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The influence of the stress state type and scale factor on the relationship between the acoustic quality factor and the residual strength of gypsum rocks in fatigue tests ☆

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ABSTRACT

The purpose of this study is to establish the influence of the stress state type and the sample sizes on the interrelationship between the acoustic quality factor Q and residual strength σ_r in the gypsum-containing rock of the Novomoskovskoye deposit (Russia) in mechanical fatigue tests. The aforementioned relationship for residual strength under uniaxial compression can be approximated to satisfactory accuracy by a logarithmic function and for the residual tensile strength by an exponential function. Cylindrical samples with a diameter of ∅30 and ∅80 mm and aspect ratio 1:2 during compression, and with a ratio of height to diameter equal to 1 in tension were tested. For these dimensions, the size effect does not influence the interdependency $\sigma_r(Q)$ under uniaxial tension, but does have an influence under uniaxial compression.

1. Introduction

The Novomoskovskoye gypsum deposit is located to the north of the city of Novomoskovsk, in the Tula region of Russia. It is one of the largest gypsum deposits in Russia and one of the largest in Europe, covering an area of 32 km^2. The main part of the deposit is about 7 km long and more than 4 km wide [1].

The total thickness of the reservoir-covering rocks varies from 72 to 130 m. They are represented by Quaternary loam and sandy–clay alluvial–diluvia deposits, mesozoic micaceous sands, lower carboniferous sands and clays, limestones and dolomites of upper devonian times. A dolomite stratum, an aquifer, sometimes highly fractured, lies above the useful layer. Between them, there is an entire area of waterproof clay ranging from 0.5 to 2 m. The useful stratum is represented by thick gypsum layers of fine-crystalline, fibrous, pale grey, sometimes dark grey or white plaster with thin (1–2 mm to 1–2 cm) layers of dolomite. The gypsum layer is between 9.5 and 19.5 m thick; most often 12–18 m, an average of 15 m. The sole formation of gypsum is at a depth of 87–142 m below the surface.

The deposit development is carried out by rooms 9.5–10.5 m high, 11 m wide, and pillars of 9 m wide. The roof at the top of rooms is 5 m thick. Failure of the pillars and the roof can lead to catastrophic consequences. It is therefore necessary to monitor the residual strength of the rocks by NDT methods without mechanical tests.

Rocks in masses are exposed to various adverse effects, gradually decreasing their strength. These effects include weathering, creeping, cracking, and plastic deformation. When the impact of these adverse factors takes place, rock strength is called residual strength. The residual strength has been the subject of numerous studies [2–5]. To define it without destroying the rock, we propose to use the dependence between the acoustic quality factor Q and residual strength σ_r received in advanced tests. As under real conditions a decrease in strength may occur over a long period of time, reduced rock testing is used to achieve the $\sigma_r(Q)$ relationship with the help of mechanical fatigue load [6,7]. To make good use of such a relationship, the type of the stress state of the object and scale factor must be taken into account.

Many publications are devoted to the influence of the stress state type on the rock strength. In Ref. [8], the influence of the

☆ Paper concerns influence of the stress state type and scale factor on interrelations of fatigue strength with acoustic quality factor of gypsum rocks.

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Lode-Nadai parameter μ on rock strength in shearing has been studied. It was shown experimentally that if μ ranges from -1 to +1, the shear strength of limestone and marble has a maximum at $\mu = 0$. The strength of rocks under different triaxial component compression is considered in [9]. Behavioural features of rocks in pre-peak and post-peak areas are described in [10]. Reference books and catalogues published on physical rock properties at different stress states are described in [11]. Thus publications that show the importance of studying the influence of the stress state on the physical properties of rocks are numerous.

The scale factor manifests itself in changing rock properties in sample and in massif. The effect of sample size [12] and that of the scale factor [13] on material properties [14] are under thorough investigation by many researchers. There are surface and volume scale effects; the former can influence the latter [15]. This influence can manifest itself in the form of increasing and decreasing the strength. The influence of sample sizes on the material response under cyclic fatigue loading is considered in [16]. In general, the increase in dimensions of samples leads to a reduction in strength [17]. This effect is due to geomaterial damage, for the evaluation of which acoustic methods are used [18].

As highlighted in the aforementioned literature, the influence of stress state type and scale effect on rock properties is an essential element to understanding rock behaviour. Such an influence on the relationship between the acoustic quality factor and residual strength $\sigma_r(Q)$ for rocks is investigated insufficiently or has not been investigated at all. This paper considers the influence of these factors on $\sigma_r(Q)$ dependence for gypsum-containing rocks. This work is a continuation of previous research by the authors [6,7,19–21].

2. Goal and strategy

The aim of this work was to study the influence of the stress state type and the scale factor on the interrelationship between the acoustic quality factor and residual strength, taking the Novomoskovskoye gypsum deposit as an example.

The main idea of the experiment was to measure the acoustic quality factor Q and the residual strength σ_r of samples subjected to different numbers of fatigue loading cycles for different degrees of damage in the geomaterial. According to these data, graphs were plotted and regression dependencies $\sigma_r(Q)$ were derived that can be then used to estimate the residual strength of rock without destroying the specimens in laboratory, and pillar-and-roof in situ.

The relationships derived from fatigue multi-cycle uniaxial compression and tension experiments were compared to determine the influence of the stress state type on the residual strength. To determine the influence of the scale factor, the relationships obtained in the test cylinder samples of two diameters of $\varnothing$30 and $\varnothing$80 mm were compared. It was predetermined by the available drilling equipment.

3. Materials and methods

3.1. Rock samples

The cylinder-shaped samples of gypsum rock of the Novomoskovskoye deposit mined underground by blasting were taken for the tests. This type of rock has been chosen because gypsum is mined around the world by both open pit and underground methods, which cause a variety of types of stress state in the rock mass, including both compression and tension.

The gypsum of Novomoskovskoye deposit is composed of several alternating layers, with the main ones as follows:

Spotted gypsum. It is light grey, often with a yellowish tinge, coarse-grained, a sometimes spotty structure due to uneven colour and inclusions of dolomite, interspersed with thinly layered gypsum lenses and overlapping layers of dark grey dolomite. Spotted gypsum is predominantly distributed among the gypsum mass.

Selenite ranges in colour from white to light blue, and has a pronounced fibrous structure sometimes formed by elongated crystals of gypsum. It has the lowest strength among the gypsum varieties. Different types of spotted gypsum and selenite samples after testing are shown in Fig. 1.

In addition, there are small quantities of a star-shaped type of gypsum.

The samples were prepared of spotted gypsum with inclusions of selenite. For uniaxial compression, test samples had the dimensions of $\varnothing 30 \times 60$ mm and $\varnothing 80 \times 160$ mm, and a height-to-diameter ratio equal to two. For tests under uniaxial tension, the Brazilian scheme and samples with dimensions of $\varnothing 30 \times 30$ mm and $\varnothing 80 \times 80$ mm with a ratio of height to diameter equal to 1 (GOST 21153.3-85) are used. 25% of the solid structure grains had a size less than 1.0 mm, from 1.0 to 2.0 mm: 50%, and from 2.0 to 5.0 mm: 25% [22].

3.2. Testing methods

Experiments on the samples were conducted by the method described in [6,7,21]. According to this method, to obtain one $\sigma_r(Q)$ interdependence curve, a group of samples of 10–12 units was selected. For monitoring the changes, the Q-measurements were performed twice: before and after fatigue loading. For each group of samples, quality factor Q measurements of intact rock were made. Three samples were tested to obtain the average value of the strength σ_{r0}. Then, each of the remaining samples was subjected to fatigue loading by cyclic stresses within the range of 2–40% of the initial strength σ_{r0} at a pre-set number of cycles N. The number of fatigue loading cycles for gypsum samples varied in the range from 20 to 100. Once cyclic loading was completed, the second measurement of quality factor Q was made. Then the residual strength $\sigma_r(Q)$ of the sample was determined by increasing loading stress until failure while measuring maximum load value. The data obtained by testing samples were used to plot the $Q(N)$, $\sigma_r(N)$, and $\sigma_r(Q)$ dependency graphs. The dependencies $\sigma_r(Q)$ were the main result of the research, while the others were complementary. The residual strength under uniaxial compression (i.e. uniaxial compressive strength) in this paper will further be denoted as σ_{ucs}, and the residual strength under uniaxial tension (i.e. uniaxial tensile strength) as σ_{uts}.

The acoustic Q factor was determined by resonant acoustic spectroscopy [23] in an excitement of the rock sample by the harmonic signal using thin piezoelectric plates according to:

$$Q = \frac{f_0}{f_{\max} - f_{\min}},$$

where f_0 is the resonant frequency, which was determined by the maximum amplitude of harmonic signal recorded at the sample; $f_{\max}$, $f_{\min}$ are the upper and lower band frequencies of signal at the $1/\sqrt{2}$ level of the amplitude maximum value at the resonance. To reduce the effect of acoustic transducers for the measurement results, the test was made by glueing thin piezo plates to the sample with beeswax. Apart from that, lightweight transducers with a small value of their own losses were chosen. Considering that the real value of the rock quality factor was less than 100, the error introduced by the transducers was insignificant.

3.3. Measuring and testing equipment

Sample excitement and measurement was performed by an experimental laboratory-scale plant, consisting of a GW Instek