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Predicting fatigue strength of rocks by its interrelation with the acoustic quality factor

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ABSTRACT

This paper presents findings regarding the interdependence of acoustic quality *Q*-factor and fatigue strength studies for specimens of sedimentary (limestone and travertine), eruptive (gabbro), and metamorphosed (marble) rocks. Test techniques included measurements of *Q* by resonance spectroscopy through sonic test, damage by mechanical load/unload cycles of number *N*, and measuring ultimate strength under uniaxial compression. Upon *Q*-factor measurement, the first specimen of each series was loaded to destruction to determine ultimate strength. Subsequent specimens underwent cyclical fatigue loading. Thereafter, *Q*-factor and residual strength of the rocks were measured. For sedimentary and eruptive rocks, strength and *Q*-factor reduction with an increase of load cycle number is observed. For metamorphosed rock their further increase with subsequent *N* increase is observed. The experimental results enabled establishment of regressional relationships between *Q*-factor and strength described by logarithmic function. The relationships may be used for predicting rock residual strength without their destruction by *Q*-factor measurement.

1. Introduction

A significant number of papers have been devoted to the interrelation of acoustic and mechanical properties of rocks, and this number is constantly growing. This is due both to the importance of the topic itself, and the diversity of types, composition, genesis, and places of rock origin. Most ongoing studies are distinguished by examination of either acoustic [13,27,22,21,1,4,5,6,18,19,20,15] or mechanical rock properties only [11,2,23,24,9,14]. Combined studies of acoustic and mechanical characteristics are typically limited to the interrelation of elastic and acoustic properties [28], strength properties and elastic wave velocities [12,17,7], and the interrelation of deformational characteristics of rocks and elastic wave velocities [32,8]. Lebedev et al. [13] provide results of the study of acoustic quality *Q* in materials with a high internal defect concentration in correlation with stressed state. Winkler and Murphy [33] analyze the interrelation of velocities and elastic wave attenuation. However, no *Q*-property connection with ultimate strength is considered. The rock strength–acoustic quality *Q* interrelation is not paid adequate attention.

At the same time, such interrelations are essential for predicting the ultimate strength of rocks based on their *Q*-factor. As compared with elastic wave velocity in assessment of rock internal structure distortion, acoustic quality *Q* is a parameter of higher sensitivity. Knowledge of such interrelations would be beneficial in predicting earthquakes and hydraulic fracturing design. Moreover, *Q* measurement will allow measurement of residual strength and life of structural elements at mining enterprises without destruction, which is important for ensuring effective and safe mining of commercial minerals [29,30] and preservation of the environment.

Time variation of rock acoustic quality–ultimate strength interrelations are of special interest. However, such tests would be so time-consuming that their result would lose any practical significance. Interrelation of the acoustic quality factor and fatigue strength of limestone under heating have been discussed earlier [31]. Now the paper considers interrelations of acoustic quality and ultimate residual strength in case of varying degree of damage brought about by cyclic fatigue loading of rock specimens of various types. Such loading results in changes of both *Q*-factor and ultimate strength, which enabled assessment of their interrelations. They will find their application in assessment of the residual strength

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and life of various structures and facilities by nondestructive measurements of their acoustic quality.

2. Materials and methods

In tests carried out for a series of specimens, acoustic quality Q and strength at uniaxial compression σ^{ucs} were measured for each specimen.

For the first intact rock specimen of the series, acoustic quality Q_0 was measured without including damage, whereupon it was tested for ultimate strength σ_0^{ucs} under uniaxial compression.

Other specimens of the series underwent load/unload fatigue cycles of different number N_i to include damage. Thereafter, acoustic quality Q_i was determined, and residual strength σ_i^{ucs}, was measured by loading to destruction, where i is a specimen sequence number within the series.

Q-factor was determined by sonic testing of the specimen by harmonic signal through measuring resonant frequency and band on the −3 dB level of the maximum range value according to the formula:

$$Q = \frac{f_0}{2\Delta f} = \frac{f_0}{f_{\max} - f_{\min}},$$

where f_0 is a resonant frequency; $f_{\min}$, $f_{\max}$ are the minimum and maximum frequencies at output amplitude at −3 dB of the signal maximum value at resonance; and $2\Delta f = f_{\max} - f_{\min}$ is the frequency bandwidth in the resonance zone within the −3 dB limit of the signal maximum. In the course of measurement, the guide value of resonant frequency was preliminary determined as:

$$f_0' = \frac{c}{2d},$$

where f_0' is an estimated value of stationary wave frequency; c is the elastic wave propagation speed; and d is the dimension of the specimen along the wave propagation direction. The true value of the resonant frequency f_0 was updated at measurements by signal maximum range.

Sonic testing of specimens was conducted using digital generator SFG-2110 and oscilloscope GDS-71022 by Good Will Instrument Co., Ltd. Cyclic loading (Fatigue Test) was carried out on an Instron 5569 versatile test loading machine with a maximum load capacity of 50 kN. For determination of ultimate strength at uniaxial compression, an Instron 150LX machine was used with a maximum load capacity of 150 kN.

Tests were conducted with sedimentary (limestone and travertine), eruptive (gabbro), and metamorphosed (marble) rocks, with specimen dimensions of (32 × 32 × 64) mm throughout the tests. To conduct one series of experiments we must have at least 8–10 samples. Samples cut from opposite parts of the extended core in the array are situated far from each other. Their properties may vary greatly. This will eliminate the possibility of setting a "pure" experiment. Therefore, samples in the form of a cuboid used in the experiments are cut from one plate of the abutting sections. This minimizes variations in properties of the samples in the series. It is technologically easier to cut out the plate samples in the form of a cuboid, which is why we have samples of this shape.

3. Experimental results

3.1. Acoustic quality/residual strength–fatigue loading cycle number relationship for sedimentary rocks (limestone and travertine)

Acoustic quality–residual strength interrelations for sedimentary rocks were determined using limestone and travertine specimens.

Two groups of specimens from Tiginskoye deposit (Russia) were tested. To achieve more stable results upon breakdown into groups, the principle was taken into account whereby the higher ultimate strength corresponds to higher elastic wave velocities. The first group (tested later under maximum cyclic load value of up to 0.3 of the destructive load $\sigma_{\max}$, i.e. $0.3\sigma_{\max}$) included specimens with lesser velocity values, whereas the second one (tested under load value of up to).

The number of load/unload cycles N_i in the first group were 0, 10, 20, 30, and 40. With bigger N_i, the specimens were destructed already in the process of fatigue loading. For the second group, N_i equaled correspondingly 0, 10, 15, 20, and 30 load/unload cycles. Despite the fact that this group included specimens with higher predicted ultimate strengths under uniaxial compression, the specimens were destructed already with the number of load/unload cycles exceeding 30.

Fig. 1 represents relations of acoustic quality Q_i and residual strength σ_i^{ucs} from the number of load/unload cycles N_i. Hereinafter, i is a specimen number in a series, and $i = 0$ corresponds to a specimen without cyclic loading.

The samples of the second group were subject to higher load testing ($0.5\sigma_{\max}$), than those of the first group ($0.3\sigma_{\max}$). This explains the fact that the second group samples were destroyed in less cycles ($N_i > 30$), while the first group samples were b destroyed at $N_i > 40$. The effect of increased load at fatigue loading was greater than that of high-strength, characterized by increased rates of elastic waves with samples of the second group.

Predictably, damage brought about during cyclic fatigue tests results in reduction of both strength and quality. It is also notable in both specimen groups that in the section of N_i from 0 to 10, the quality Q_i decreases faster than the ultimate strength. Thus, for the first group of specimens relative Q-factor reduction is 0.23 and strength reduction 0.12, while for the second group it is 0.3 and 0.17, respectively.

Higher importance of these values for the quality means that Q features high sensitivity toward the damaged condition and may be used for prediction of ultimate strength at the early stages of geomaterial destruction. Another specific feature should be pointed out. As the curves of both quality and residual strength for both groups are close to each other, whereas high loads in cyclic tests led to a reduced number of cycles to destruction, it may be suggested that quality reflects ultimate strength change. This reflects the magnitude of load to a significantly lesser extent.

The next test series was conducted with travertine specimens from a deposit in the Denizli area (Turkey). The maximum cycle load in this series was 0.1 of the initial ultimate strength. The number of cycles N_i equaled 0, 10, 20, and 30. The small magnitude of the chosen load was due to the fact that the travertine featured

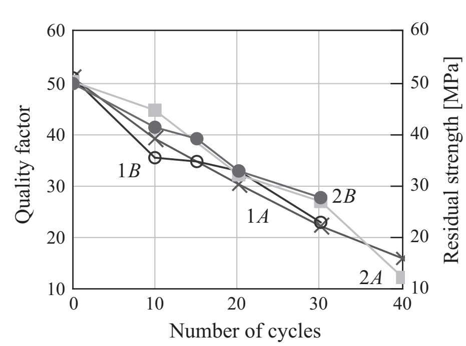

Fig. 1. Relationship curves between acoustic quality Q_i (curves 1)/residual strength σ_i^{ucs} (curves 2) and number of load/unload cycles N_i for limestone from Tiginskoye deposit under maximum load in cycles up to 0.3 (curves *A*) and 0.5 (curves *B*) of the destructive load.