-slip stage (kl1) increased, at pressures ranging from 5 to 20 MPa, from approx. 30 MPa/mm to approx. 110 MPa/mm.

**Figure 7.** Effect of confining pressure and discontinuity orientation (30°, 45°) on longitudinal stiffness of samples.

**Figure 8.** Effect of confining pressure on longitudinal stiffness of samples affected by 60° angle of discontinuities.

Higher inclination angles between the discontinuity and the vertical axis correspond to greater longitudinal stiffness of the sample. For example, in the case of test samples with a pressure of 20 MPa,
the values of linear longitudinal stiffness coefficient (kl2) of the advanced stage of deformation were as follows: 6 MPa/mm for 30° orientation, 32 MPa/mm for 45° orientation (figure 7) and 101 MPa/mm for 60° orientation (figure 8).

Samples with discontinuities oriented at the angle of 60° were destroyed (macro-cracks in the rock material), which allowed to determine their secant stiffness coefficients corresponding to the strength limit (ks). The largest values, equal to 92 MPa/mm, corresponded to a pressure of 5 MPa and decreased to 78 MPa/mm at a pressure of 20 MPa (figure 8).

4. Summary
To summarise the results of tests on rock samples fractured by singular discontinuities which were subjected to tri-axial compression, it was found that their strength grows with the increase of the confining pressure. Higher values of the angle at which the discontinuity is oriented towards the axis of the sample corresponds to higher strength. The rate of strength increase is the greatest for samples with cracks oriented at the smallest angle (30°) and decreases with the increase of this angle. (figure 6).

The values of the longitudinal stiffness coefficient increase significantly with the increase of the confining pressure.

The laboratory test results presented in this paper are consistent with those in the contemporary literature. Both the strength and stiffness coefficients increase with a rise of the confining pressure [12, 13, 14, 15, 16, 17, 18]. Such consistency can be obtained in terms of trends in the behaviour of models affected by discontinuities, because, as mentioned earlier, studies on the behaviour of samples affected by discontinuities under tri-axial compression were most often carried out on composite materials and at low confining pressures.

5. References
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