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ANALYSIS OF THE LIMIT STATE OF GRANITE BY SOME INDICATORS UNDER CONDITIONS OF VARIABLE COMPRESSIVE LOADING

***Abstract**: This article presents the results of modeling a compression test on granite and analyzes the state of the material under various compressive forces. For a standard specimen with a diameter of 40 mm and a height of 60 mm, a compressive force (4.381761 MN) was determined, at which effective plastic strain is detected in the material, which does not lead to residual deformations in granite based on the yield function. At the same time, an increase in the compressive force by more than two times leads to the formation of residual stresses in the granite in* *the less compressed volumes of the specimen. The traction of the deformed specimen was also calculated for the two compression forces considered.*

Key words: *granite, compression testing, effective plastic strain, yield function, compression force, traction.*

Language: *English*

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1. Introduction

Granite is a natural stone that is used as a construction material due to its high compressive strength, resistance to weathering, and aesthetic appeal. It is often used in construction for foundations, load-bearing walls, columns, and flooring, providing long-term stability and durability. Its resistance to abrasion and corrosion makes it suitable for both indoor and outdoor applications, although its weight and cost may be limiting factors. Proper methods of stone extraction and finishing enhance its performance and visual qualities, making granite a preferred choice for architectural and engineering projects.

Standard mechanical tests [1-2] are performed to determine the ultimate properties of granite. When compressed, granite exhibits both elastic and plastic properties, depending on the magnitude of the applied stress [3-5]. Initially, at low stresses, granite deforms elastically, which means that it returns to its original shape after the load is removed due to the reversible arrangement of atoms and mineral grains. When the stress exceeds a certain elastic limit, the deformation becomes plastic, causing irreversible changes in the mineral structure and grain boundaries [6]. Typically, granite remains within the elastic range until a certain point, but if the compression continues to increase, the material eventually approaches the yield point, where plastic deformation becomes prevalent, potentially leading to cracking or failure of the rock [7-10]. The purpose of this study is to determine the boundary between the elastic and plastic states of granite under static variable load.

2. Materials and methods

The calculation of the ultimate state of granite under compression was implemented in a two-dimensional setting in the Comsol Multiphysics package. The standard compression test specimen model was a rectangle on a plane with a width of 60 mm (the size determines the height of the specimen) and a length of 40 mm (the size determines the diameter of the specimen). The next step in modeling the granite compression test was to set the following model properties:

1. Density is a measure of how much mass is contained in a given volume. The granite model has a density of 2600 kg/m^3.

2. The Young's modulus determines the material's resistance to elastic (restorable) deformation under load. For the granite model, the value of 60×10^9 Pa is adopted.

3. The Poisson's ratio characterizes the ratio of relative transverse compression to relative longitudinal tensile. For the granite model, a value of 0.25 is adopted, which defines the material under study as a brittle solid.

4. Coefficient of thermal expansion characterizes the relative change in volume or linear dimensions of a body with an increase in temperature by 1 K at constant pressure. For the granite model, the value of 7×10^{-6} 1/K is adopted.

5. Heat capacity at constant pressure determines the amount of heat required to change the temperature of a substance at constant pressure. For the granite model, the value of 850 J/(kg×K) is adopted.

6. Thermal conductivity is a property of the material that determines its ability to conduct heat. For the granite model, the value of 2.9 W/(m×K) is adopted, which indicates the low thermal conductivity of granite.

7. Hoek-Brown *m* parameter is a material constant that characterizes the hardness and friction coefficient of the rock. For the granite model, the value of 4.11 is adopted. This particular value is widely referred to in the geotechnical literature as the "best-suited" parameter for modeling certain types of fractured rocks.

8. Hoek-Brown *s* parameter is a material constant that reflects the degree of fracturing or fragmentation of the rock. For the granite model, the value of 1 is adopted, which is typical for perfectly preserved rock specimens.

9. Intact rock parameter describes the physical and mechanical properties of intact, undamaged blocks of the rock. For the granite model, the value of 30 is adopted.

10. Geological strength index is a rock characterization system used to evaluate geomechanical properties, particularly strength. For the granite model, the value of 85 is adopted, which indicates the absence of damage to the material.

11. Disturbance factor that quantifies the reduction in rock strength and stiffness caused by blast damage and stress relaxation during excavation. For the granite model, the value of 0.5 is adopted, which indicates mechanical excavation of the material.

12. Uniaxial tensile strength is taken to be 12 MPa. A property that determines the maximum strength of granite before failure.

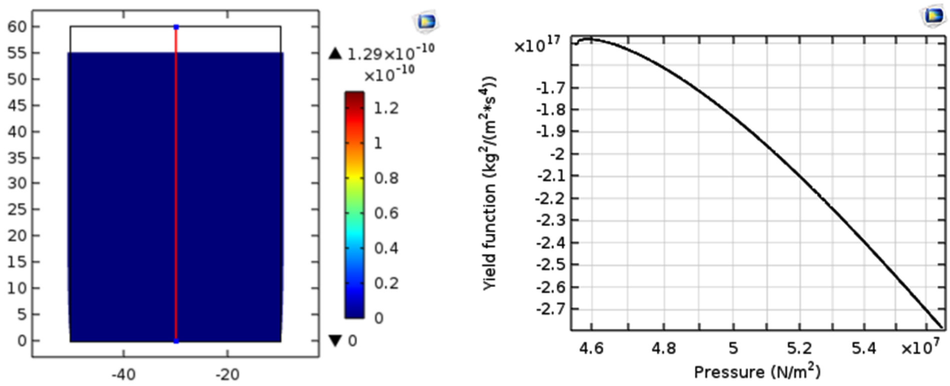
13. Uniaxial compressive strength is taken to be 250 MPa. A fundamental geomechanical property that determines the maximum axial compressive stress that a standard specimen can withstand before catastrophic failure under zero lateral (confining) pressure.

14. Biaxial compressive strength is taken to be 375 MPa. This is the maximum stress that a material can withstand when subjected to simultaneous compressive loads along two orthogonal (perpendicular) axes, with the third axis remaining unstressed.

The process of granite compression was reconstructed by setting boundary conditions. One of the faces of the specimen model (defining the lower base) was rigidly fixed, and a variable force simulating compression was applied to the opposite face in the direction of the *Y* coordinate axis. High accuracy of the modeling results was achieved by generating a mesh on the model area with the following statistics: minimum element quality – 0.7528, average element quality – 0.9912, triangular elements – 17064, edge elements – 334, vertex elements – 4, maximum element size – 0.6 mm, minimum element size – 0.0012, curvature factor – 0.2.

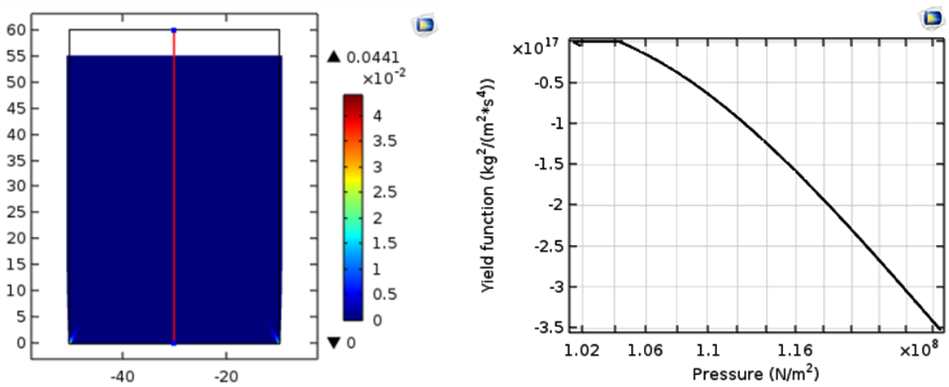
3. Results and discussion

The state of granite under two compressive forces is shown in the Figures 1 and 2. The images on the left determine the deformed state of the specimen in longitudinal section under compression. According to the values on the scale on the left, the height of the deformed specimen decreased by 8.3% of the original height of the specimen. The color palette in the cross-section of the specimen model demonstrates the intensity of effective plastic strain with numerical values on the scale located to the right of the image of the specimen model. The graphs on the right characterize the dependencies of the yield function of granite on the pressure arising in the material. The calculated values for two coordinate axes were obtained from a cut of the longitudinal section of the deformed specimen, indicated by the red line in the image on the left.



a *b*

Figure 1. Contours of the distribution of effective plastic strain in the specimen model (*a*) and the dependence of the yield function of granite on the pressure arising in the material under a compressive force of 4.381761 MN (*b*).



a *b*

Figure 2. Contours of the distribution of effective plastic strain in the specimen model (*a*) and the dependence of the yield function of granite on the pressure arising in the material under a compressive force of 9.8 MN (*b*).

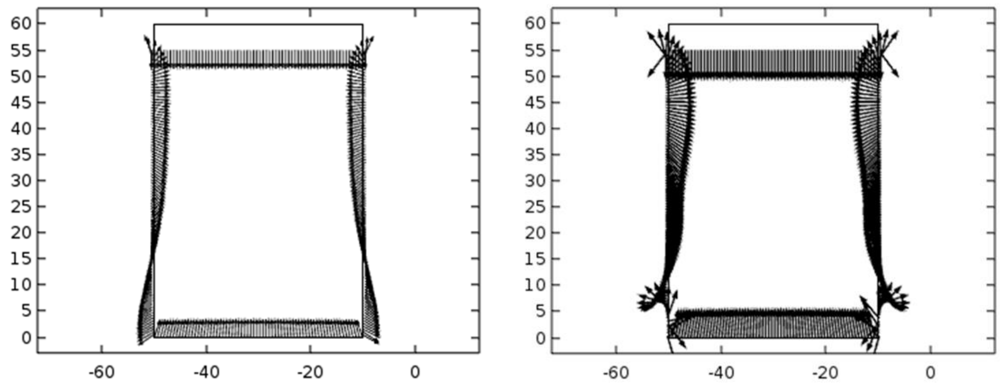
The yield function of a material is a mathematical criterion used to determine the boundary between elastic and plastic deformation of the rock. The numerical value of the function determines the response of the material to the applied stress. If the yield function has a negative value, then the material is subject to elastic deformations. If the yield function is zero, then the granite has reached the elastic limit and plastic deformation or failure occurs. Positive values of the yield function lead to unacceptable (plastic) deformations in the granite.

Analyzing the results of finite element modeling of granite compression, we can conclude that effective plastic strain of minimum intensity occurs in the volume of the material under a compressive force of 4.381761 MN. In this case, the yield function in the section under consideration has negative values, which indicates elastic deformations of granite. With an increase in the compressive force to 9.8 MN, a zero value of the yield function is observed in local volumes of the specimen subjected to pressure in the range of $1.015\times10^8 \ldots 1.043\times10^8$ N/m^2, which indicates the occurrence of plastic deformations. At higher pressure values, elastic deformations predominate in the material.

The tractions of the deformed specimen are shown in the Figure 3. The deformed specimen was subjected to the following loads of varying intensity:

1. The compression force is 4.381761 MN. The upper and lower bases of the specimen are subjected to compressive pressure and resistance pressure, respectively. A tangential force is observed on the side surfaces, causing a shift in the material. At 2/3 of the height of the specimen, compressive forces predominate, and closer to the lower base, tensile forces predominate.

2. The compression force is 9.8 MN. The intensity of the compressive pressure and the resistance pressure increases at the upper and lower bases of the specimen. On the side surfaces, variable compressive forces prevail along the height of the specimen. At the same time, in the direction towards the lower base of the specimen, the compressive forces decrease.



a ***b***

Figure 3. Traction of the deformed specimen at compressive forces of 4.381761 MN (*a*) and 9.8 MN (*b*).

4. Conclusion

Based on the analysis of the calculation results, the following conclusions can be drawn:

1. The state of the granite specimen under two compressive forces was compared. Effective plastic strain of granite occurs under a compressive force of 4.381761 MN, but according to the yield function, elastic deformations predominate in the volume of the specimen, which do not cause cracking and failure of the material. When the compressive force increases to 9.8 MN and in the volume of material subjected to pressure in the range of $1.015\times10^8 \ldots 1.043\times10^8$ N/m^2, residual deformations occur.

2. The intensities of distribution of compressive and tensile forces on the specimen were determined. In the first case (the force is 4.381761 MN), a uniform distribution of the traction of the deformed specimen is observed. Moreover, along the side surfaces at 2/3 of the height of the specimen, compressive forces predominate, and closer to the lower base, tensile forces predominate. At maximum load, the material is subjected mainly to compressive forces, decreasing towards the lower base of the specimen.

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