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STUDY OF STRENGTH REDUCTION IN NATURAL STONE UNDER REPEATED NON-DESTRUCTIVE DYNAMIC LOADING

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ABSTRACT. This paper investigates the reduction of strength in natural stone under repeated non-destructive dynamic loading, which is essential for assessing the suitability of deposits for selective extraction of block stone in crushed stone quarries. A laboratory testing methodology is proposed based on repeated impacts of a spherical striker on stone samples, simulating the development of tensile stresses and accumulation of microcracks in the rock mass. Numerical modelling using Ansys AUTODYN was applied to establish relationships between the impact kinetic energy and induced tensile stresses. Experimental studies were carried out on granite, gabbro, and labradorite samples from more than ten deposits in Ukraine. Strength degradation was evaluated using an ultrasonic method by measuring the propagation velocity of surface waves after each loading cycle. The results indicate that most rocks fail when their strength decreases by 11% to 41.5%. Based on the obtained data, natural stone was classified into three groups according to resistance to repeated dynamic loading: high, medium, and low durability. It was found that fatigue strength is significantly influenced by quartz content and rock structure. Coarse-grained rocks and those with a high content of accessory minerals exhibit lower resistance to cyclic loading. The practical significance of the study lies in predicting disturbed zones within quarry rock masses, which enables optimisation of block stone extraction.

Key words: natural stone, dynamic loading, fatigue strength, ultrasonic testing, selective extraction.

Introduction

During mass blasting at crushed stone quarries, repeated dynamic loads of varying energy and frequency induce intensive microcrack development throughout the rock mass. Since rocks are substantially weaker in tension than in compression, strength degradation under explosive loading is driven predominantly by tensile stresses – making tensile strength the most appropriate criterion for assessing rock damage in quarry conditions.

Information on the reduction in the strength of natural stone in certain areas of the quarry is essential for effective selective extraction of natural stone blocks at crushed stone quarries. A preliminary assessment of the suitability of a building stone deposit for selective extraction can be performed by conducting laboratory tests. Under laboratory conditions, it is possible to assess the weakening of rock strength under the action of cyclic dynamic loads using non-destructive methods. Analysis of the intensity of blasting operations and the resistance of rocks to cyclic dynamic loads will allow zoning of the quarry, where damaged and undamaged areas of the rock mass can be identified for each deposit.

Currently, the nature of dynamic rock destruction remains not fully understood, especially under conditions of cyclic loading (Xiao et al., 2010). During cyclic loading, some materials become stronger and more plastic, while others become weaker and more brittle (Bagde and Petros, 2005). For rocks, a decrease in strength during cyclic dynamic loading is characteristic, particularly during blasting operations, which is why there is a need to predict the strength characteristics of the rock (Stavrogin and Tarasov, 2001).

The effect of cyclic loads on the fatigue properties of rocks has been studied by various researchers. Bagde and Petroš (2009), based on the results of a study of fatigue and dynamic energy change in sandstone and conglomerate, established that the microstructure, texture of the stone, and quartz content affect the weakening of rock strength under cyclic dynamic loads, and that microcracks were the main cause of fatigue. Laboratory studies have shown that the behaviour of rock under dynamic cyclic loading is significantly influenced by the frequency and amplitude of the load, with the dynamic fatigue strength and dynamic axial stiffness of the rock decreasing with increasing frequency and amplitude (Vaneghi et al., 2018). Momeni et al. (2015), based on the results of a study of the behaviour of Alvand granite under different maximum loads with variable frequency and amplitude, concluded that with an increase in the cyclicity of loading, the level of resistance to destruction decreases and plastic behaviour becomes dominant in each cycle. However, due to the brittleness of the rock and the low loading rate at low frequencies, it was not possible to trace the process of accumulative damage of the granite. Singh (1989) and Momeni et al. (2015) established that natural stone is destroyed after a small number of cycles and has a shorter service life with an increase in the energy of dynamic loading. More recently, Zhou et al. (2018) confirmed this pattern for granite under low-cycle repetitive compressive impacts using a split Hopkinson pressure bar, demonstrating that cumulative damage energy increases nonlinearly with impact number. Li et al. (2022) further showed that under repeated dynamic tension – the stress regime most directly relevant to blast-induced failure – granite exhibits fatigue thresholds of 0.49–0.71 times the critical impact stress, with peak strength decreasing progressively with each loading cycle. Physical and mechanical properties of granites can be determined by the ultrasonic method (Vasconcelos et al., 2008), and this also applies to strength characteristics and accumulative damage assessment (Korobiichuk, 2016). Yang et al. (2018) demonstrated that damage accumulation under cyclic loading is reliably tracked by changes in ultrasonic wave velocity and elastic modulus, confirming the suitability of ultrasonic monitoring as a non-destructive tool for fatigue assessment in brittle geomaterials.

The presented studies demonstrate that rock texture and quartz content influence strength degradation under cyclic dynamic loading. However, the existing data remain contradictory, which is attributable to the unique texture and structural characteristics of natural stone at each individual deposit. Crucially, previous investigations have focused predominantly on uniaxial cyclic compressive loading under controlled laboratory conditions, whereas the response of rocks to repeated low-energy impact loading – directly analogous to the stress regime induced by blasting in quarries – has received considerably less attention. Moreover, no systematic classification of natural stones from Ukrainian deposits according to their resistance to repeated dynamic loading has been proposed to date. Consequently, the available data are insufficient for solving the practical problem of predicting granite strength degradation within crushed stone quarries and optimising the selective extraction of block stone.

The aim of the present study is to establish quantitative patterns of strength degradation in natural stone samples from more than ten Ukrainian deposits under repeated non-destructive dynamic loading, to develop a classification of rocks according to their fatigue resistance, and to provide a practical basis for predicting disturbed zones in quarry rock masses for the purposes of selective block stone extraction.

Materials and methods

Studies on the reduction of natural stone strength under repeated non-destructive loading were carried out in order to establish quantitative patterns of the development of damage and reduction of natural stone strength depending on the number of loadings.

Theoretical model of stress distribution under impact

To assess the magnitude of the stress that occurs in a rock piece when an impactor is dropped onto it, a theoretical problem of the destruction of a piece located on a sandy base under impact by an impactor was considered. Let a sample with mass m_1 lie on an elastic base, onto which an impactor with mass m_2 falls with the velocity of the centre of mass V_2. It is assumed that the impact of the impactor is carried out on a flat section of the piece surface along a straight line across its width C (Figure 1). The interaction between the piece and the impactor occurs at a certain point A.

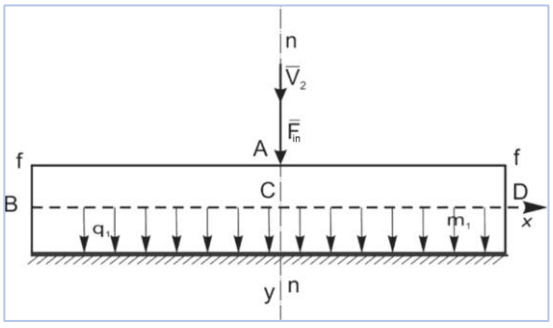


Fig. 1. Scheme of load distribution in a rock piece when an impactor is dropped onto it

Upon impact at point A, interaction forces will arise that act for a short time t_1. The influence of the displacement of the pieces on the process of their collision and motion during this process will be neglected. The collision occurs in two stages. During the first stage, maximum convergence of the contacting areas takes place with an increase in the interaction force to its maximum value, while in the second stage, unloading of the stressed state of the collided pieces occurs and the interaction force decreases to zero. In the initial period of collision, elastic waves will begin to propagate in both pieces, which will quite quickly transform into shear waves.

Therefore, the first (in time) possible variant of piece destruction will occur when the shear stresses that arise in the pieces in the shear waves reach their limiting values τ_{sh}.

$$\tau_{sh} = \rho c_2 V_{2y}, \quad (1)$$

where τ_{sh} – limiting shear stress in the rock piece (MPa);
ρ – density of the rock (kg/m³);
c_2 – velocity of propagation of transverse (shear) waves (m/s), defined as $c_2 = \sqrt{(G/\rho)} = \sqrt{\frac{E}{2\rho(1+\nu)}}$, where G is the shear modulus (Pa), E is the elastic modulus (Pa), and ν is Poisson's ratio (dimensionless);
V_{2y} – component of the impactor velocity normal to the sample surface at the moment of impact (m/s).

As the interaction of the pieces intensifies and after several superpositions of elastic waves in the pieces, a certain stress-strain state arises that reaches its extreme value at the end of the first stage of collision of the pieces at the maximum interaction force. The interaction force F_{in} is balanced according to d'Alembert by inertia forces continuously distributed throughout the entire piece. Under the action of this force and the moment that arises, bending of the piece occurs.

The value of the bending moment *M* will be equal to:

$$M = \frac{F_{in} x^2}{a} \quad (2)$$

where *M* – bending moment in the cross-section of the piece (N·m); F_{in} – interaction force between the impactor and the piece, balanced by d'Alembert inertia forces distributed continuously along the piece (N); x – coordinate of the cross-section where the bending moment reaches its maximum value (m); a – length of the rock piece along the impact axis (m).

The stress state in the piece is equal to:

$$\sigma = \frac{MY}{l_1}, \quad (3)$$

where σ – normal (tensile) stress at the outermost fibre of the cross-section (MPa); M – bending moment at the critical cross-section, determined from equation (2) (N·m); Y – distance from the neutral axis to the outermost point of the cross-section (m); l_1 – second moment of area (moment of inertia) of the cross-section about the neutral axis (m⁴), defined as $l_1 = a \cdot b^3/12$, where b is the thickness of the piece (m).

Since $V_2 \sim F_{in}$, $F_{in} \sim M$, and $M \sim \sigma$, it follows that $V_2 \sim \sigma$, that is, the destruction stresses of the pieces are directly proportional to the velocity of dropping the impactor onto them.

Physical analogue of tensile failure under impact loading

The repeated impact of a spherical striker on the upper surface of a rock sample resting on a sand base was adopted as a physical analogue of tensile failure for the following reasons. When the striker contacts the sample surface, a

compressive stress pulse propagates downward through the sample thickness. Upon reflection from the lower free surface, this pulse undergoes a phase inversion and re-enters the sample as a tensile wave. The resulting tensile stresses act transversely to the sample midplane, replicating the stress regime responsible for rock failure under blast loading in a quarry rock mass, where tensile waves generated by explosive detonation propagate radially outward and interact with free surfaces and pre-existing discontinuities. Furthermore, the bending mechanism induced by the impact – in which the interaction force F_{in} (Figure 1) is balanced by distributed inertia forces along the sample length, generating a bending moment M with maximum tensile stress at the outermost fibre of the critical cross-section (equation 3) – is physically equivalent to Brazilian disc splitting, a widely accepted indirect tensile test for brittle geomaterials (Stavrogin and Tarasov, 2001). The blast-induced damage context is further supported by Shadabfar et al. (2021), whose review of analytical, numerical, and experimental models of single-hole blasting damage confirms that tensile stress waves radiating from the blast epicentre govern the extent of the fractured zone – directly supporting the choice of tensile strength as the failure criterion in the present study. It is acknowledged that this analogy has inherent limitations: the stress field under impact is three-dimensional and transient, whereas classical tensile tests assume quasi-static uniaxial loading. Nevertheless, the proportionality $V_2 \sim \sigma$ (derived from equations 1–3) confirms that the impactor drop velocity controls the magnitude of induced tensile stress, providing a controllable and reproducible experimental parameter for fatigue testing under repeated sub-failure loading.

The multiple non-destructive loading of granite pieces by dropping a spherical impactor onto them served as an analogue of the process of multiple loading of natural stone samples. In this process, both the drop height of the impactor and the number of load applications were varied.

Numerical modelling using Ansys AUTODYN

To quantify the stress state induced in rock samples during impact loading, numerical simulations were performed using Ansys AUTODYN R16.0 (ANSYS Inc., Canonsburg, PA, USA). This software was selected for the following reasons: (1) it implements an explicit time-integration solver specifically designed for short-duration dynamic and impact events, which is essential for modelling high strain-rate loading with durations in the order of 10^{-4} s; (2) it supports the finite element method combined with Lagrangian mesh formulations, enabling accurate tracking of stress wave propagation and material deformation in brittle solids such as granite; (3) it allows direct computation of both compressive and tensile stress distributions throughout the sample volume, which is critical given that tensile failure governs rock degradation under blast-induced loading.

The numerical model reproduced the experimental geometry: a 200×200×30 mm rock sample resting on a sand base, impacted by a 1 kg spherical striker dropped from heights of 15 to 50 cm, corresponding to kinetic energies of 1.47 to 4.9 J. The dynamic analysis employed the explicit solver with a time step smaller than the Courant time step – defined as the time required for a stress wave to traverse one finite element – to ensure numerical stability. Nodal accelerations were resolved directly at each time step without iteration, with displacements and stresses updated sequentially. The simulation output confirmed a linear relationship between impactor drop velocity and induced tensile stress, validating the analytical proportionality $V_2 \sim \sigma$ derived from equations (1) – (3) and providing quantitative estimates of both compressive and tensile stress distributions along the sample length at each tested drop height (Figure 2).

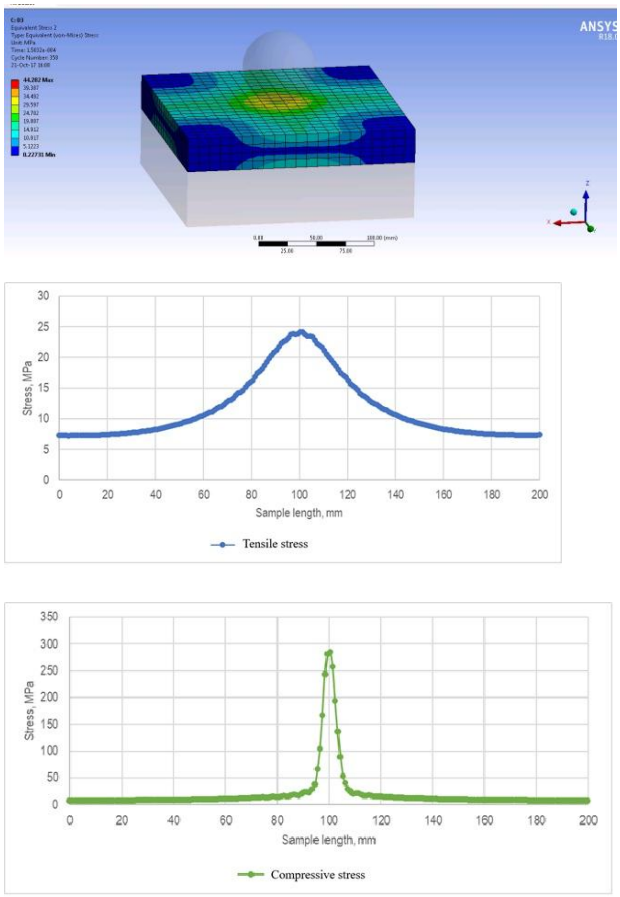


Fig. 2. Digital model of load distribution in rock fragment when an impactor is dropped onto it from a height of 15 cm

Laboratory testing programme

Laboratory studies were carried out to solve two main tasks: (1) to determine the impact velocity of rock fragments at which their failure occurs; (2) to establish quantitative relationships governing the development of damage and the reduction in strength of granite fragments depending on the velocity and the number of load applications.

The loading of natural stone samples was investigated using a special testing setup (Figure 3), consisting of: (1) a drop tower frame; (2) height markings; (3) a spherical steel impactor with a mass of 1 kg; (4) a sand cushion of at least 100 mm thickness; (5) the stone sample; (6) the base of the drop tower. Repeated non-destructive loading of granite fragments was performed by dropping the spherical impactor onto them, which is analogous to tensile testing of a granite specimen.

For each rock type, tests were conducted on four samples measuring 200×200×30 mm with a sawn surface texture. Each sample, in an air-dry state (natural moisture condition), was placed at the centre of a box on a levelled sand layer at least 100 mm thick. Impacts were then applied to the geometric centre of the sample using the falling weight of 1 kg. The first impact was applied from a height of 15 cm, and for each subsequent impact the height was increased by 5 cm. After each impact, the samples were inspected visually. Testing continued until visible cracks appeared in the sample or complete failure occurred.

During the tests, the underlying sand layer was continuously levelled. The indicator of rock resistance to impact loading was taken as the minimum drop height (in centimetres) at which cracks appeared in the sample or its destruction occurred. Rock resistance to impact loading was calculated as the arithmetic mean of the results obtained from four specimens.

The determination of rock resistance to repeated impact loading was carried out on similar samples; however, all impacts were applied from the same fixed height until sample failure occurred as a result of the accumulation of damage from previous loadings. The critical number of loadings *n* corresponded to the number of drops of the spherical impactor from the selected height that caused sample failure through accumulation of damage from preceding impacts.

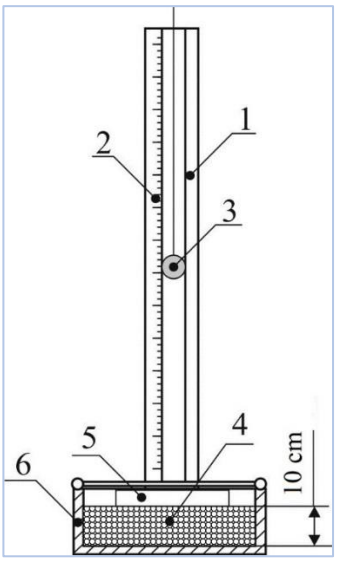


Fig. 3. Installation for testing the loading of natural stone samples:
1 – drop tower (impact rig frame); 2 – height markings; 3 – metal weight (ball) with a mass of 1 kg; 4 – sand cushion; 5 – stone sample; 6 – base of the drop tower (impact rig)

Ultrasonic monitoring

Before testing, the velocity of surface ultrasonic wave propagation in the stone sample was measured using a UK-14 MP ultrasonic device. After each drop of the weight, the velocity of the surface ultrasonic wave in the sample was measured in four directions, and the obtained data were averaged. The specific impact energy applied to the sample was calculated for each drop height, and the cumulative specific impact energy was accumulated across all loading cycles. The relationship between ultrasonic wave velocity and cumulative specific impact energy was used to monitor the progressive accumulation of internal damage in each sample. This approach is consistent with Yang et al. (2018), who demonstrated that ultrasonic wave velocity reliably tracks damage accumulation under cyclic loading in brittle geomaterials, and with Vasconcelos et al. (2008) and Korobiichuk (2016), who established robust correlations between ultrasonic velocity and the mechanical properties of granites.

Experimental studies were carried out on granite, gabbro, and labradorite samples from more than ten deposits in Ukraine - Table 1. The deposits tested included Tokivskyi, Koretskyi, Bukynske (gabbro), Maslavskyi, Leznikivskyi, Novodanylivskyi, Lukovetskyi, Vasylivskyi, Mezhyrichskyi, Kapustynskyi, Dobryn (labradorite), Didkovetskyi, and Zhezhelivskyi. Grain size ranged from fine-to-medium (Tokivskyi, Koretskyi, Bukynske gabbro) to coarse-grained (Lukovetskyi, Kapustynskyi, Dobryn labradorite), and quartz content varied from 0.6% (gabbro) to 30.4% (Tokivskyi granite), providing a representative range of mineralogical and textural characteristics for the classification of fatigue resistance.

Results and discussion

Rock resistance to single impact loading

Tests of rock resistance to single impact loading showed that the minimum drop height at which cracking or failure occurred varies from 35 to 55 cm across the tested deposits (Figure 4). Rock resistance to impact loading was calculated as the arithmetic mean of the results obtained from four specimens. The lowest values were observed for the red medium-grained granite of the Lezniki deposit (35 cm) and the Dobryn labradorite (35 cm), while the highest resistance was demonstrated by the grey medium-grained granite of the Zhezheliv deposit (55 cm). All remaining deposits showed approximately equal resistance to single impact loading, with values clustering around 40–45 cm.

These results indicate that single impact resistance alone is not a sufficient criterion for evaluating rock suitability for selective block stone extraction, since deposits with similar single-impact resistance (e.g., Tokivskyi and Vasylivskyi granite, both 45 cm) may differ dramatically in their response to repeated sub-failure loading, as demonstrated in the sections below.

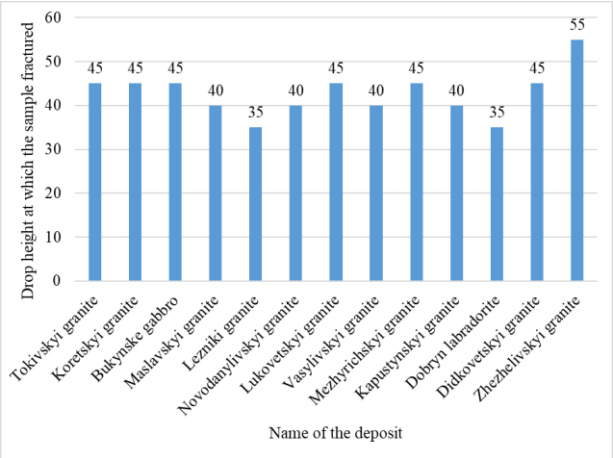


Fig. 4. Results of tests on rock resistance to impact loading

Strength reduction under repeated impact loading at low energy (drop height 15 cm, E = 1.47 J) showed significant differences in fatigue resistance among the tested rocks, with failure occurring after 25 to 1400 impacts.

In determining the reduction in strength of natural stone samples under repeated impact-induced loading, it was found that not all rock types can withstand repeated dynamic loading with low impact energy of 1.47 J (Figure 5, Table 1). The number of impacts sustained before failure at this energy level varied from 25 (Dobryn labradorite) to 1400 (Zhezhelivskyi granite), representing a 56-fold difference between the least and most resistant deposits.

The highest resistance at a specific energy of 1.47 kJ/m³ (Table 1) was observed in samples of granite from the Korets deposit (1000 impacts), Zhezheliv deposit (1400 impacts), Tokiv

deposit (1100 impacts), as well as gabbro from the Bukynske deposit (1350 impacts). Most of these rocks are medium-grained. The least resistant were granites from the Vasyliv deposit (54 impacts), Didkovychi deposit (36 impacts), Mezhyrich deposit (36 impacts), and Kapustyn deposit (47 impacts), as well as Dobryn labradorite (25 impacts). Most of these rocks are coarse-grained.

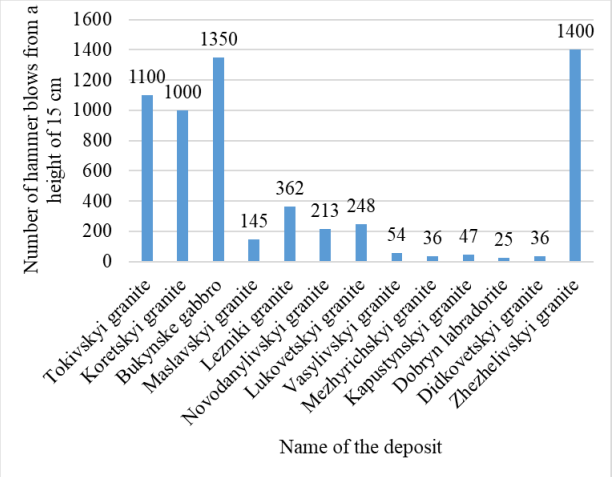


Fig 5. Results of dropping a weight from a height of 15 cm onto natural stone samples

After each drop, the velocity of ultrasonic wave propagation in the sample was measured in four directions and the obtained data were averaged. The relationship between ultrasonic wave velocity and cumulative specific impact energy at a drop height of 15 cm is shown in Figure 6.

Table 1. *Results of the study on the failure of stone samples under repeated dynamic loading*

Rock type	Number of impacts of the weight from a drop height, cm						
	15	25	30	35	40	45	50
Tokivskyi granite	1100	18	10	7	6	5	3
Koretskyi granite	1000	17	11	5	4	4	3
Bukynske gabbro	1350	107	6	-	-	-	-
Maslavskyi granite	145	7	6	4	4	2	2
Lezniki granite	362	8	6	3	2	2	2
Novodanylivskyi granite	213	13	7	6	4	3	3
Lukovetskyi granite	248	7	6	5	4	4	3
Vasylivskyi granite	54	7	3	-	-	-	-
Mezhyrichskyi granite	36	8	7	6	5	-	-
Kapustynskyi granite	47	6	5			-	-
Dobryn labradorite	25	3	3			-	-
Didkovetskyi granite	36	3	5			-	-
Zhezhelivskyi granite	1400	75	22	7	7	4	4

The curves reveal a characteristic three-phase pattern consistent with the fatigue failure model described by Xiao et al. (2010): an initial Phase I of stable ultrasonic velocity (microcrack closure and stable propagation), followed by a gradual Phase II decline (accelerated crack coalescence), and a rapid Phase III drop to zero immediately prior to macroscopic failure. The transition from Phase I to Phase II at a specific impact energy of 1.47 kJ/m³ occurred at cumulative specific energies of 500–800 kJ/m³ for high-resistance rocks, 130–150 kJ/m³ for medium-resistance rocks, and 25–90 kJ/m³ for low-resistance rocks – a threefold to twentyfold difference that underscores the practical significance of the proposed classification for quarry zoning.

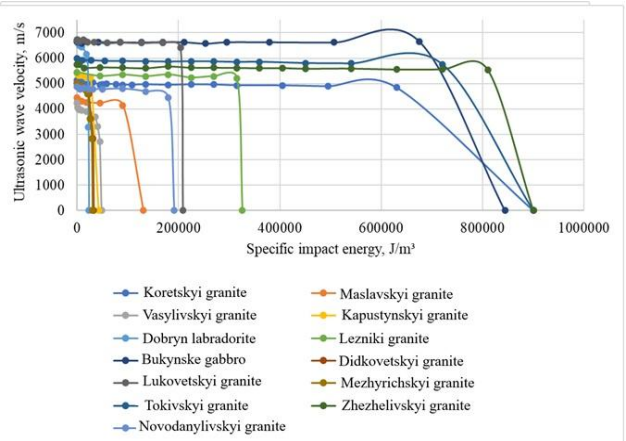


Fig. 6. Dependence of ultrasonic wave propagation velocity on cumulative specific impact energy at a drop height of 15 cm

Strength reduction at intermediate and high impact energies (drop heights 25–50 cm)

When the weight was dropped from a height of 25 cm (specific impact energy of 2.45 kJ/m³), the differences in the number of impacts sustained before failure narrowed considerably compared to the 15 cm results (Figure 5, Table 1). The most resistant to impact were granite from the Zhezheliv deposit (75 impacts) and gabbro from the Bukynske deposit (107 impacts), while the least resistant were granite from the Didkovychi deposit (3 impacts) and Dobryn labradorite (3 impacts).

At a specific impact energy of 2.94 kJ/m³ (drop height of 30 cm), a tendency toward further reduction in differences between sample properties was observed. The most resistant were granites from the Tokiv deposit (10 impacts), Korets deposit (11 impacts), Novodanyliv deposit (7 impacts), and Mezhyrich deposit (7 impacts), as well as Zhezheliv granite (22 impacts). However, it is notable that at low specific impact energy (15 cm), the Mezhyrich deposit showed relatively weak results and proved to be among the least impact-resistant deposits, whereas at 30 cm it performed comparably to high-resistance granites. This reversal suggests that the Mezhyrich granite possesses a relatively high threshold energy for crack initiation, but once microcracks are initiated, they propagate rapidly – a behaviour consistent with the brittle fracture mechanics framework described by Xiao et al. (2010), where rocks with lower initial crack density exhibit a compressed Phase II prior to failure.

At specific impact energies of 3.43 kJ/m³ (40 cm) and 3.92 kJ/m³ (45 cm), the differences in failure indicators between samples became negligible, with most deposits sustaining 2–7 impacts before failure. At the highest tested energy of 4.9 J (drop height 50 cm), the deposits that retained meaningful resistance were Zhezhelivskyi, Tokivskyi, Koretskyi, and Novodanylivskyi granites (medium-grained) and Lukovetskyi granite (coarse-grained), sustaining 2–4 impacts each.

With increasing impact energy from 1.47 J to 4.9 J, the fatigue strength of all tested granites decreased sharply, and the transition from Phase I to Phase II occurred at cumulative specific energies of only 10–30 kJ/m³ – an order of magnitude lower than at 1.47 J. This is consistent with the energy-

dependent failure model of Bagde and Petroš (2009), who demonstrated that dynamic fatigue life decreases nonlinearly with increasing load amplitude, and with Singh (1989), who established that natural stone is destroyed after fewer cycles as loading energy increases. Zhou et al. (2018) similarly confirmed for granite under low-cycle repetitive compressive impacts that cumulative damage energy increases nonlinearly with impact number, with fatigue life reducing sharply at higher impact stress levels.

Strength loss quantified by ultrasonic monitoring

The use of ultrasonic monitoring during impact strength testing of stone samples made it possible to establish the percentage of strength loss at the moment of macroscopic failure for each deposit (Figure 7). Samples from the Tokiv deposit and Korets deposit granites, as well as gabbro from the Bukynske deposit, failed with a relatively small loss of strength of 11.6 %, 11.7 %, and 14.2 %, respectively – indicating that these rocks maintain the vast majority of their original strength up to the point of sudden brittle failure. Overall, the stone samples failed at a strength loss ranging from 11 % to 41.5 %.

This range is broader than that reported by Momeni et al. (2015) for Alvand granite under uniaxial cyclic loading (approximately 15–30 % strength reduction prior to failure), which can be explained by the greater variability in mineralogical composition, grain size, and accessory mineral content among the thirteen rock types tested in the present study. The results of Singh (1989) for greywacke under cyclic loading are also consistent with the present findings in that rocks with higher initial stiffness – reflected in higher initial ultrasonic wave velocities – demonstrated greater resistance to fatigue-induced strength degradation. Li et al. (2022) further confirmed that under repeated dynamic tension, peak strength decreases progressively with each loading cycle and that total dissipated energy for fatigue failure increases linearly with fatigue life – a pattern reflected in the ultrasonic velocity curves obtained in the present study.

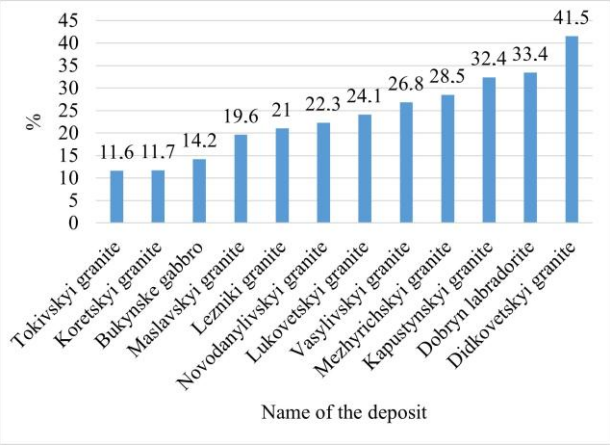


Fig. 7. Reduction in strength of natural stone samples during impact-induced failure

Factors governing fatigue resistance: mineralogical composition, grain size, and accessory minerals

The observed differences in fatigue resistance among the tested deposits can be attributed to three principal interacting factors: mineralogical composition, grain size, and accessory mineral content.

Mineralogical composition and quartz content. Granites with high resistance to repeated dynamic loading (Tokiv, Korets, Zhezheliv granites; Bukynske gabbro) contain 23–30 % quartz and 50–65 % feldspar and plagioclase and have a medium-grained structure. The elevated quartz content is consistent with findings by Bagde and Petroš (2009), who established that quartz content is a primary determinant of fatigue resistance in crystalline rocks, attributing this to the high hardness and strong covalent bonding of the SiO_2 lattice, which impedes microcrack initiation and propagation under cyclic loading. In the present study, granites with quartz content below 15 % (Maslavskyi, Leznikivskyi, Novodanylivskyi, Lukovetskyi granites) demonstrated medium resistance and failed with a strength loss of 19–24 %, confirming the positive correlation between quartz content and fatigue strength. Granites with medium resistance contain 10–15 % quartz and 55–80 % feldspar and plagioclase and also have a medium-grained structure.

Grain size effect. Coarse-grained rocks (Kapustyn granite, Dobryn labradorite) consistently exhibited lower resistance to cyclic loading compared to medium-grained rocks of similar mineralogical composition. This finding aligns with the theoretical framework of Griffith crack theory and is supported by Akesson et al. (2004), who demonstrated that cyclic loading in granite promotes the formation of new microcracks and extension of pre-existing ones within constituent minerals, with the rate of crack propagation proportional to grain boundary length – a parameter that increases directly with grain size. The greater the grain size, the lower the energy threshold required to propagate existing microcracks to a critical length, resulting in earlier macroscopic failure. Yu et al. (2020) confirmed through combined experimental and numerical modelling that under repeated dynamic loading, irreversible sliding between particles at crack tips generates concentrated lateral tensile stress which – once it exceeds the local strength limit – drives crack initiation and propagation independently of the applied bulk compressive load. This mechanism is amplified in coarse-grained rocks where longer grain boundaries provide more extensive sliding surfaces.

Accessory mineral content. Vasyliv granite represents a distinct case where accessory mineral content overrides the beneficial effect of relatively high quartz content. Despite containing 20–27 % quartz – comparable to high-resistance granites – Vasyliv granite exhibited low fatigue resistance and failed with a strength loss of 24.1 %, owing to its exceptionally high content of accessory minerals (up to 22 %). Accessory minerals – predominantly biotite and hornblende in the studied samples – are characterised by pronounced cleavage planes and lower elastic moduli compared to quartz and feldspar. Under cyclic loading, stress concentrations develop preferentially at the interfaces between accessory minerals and the surrounding matrix, accelerating microcrack coalescence and reducing the overall fatigue life of the rock (Momeni et al., 2015). A similar mechanism was reported by Vaneghi et al. (2018) for sandstone and granodiorite under uniaxial cyclic loading, where mineral interface boundaries served as dominant crack initiation sites.

Natural stone with low resistance to repeated dynamic loading contains 18–27 % quartz and 42–90 % feldspar and plagioclase and has either a medium-grained (Vasyliv granite) or coarse-grained (Kapustyn granite, Dobryn labradorite) structure. Samples in this group failed with a strength loss of 28–41.5 %.

Classification of natural stone by fatigue resistance

Depending on the energy capacity of failure at a specific impact energy of 1.47 kJ/m³, natural stone can be conditionally divided into three groups (Figure 8):

A. High resistance to repeated dynamic loading – energy capacity of failure 147 kJ/m³ and above. This group includes Zhezhelivskyi, Tokivskyi, and Koretskyi granites, as well as Bukynske gabbro. These rocks contain 23–30 % quartz, have a medium-grained structure, and failed with a relatively small strength loss of 11–14 %. Phase II of the fatigue test (stable crack propagation) is short in duration, resulting in fewer disturbances in the stone and sudden brittle failure with minimal preceding deformation.

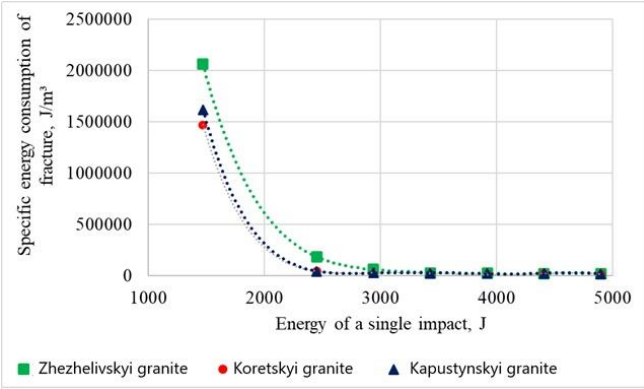


Fig. 8. Dependence of the energy capacity of failure of natural stone with high resistance to repeated dynamic loading on the energy of a single impact

B. Medium resistance to repeated dynamic loading – energy capacity of failure 15–147 kJ/m³. This group includes Leznikivskyi, Maslavskyi, Novodanylivskyi, and Lukovetskyi granites. These rocks contain 10–15 % quartz and 55–80% feldspar and plagioclase, have a medium-grained structure, and failed with a strength loss of 19–24 %.

C. Low resistance to repeated dynamic loading – energy capacity of failure below 15 kJ/m³. This group includes Vasylivskyi and Kapustynskyi granites and Dobryn labradorite. These rocks contain 18–27 % quartz and 42–90 % feldspar and plagioclase, have a medium-to-coarse-grained structure, and failed with a strength loss of 28–41.5 %.

The energy capacity of failure for individual deposits is described by quadratic regression equations, reflecting the nonlinear decrease in fatigue life with increasing single-impact energy. For Zhezheliv deposit granite:

$$E_r = 0{,}3624P_r^2 - 2703{,}2P_r + 5 \cdot 10^6, J. \quad (8)$$

where E_r is the specific energy capacity of failure of the rock sample (J/m³) and P_r^2 is the energy of a single impact (J). This nonlinear pattern is consistent across all three resistance groups and in agreement with the general fatigue behaviour of brittle geomaterials reported in the literature (Xiao et al., 2010; Vaneghi et al., 2018; Zhou et al., 2018).

Practical implications for selective block stone extraction

Although the conducted studies do not allow full modelling of natural stone disturbance in a rock mass – where more complex fracture mechanisms operate simultaneously – they provide a practical basis for assessing the suitability of strong rocks for the by-product extraction of monolithic blocks in crushed stone quarry conditions.

Granites from the Zhezheliv deposit, Tokiv deposit, and Korets deposit are capable of sustaining small repeated loads with minimal strength loss, which indicates that monolithic zones within these quarries can be developed for dimension stone extraction even in proximity to blast epicentres. On the other hand, at the Vasyliv deposit, Kapustyn deposit, Didkovychi deposit, Mezhyrich deposit, and Dobryn labradorite deposit, even the most remote monolithic zones from the explosion epicentre may be affected by technogenic fractures resulting from cumulative blast-induced damage. This finding is consistent with the blast damage review of Shadabfar et al. (2021), who confirmed that tensile stress wave attenuation with distance from the blast source is the primary factor governing the extent of the fractured zone in quarry rock masses.

The proposed method for assessing strength degradation of rocks under cyclic dynamic loading is more informative compared to the standard method for determining rock resistance to single impact loading (State Committee of Ukraine, 2004), since it captures the cumulative damage process and allows quantitative prediction of the fatigue life of each deposit under realistic quarry loading conditions. Based on these studies and the analysis of blasting intensity at a given quarry, it is possible to evaluate the degree of natural stone disturbance within a deposit and to delineate zones suitable for selective block stone extraction with sufficient confidence for practical application.

Conclusions

1. Although the conducted studies do not allow full modelling of natural stone disturbance in a rock mass, they provide an opportunity to assess the suitability of strong rocks for the by-product extraction of monolithic blocks in crushed-stone quarry conditions. For example, granites from the Zhezheliv deposit, Tokiv deposit, and Korets deposit are capable of sustaining small repeated loads, which makes it possible to develop their monolithic zones for dimension stone extraction. On the other hand, at the Vasyliv deposit, Kapustyn deposit, Didkovychi deposit, Mezhyrich deposit, and Dobryn deposit, even the most remote monolithic zones of natural stone from the explosion epicenter may be affected by technogenic fractures.

2. The proposed method for assessing strength degradation of rocks under cyclic dynamic loading is more informative compared to the standard method for determining rock resistance to impact loading. Based on these studies and the analysis of blasting intensity, it is possible to evaluate the degree of natural stone disturbance within a deposit.

3. The investigation describes the nature of strength reduction in natural stone samples with increasing impact energy and number of load cycles. Most of the studied rocks exhibit high resistance to repeated dynamic loading with low impact energy, which indicates high fatigue strength of the rocks.

4. The obtained data make it possible to distinguish three groups of natural stone at a specific impact energy of 1.47 kJ/m³, where the transition from the initial phase (Phase I) of the fatigue test to the steady-state phase (Phase II) occurs at cumulative specific energies of 500–800 kJ/m³, 130–150 kJ/m³, and 25–90 kJ/m³. In rocks with high fatigue resistance to low dynamic loads

(Figure 6), Phase II (stable crack propagation) is short in duration, resulting in fewer disturbances in the stone. With increasing impact energy (4.9 J), the fatigue strength of granites decreases sharply, and the transition from Phase I to Phase II occurs at a cumulative specific energy of 10–30 kJ/m³.

5. The results also show that the fatigue strength of granites is influenced by quartz content: with increasing quartz content, strength increases. However, granite texture has an equally important effect: with increasing grain size, despite a high quartz content, fatigue strength decreases. An increase in accessory minerals in granites leads to a reduction in fatigue strength.

References

Akesson, U., Stigh, J., Lindqvist, J. E., & Göransson, M. (2004). The influence of foliation on the fragility of granitic rocks, image analysis and quantitative microscopy. *Engineering Geology, 73*(3–4), 167–180. https://doi.org/10.1016/j.enggeo.2004.01.003

Bagde N., & Petros V. (2005). Fatigue properties of intact sandstone samples subjected to dynamic uniaxial cyclical loading. *International Journal of Rock Mechanics and Mining Sciences, 42*, 237–250. https://doi.org/10.1016/j.ijrmms.2004.08.008

Bagde, M. N., & Petroš, V. (2009). Fatigue and dynamic energy behaviour of rock subjected to cyclical loading. *International Journal of Rock Mechanics and Mining Sciences, 46*(1), 200–209. https://doi.org/10.1016/j.ijrmms.2008.05.002

Korobiichuk, V. (2016). Study of ultrasonic characteristics of Ukraine red granites at low temperatures. *International Conference on Systems, Control and Information Technologies*, 653–658. https://doi.org/10.1007/978-3-319-48923-0_69

Li, R., Zhu, J. B., Qu, H., Zhou, T., & Zhou, C. (2022). An experimental investigation on fatigue characteristics of granite under repeated dynamic tensions. *International Journal of Rock Mechanics and Mining Sciences, 158,* 105185. https://doi.org/10.1016/j.ijrmms.2022.105185

Momeni, A., Karakus, M., Khanlari, G.R., & Heidari, M. (2015). Effects of cyclic loading on the mechanical properties of a granite. *International Journal of Rock Mechanics and Mining Sciences, 77*, 89–96. https://doi.org/10.1016/j.ijrmms.2015.03.029

Shadabfar, M., Gokdemir, C., Zhou, M., Kordestani, H., & Muho, E. V. (2021). Estimation of damage induced by single-hole rock blasting: a review on analytical, numerical, and experimental solutions. *Energies, 14*(1), 29. https://doi.org/10.3390/en14010029

Singh, S.K. (1989). Fatigue and strain hardening behaviour of graywacke from the flagstaff formation. *New South Wales Engineering Geology*, *26*(2), 171–179. https://doi.org/10.1016/0013-7952(89)90005-7

State Committee of Ukraine for Technical Regulation and Consumer Policy Kyiv (2004) *Natural stone test methods – Determination of rupture energy* (DSTU EN 14158:2004).

Stavrogin, A. N., & Tarasov, B. G. (2001). Experimental physics and rock mechanics [Monograph]. *CRC Press*, 356.

Vaneghi, G. R., Ferdosi, B., Okoth, A. D., & Kuek, B. (2018). Strength degradation of sandstone and granodiorite under uniaxial cyclic loading. *Journal of Rock Mechanics and Geotechnical Engineering, 10*(1), 117–126. https://doi.org/10.1016/j.jrmge.2017.09.005

Vasconcelos, G., Lourenço, P. B., Alves, C. A. S., & Pamplona, J. (2008). Ultrasonic evaluation of the physical and mechanical properties of granites. *Ultrasonics*, *48*(5)*,* 453–466. https://doi.org/10.1016/j.ultras.2008.03.008

Xiao, J. Q., Ding, D. X., Jiang, F. L., & Xu, G. (2010). Fatigue damage variable and evolution of rock subjected to cyclic loading. *International Journal of Rock Mechanics and Mining Sciences, 47*, 461–468. https://doi.org/10.1016/j.ijrmms.2009.11.003

Yang, S., Nong, Z., Feng, X., Kan, J., Pan, D., & Qian, D. (2018). Experimental investigation of sandstone under cyclic loading: damage assessment using ultrasonic wave velocities and changes in elastic modulus. *Shock and Vibration, 2018,* 1–13. https://doi.org/10.1155/2018/7845143

Yu, Z., Zhao, D., Tang, Q., & Wang, M. (2020). Experimental and numerical investigation of the fatigue behaviour and crack evolution mechanism of granite under ultra-high-frequency loading. *Royal Society Open Science, 7*(4), 200091. https://doi.org/10.1098/rsos.200091

Zhou, T., Dong, S. L., Zhao, G. F., Zhang, R., Wu, S. Y., & Zhu, J. B. (2018). An experimental study of fatigue behaviour of granite under low-cycle repetitive compressive impacts. *Rock Mechanics and Rock Engineering, 51*(10), 3157–3166. https://doi.org/10.1007/s00603-018-1515-0