The Influence of Size Effect on Strength and Deformation Characteristics of Different Types of Rock Samples

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Abstract. This paper presents the results of the experimental study of the influence of sizes effect on the strength and deformation characteristics of samples of hornfels, limestone, sandstone, siltstone and ore-bearing rocks. Tests were performed on cylindrical samples of three sizes of diameters - 10, 30 and 60 mm under uniaxial compression and tension loading. The results of the study demonstrated that the values of ultimate strength decrease when the size of samples increases for the samples of cornea, limestone, sandstone and siltstone. The ultimate strength increases with increasing of sample size for ore-bearing rocks containing viscous inclusions. The samples of smaller size of ore-bearing rocks exhibit a brittle character of the fracture for all types of rocks, and the viscosity of fracture increases with increasing size of samples. the obtained regularities were analysed from the positions of otwo types of size effect (volume and surface).

1. Introduction
Rocks are structurally inhomogeneous, contain heterogeneous singularities of various sizes, cracks and textural features, which have together a weakening effect on rock strength. Due to this fact the scale factor is an inevitable consequence of changes of engineering and petrographic characteristics depending on the size and shape of the studied volumes of rocks. Based on numerous experimental studies, it was found that the strength of geometrically similar rock samples of different sizes varies. F number of studies asserts that when the sample size increases, their strength decreases [1-4]. However, some of studies which were performed on various rocks and geomaterials under varying rates of loading, were demonstrated that the strength increases with increasing sample size [5-12]. In addition, two other opinions are: the strength does not change with increasing sample size [13]; the strength increases to a certain value and then falls with increasing sample size [14, 15].

The explanation of such discrepancy of results was first given in [16, 17]. Two types of size effect can be observed – the volume (main) size effect and the surface size effect. The volume size effect is that the probability of a defect (crack, weak layer, weak inclusion, etc.) increases with increasing of the size of real objects having inhomogeneous structure. It follows that the strength of the rock sample will always be higher than the strength of rock massive. The surface size effect is important for testing of samples of small sizes. The volume size effect is the main one when moving from a sample to rock massif. The surface size effect can enhance the volume size effect in some cases, and reduce it in others, depending on the nature of surface defects. The attempt was made in [18, 19] to take into account both types of scale effects, as well as their transformation into one another.
2. Test procedure, equipment and test samples
The experiments were carried out on cylindrical samples of different rocks: hornfels, chalkstone, sandstone, siltstone, rich ore, cuprous ore, interspersed ore of three different diameters: \( d = 10, 30, 60 \) mm and the ratio of height \( h \) to diameter of \( h/d = 2 \) for test under uniaxial compression loading and \( h/d = 1 \) for tension loading. Photos of some samples are shown in Fig. 1. The following equipment was used for research: for testing of samples of diameter \( d = 10 \) mm – Deben Microtest micropress, for samples of diameter \( d = 30 \) and 60 mm – Instron 8802 servohydraulic press. Samples of each diameter were tested under uniaxial compression and tension loading (Brazilian test). Two or three samples were used for each size and type of test. Loading was carried out in a “hard” mode, the rate of movement of the movable traverse of the presses was 0.1 mm/min. The stress, axial and transversal deformations of samples were continuously recorded during the tests under compression loading and the stress – under tension loading. The strength characteristics of the testing samples are demonstrated in Table 1 and Fig. 2.

![Figure 1](image)

**Figure 1.** The samples of siltstone of diameter \( d = 60, 30 \) and 10 mm.

3. The results of experiments
The analysis of the test results demonstrated in Fig. 2 and table 1 allows us to conclude that values of strength limit increase with the increase of the sample diameter from 10 to 60 mm for the group of ore-bearing samples under compression loading: for rich ore – by 1.4 times; for cuprous ore – by 1.3 times and for interspersed ore – by 1.2 times. The tensile strength also increases with increasing diameters from 10 to 60 mm: by 1.4 for rich ore and by 1.3 times for cuprous and interspersed ore.

The results of testing of samples of hornfels, sandstone and siltstone demonstrated the opposite trend. The strength properties decrease with increasing of size of the samples. The strength limit decreases for hornfels under compression loading by 1.3 times and tensile loading – by 1.4 times; for limestone – under compression by 1.4 times, under tension by 1.3 times; for sandstone – under compression by 1.4 times and under tension by 1.3 times and for siltstone – under compression by 1.3 times and tension – by 1.3 times.

The analysis of the character of deformation and destruction process of the samples was carried out using video data of the sample surface and “stress–strain” diagrams under compression loading by Deben Microtest micropress. As an example, fig. 3 and 4 demonstrate photos of the fragments of the surface of rich ore and siltstone samples of diameter of 10 mm and the corresponding “stress–strain” diagrams at the moment preceding the failure (Fig. 3a, 4a) and similar data for the subsequent time frame corresponding to the moment of the appearance of the main crack (Fig. 3b, 4b). Fig. 3c, d and 4c, d show “stress-strain” diagrams obtained for the samples of diameters of 30 mm from the same rocks under compressing loading too.

The values of Young's module \( E \) and module of decrease \( M \) were calculated on the section of increased load and section of behind limit deformation of “stress–strain” diagram for samples of diameters of 10 and 30 mm. The average values of \( E \) and \( M \) modules are given in the table. 2. From the comparison of values of \( E \) and \( M \) modules, it can be concluded that the module of decrease \( M \)
exceeds the Young's module $E$ for all samples of small diameter (10 mm). The samples are shock hazardous and destruction is brittle.

The module of decrease $M$ is less than the Young's module $E$ for ore-bearing samples of medium diameter (30 mm) in all cases. The plastic properties of such rocks increase, and the nature of destruction becomes more viscous with the increase of diameters of the samples. Siltstone samples are characterized by brittle fracture for both values of sample diameters.

**Table 1.** The ultimate strength of rock samples of three sizes.

| Name of the rock     | Compression strength, MPa | Tensile strength, MPa | Diameter of the sample, mm |
|----------------------|---------------------------|-----------------------|---------------------------|
| Rich ore             | 113                       | 10,2                  | 60                        |
|                      | 95                        | 8                     | 30                        |
|                      | 63                        | 3,4                   | 10                        |
|                      | 164                       | 25,5                  | 60                        |
| Cuprous ore          | 150                       | 23                    | 30                        |
|                      | 87                        | 13,1                  | 10                        |
|                      | 102                       | 19,9                  | 60                        |
| Impregnated ore      | 90                        | 17                    | 30                        |
|                      | 71                        | 12,1                  | 10                        |
|                      | 62                        | 21,4                  | 60                        |
| Hornfels             | 103                       | 27                    | 30                        |
|                      | 123                       | 29,9                  | 10                        |
|                      | 34                        | 7,8                   | 60                        |
| Chalkstone           | 67                        | 12                    | 30                        |
|                      | 109                       | 17,04                 | 10                        |
|                      | 112                       | 13,7                  | 60                        |
| Sandstone            | 143                       | 19                    | 30                        |
|                      | 161                       | 22,8                  | 10                        |
|                      | 152                       | 21,5                  | 60                        |
| Siltstone            | 183                       | 28                    | 30                        |
|                      | 223                       | 34,6                  | 10                        |

The revealed regularities of changes of the strength and deformation characteristics of samples can be explained by the development of the volume size effect and the surface size effect, depending on elemental composition of rock and it the propensity to viscous or brittle destruction.

The compression and tensile strength increases with increasing sample size for rocks containing viscous inclusions (ores containing copper, zinc, lead, tin). The plasticity of such rocks contributes to the healing of micro-cracks that are developing at the stage of plastic deformation of the rock and makes it difficult for micro-cracks to develop into macro-cracks and the initiation of sample destruction. In addition, the surface size effect is more pronounced for samples of smaller sizes – the violation of the surface layer of the sample during processing. Moreover, the more significant the surface effect is the smaller the sample.
Figure 2. “Ultimate strength-diameter” diagrams of rock samples under compression loading (a, c) and tensile loading (b, d) for rich ore (curve 1), cuprous ore (2), impregnated ore (3), hornfels (4), chalkstone (5), sandstone (6), siltstone (7).

Table 2. Values of Young's module $E$ and module of decrease $M$ of ore-bearing rocks and siltstone.

| Name of the rock     | Diameter $d=10$ mm $E$, GPa $M$, GPa | Diameter $d=30$ mm $E$, GPa $M$, GPa |
|----------------------|--------------------------------------|--------------------------------------|
| Rich ore             | 18,301 21,323                        | 16,406 8,972                         |
| Cuprous ore          | 15,002 18,541                        | 12,453 7,991                         |
| Impregnated ore      | 17,923 19,837                        | 15,672 10,323                        |
| Siltstone            | 13,724 15,685                        | 11,839 13,452                        |

The compression and tensile strength decreases when the size of samples of hornfels, chalkstone, sandstone, siltstone increases. Such regularity of change of strength properties is explained by the volume size effect. The probability of occurrence of any defects (cracks, weak inclusion, etc.) is higher for large bodies of real inhomogeneous structure. Therefore the strength of samples must inevitably fall with increasing of the volume.
Figure 3. Photos of the fragments of the surface of rich ore sample of diameter of 10 mm and the corresponding “stress–strain” diagrams at the moment preceding the failure (a) and similar data for the subsequent time frame corresponding to the moment of the appearance of the main crack (b); “stress-strain” diagrams of two rich ore samples of diameter of 30 mm under compressing loading (c, d).

Figure 4. Photos of the fragments of the surface of siltstone sample of diameter of 10 mm and the corresponding “stress–strain” diagrams at the moment preceding the failure (a) and similar data for the subsequent time frame corresponding to the moment of the appearance of the main crack (b); “stress-strain” diagrams of two siltstone samples of diameter of 30 mm under compressing loading (c, d).
4. Conclusion
The experimental study was carried on cylindrical samples of three different diameters of 10, 30 and 100 mm of following rocks: hornfels, chalkstone, sandstone, siltstone, rich ore, cuprous ore, interpersed ore under uniaxial compression and tension. The regularities of changes of ultimate strength, Young's modules and the modules of decrease depending on sample size and rock's tendency to viscous or brittle destruction (composition of rock) were obtained. The strength of the samples of hornfels, chalkstone, sandstone, siltstone decreases when their size increases. This regularity of changes of strength properties may be explained by the volume (main) size effect. The values of ultimate strength increase with increasing of sample size of rocks containing viscous inclusions (ores containing copper, zinc, lead, tin). The values of module of decrease $M$ exceed the Young's module $E$ for the samples of small diameter (10 mm) for all types investigated rocks. The samples are shock hazardous and destruction is brittle. The values of module of decrease $M$ are less than the Young's module $E$ for ore-bearing samples of diameter of 30 mm in all tests. The plasticity of such rocks contributes to the healing of micro-cracks that develop at the stage of plastic deformation of the rock, makes it difficult for micro-cracks to grow into macro-cracks and balks the onset of sample destruction. Smaller samples exhibit a brittle fracture pattern and their fracture toughness increases with increasing sample size.

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Acknowledgments
This study has been carried using equipment of the Shared Use Center of Geomechanical, Geophysical and Geodynamic Measurements, Siberian Branch, Russian Academy of Sciences.