International Journal of Mining Science (IJMS)
Volume 4, Issue 2, 2018, PP 31-43
ISSN 2454-9460 (Online)
DOI: http://dx.doi.org/10.20431/2454-9460.0402004
www.arcjournals.org

Features and the Ability to Replace the Interdependencies between the Acoustic Quality Factor and the Strength of Limestone under the Influence of Different Physical Nature

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Abstract: *This article presents the results of studies of limestone samples from the Sary-Tash deposit. The samples were subjected to various types of influences, such as mechanical cyclic fatigue tests, thermal cycling tests when heated to 600°C, and thermal tests during freezing/thawing. Relationships between the acoustic quality factor (Q-factor) and strength were obtained for different types of tests. For mechanical fatigue tests and thermal tests when freezing/thawing, similar dependences of the Q-factor and strength were obtained, which are approximated by logarithmic dependencies* $\sigma_m = 0.25 \cdot ln(Q) + 1.04$ *for mechanical testing, and* $\sigma_f = 0.23 \cdot ln(Q) + 1.07$ *for thermal testing by freezing/thawing. For thermal testing when heated up to 600°C, the form of the relationship between the acoustic Q-factor and strength has a more complicated character. The estimation of the possibility of substituting one type of test with the other was carried out by checking the statistical hypotheses about the equality of the regression dependencies' coefficients. The calculations showed that the differences in the coefficients* a_0 *and* a_1 *for mechanical and thermal tests during freezing/thawing were insignificant. This fact confirms the possibility using data interchangeably, and of reducing the duration and cost of tests.*

Keywords: *Rock, Acoustic, Quality factor, Strength, Fatigue tests, Limestone*

1. Introduction

The assessment of the strength of rocks and other materials using direct methods is achieved through their destruction. However, this approach is unacceptable for real objects, such as pillars and roofs of underground excavations, tunnel linings and the surrounding rock mass, construction sites and other analogous objects. Currently, work is underway on the development of methods of non-destructive evaluation of the strength and life of rocks around mine workings and underground structures for various purposes, which is necessary to ensure a high level of security for the personnel, security of facilities, and safety of the environment. These methods are indirect and use the regression relationship between the strength and other physical properties and characteristics, such as the speed of longitudinal and transverse elastic waves. They were described in papers by Kashnikov et al. (2017), Matin et al. (2017), Renner et al. (2000), and others.

It should be noted that the speeds of elastic waves poorly reflect the destruction of rocks in the early stages of their development, which is not conducive to the timely adoption of measures to prevent the catastrophic consequences of failure. It is established that the dynamic characteristics of elastic waves and vibrations, such as their decrement and damping factor, acoustic or seismic quality factor, and loss factor (inverse quality factor) are more sensitive to degradation leading to strength loss. A significant contribution to the solution of the problem of non-destructive testing of strength is the study of the dependency between the acoustic or seismic quality factor Q (Q-factor) and strength σ.

A considerable number of studies have been devoted to the definition of the Q-factor and the characteristics of wave attenuation of rocks. It was described at seismic frequency band by Aki (1980), Calvet et al. (2013), Wang et al. (2017), Sun et al. (2016), Tonn (1989), Dupuy et al. (2016), Zhang et al. (2016), Dobrynina (2011), Predein et al. (2017) and at ultrasonic frequency band by Wanniarachchi et al. (2017), Sang et al. (2015), Wang et al. (2015), Liu et al. (2005). Dependencies between the quality factor, speed of elastic waves, and pressure are considered by Jones (1995), Molnar et al. (2016). Mathematical dependencies of the Q-factor of rocks for longitudinal waves at various pressures and deformations are considered by Yarushina et al. (2010). From these works, it follows that the methods of measuring the quality factor Q and its reciprocal value Q^{-1} of rocks have been determined well enough. However, these publications have not considered the equations relating the Q-factor with strength, which would allow the use of these dependencies for non-destructive evaluation.

The experimental determination of the Q-factor, velocity of elastic waves, and strength of concrete were considered by Rhazi et al. (2010). Although an indirect dependence of the Q-factor on the strength through the relationship between the Q-factor and Vp was determined, the direct dependence between the quality factor and strength was not studied.

2. OBJECTIVES

Due to the lack of direct studies of the interdependencies between acoustic quality factor Q and the strength of rocks for the non-destructive evaluation of their strength, the authors conducted several studies in this direction. The question was raised about the need to study the dependencies between durability and the acoustic quality factor Q was described by Voznesenskii et al. (2013). It is necessary to assess the reserve of the roof rocks of underground mines and other structures. The first results of research on rock samples giving the dependencies between the acoustic Q-factor and the durability of limestone obtained when they are heated to different temperatures were published by Voznesenskii et al. (2015a). A number of results were obtained under fatigue cyclic mechanical loading specimens of various rocks to determine the uniaxial compression strength (UCS) and uniaxial tensile strength (UTS). $Q-\sigma_{UCS}$ dependencies for limestone, travertine, gabbro, and marble are described by Voznesenskii et al. (2015b). It has been shown that for limestone, gabbro, and travertine both the strength and the Q-factor monotonically decrease with an increasing number of cycles of fatigue loading, but this dependence in marble is non-monotonic—initially, both values decrease and then increase. The influence of the stress state type and scale effect on the dependences of $Q-\sigma_{UCS}$ and $Q-\sigma_{UTS}$ was investigated by Voznesenskii et al. (2016). It was shown that the scale factor strongly influences the dependence of $Q-\sigma_{UCS}$ in compression, and its influence is weaker on the dependence $Q-\sigma_{UTS}$ under tension. The dependence of the $Q-\sigma_{UCS}$ for rock salt at different load levels in the fatigue cyclic loadings was investigated by Voznesenskii et al. (2017). There were non-monotonic changes in both the quality factor and strength, depending on the number of cycles of fatigue loading. Thus, it is possible to draw a conclusion about the fundamental difference between the types of dependencies $Q-\sigma_{UCS}$ for different rocks.

The aim of this paper is to investigate the same rock, limestone, but for different types of fatigue cyclic influences: mechanical (loading and unloading), heating (increasing/decreasing temperature), and freezing/thawing.

The studies described here are part of a series of investigations on the creation of a non-destructive testing method of the strength of the lining and rock mass around underground openings in mines, tunnels, and underground and surface structures for various purposes.

The practical output of this work is the development of methods for the accelerated testing of rocks while retrieving dependencies between the acoustic Q-factor and strength, when one type of impact is replaced by another with the aim of reducing the time and cost of testing.

3. MATERIALS AND METHODS

3.1. Rock Samples

The experiments were conducted on samples of travertine-like limestone from the Sary-Tash deposit. This deposit is located in the Republic of Kyrgyzstan in the territory of Uzgen district, Osh region. The samples were made in prism form with the following dimensions: base, 30x30 mm and height, 60 mm, for all 36 pieces. All of the samples were divided into three groups of 12 pieces. The surface of a limestone sample is shown in the Fig. 1.

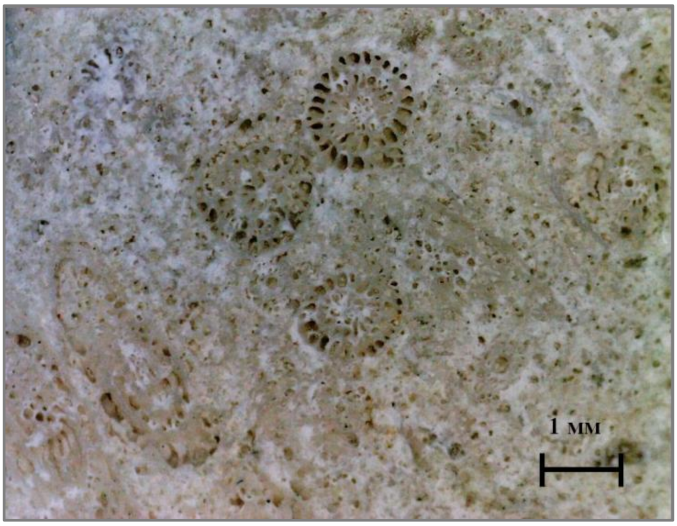

Fig1. *Surface of a limestone sample from the Sary-Tash deposit*

The samples are cut from one plate, and these areas were close to each other in the massif, which was necessary to ensure proximity properties, in contrast to the cylindrical specimens made from a single core of long length.

The study of the mineral composition of the samples was conducted using x-ray diffraction on the computerized device ADP2 — 01 using Fe Kά radiation. Spectrum analysis (Fig. 2) showed that the limestone samples consist of pure calcite ($CaCO_3$). The spectra of the samples coincide with the spectrum reflectance of this mineral. Impurities consisting of other phases (minerals) of an amount of more than 1–3% by weight were absent.

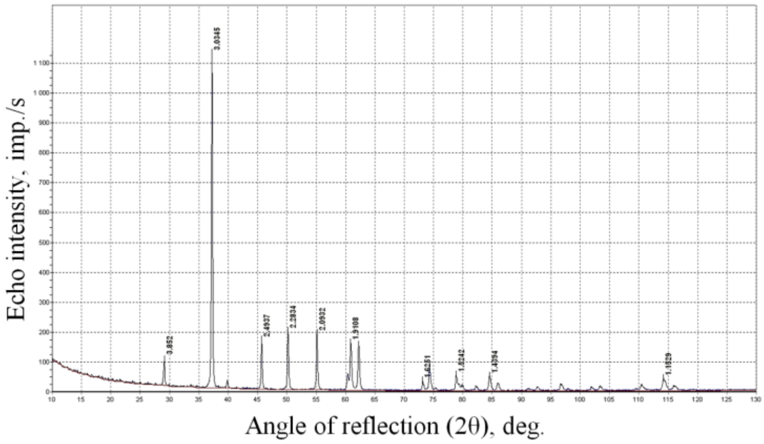

Fig2. *The results of the investigations of the mineral composition of the limestone samples*

3.2. Equipment for Experiments

3.2.1. Mechanical Equipment

Mechanical tests were conducted using the universal test machines Instron 5569 and Instron 300 DX, specifications of which are given in Table 1. The Bluehill software controlled these machines. Mechanical tests included the determination of the initial strength of the rock samples by their single load to failure. Fatigue cyclic loading of the remaining samples underwent various numbers of cycles of loading-unloading, after which the measurement of the acoustic quality factor and determination of the strength of each sample by its destruction was performed.

Table1. *Main technical specifications of Instron universal test machines*

Parameters	Instron 5569	Instron 300 DX
Maximum limit load, kN	50	300
The limits of permissible relative error of measurements of maximum load, %	±0.5	±0.5

The maximum speed of the mobile traverse, mm/min	500	76
Limits of permissible relative error of speed adjustment of the traverse, %	±0.1	±0.25
Limits of permissible absolute error of the displacement transducer, mm	±0.015	±0.013

3.2.2. Heating Equipment

Fatigue tests under heating were carried out on the installation described by Voznesenskii et al. (2007), Shkuratnik et al. (2015). The scheme of the installation is represented in Fig. 3. A Nabertherm RT 50/250/11 tube furnace (1) with controller (2) of type P 320 was used for the volumetric heating of samples. The stove allowed the heating of samples at a given rate up to 1100°C, with up to four stages of heating and exposure at each stage within specified time periods. The mode of heating and exposure was set by the controller. A sample (4) was placed in the heating pipe (3), which was connected with acoustic emission transducers (AE) (7, 8) through the waveguides (5, 6) made of quartz glass. They were connected to the first and second instrument channels. Quartz rods were used as the waveguides, each of them with a length of 280 mm. The ends of the heating pipe were closed by insulating plugs (9, 10). The thermocouple (11, 12) was connected to the respective measuring instrument channels to measure the temperature inside the sample during heating in a drilled hole. A weight (13) was used to secure the AE transducers, waveguides, and rock sample. The temperature of the sample was recorded using the A-Line 32D acoustic emission system (LLC "Interunis", Moscow, Russia) (14) on the parametric channel. In addition, this allowed AE in the frequency band of 30–500 kHz to be recorded during the heating of the samples.

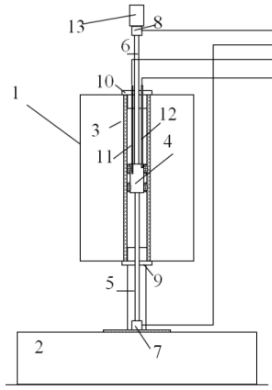

Fig3. *A schematic of the laboratory setup used to study the acoustic emission of rocks undergoing heating*

3.2.3. Acoustic Equipment

Measurement of the acoustic *Q*-factor of the limestone samples was conducted by the resonance method, using the experimental setup shown in Fig. 4.

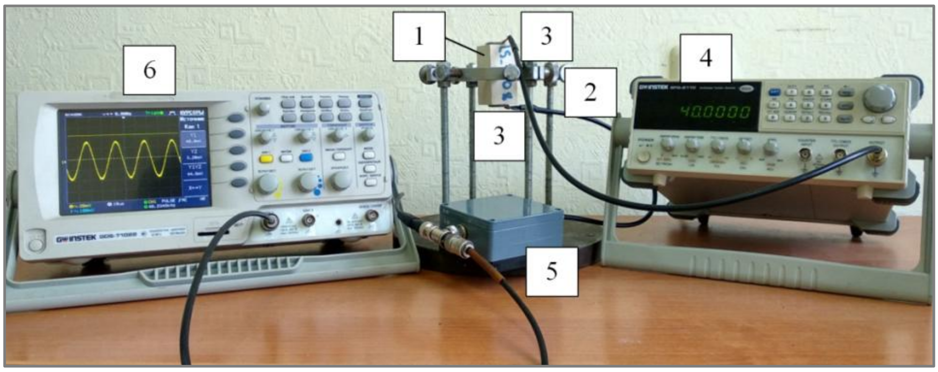

Fig4. *The measuring setup for the investigation of the acoustic quality factor of limestone samples: 1 - limestone sample; 2 - holder; 3 - piezoelectric transducers; 4 - generator SFG-2110; 5 - preamplifier; 6 - GDS-71022 digital oscilloscope*

The output of the harmonic generator (4) was connected to the piezoelectric transducer (3) located on the sample (1) top. The receiving piezoelectric transducer (3) was located on the sample bottom, and was connected through the preamplifier (5) with the oscilloscope (6).

3.2.4. Experimental Methods

The methodology of the laboratory experiments used to determine the effect of various factors on the relationship of the acoustic Q-factor and strength of rocks included: creating damage to the geomaterial with mechanical or thermal cyclic fatigue tests, the measurement of the acoustic Q-factor, and determination of ultimate strength in uniaxial compression.

Each group of specimens was subjected to its own set of influences. The acoustic quality factor and velocity of propagation of elastic waves of the limestone were measured before beginning the experiments on all samples. Three samples were selected in this data for testing uniaxial compression with the goal of averaging and determining the initial strength values, which amounted to 33.62 MPa. The experiments included three types of tests: mechanical, thermal by heating up to 600°C, and thermal freezing/thawing when the rock was saturated with water. The speed of longitudinal and transverse elastic waves, and acoustic (mechanical) Q-factor were measured on all the samples before and after the impact.

Mechanical tests included determining the values of ultimate strength under uniaxial compression and cyclic fatigue tests with different number of cycles N, from 10 to 60. The load maximum value in each cycle was equal to 60% of the mean strength, i.e. 20.17 MPa. After subjecting the sample to the required number of cycles, the acoustic Q-factor was measured, and then the sample was destroyed on the compression machine to determine the strength.

In the first series of heating tests, the samples were heated to a temperature of 600°C for 2 hours, and then aged at this temperature for 30 minutes. The sample was then cooled at room temperature, and the cycle of heating was repeated. The number of heating cycles N was between one and six. The choice of this temperature is due to the fact that, at a given temperature, the dissociation of calcite begins according to the reaction $CaCO_3$=CaO+CO_2, in accordance with [29]. The formation of carbon dioxide (up to 44% by weight) and porous calcium oxide occurred, which caused an irreversible decrease in strength. The sample acoustic Q-factor was measured after completing the required number of cycles. Thereafter, the specimen was subjected to destruction to determine the strength.

Fatigue tests by freezing/thawing took place in a similar way. First, the samples of the limestone were immersed in water for two hours, whereby their saturation with water occurred. Water saturation was approximately 7.6% (8 g of water with an average mass of samples of 105 g). After saturation, the samples were placed in a freezer at a temperature of -40°C, where they were frozen for four hours, then removed and thawed at room temperature. The number of freezing cycles N ranged from 1 up to 35. After completing a certain number of cycles, as in the above-described test, the acoustic Q-factor was measured. The sample was then destroyed to determine its strength.

4. RESULTS

4.1. Mechanical Fatigue Tests

The results of mechanical testing are presented in Table 2 and in Fig. 5.

Table2. *Summary table for mechanical fatigue tests*

Specimen	Number of cycles	Force F, N	Strength, MPa		Quality factor Q	
LS_1_01	0	29770	33.18	Mean 33.62	30.70	Mean 21.90
LS_2_01	0	32870	36.45		15.30	
LS_3_01	0	28210	31.24		19.55	
LS_1_02	10	28630	32.00		13.29	
LS_1_03	20	28100	31.04		11.34	
LS_1_04	30	25390	28.08		7.54	
LS_1_05	40	22100	24.51		6.83	
LS_1_07	60	19470	21.59		5.20	

Both the quality and the strength monotonically decreased with an increasing number of fatigue cycles. The sharp drop in Q-factor by 68%, or 2.9 times, was observed when the number of cycles reached 30. At the same time, the strength decreased by 16%, or 1.19 times. The approximation of the dependency of the exponent $y = a_0 \exp(-N/a_1)$ has the following form for strength:

$$\sigma_m = 34.47 \cdot \exp\left(-\frac{N}{131.99}\right) \text{ (MPa)}$$

where the coefficient of determination $R^2 = 0.96$ and root mean square (RMS) error is 2.02 MPa, the approximation of the dependencies here and below was made using the Statistica software.

For Q there is:

$$Q = 20.57 \cdot exp\left(-\frac{N}{33.47}\right)$$

where the coefficient of determination $R^2 = 0.95$ and the standard error is 3.14.

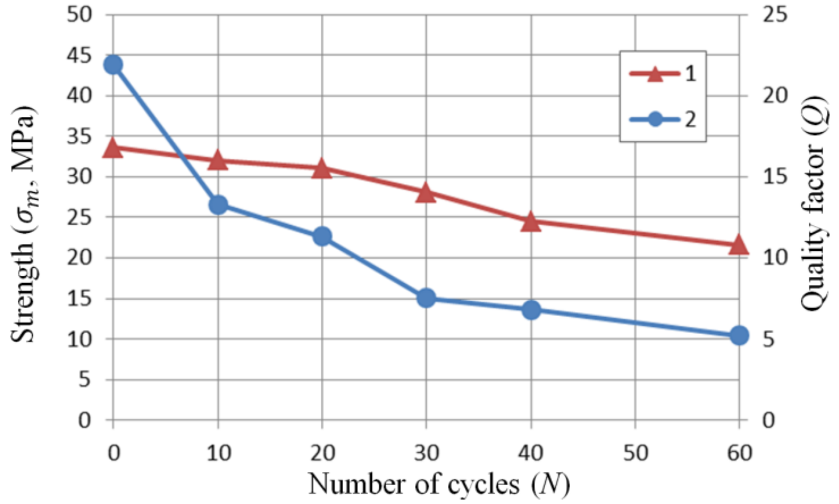

Fig5. *Graph of strength σ_m (1) and Q-factor (2) against the number of cycles for mechanical fatigue tests*

The obtained results allow the exclusion of the number of fatigue cycles, and the determination of the regression interdependence of the strength versus the Q-factor—the graph is presented in Fig. 6. The analytical expression has the form:

$$\sigma_m = 8.42 \cdot ln(Q) + 9.22 \text{ (MPa)}$$

where the determination coefficient $R^2 = 0.89$ and the RMS error is 3.45 MPa.

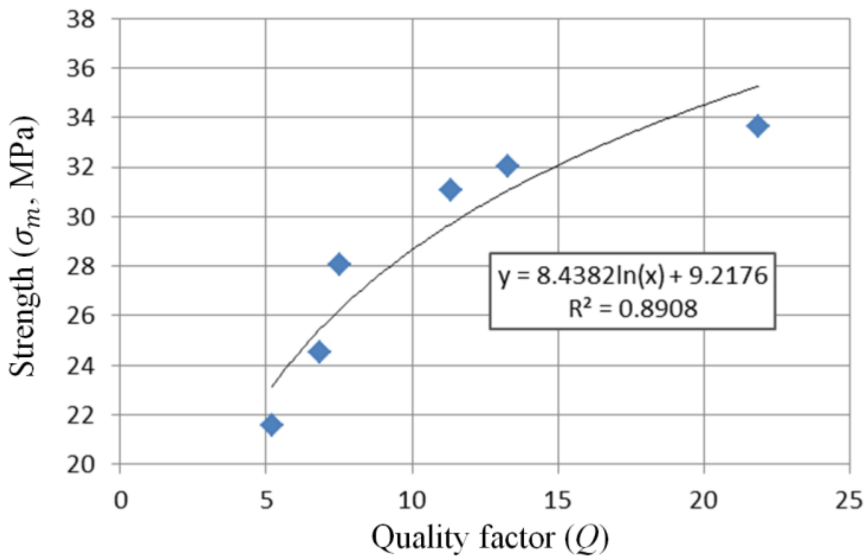

Fig6. *The relationship between the strength and the quality factor for mechanical fatigue tests*

4.2. Thermal Testing When Heated Up To 600°C

The results of the thermal tests under cyclic heating to 600°C are presented in Table 3 and in Fig. 7.

Table3. *Summary table of the thermal testing results when heated up to 600°C*

Specimen	Number of cycles N	Force *F*, *N*	Strength, MPa		Quality factor *Q*	
LS_1_01	0	29770	33.18	Mean 33.62	30.70	Mean 21.90
LS_2_01	0	32870	36.45		15.30	
LS_3_01	0	28210	31.24		19.55	
LS_2_02	1	26540	29.49		11.95	
LS_2_03	2	22690	25.21		10.80	
LS_2_04	3	21280	23.64		23.33	
LS_2_05	4	25680	28.53		31.00	
LS_2_06	5	20640	22.93		23.80	
LS_2_07	6	19830	22.03		14.05	
LS_2_08*	2	26350	29.28		11.08	
LS_2_09*	4	24360	27.07		25.22	

** Additional tests to check the strength increases and the quality factor for the 4th cycle*

A feature of the thermal effect is a non-monotonic change in the strength and quality factor dependency on the number of heating cycles. The strength during the 4th heating cycle shows an increase of 20% compared with the strength after the 3rd cycle. The quality factor shows a similar increase during the 3d and 4th cycles, which begins after the 2nd cycle. The decrease in both strength and *Q*-factor was observed after the 4th cycle.

Additional tests were carried out during the 2nd and 4th cycles of heating to check the non-monotonic changes in the strength and quality factor, the results of which are shown in Table 3. These measurements gave similar results to those obtained previously. Table 3 also shows these results.

Both curves in Fig. 7 have several characteristic points. In section *A*, the strength and *Q*-factor decreased, with the strength decreasing by 25.0% and the quality factor decreasing by 50.7%. In section *B*, the *Q*-factor began to increase, but the strength continued to decrease. In section *C*, both *Q*-factor and strength increased before the 4th cycle. In the last section, *D*, the quality and strength values decreased.

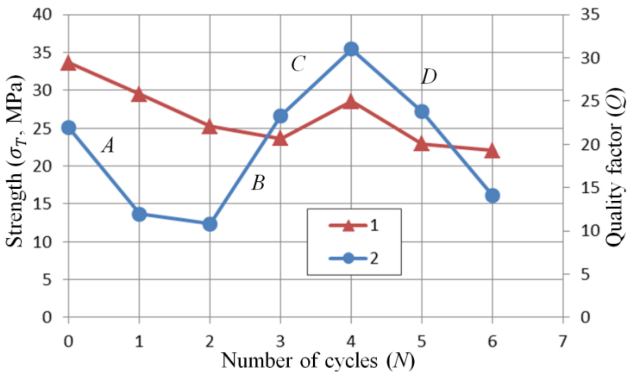

Fig7. *Graph of strength (1) and Q-factor (2) against the number of cycles for thermal testing when heated up to 600°C*

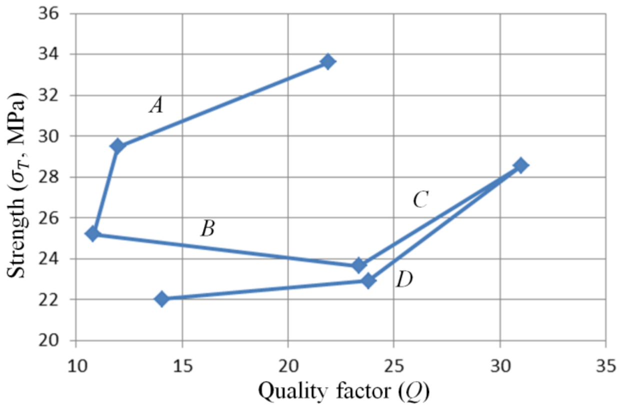

Fig8. *The relationship of strength and Q-factor during thermal testing when heated up to 600°C*

The curve between the quality factor and strength (Fig. 8) in this case is more complex than similar curves constructed for other influences. It reflects the non-monotonic changes in quality factor and durability.

4.3. Thermal Tests for Freezing/Thawing

The results of the thermal tests for the freezing/thawing cycles are shown in Table 4 and in Fig. 9.

Table4. *Summary table for freezing/thawing thermal tests*

Specimen	Number of cycles N	Force F, N	Strength, MPa		Quality factor Q	
LS_1_01	0	29770	33.18	Mean 33.62	30.70	Mean 21.90
LS_2_01	0	32870	36.45		15.30	
LS_3_01	0	28210	31.24		19.55	
LS_3_02	1	26540	29.49		10.00	
LS_3_03	2	28210	31.34		9.51	
LS_3_04	3	28670	31.86		9.23	
LS_3_07	6	30310	29.10		5.90	
LS_3_09	10	24340	27.04		3.80	
LS_1_09	20	16370	18.19		4.50	
LS_1_08	35	16140	17.93		4.00	

The quality factor monotonically decreased with an increasing number of cycles. It is worth noting that the value of Q decreased by 73%, or 3.7 times, by the 6th cycle. The strength had a non-monotonic pattern of decline during the first few cycles, but it began to decrease monotonically after the 4th cycle. By the 6th cycle, the strength decreased by 13%, or 1.15 times. The approximation of the dependency exponent for strength has the following form:

$$\sigma_f = 20.13 \cdot exp\left(-\frac{N}{21.56}\right) + 12.94\ (MPa)$$

where the coefficient of determination R^2 = 0.92 and the RMS error is 4.55 MPa. For the Q-factor:

$$Q = 16.22 \cdot exp\left(-\frac{N}{1.38}\right) + 4.87$$

where the determination coefficient R^2 = 0.93 and the standard error is 4.23.

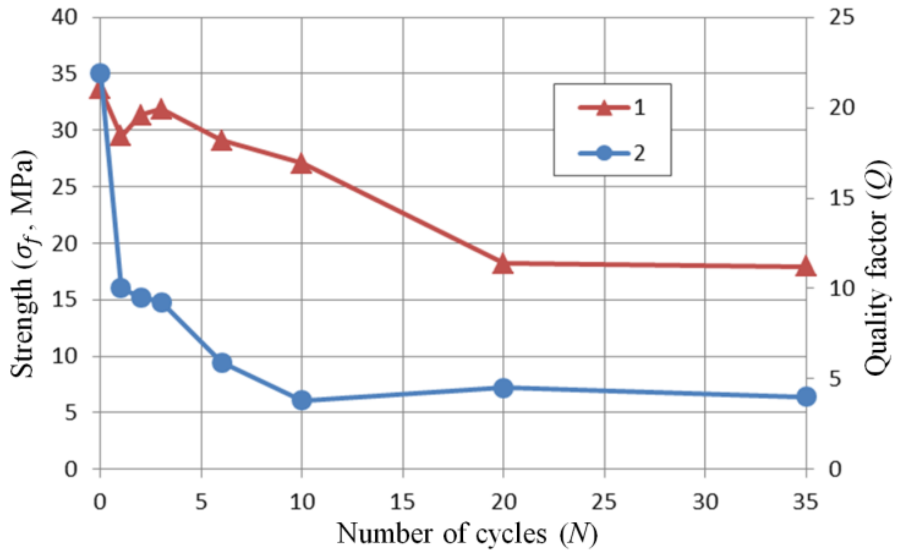

Fig9. *Graph of strength (1) and Q-factor (2) against the number of cycles for thermal testing by freezing/thawing*

The results obtained allowed the exclusion of the number of fatigue cycles and the determination of the regression dependence of the strength on the Q-factor, the graph of which is shown in Fig. 10. The analytical expression has the form:

$$\sigma_f = 7.84 \cdot ln(Q) + 11.77\ (MPa)$$

where the determination coefficient R^2 = 0.60 and the standard error is 10.11 MPa.

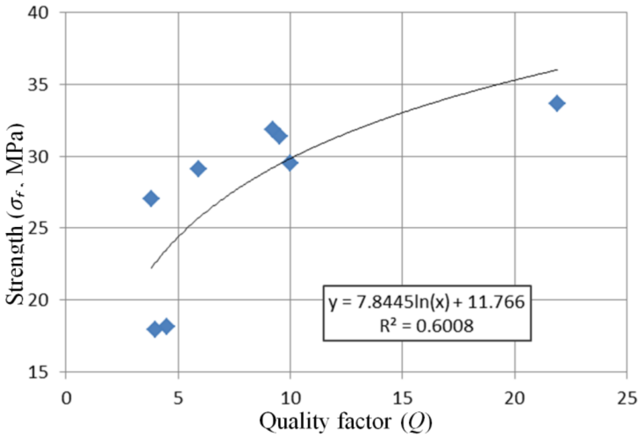

Fig10. *The relationship between strength and Q-factor for thermal testing by freezing/thawing*

5. Discussion

Graphs of the total acoustic emission events during heating up to 600°C, depending on the number of heating cycles N, were created to check the validity of the results obtained regarding the observed non-monotonic change of the Q-factor and the strength of the limestone. The graphs for the three samples tested for strength after four, five, and six cycles of heating are shown in Fig. 11.

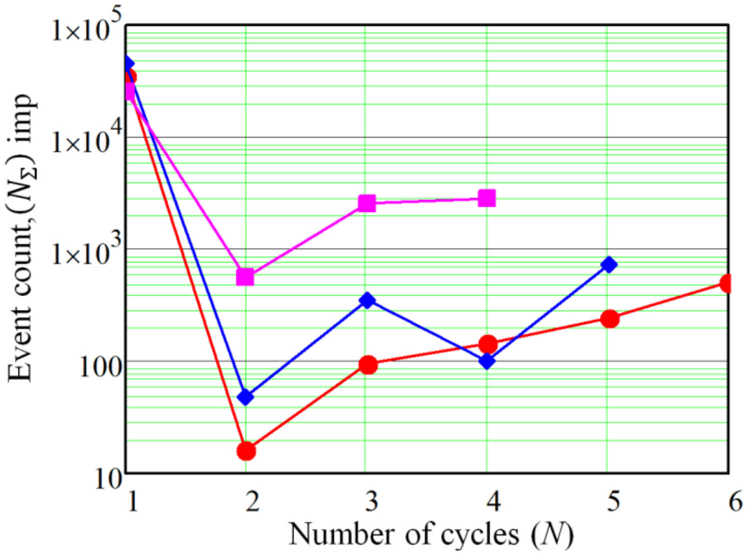

Fig11. Graphs of the number of acoustic emission events during cycles of heating up to 600°C

The graphs show a significant number of AE-pulses during the first heating cycle (which is associated with the destruction of a large number of internal connections), a sharp decline during the second cycle of heating, and a slow increase during subsequent cycles. One of the reasons for this change may be the restoration of internal connections, during the absorption of moisture from the air, with the formation of slaked lime that have a binding effect on the structure. A breakdown of connections occurs during the next cycle of heating, accompanied by an increased number of pulses of the AE compared to the previous cycle. It can be concluded that the cyclic heating of limestone is accompanied by both a decrease and an increase in strength. The combination of these two processes leads to the non-monotonic change in strength and Q-factor shown in Fig. 8.

Let us make a comparison of the researches results of different cyclic influences on the $Q - \sigma_{UCS}$ dependencies.

First of all, the comparison between graphs of the dependencies presented above in Fig. 6, 8, 10 should conclude about the difference of the curves obtained at heating to 600°C, and of the curves for other tests, which is caused by non-monotonic change in measured value on the number of fatigue cycles N. Thus, the first thing to note is the fundamental difference between these curves, caused by fundamental features of the physics of the process. The initial phase of monotonic changes was highlighted from the curve of Fig. 8, for which the function below was designed, approximating the interdependence of $Q - \sigma_{UCS}$ for comparison with other impacts. Approximating functions for other impacts were calculated on full dataset for each test under cyclic mechanical loading and the cycles of freezing and thawing.

When comparing the dependences $Q - \sigma_{UCS}$ obtained with different types of impacts, it is advisable to use not absolute but relative values. This allows obtaining more generalized conclusions compared to the original dependency graphs, expressed in absolute units. In the work comparison with each other dependency between the quality factor Q and strength σ_{UCS} under uniaxial compression, expressed in relative units with ratio to their initial values Q_0 and σ_{UCS0} obtained prior to impacts. These dependencies are represented in Fig. 12, the following corresponding equations with the parameters of the approximation accuracy. Based on the approximated logarithmic function of the form $\xi = a_0 \cdot \ln(\gamma) + a_1$, where $\xi = \sigma_{UTS}/\sigma_{UTS0}$ — ultimate strength under uniaxial compression and $\gamma = Q/Q_0$, normalized values relative to the initial absolute value of the undisturbed samples. Logarithmic function most closely matches the nature of the change of both variables for all types of tests.

The approximating function for the mechanical testing takes the form (circles in Fig. 12)

$$\xi_m = 0.25 \cdot ln(Q) + 1.04$$

where $\xi_m = \sigma_{UCS}/\sigma_0$ – the relative strength mechanical cyclic tests with a coefficient of determination R^2 = 0.89 and RMS error of 0.1.

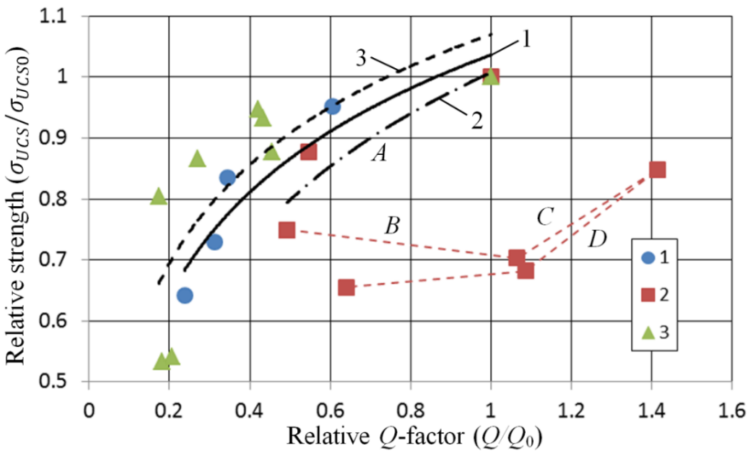

Fig12. *The relationship of the relative strengths σ_m, σ_T, σ_f and the acoustic Q-factor for different types of fatigue tests: mechanical (1), heating up to 600°C (2), at thermal freezing/thawing (3)*

The approximating function for the initial phase A during thermal testing when heated up to 600°C (squares in Fig. 12) has the form

$$\xi_T = 0.30 \cdot ln(Q) + 1.01$$

where $\xi_T = \sigma_{UCS}/\sigma_0$ — when the coefficient of determination R^2 = 0.85 and RMS error of 0.07. Due to the small number of experimental points, approximation curve is given for the illustration. Comparisons with other types of tests it is not possible.

The approximating function for thermal testing by freezing/thawing (triangles in Fig. 12) is expressed as follows

$$\xi_f = 0.23 \cdot ln(Q) + 1.07$$

where $\xi_f = \sigma_{UCS}/\sigma_{UCS0}$ — when the coefficient of determination R^2 = 0.60 and the RMS = 0.3.

To assess the possibility of substituting one type of testing for others, check a statistical hypothesis about the equality of the coefficients of regression dependences $\xi = a_0 \cdot \ln(\gamma) + a_1$ for mechanical fatigue tests and thermal testing by freezing/thawing. The original data of the average values obtained using the software Statistica, as well as t-criterion and its critical value t_c obtained using programs written in Mathcad, are given in Table 5.

Table5. *The regression coefficients $\xi = a_0 \cdot ln(\gamma) + a_1$ and t-criterion for mechanical fatigue test and thermal tests by freezing/thawing*

	Mechanical fatigue tests		Thermal testing by freezing/thawing		t-criterion	Critical value
	Estimate	Standard error	Estimate	Standard error	t	t_c
a0	0.25	0.0439	0.23	0.0777	0.608	2.179
a1	1.04	0.0411	1.07	0.0960	0.769	2.179

t-criterion was calculated according to the formula

$$t = \frac{|\overline{a_m} - \overline{a_f}|}{\sqrt{S_d}},$$

where t is the unequal variances t-test, and $\overline{a_m}$ and $\overline{a_f}$ are the average values of the coefficients a_0 and a_1 of the logarithmic function,

$$S_d = \frac{(n_m - 1) \cdot S_m^2 + (n_f - 1) \cdot S_f^2}{n_m + n_f} \cdot \left(\frac{1}{n_m} + \frac{1}{n_f}\right),$$

where S_d is the variance joint sampling; n_m and n_f are the sample sizes for mechanical fatigue tests and thermal tests during the freezing/thawing; S_m and S_f are the standard errors of the regression coefficients.

The calculation was performed at a significance level of $\alpha = 0.05$. As can be seen from Table 5, the values of t for the coefficients a_0 and a_1 is less than the critical values $t_k = 2.179$. Therefore, the differences in the coefficients a_0 and a_1 for mechanical and thermal tests during the freezing/thawing are insignificant, and the hypothesis of their equality can be accepted. This confirms the possibility of replacing testing by freezing/thawing to mechanical testing under cyclic loading and to reduce the duration and cost of trials.

6. Conclusion

Fatigue processes can be diverse and include not only mechanical processes, and chemical, thermal conversion, which dramatically changes the fatigue processes and their results.

Fatigue processes may be accompanied by both destruction of the material resulting in lower strength and by processes to increase its strength.

Replacement of one kind of testing other kind of valid in some cases, when the similarity of the physical processes, as, for example, under cyclic mechanical loading and freezing/thawing, which would reduce the time and cost of testing.

The decision on replacement based on Q-σ_{UCS} that occur during prolonged decrease in strength at constant mechanical stress and other influences, dependencies, resulting in reduced fatigue cyclic loadings will require additional research.

Acknowledgments

This work has been carried out under the auspices of the Russian Foundation for Basic Research, Grant No. 17-05-00570, and with financial support from the Ministry of Education and Science of the Russian Federation in the framework of increase Competitiveness Program of NUST ‘‘MISIS”, implemented by a governmental decree dated 16th of March 2013, No. 211.

The authors express their gratitude L. Y. Didovic, Ph. D. A. V. Podgaetsky, A. A. Komissarov for their help and useful discussion of experimental results, and also to unknown reviewers for their attentive reading of the manuscript and valuable remarks.

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Citation: *Voznesenskii Aleksandr Sergeevich et.al, (2018). Features and the Ability to Replace the Interdependencies between the Acoustic Quality Factor and the Strength of Limestone under the Influence of Different Physical Nature, International Journal of Mining Science (IJMS), 4(2), pp.31-43, DOI: http://dx.doi.org/10.20431/2454-9460.0402004*