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Experimental and numerical research of jointed rock mass anisotropy in a three-dimensional stress field

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Abstract

Joints often have a significant influence on material characteristics. The discontinuities' coalescence mechanism and complex jointed rock mass structure as a composite need to be further explored. In this study, compression and shear tests were carried out on a jointed rock mass. The purpose of the jointed rock mass behaviour study was to determine the deformation-strength dependencies and to determine the parameters for a quantitative assessment of the joints' influence on mechanical characteristics. The results show that compression strength depends on the materials' structure, and there is a detailed description of the joints' orientation influence on stress-strain dependencies during compression experiments. The numerical method used in this study could be used for the modelling of composite materials and their properties.

Keywords:

jointed rock mass; discontinuities; numerical simulation; uniaxial compression strength; anisotropy

1. Introduction

A rock mass and its mechanical properties are the main object of study for solving problems of rock mechanics. In a rock mass there is a redistribution of the stress state as a result of the development of underground space, so a prerequisite for geomechanical studies is to obtain a set of data on the stresses, structural parameters and mechanical properties of the rocks and the rock mass itself, which is composed of rocks. This issue is fundamental and is considered when solving any practical geomechanical problem. In laboratory conditions, it is possible to obtain rock sample parameters and the geotechnical task is to obtain the mechanical parameters of a jointed rock mass. The mechanical properties of the rock mass are quantitatively less than those of the rock sample. The rock mass is characterized by the existence of distributed joints whose properties and geometry strongly affect the mechanical behaviour of jointed rock masses (**Yang et. al., 2015**). It is of great importance to study the failure process and scale the effect of the jointed rock mass in the field of rock mechanics and mining engineering (**Wang et. al., 2016**).

Specific conditions of rock formation and bedding convey the structural and mechanical features which cannot be determined in practice by tests of samples separated from the rock mass. The experimental results of rock mechanical properties are paradoxical from the point of view of classical theory. Deformation modules determined upon compression of large prisms of the rock mass were by 50-100 times lower than those determined for regular samples and the coefficient of transversal deformation was higher than 0.5 (**Stavrogin and Protosenya, 1985**). These results can be explained only by accounting for the specific features, specific for the rock mass under its conditions of its natural existence. The presence of discontinuities in the jointed rock mass is the main reason for quantitative mechanical property differences. The formation of rock discontinuities is generally associated with tectonic processes, magmatic activity, sedimentation, and weathering processes (**Yanuardian et. al., 2020**).

Real rocks are always characterized by a structure comprised of grains interacting along various defects, cracks, and pores. The heterogeneity of a medium always adds significant divergence between the experimental results and classical theories. It has been experimentally established that the strength of real materials is always by 10^2-10^3 times lower than the theoretical strength calculated by the condition of overcoming the interactions between single atoms of the crystalline lattice. Experimental studies were carried out by Volkov (**Volkov, 1960**) Brady (**Brady, 1969; Brady, 1970**), and others (**Barton, 2013; Sánchez-Martín et. al., 2020; Smirnova et. al., 2021**).

The heterogeneity of a jointed rock mass exerts a significant influence on its mechanical behaviour, which is

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stipulated by numerous reasons: heterogeneity of composition and physical state caused by lithological variations of the rock mass, the layering pattern, orogeny, discontinuities, including separate large violations and the crushing zone, as well as weathering, hydrogeological regime, heterogeneity of the stress state of the rock mass related to natural and technogenic factors, scale heterogeneity, stipulated by qualitative and quantitative differences of rock properties in selected bulks of various sizes.

Studies of strength, deformation, and destruction of rocks are based on experiments. The most complete data on strength, deformation, and destruction of rocks under volumetric stress state with consideration for the influence of deformation speed, moisture content, temperature, and filtrating properties are presented in the monographs (**Stavrogin and Protosenya, 1979; Mirzaev et. al., 1984; Stavrogin and Protosenya, 1985; Stavrogin and Protosenya A.G., 1992**).

Under the action of static and dynamic loads, the rocks around mining areas are transferred into an ultimate state and destroyed under conditions of heterogeneous volumetric stress state; in addition, dynamic destruction of rocks occurs in the form of rock and sudden bumps. Therefore, the issues of the stability of underground facilities with consideration for the jointing of a rock mass are especially important for the mining industry (**Trushko, 2019; Kozlovskiy, 2021; Kiselev et. al., 2021**). Their solution influences investments in mining projects, mining technologies, the safety of mining operations, and the profitability of mining companies (**Morozov et. al., 2019**). The mentioned issues are related to the analysis of geomechanical processes in rock masses using equations of state from the initiation of loading and up to complete loss of bearing capacity upon variation of the stress state. Herewith, it is nearly impossible to analyze the superlimit stage of the deformation of a rock mass under laboratory or natural conditions.

Nowadays, scientific investigations based on real and virtual experiments are intensively carried out. Numerical simulation provides a cardinally different approach to the solution of the predetermined problems in comparison with the aforementioned approaches since it allows for the introduction of a higher number of active factors and a more real state approach for the rock mass (**Stavrogin and Protosenya, 1979; Ignatiev et. al, 2019**). Such research of geomechanical predictions leads to a reduction of geotechnical risks caused by a high level of uncertainties (**Korshunov et. al, 2020**).

At present, the design concepts of underground facilities and mining areas are deeply modified. Designers and developers are not satisfied with designing by analogy comprised of the reproduction of previous successful underground structures. Moreover, complicated conditions of underground construction (permafrost, high seismic activity, high depths, geotectonic phenomena, etc.) leave few possibilities to design by analogy.

At the same time, requirements for the development of underground structures, their substantiation, correspondence to physical essence of the phenomena and mechanical processes become more and more stringent. Designing is no longer based on empirical equations, but the application of numerical methods of solid-state mechanics upon the solution of actual engineering tasks is widely accepted.

Taking this into account, a jointed rock mass should be reasonably considered as a noncontinuous and anisotropic medium during the analysis of mechanisms of its destruction. From a practical point of view, it is important to have an idea of the real distribution of stress and strain tensors in the rock mass, so it should be concluded that the solving of geomechanical problems in the jointed rock mass requires a special approach to the design. In this paper, we consider first-order anisotropy due to the ordered bedding of rocks in the form of a series of blocks separated by tectonic fractures.

2. Experimental studies of mechanical properties of rock

Hard monolith rocks characterized by the nearly complete absence of, or at least 2-3 explicit systems of tectonic discontinuities were selected for studies based on petrographic and strength properties. Studies of the selected hard monolith rock characterized by a nearly complete absence of discontinuities were carried out under uniaxial compression of cylindrical (the length of the cylinder was equal to 2-2.5 of its diameter, the diameter was from 50 to 70 mm) and cubic samples (50´50´50 mm). Tests were performed according to the Russian standard «Rocks. Methods for determination of axial compression strength». Fifty-two (26 for samples from Tekeli Mine and 26 for Krivoi Rog Basin Mine (see **Figure 1**)) uniaxial compression tests were performed on rock samples. Cylindrical samples were produced of cores. In order to measure longitudinal and transversal deformations, DC resistance sensors were fixed on the side surfaces of samples. The load was increased step by step during the tests. The ultimate strengths of mined rocks upon uniaxial compression varied in the range of 160-330 MPa. Such a wide range of variations of strength properties was attributed to the variance of rocks in terms of material composition and properties of structure and texture. Shaly bedded rocks were characterized by a significant divergence of strength properties. Herewith, with a decrease in the general strength of rocks, this difference became more noticeable, i.e. the anisotropy coefficient of rock decreased upon compression (see **Figure 1**). The anisotropy coefficient was defined as the ratio of the ultimate strength of rocks upon loading parallel to the lamination plane and the ultimate strength under loading perpendicular to the lamination. **Figure 1** illustrates variations of the anisotropy coefficient for rocks of various material composition based on

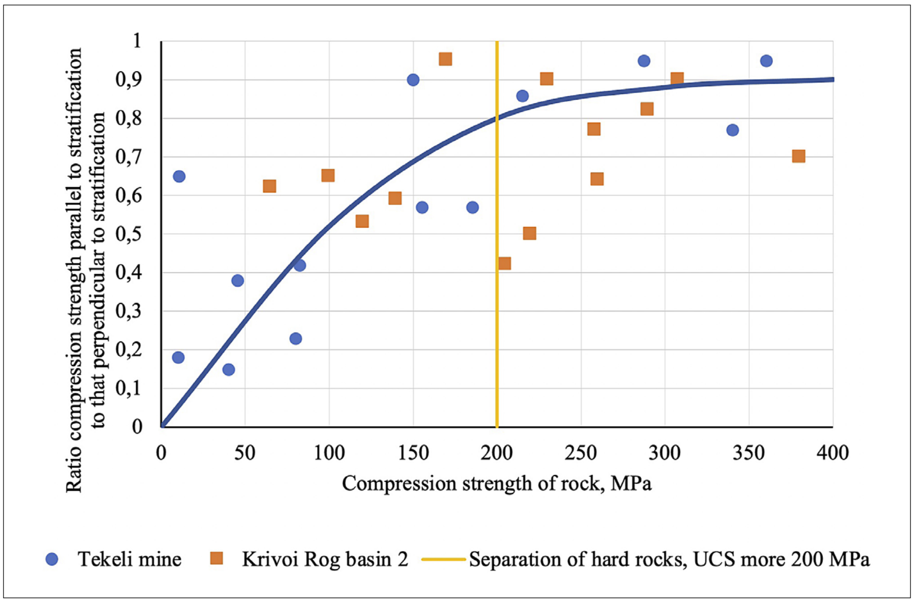

Figure 1: Variation of anisotropy coefficient of rock strength upon uniaxial compression

Figure 2: MTS816 rock mechanics experimental system

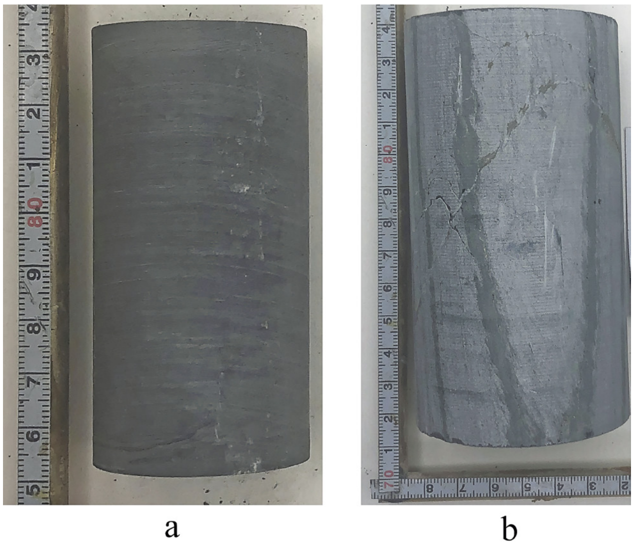

Figure 3: Rock samples: (a) - rock stratification across the sample axis, (b) - rock stratification along the sample axis

the data for Tekeli Mine (blue circles in **Figure 1**) and Krivoi Rog Basin (orange squares in **Figure 1**, **Mirzaev et. al., 1984**). Tekeli Mine is located 310 km from Almaty and 40 km from Taldykorgan (Kazakhstan), Krivoi Rog Basin is in the Dnepropetrovsk region of Ukraine.

Rocks with a uniaxial compression strength (UCS) less than 200 MPa have explicit discontinuities of tectonic origin, in terms of the quantitative-mineralogical composition and tectonic features, these rocks are characterized by their variety and distinguished by an increased content of carbonaceous, clayey and similar materials which reduce the cohesion between grains and crystals. The presence of the above factors is the reason for the manifestation of the uniaxial compression strength anisotropy for rocks with UCS less than 200 MPa (see **Figure 1**).

Rocks with a UCS of more than 200 MPa are characterized by solidity, the absence of discontinuities. This characteristic of hard rock is the reason for the less pronounced anisotropy of uniaxial compression strength in average 0.7-0.95 (see **Figure 1**).

2.1. *Rock destruction during uniaxial compression tests*

The MTS816 rock mechanics experimental system (see **Figure 2**) was used to investigate the strength of the rock. The MTS Model 816 system is engineered for rock mechanics research testing that involves rock samples. It can be configured for uniaxial, triaxial or direct shear testing, and its compact frame is easy to locate in the lab. The examples of rock samples are shown in **Figure 3** (**a**) with rock stratification across the sample axis

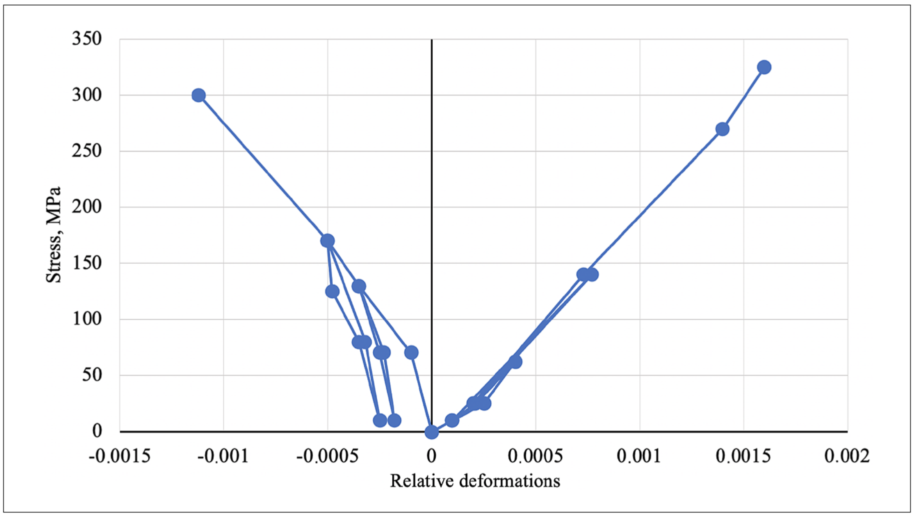

Figure 4: Uniaxial rock compression perpendicular to stratification

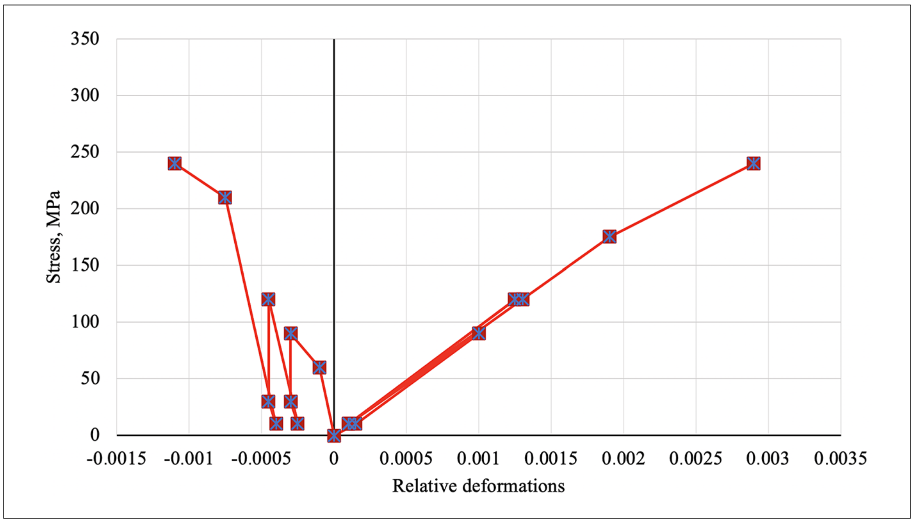

Figure 5: Uniaxial rock compression parallel to stratification

and **Figure 3** (**b**) with rock stratification along the sample axis.

The diagrams of deformation of hard rock samples under load are shown in **Figure 4** and **Figure 5**. The tests were performed with sample unloading at the elastic stage of deformation aimed at the determination of the most correct dependence of deformation at the sublimit stage. The axial main stress $\Delta\sigma_1$ is shown on the vertical axis. The right side of the horizontal axis shows relative deformations (linear deformations along the vertical) ε_1, the left side shows relative transversal deformations ε_2 (linear deformations in horizontal plane). ε_i is determined by **Equation 1**:

$$\varepsilon_i = \frac{\Delta\varepsilon_i}{\varepsilon_b} = \frac{\varepsilon_f - \varepsilon_b}{\varepsilon_b} \qquad (1)$$

where:

- ε_i – the main axial deformations ε_1 or ε_2;
- $\Delta\varepsilon_i$ – the relative elongation along the considered direction;
- ε_f – the deformation determined by variations along the considered direction;
- ε_b – the initial size of tested sample.

2.2. Analysis of over limit stage of hard rock deformation

Analysis of the complete stress-strain diagrams, including the super limit region is located beyond the ultimate strength which makes it possible to detect the overall reserve of bearing capacity, while taking into account this ultimate case when failure surfaces are formed in the material with a complete loss of coherence, and the resistance against external loads is generated by friction forces on the surface of destruction. These considerations result in the assumption that a jointed rock mass can be hypothetically simulated by the model of a rock sample at the super limit deformation stage, when failure takes place along the generated weakening surfaces. Therefore, further stages were devoted to analysis of the super limit deformation stage of rock.

A highly rigid press provides the possibility to control deformation beyond the ultimate strength, that is, to apply such an amount of power to a sample which is sufficient for its destruction. Therefore, a sample in a rigid press never has a dynamic nature of destruction. Deformation takes place without sound and dynamic effects

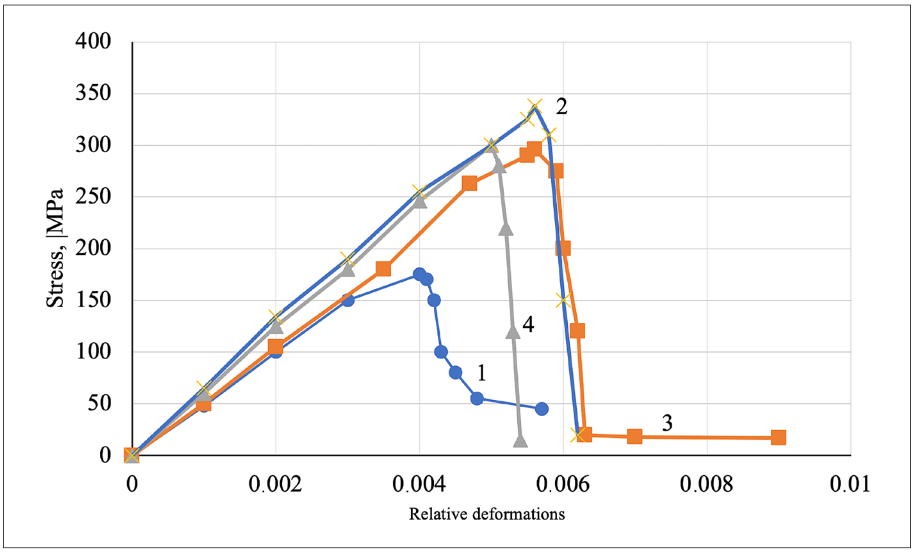

Figure 6: Stress as a function of deformation of rocks: (biotite granite (1), biotite plagiogranite (2), plagiogranite (3), diabase (4))

Table 1: Experimental mechanical properties of rocks

№	Rock type	E, GPa	M, GPa	σ_p, MPa	σ_e, MPa	$\Delta\varepsilon_1^p$	$\Delta\varepsilon_1^a$	ν
1	Biotite granite	55	185	175.0	144.0	0.63	0.63	0.17
2	Biotite plagiogranite	57	417	293.0	250.0	0.36	0.36	0.24
3	Plagiogranite	60	800	335.0	290.0	0.2	0.2	0.18
4	Diabase	67	1300	295.0	260.0	0.28	0.28	0.22

up to a complete loss of bearing capacity. After the achievement of ultimate strength in a low rigid press, a sample is deformed by elastic energy accumulated in the loaded parts of the press. Thus, the process becomes uncontrollable. The sample is destroyed violently and sometimes explosion-like. This takes place because the amount of accumulated energy is high. This leads to dynamic effects accompanying the failure of brittle material. The experimental data (see **Figure 6**) were obtained through the use of a press with a rigidity of $2\cdot10^{10}$ N/m, which was provided by a solid metal frame, wedge loading self-braking pair, and pulsed hydraulic system in the body.

The experimental data on strength and deformation properties of rocks are summarized in **Table 1**: Young module E, module of decrease M, ultimate strength and ultimate elasticity, deformations ε_1^p and ε_1^a, and Poisson ratio ν.

Material brittleness is determined by the decrease slope of a deformation curve at the superlimit stage of deformation. The module of decrease of brittle rocks upon uniaxial compression can be more than two times higher than Young's module of these rocks, which is generally in the range of 10^5 MPa.

2.3. Numerical geomechanical model of jointed rock mass failure

Numerical approaches with the application of discrete medium mechanics make it possible to consider using them for the analyzation of the complexity of structures designed in a jointed rock mass, and the necessary condition for this is detailed information about the geological structure and the rock mass structure at this site. Underground space during mining or during the implementation of projects of underground construction can include the existing facilities interacting between each other or being designed with a complex spatial location. Conventional methods of geomechanical analysis based on analytical and semi-empirical procedures partially allow for the consideration of the features of development of geomechanical processes in the vicinity of underground facilities. The application of numerical methods for the analysis of complex spatial structures of underground facilities with the required high reliability is not a completely solved issue, where the accumulation and analysis of knowledge are still in progress, however, this approach has extremely important advantages (**Min et. al., 2003**). Numerical analysis, contrary to classic procedures, is well adopted to solve 3D problems (**Ivars et. al., 2011; Yang et. al., 2015**). At present, the capacity of modern highly efficient equipment allows for the prediction of the expected geomechanical processes in the vicinity of underground facilities of complex 3D configuration without significant simplifications, with consideration of the stages of their construction and complicated behaviour of the rock mass (**Esmaieli et. al., 2010**).

Numerical models and predictions are analysed in this work using the theory of elasticity, plasticity, and the theory of destruction. The experimental methods are used for various aims:

- to obtain and to verify physical equations of state and determination of quantitative mechanical properties of rocks and rock masses;
- to analyse models of behaviour of rock mases, which can hardly be analytically predicted;
- to verify assumptions upon construction of flowcharts and to introduce empirical coefficients into predictions in order to compensate imperfections of these flowcharts;
- to analyse qualitative and quantitative deformation patterns of a rock mass using numerical models (**Amadei, 1988**).

During elastic deformations in a rock mass, the existing jointing system is being developed. It should be mentioned that the value of failure deformations of highly jointed rocks is 50-100 times higher than the failure deformations obtained under laboratory conditions for rocks, which can be attributed to determining the influence of discontinuities, properties along contacts. As demonstrated by the studies under natural conditions, the existence of numerous cracks significantly weakens the elastic properties of a rock mass. The coefficient of weakening of elastic properties (the ratio of the ultimate elasticity to the ultimate strength of a sample) varies in the range of 0.02-0.16. The elasticity module decreases for hard low-jointed rocks by 8-15 times and for high-jointed rocks by 250-400 times (**Mirzaev et. al., 1984**).

The formulated problem was solved by mathematical simulation using the finite element method in Simulia Abaqus software where the rock strength was determined by the Coulomb conditions, and the mechanical behaviour along the interaction contact of rock blocks was described by the Barton nonlinear strength criterion. The jointing systems were selected for analysis, which generated mass structure with the block sizes from 0.02×0.05×0.03 m to 0.3×0.5×0.4 m and from 0.4×1.3×0.5 m to 1×1.5×1 m. The constructed geomechanical models were applied for the selection and development of a predicting flowchart: the model for predetermined initial and boundary conditions; the size of the considered area was selected, and the method of analysis of the occurring mechanical processes in the mass was determined.

From a practical point of view, attention should be paid only to the analysis of complete stress-strain diagrams of the rock mass including its descending (super limit) branch. This condition is possible when a jointed rock mass is simulated in discrete formulation.

While applying the proposed procedure, a rock mass is considered as a discrete medium, and a numerical experiment is carried out according to the flowchart of preset deformations. Upon implementation of the flowchart of preset deformations, when vertical movements are applied to a sample of a jointed rock mass fixed on an absolutely rigid plate, the stresses on contact between the rock blocks in the sample increase, which leads to rock mass sample deformations, and propagation of shearing discontinuities. If the stresses exceed the ultimate value, the links between the blocks are broken, the blocks are capable of moving regardless of each other, leading to the development of deformations and failure of the discrete medium. In order to analyse the anisotropy of a jointed rock mass's mechanical properties, the numerical models were constructed with a width of 4 m and a height of 8 m, where the discontinuities' inclination angle rotated at an increment of 15°. These studies were performed with hard rocks characterized as follows: ρ= 2760 kg/m^3, elasticity module E=50 GPa, Poisson ratio ν = 0.255, angle of internal friction φ = 27°, and cohesion c = 30 MPa.

3. Results

3.1. Simulation of mechanical interactions between rock slabs along a discontinuity

The mechanical processes occurring in a jointed rock mass are characterized by increased deformation, which is expressed in exceeded relative deformations regarding a reference rock sample. This takes place due to the movement of structural blocks regardless of each other. Herewith, on the contact between them, which can be continuous, pointwise, or local, friction forces (shearing stresses) appear. To correlate vertical stresses acting along a normal to crack plane and friction forces, Barton developed the first nonlinear strength criterion based on numerous experiments (**Barton, 2013**).

The following mechanical performances were experimentally determined upon contact interaction of rock blocks: the residual angle of internal frictions was 28°, cohesion was 4.9 kg/m^2, and the compression strength of the discontinuity wall was 20 MPa. The results of shear tests are illustrated in **Figure 7**.

Therefore, it would be reasonable to describe the behaviour of rock on interaction contact between blocks along a discontinuity by using the Barton nonlinear strength criterion (**Barton, 2013**). Since cohesion of rock on a discontinuity surface is nearly absent, in the case of continuous surfaces of extended cracks, the shearing stresses can be accepted only by friction. Shear resistance in this case will be described by **Equation 2**:

$$\tau_{ult} = \sigma_n \cdot tg(JRC \cdot \lg \frac{JCS}{\sigma_n} + \varphi_{res}) \tag{2}$$

where:

JRC – the coefficient of discontinuity roughness;

JCS – the compression strength of a discontinuity wall, MPa;

σ_n – the normal active stress, MPa;

φ_{res} – the residual angle of friction, degrees.

Studies have demonstrated that upon impingement of two rough surfaces, the surface area of real contacts is

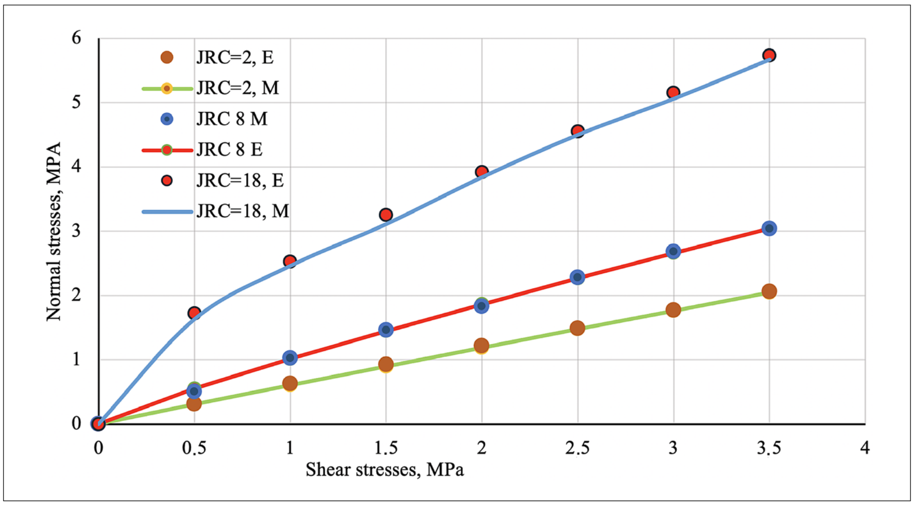

Figure 7: Certificate of rock strength in terms of interaction contact at various parameters of discontinuity roughness, where E: experimental results, M: simulation results of shear test

nearly zero and the contact stresses occur only in contacting points. With an increase in normal load, the surface area of contact increases because of the elastic deformation of roughness irregularities and their subsequent destruction. The Barton nonlinear strength criterion applied to the surface contacts of rock blocks (**Equation 2**) upon simulation in Simulia Abaqus software allows for the obtainment of high agreement with experimental data, the error is not higher than 0.5%.

3.2. Numerical experiments of uniaxial compression of jointed rock mass

Jointed rock masses as subjects of investigations are characterized by a significant mechanical feature: the existence of stress state before the initiation of mining works. This feature complicates the application of an analytical solution, and in the case of discrete formulation of the problem, the solution is impossible. The initial stress state of a rock mass is, in general, a function of spatial and time coordinates. Thus, the factors influencing on its formation should be reasonably subdivided into those acting constantly and everywhere and those acting temporarily and locally. The authors consider only the first case, namely: gravitational field, physic-mechanical properties, and structural and mechanical features. This work discusses the progressing regime of jointed rock mass failure, which is manifested in a comparatively long time interval and its results are a gradual release of energy characterized by an increase in the number of discontinuities and their propagation along and inside rock blocks.

During deformation, first micro shears take place, which lead to the formation of tearing microcracks (**Yakovlev et. al., 2021**). At the next deformation stage, strengthening takes place leading to an increase in stresses in the mass. Then the shear deformations are accompanied by the generation of voids and an increase in the volume. These two processes determine the ultimate strength of the jointed rock mass. Therefore, at the initiation of loading, the deformation of rock mass is linear (see **Figures 8** to **15**). When the ultimate elasticity is achieved, regions of irreversible deformations appear, which continue up to the ultimate strength corresponding to the maximum load. At this stage, shears along the contacts between rock blocks are developed, and the main shear surface is generated (see **Figures 9, 11, 13, 15**). After the maximum load, a region of superlimit deformation appears, which continues up to the ultimate residual strength. Therefore, the rock mass is destroyed over the generated main slip surface with maximum shearing stresses and regions of higher stresses.

An increase in strength with lateral pressure can be attributed to internal friction which increases with lateral pressure. Based on the results of numerical experiments, the following conclusions can be obtained: the rock mass is destroyed by shear and fracture, with the fracture stress, residual strain and shear orientation angle depending on the type of stress state and the angle of slope of the joint in the rock mass with respect to the horizontal plane. The higher the lateral pressure, the higher the shear resistance along the contact between rock blocks. Faults are the reasons for the nucleation of shear discontinuities during deformation of the rock mass. The concentration of stresses on the surface of defects leads to the formation of shear fractures.

The physical meaning of the stress region constrained between the ultimate elasticity and the ultimate strength is that a certain number of shear planes are selected here. Separate elements located between them do not participate in residual deformation but behave as a continuous medium experiencing only elastic deformations. The aforementioned behaviour of the jointed rock mass upon deformation was experimentally confirmed under laboratory conditions using pressure equipment (**Mirzaev et. al., 1984**).

Figure 16 compares the results of the numerical experiment of volumetric compression (lateral pressure of 30 MPa) of the jointed rock mass (2) with the results of uniaxial compression of the rock core (1). A comparison

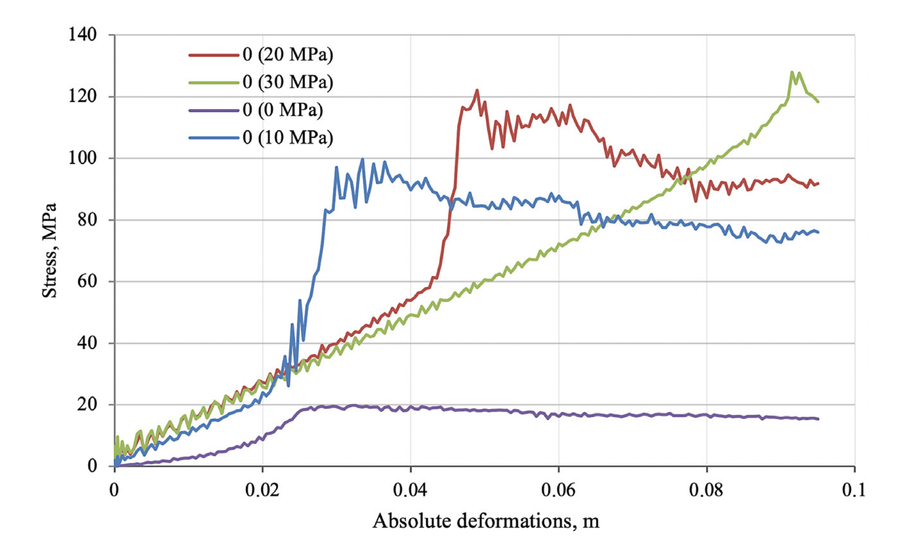

Figure 8: Tests of the jointed rock mass in 3D stress state at a 0° inclination angle of the main joint pattern

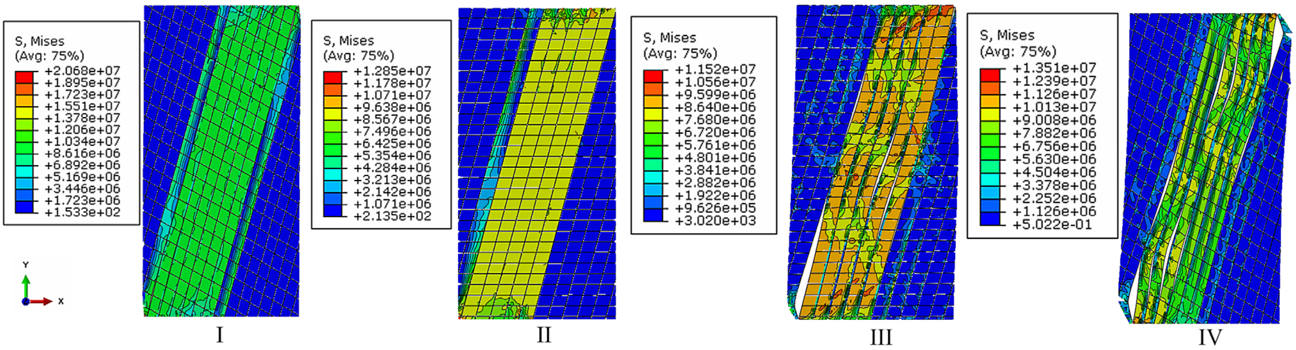

Figure 9: UCS virtual experiment stress-strain diagrams for the jointed rock mass with a 0° inclination angle of the main joint pattern where: I, II, III, IV are stages of deformations where 10%, 25%, 75%, 100% of the elastic deformations are realized accordingly.

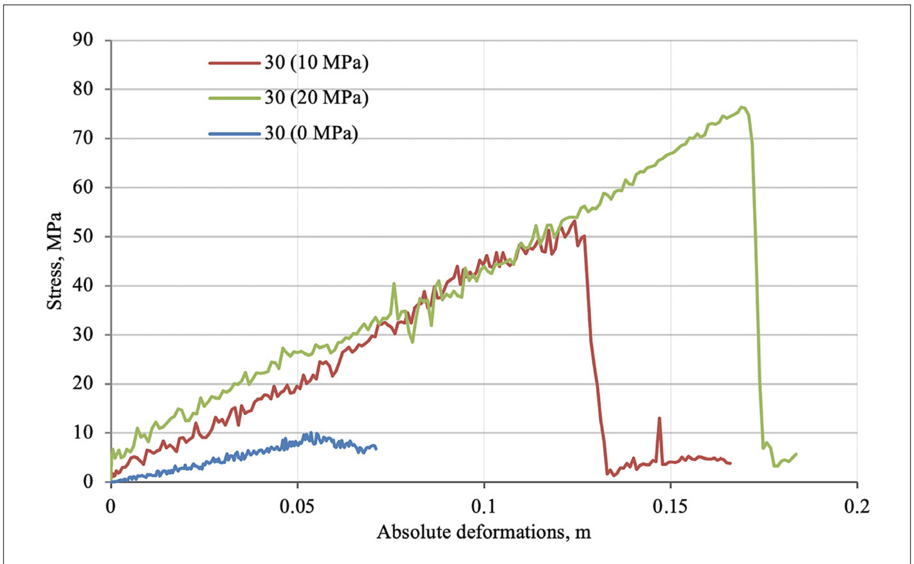

Figure 10: Tests of the jointed rock mass in 3D stress state at a 30° inclination angle of the main joint pattern

shows qualitative convergence of the results. The deformation plots show elastic stages of deformation with subsequent brittle destruction.

Heterogeneity of the structure is the reason for the specified behaviour of the rock mass during deformation and failure under conditions of complex stress states and

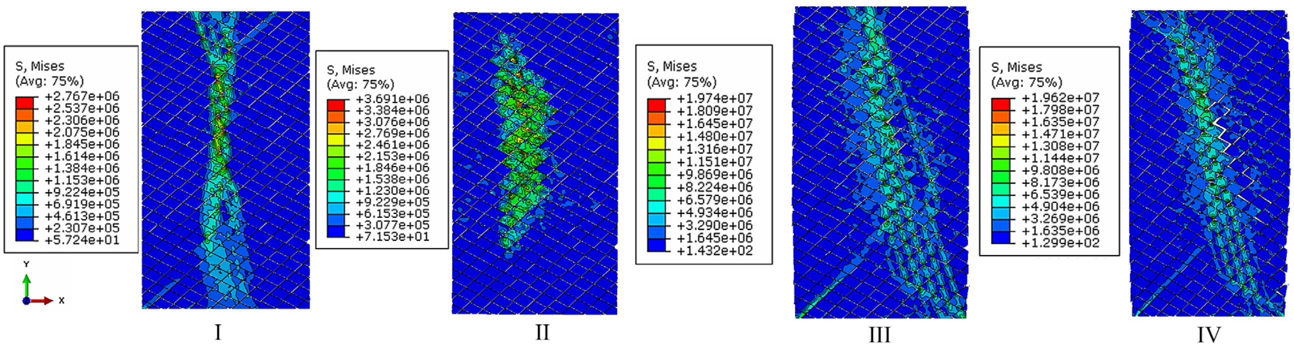

Figure 11: UCS virtual experiment stress-strain diagrams for the jointed rock mass with a 30° inclination angle of the main joint pattern where: I, II, III, IV are stages of deformations where 10%, 25%, 75%, 100% of the elastic deformations are realized accordingly

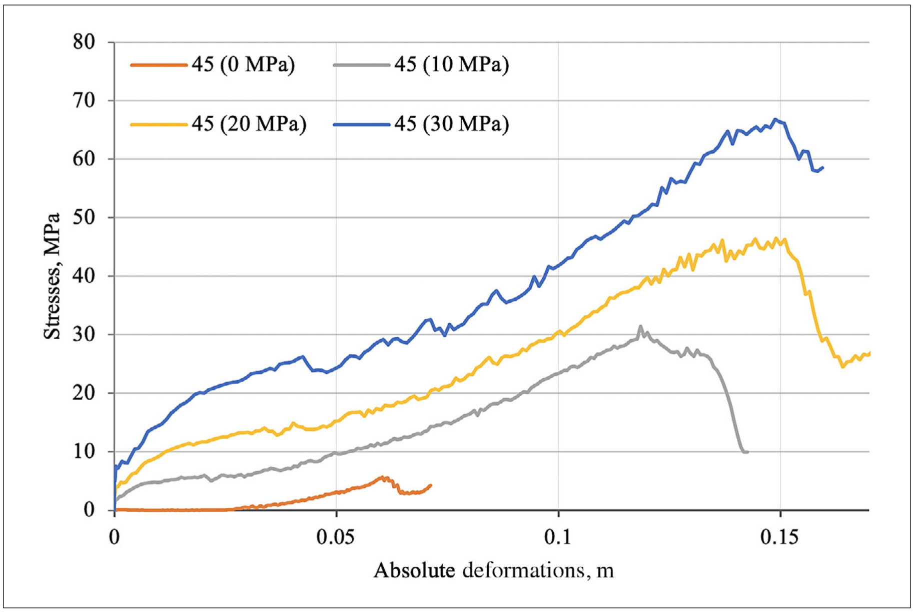

Figure 12: Tests of the jointed rock mass in 3D stress state at 45° inclination angle of the main joint pattern

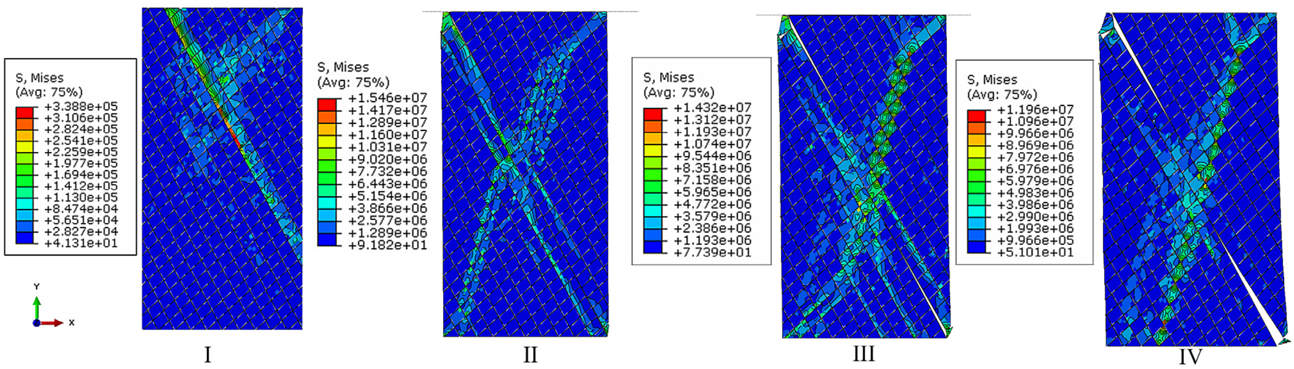

Figure 13: UCS virtual experiment stress-strain diagrams for the jointed rock mass with a 45° inclination angle of the main joint pattern where: I, II, III, IV are stages of deformations where 10%, 25%, 75%, 100% of the elastic deformations are realized accordingly

variation of the loading speed. The most significant feature is the effect of increasing volume (dilatancy) during irreversible deformation under conditions of triaxial non-uniform compression and the existence of the maximum and descending (super limit) branch in stress–strain diagram (see **Figure 10**). This result confirms considerations about the possibility to simulate failure of the jointed rock mass and to analyse the super limit stage of deformation. It is obvious that upon uniaxial compression, the jointed rock mass would be destructed easier

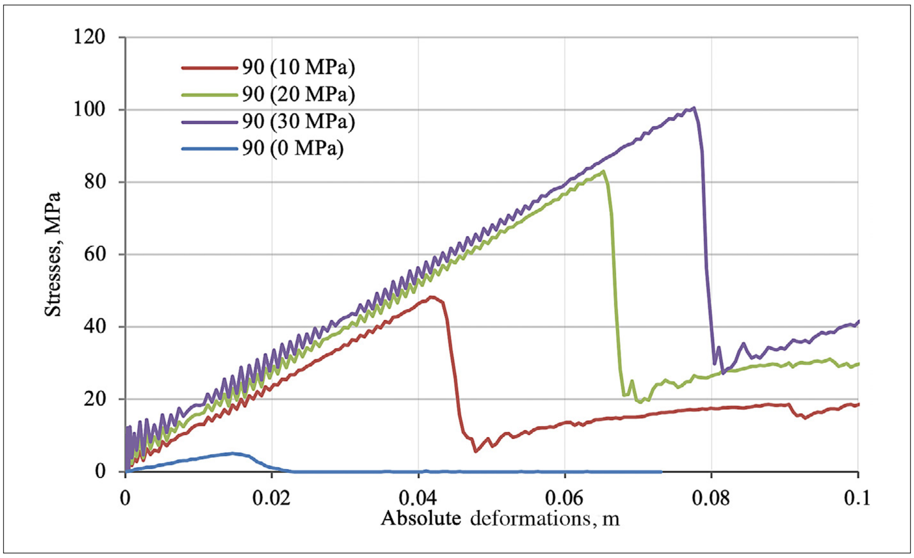

Figure 14: Tests of the jointed rock mass in 3D stress state at a 90° inclination angle of the main joint pattern

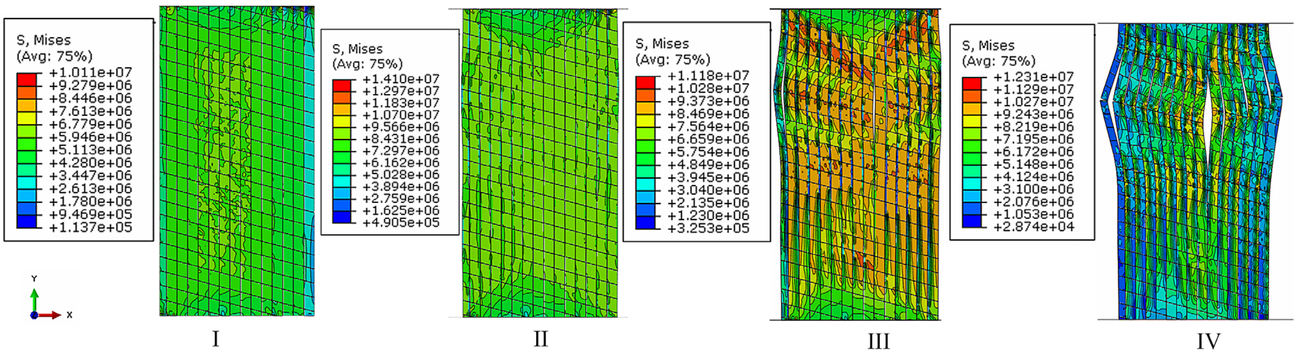

Figure 15: UCS virtual experiment stress-strain diagrams for the jointed rock mass with a 90° inclination angle of the main joint pattern where: I, II, III, IV are stages of deformations where 10%, 25%, 75%, 100% of the elastic deformations are realized accordingly

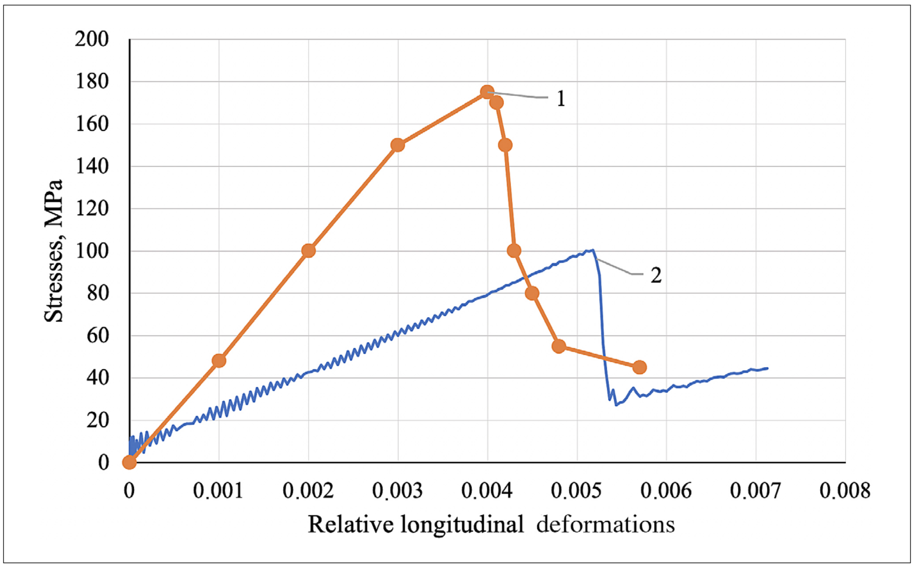

Figure 16: A comparison of compression tests of a hard rock sample (1) and a jointed granite rock mass at 90° of the joint pattern inclination (2)

regarding its solid core (the strength varies by 36 times). Therefore, the comparison is carried out with volumetric compression of the jointed rock mass at a lateral pressure of 30 MPa (see **Figure 14**).

4. Discussion

Based on the obtained results, it can be mentioned that the deformation pattern of the jointed rock mass

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upon relatively moderate loading at the initial time is characterized by significant residual deformations, which is evidence that increasing the load leads to the consolidation of rocks, and increases their rigidity due to the closing of existing cracks. Then, upon loading, the rock mass is deformed as an elastic solid, residual deformations sharply increase after reaching ultimate elastic deformations, and at the final stage, high deformations of the rock mass are observed at even a slight increase in external load.

Complexity and variance of the jointed rock mass do not allow for the consideration of all features of their structure, therefore, during studies, only the most significant ones are considered (**Jaeger et. al., 2007**). They are as follows: block structure of the rock mass, the shape and size of unit blocks, their orientation, and contacts between them. Rock mass is generally considered as a set of hard elements continuous with each other along the existing system of cracks, the width of which is negligible in comparison with the sizes of elements. It follows from the aforementioned that the complexity of the geological structure of the jointed rock mass leads to the necessity to consider not the rock mass itself but its idealized representation, that is, a geomechanical numerical mathematical model. The numerical model of the heterogeneous rock mass was developed as follows: the discontinuities' structure was highlighted and analysed based on engineering and geological data reflecting peculiarities of the geometrical structure of the rock mass and determining the shape of the blocks; geometrical shapes of solid blocks were selected for models and boundary conditions; using previously obtained data, a geomechanical model containing information about mechanical properties of rocks was developed; block geometrical models of the rock mass (solid blocks) were developed; and predictions were made and the results were numerically estimated. Herewith, analysis of the geometrical parameters of the considered object leads to the conclusion that its boundary surfaces are comprised of multiconnected regions, which upon consideration, significantly complicates the solution to the problem.

The results of numerical simulations of the jointed rock mass using different geomechanical models by **Peitao, 2016** and **Qibin, 2020** demonstrated that uniaxial compression strength is significantly affected by the existence of the discontinuities. **Peitao, 2016** concluded that uniaxial compression strength depends on the size of the jointed rock mass and the orientation angle of the system of discontinuities. Among other things, it is important to underline that the uniaxial compression strength anisotropy is different for samples of a jointed rock mass with different sizes (**Peitao, 2016**). A similar trend is observed in the studies performed in this work. Though, the presence of lateral load does not affect the manifestation of anisotropy to such an extent, so for each case with a certain system of discontinuities, an increase in lateral load will approximately similarly lead to an increase in uniaxial compressive strength (see **Figures 8** to **15**).

Qibin, 2020 studied the effects of different joint parameters on the strength and failure behaviour of the jointed rock mass. The results show that the existence of joints degrades the mechanical behaviour of the rock mass and imposes a significant effect on the peak strength of the samples. With a change in the spatial orientation of the system of discontinuities, the difference in strength can reach 3 times (**Wang, 2017**; **Qibin, 2020**).

Strong anisotropy of tensile behaviours and spatial anisotropic deformation have been found in transversely isotropic rock discs by **Wang, 2018**. There is seldom attention paid for an insightful analysis of anisotropy and spatial variability of tensile behaviours for jointed rock masses. The results indicated that the stratified rock discs displayed distinct anisotropy and directionality in tensile strength, manifested by the decreasing strength with the inclination angle. The described anisotropy (**Wang, 2018**) is equal to the experimental results in **Figure 1**. Specifically, hard rocks also defined the strength anisotropy caused by the structure of the rocks.

Rao, 2011 approves that the strength of a rock mass at a site is generally influenced by joint geometry and the stress state that it experiences, and described experiment results where the strength anisotropy in a rock mass under polyaxial compression is demonstrated. The experiment results (**Rao, 2011**) have qualitative convergence with the results obtained in this work.

5. Conclusions

In this paper, the results of UCS research for rock samples using rock mechanics experimental system in laboratory and rock mass using numerical modelling were described. The conclusion is divided into two parts: rock sample UCS experiments and rock mass UCS experiments.

The fracture of rocks with high elastic properties occurs with a sound effect. All the tests performed in this paper are characterized by the presence of elastic deformation and subsequent brittle fracture stages. From a practical point of view, the issue of testing rock samples is studied in detail in world practice. Of greater interest is the question of determining the mechanical characteristics of the jointed rock mass, since the presence of discontinuities in it leads to a decrease in the mechanical characteristics relative to the sample of rock of which the rock mass is composed. This paper proposes an approach that allows for the conducting of virtual tests over a jointed rock mass and the determination of its mechanical properties. This approach is important for geotechnical practice since laboratory experiments over a rock mass with dimensions of sides more than 2 m are practically impossible and expensive.

According to the results of research conducted by numerical simulation of rock mass experiments, it's possible to make conclusions that the physical essence of residual stresses in the jointed rock mass and mechanism of their occurrence are not studied in detail due to an insufficient number of real experiments and the complicated procedure of their interpretation related to contributing factors of uncertainty of boundary conditions. Numerical simulation of virtual tests allows for the analysis of the stage of superliminal deformation of the numerical model, but the analysis of boundary conditions in real observations for correlation with numerical predictions is uncertain. Obviously, in any practical problem, mining and geological uncertainty is important and assumptions are essential for a mining engineer, but a multifunctional geomechanical analysis is needed to assess geoengineering risks and to present possible deviations and varying mechanical parameters of rocks, especially in complex mining and geological conditions. The application of the finite element method to develop a numerical mathematical geomechanical model of a rock mass or solid block in explicit form allows for the tracking of the character of failure and block displacement under loading, to estimate the number and size of tensile cracks, and to monitor the course of dilatancy attenuation during nonelastic deformations.

The following conclusions can be made:

- heterogeneous distribution of stresses and deformation in a rock mass are the determining factor of decrease in strength upon variation of the jointing inclination angle;
- the proposed procedure makes it possible to predict the stress–strain state of a rock mass characterized by block structure with explicit consideration for structure and contact conditions between rock blocks. Cracks are the reason of spatial variance of mechanical properties of a rock mass resulting in the heterogeneous distribution of stresses in a rock mass;
- a numerical geomechanical model of a jointed rock mass, presented by a discrete medium, takes into account the contact conditions between the rock blocks, the structure of the jointed rock mass in explicit form, makes it possible to simulate the formation and development of shear and tension cracks, to obtain dependence of the rock mass deformation in σ-ε coordinates, the deformation anisotropy is considered in explicit form during rock mass failure.

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SAŽETAK

Eksperimentalno i numeričko istraživanje anizotropije raspucale stijenske mase u trodimenzionalnome stanju naprezanja

Pukotine često imaju znatan utjecaj na karakteristike materijala. Mehanizam skupa diskontinuiteta i složena struktura raspucale stijenske mase kada se sagleda kao kompozit zahtijeva dodatno istraživanje. U ovome istraživanju provedena su tlačna i posmična ispitivanja čvrstoće na raspucaloj stijenskoj masi. Istraživanje ponašanja raspucale stijenske mase provedeno je sa svrhom utvrđivanja ovisnosti deformacije i čvrstoće te određivanja parametra za kvantitativnu ocjenu utjecaja pukotina na mehanička svojstva. Rezultati pokazuju da tlačna čvrstoća ovisi o strukturi materijala te je detaljno opisan utjecaj orijentacije pukotina na odnos naprezanja i deformacija tijekom ispitivanja tlačne čvrstoće. Numerička metoda korištena u istraživanju može se iskoristiti za modeliranje kompozitnih materijala i njihovih svojstava.

Ključne riječi:
raspucala stijenska masa, diskontinuiteti, numerička simulacija, jednoosna tlačna čvrstoća, anizotropija

Author’s contribution

Pavel Verbilo (Ph.D., Assistant) provided the UCS experiments, developed the methodology, processed the numerical modelling results, designed graphic material, and wrote parts of the article. **Maxim Karasev** (Ph.D., Professor) provided the scientific support for the relevance of the research being carried out, introduced revisions to the text of the article, and wrote parts of the article. **Nikita Belyakov** (PhD., Associate Professor) provided the numerical modelling, processed numerical modelling results, and wrote parts of the article. **Grigirii Iovlev** (PhD., Assistant) performed the numerical modelling, and wrote parts of the article.