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WEAKENING OF ROCK STRENGTH UNDER THE ACTION OF CYCLIC DYNAMIC LOADS

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Представлено результати експерименту з оцінки зниження міцності природного каменю при багаторазовому динамічному навантаженні. Встановлено, що на втомну міцність гранітів впливає вміст кварцу, зі збільшенням кварцу міцність зростає. Як виявилося, текстура граніту має не менший влив на міцність каменю, зі збільшенням зерен в граніті, незважаючи на значний вміст кварцу, втомна міцність каменю знижується. Збільшення акцесорних мінералів в гранітах призводить до зменшення втомної міцності

Ключові слова: природний камінь, енергоємність руйнування, опір ударним діям, динамічні навантаження, поширення ультразвукової хвилі

Представлены результаты эксперимента по оценке снижения прочности природного камня при многократном динамическом нагружении. Установлено, что на усталостную прочность гранита влияет содержание кварца, с увеличением кварца прочность возрастает. Как оказалось, текстура гранита имеет не меньшее влияние на прочность камня, с увеличением зерен в граните, несмотря на значительное содержание кварца, усталостная прочность камня снижается. Увеличение акцессорных минералов в гранитах приводит к уменьшению усталостной прочности

Ключевые слова: природный камень, энергоемкость разрушения, сопротивление ударным действиям, динамические нагрузки, распространение ультразвуковой волны

1. Introduction

Destructions resulting from a long-lasting exposure to repeated or variable loads are called fatigue destruction. The largest stresses at which a sample of rock can for a long time maintain stability (solidity) under conditions of variable loads without breaking are called the limit of fatigue strength. This phenomenon was first discovered by the German scientist V ler, a railroad engineer who developed the procedure for determining the limit of fatigue strength and formulated several laws of fatigue durability of parts and assemblies in the railroad rolling stock.

During massive explosions at gravel quarries, rocks undergo intensive microcracking, which weaken the mountain rock. A rock massif accepts loads that vary in energy and fluctuation frequency depending on the distance to the epicenter of the massive explosion. When extracting selectively the blocks of natural stone in gravel quarries, it is necessary to have information about the declining strength of natural stone in certain areas of the quarry. It is known that rocks withstand stresses at compression well while may break at stretching. Thus, the weakening of strength of rocks under explosive load occurs mainly under the influence of stresses at stretching. Given the above, it is necessary to accept as a criterion of rocks strength the ultimate tensile strength.

The estimation of suitability of a deposit of rock for selective extraction is possible by conducting laboratory tests. Under laboratory conditions, it is possible to assess the weakening of strength of rocks under the action of cyclic dynamic loads using nondestructive methods. Analysis of the intensity of carrying out blasting operations, as well as the resistance of rocks to cyclic dynamic loads, will make it possible to split a quarry into zones where it would be possible for each deposit to isolate damaged and undamaged areas of the rock massif.

2. Literature review and problem statement

It is known that the mechanical properties of rocks under the influence of dynamic loads are different from static loads [1]; the nature of dynamic fracture of stone remains insufficiently studied, especially under conditions of a cyclic loading [2]. During cyclic loading, some materials become stronger and more plastic, while others get weaker and more brittle [3]. The strength of rock is reduced during cyclic dynamic loads when conducting blasting operations, which is why an important role belongs to the prediction of strength characteristics of rock [4]. This initiated serious research into a change in the mechanical properties of rocks depending on various conditions of loading [5] and destruction [6]. Many researchers studied the effect of cyclic loads on fatigue properties of rocks, for example, author of [7] performed a series of tests to examine fatigue and a dynamic change in energy in sandstone and conglomerate. The scientists concluded that the microstructure, texture of stone, as well as quartz content in samples of rocks affect the weakening of strength of rocks under the action of cyclic dynamic loads, and that microcracks were the main cause of fatigue. Laboratory study [8] showed that the frequency of load, as well as amplitude, is of great importance in the behavior of a rock under conditions of dynamic cyclic loading. Dynamic fatigue strength and dynamic axial hardness of rock decrease with increasing frequency and amplitude of the load. Authors of [9] studied behavior of Alvand granite under different maximum loadings, with varying frequency and amplitude. They draw a conclusion on that the growing cycles of loading decrease the level of resistance to fracture, while plastic behavior becomes dominant in each cycle. Because of the fragility of rock and a low rate of loading at low frequencies, the accumulation process of granite destruction could not be observed. An analysis of the scientific literature revealed that the cumulative destruction of granite can be determined using the ultrasonic method [10], which was effectively employed to investigate strength characteristics of granite [11].

Modern research indicates that the texture of natural stone and quartz content exert an impact on the weakening of strength of rocks under the action of cyclic dynamic loads. However, the data we found suggest that some of the results are conflicting, which is associated with a different texture and structure of natural stone, which is unique for each deposit. Thus, the available data on weakening the strength of rocks under the action of cyclic dynamic loads remain insufficient for solving practical tasks on forecasting the strength of granite in gravel quarries.

3. The aim and objectives of the study

The aim of present work is to establish patterns in the weakening of strength of rocks under the action of cyclic dynamic loads.

To accomplish the aim, the following tasks have been set:

– to determine the resistance of rock to impact actions;

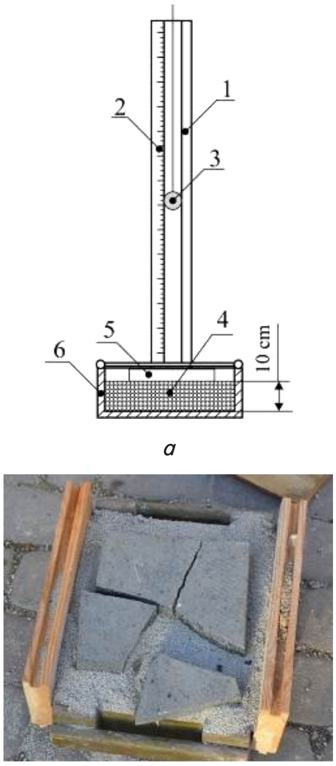
– to determine the resistance of rock to multiple impact actions.

4. Materials and methods of research

We applied as the analogue of the process of multiple loading the samples of natural stone the repeated non-destructive loading granite segments by dropping a spherical weight onto them.

To conduct field research, we designed a set-up using which we dynamically loaded the samples of natural stone (Fig. 1).

Repeated non-destructive loading of granite segments implied dropping a spherical weight on them, which is analogues to testing a sample of granite for stretching; at the same time, we changed the height of a falling weight and the number of loadings.



a

b

Fig. 1. Set-up for loading the samples of natural stone: *a* — set-up for loading; *b* — layout of the destroyed sample; 1 — set-up body in the form of a pipe with a stand; 2 — scale for measuring height; 3 — metal layer with a weight of 1 kg; 4 — layer of sand; 5 — sample of the tested stone; 6 — wooden box

Resistance of rock to impact action was determined in line with a procedure according to GOST 30629-2011 "Facing materials and articles made of rock. Testing methods."

We made four samples of rock the size of 200×200××30 mm in order to perform tests. Geometric center was determined for each sample. Surface texture of the samples had to be sawn. A sample in the light-dry state (the state of natural moisture content) was placed at the center of the box atop the levelled layer of sand with a thickness of not less than 100 mm. Then the samples were exposed to the impacts from a falling weight at the geometric center of the sample. The first impact was applied from a height of 15 cm; each next impact was applied when lifting a weight successively by 5 cm. The weight was 1 kg. The samples were examined after each impact. Testing was conducted for as long as the sample did not show visible cracks or until the sample was destroyed. During testing, the underlying layer of sand was continually levelled. An indicator of the resistance of rock to an impact action is taken to be the minimum height from which a weight drops (in centimeters) at which the sample showed cracks or was destroyed.

Determining the resistance of rock to repeated impact action was carried out using rock samples the size of 200×200×30 mm. Geometric center was determined for each sample. The texture of the surface of samples was sawn. Repeated dropping of a weight was carried out from the same height until destruction of the samples as a result of the accumulation of disruptions from previous loading. Before testing, we measured the rate of propagation of the surface ultrasonic wave in a sample of stone using the ultrasonic device UK-14MP; after each dropping of a weight, we measured rate of the surface ultrasonic wave in the sample in four directions: the data derived were averaged.

5. Results of testing rocks for the resistance to impact actions

Testing the resistance of rock to impact action (Fig. 2) has shown that the resistance of rocks to impact ranges from 35 to 55 cm. The resistance of rock to impact action was measured as the mean arithmetic value of the results of testing of four samples. The worst indicators were demonstrated by the red medium-grained granite from the Leznikivski deposit and by the Dobrynsky labradorite. The best resistance of rock to impact action was demonstrated by grey medium-grained granite from the Zhezhelivski deposit. All other deposits displayed approximately the same resistance to impact.

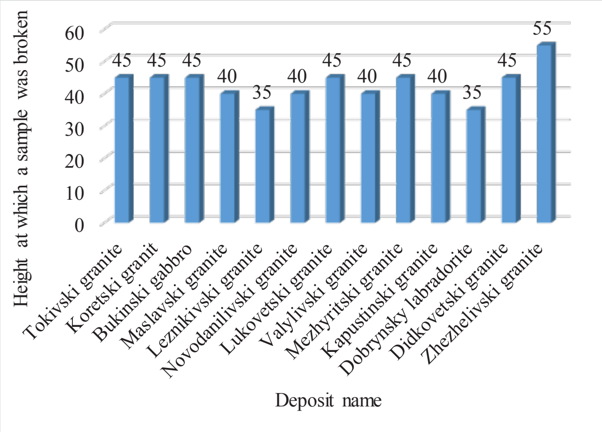


Fig. 2. Results of testing the resistance of rock to impact action

When determining a decrease in the strength of samples of natural stone at breaking by the impact action it was found that repeated dynamic loads with a low energy of the impact (1.47 J) were not tolerated by all rocks (Fig. 3).

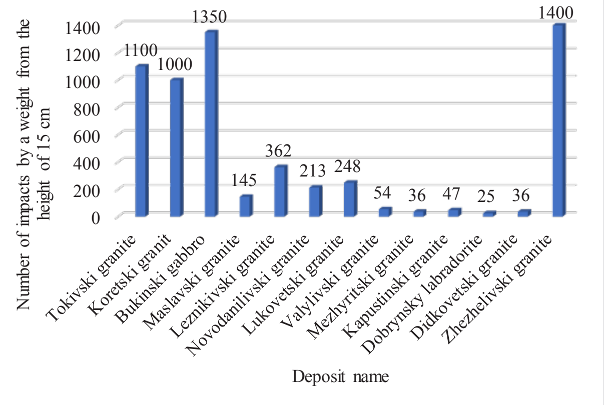


Fig. 3. Results of dropping a weight from the height of 15 cm on the samples of natural stone

We also calculated specific energy of the impact from a weight on the sample of natural stone. Dependence of the propagation velocity of an ultrasonic wave on the total specific energy of the impact is shown in Fig. 4.

Hence, we can conclude that at specific energy of the impact at 1.47 kJ/m^3, the resistance to impact would be demonstrated by Koretski, Zhezhelivski, Tokivski, Leznikivski deposits of granites, as well as gabbro from Bukinski deposit. The least resistant were Valylivski, Didkovetski, Mezhyritski, Kapustinski granite deposits and Dobrynsky labradorite. Note that Koretski, Zhezhelivski, Tokivski, Leznikivski, Valylivski, Didkovetski, Mezhyritski deposits of granites have the same grain size – medium-grained. Kapustinski, Lukovetski deposits of granites and Dobrynsky labradorite deposit have a coarse-grained structure.

When a weight was dropped from a height of 30 cm, indicators for a decrease in the strength of samples of natural stone at breaking by impact action differ insignificantly.

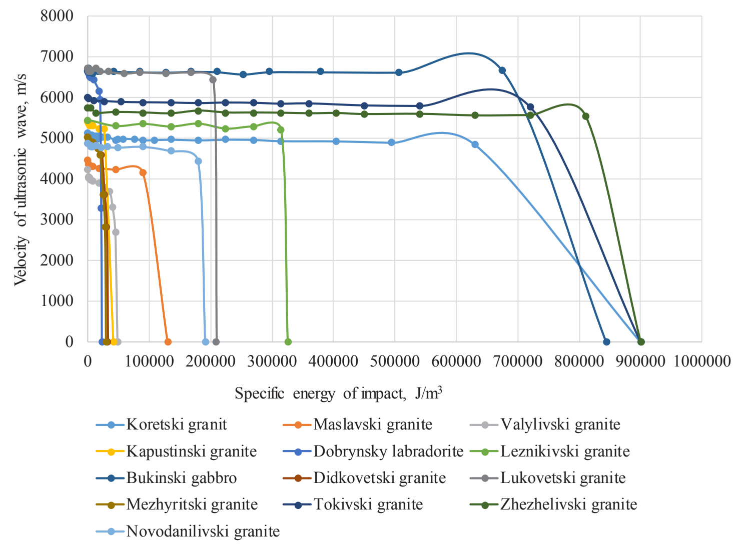


Fig. 4. Dependence of the propagation velocity of an ultrasonic wave on the total specific energy of the impact, dropping height is 15 cm

The results that were obtained at repeated dropping of a weight from the height of 50 cm until the sample broke are shown in Fig. 5.

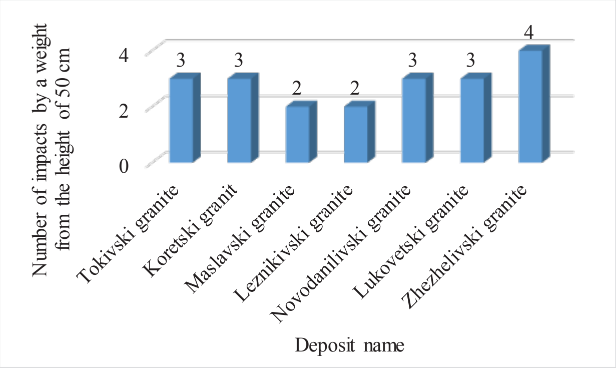


Fig. 5. Results of repeated dropping of a weight from the height of 50 cm on samples of natural stone

At a considerable energy of the impact (4.9 J) from a weight, Zhezhelivski, Tokivski, Koretski, Novodanilivski (medium-grained), Lukovetski (coarse-grained) granite deposits proved to be resistant.

The chart shown in Fig. 6 demonstrates that the total specific energy capacity of the samples was within 20–40 kJ.

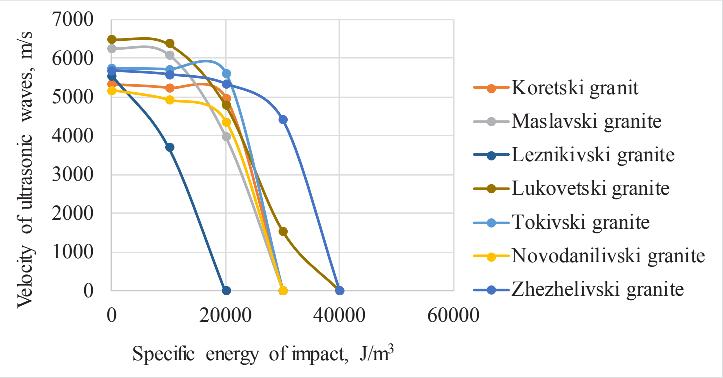


Fig. 6. Dependence of the propagation velocity of an ultrasonic wave on the total specific energy of the impact, dropping height is 50 cm

The application of the ultrasonic control when testing the stone samples for strength at impact action has allowed us to establish that the samples from Tokivski, Koretski granit deposits and Bukinski gabbro were destroyed with a low loss of strength, 11–14 % (Fig. 7). In general, the stone samples were destroyed with a strength loss of 11–41.5 %.

Depending on the energy capacity of destruction, we can conditionally divide the natural stone into three groups: with a high resistance to repeated dynamic loads – 147 kJ and larger at the impact energy of 1.47 kJ (Fig. 8); with an average resistance to repeated dynamic loads – 15–147 kJ at the impact energy of 1.47 kJ, with a low resistance to repeated dynamic loads – below 15 kJ at the impact energy of 1.47 kJ.

Granites with a high resistance to repeated dynamic loads on the energy of a single impact, shown in Fig. 10, contain quartz within 23–30 %, feldspar and plagioclase – 50–65 %, and have a medium-grained structure. The samples were destroyed with a small loss of strength. Dependence of energy capacity of the destruction of natural stone with a medium resistance to repeated dynamic loads on the energy of a single impact is shown in Fig. 9.

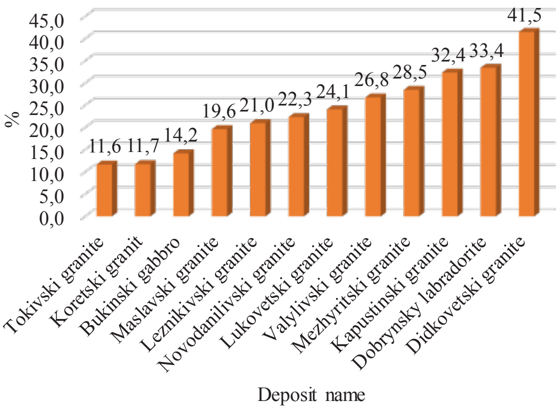


Fig. 7. Decrease in the strength of samples of natural stone at breaking by impact action

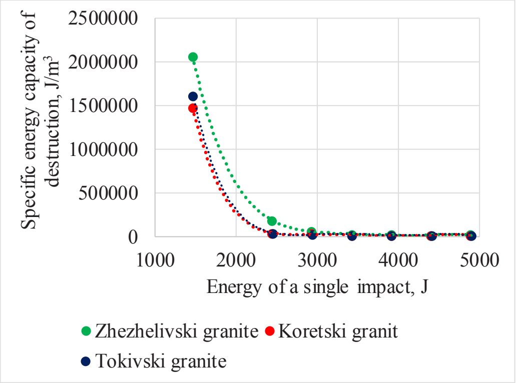


Fig. 8. Dependence of energy capacity of the destruction of natural stone with a high resistance to repeated dynamic loads on the energy of a single impact

The natural stone with a medium resistance to repeated dynamic loads from a single impact contains quartz within 10–15 %, feldspar and plagioclase – 55–80 %, and has a medium-grained structure. The samples were destroyed with a strength loss of 19–24 %. Dependence of energy capacity of the destruction of natural stone with a low resistance to repeated dynamic loads on the energy of a single impact is shown in Fig. 10.

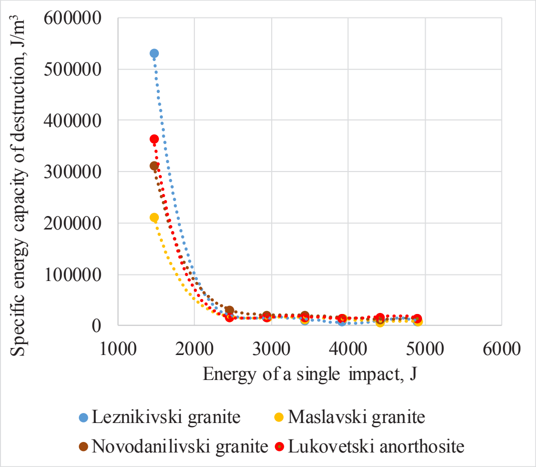


Fig. 9. Dependence of energy capacity of the destruction of natural stone with a medium resistance to repeated dynamic loads on the energy of a single impact

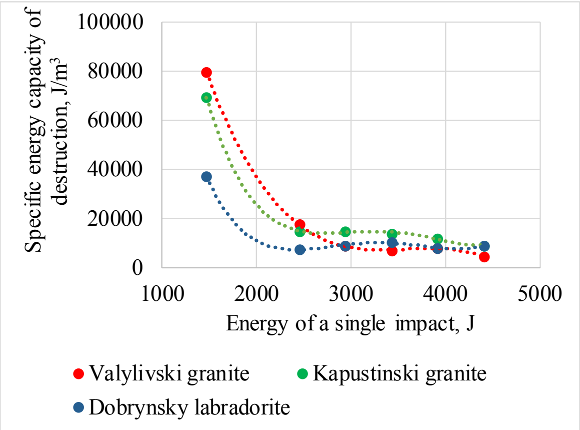


Fig. 10. Dependence of energy capacity of the destruction of natural stone with a low resistance to repeated dynamic loads on the energy of a single impact

The natural stone with a low resistance to repeated dynamic loads from the energy of a single impact contains quartz within 18–27 %, feldspar and plagioclase – 42–90 %, and has medium-grained (Valylivski granite) and coarse-grained (Kapustinski granite, Dobrynsky labradorite) structure. The samples were destroyed with a strength loss of 28–41 %. It should be noted that Valylivski granite with a quartz content of 20–27 % has the largest content of accessory minerals, to 22 %, which affected its impact strength.

6. Discussion of results related to the weakening of strength of rocks under the action of cyclic dynamic loads

The obtained experimental dependences demonstrate a general character of an increase in the strength of samples of natural stone at different impact energies and number of loads. The research described in this paper does not make it possible to model the destruction of natural stone in a massif as the more complex mechanisms of destruction act there. However, the study allows us to assess the feasibility of solid rocks to the accompanying extraction of monolithic stone blocks under conditions of gravel quarries. Thus, for example, small repeated loads can be tolerated by granites from the following deposits: Zhezhelivski, Tokivski, Koretski. Given this, we can assert that the gravel quarries of these deposits can be used to develop solid areas with stone blocks. The research results also show that at the following granite deposits: Valylivski, Kapustinski, Didkovetski, Mezhyritski, as well as Dobrynsky labradorite, monolithic areas of natural stone, even those furthest from the epicenter of the explosion, could be disrupted by anthropogenic cracks.

The proposed procedure for estimating the weakening of strength of rocks under the action of cyclic dynamic loads is more informative than the standard procedure for determining the resistance of rock to impact action. Based on our research and an analysis of the intensity of performing blasting operations, it is possible to assess the degree of destruction of natural stone in the massif within the same deposit.

The results reported here showed that the crucial role belongs to the energy of an impact, rather than the number of impacts. Similar data were obtained by other researchers [9, 12] who found that natural stone is destroyed at a small number of cycles and has a lower life cycle at increasing energy of dynamic load. Most of the examined rocks have a high resistance to repeated dynamic loads with a low energy of the impact. It testifies to the high fatigue strength of rocks [8]. The data obtained allow us to distinguish three groups of natural stone at a specific impact energy of 1.47 kJ/m^3, in which a transition from the initial phase (phase I) of fatigue test to the phase of uniform velocity (phase II) starts at the total specific energy of 500–800 kJ/m^3, 130–150 kJ/m^3 and 25–90 kJ/m^3. Fig. 7 shows that in rocks with a high fatigue strength against small dynamic loads, phase II of fatigue test (stable crack propagation) lasts over limited time, which creates less disruptions in the stone. With increased energy of the impact (4.9 J) from a weight the fatigue strength of granite sharply decreases; in this case, a transition from the initial phase (phase I) of fatigue test to the phase of uniform velocity (phase II) occurs at the total specific energy of 10–30 kJ/m^3.

At the same time, the fatigue strength of granites is affected by the content of quartz; an increase in quartz leads to increasing strength. As it turned out, the texture of granite exerts not a less impact on the strength of stone; an increase in grains in granite leads, despite a considerable content of quartz, to a decrease in the stone fatigue strength. Increasing accessorial minerals in granites results in a decrease in the fatigue strength.

7. Conclusions

1. Testing the deposits of solid natural stone for the resistance of rock to impact action in line with the standard procedure (GOST 30629-2011, “Facing materials and articles from rocks. Testing methods”) showed that the resistance ranges from 35 to 55 cm. Most of the rocks ranged within 40–45 cm. In this case, it is difficult to sort rocks for fatigue strength, so a given procedure is effective for assessing the resistance of natural stone to a single impact.

2. The established resistance of rock to repeated impact action showed that at a low specific energy of the impact (1.47–2.7 kJ/m^3) there are the granites (Zhezhelivski, Tokivski, Koretski deposits) that are almost not destroyed. These very deposits are suitable for the accompanying extraction of blocks of natural stone under conditions of gravel quarries. Building structures from these fields can be used in facilities and buildings that are exposed to vibration. At the impact specific energy above 3 kJ/m^3 the resistance of granites to repeated impact actions differs insignificantly; an increase in the impact specific energy leads to a decreasing difference in resistance. By applying a nondestructive control, we found that granites lose their strength prior to destruction from 11.6 to 41.5 % because of anthropogenic microcracking. The fatigue strength of granites is affected by the content of quartz; an increase in quartz results in increasing strength. It turned out that the texture of granite exerts not a less impact on the strength of the stone. An increase in grain size in granite leads, despite a considerable content of quartz, to a decrease in the stone fatigue strength. Increasing accessorial minerals in granites results in a decrease in fatigue strength.

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