Effect of water on fracture of rocks under diametral compression

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Abstract. The researchers study the effect of water on the strength of small-size specimens made of metamorphic rocks (carbonaceous quartzite, serpentine) and an analog of sedimentary rocks (sand-and-cement mixture, or artificial sandstone) exposed to diametral compression. It is found that the specimens exhibit the same brittle deformation behavior after water storage for a day. All specimens show reduced strength while quartzite and serpentine feature a decrease in deformability down to failure. Microscopic fracturing is viscoelastic and independent of water. It is suggested that the influence of water on the deformation behavior of the specimens can be explained by the Rebinder effect.

Water environment has a considerable influence on mechanical properties of rocks. For instance, water penetrated in a material changes its elastic and strength characteristics [1–3]. These changes should be taken into account in geomechanical assessment-based grounding of mining, e.g. in the stability designs of mines and underground structures. Such calculations need data on mechanical characteristics of rocks [4]. It is difficult to carry out physical tests of large specimens of rock, including the requirement of pre-set shaping. For instance, for the Brazilian tests, specimens need to be shaped as disks with a diameter of 10–15 cm, and it is difficult achieve evenness and parallelism of the face surfaces of such disks. Furthermore, such large-scale experimentation needs expensive testing machines. With smaller size specimens, the manufacturing procedure is much simpler, the test are essentially less expensive, and different-scale metallography of the specimens becomes possible without the loss in their integrity [5]. This study focuses on the influence exerted by water on the mechanical properties and fracturing behavior in small-size specimens of rocks in indirect tensile tests (Brazilian testing).

It was chosen to test metamorphic rocks (coaly quartzite, serpentinite) and a sedimentary rock analog (artificial sandstone or cement-and-sand mixture) [6]. The specimens of quartzite and serpentinite were shaped as disks with a diameter of 5 mm and a thickness of 3 mm; the artificial sandstone disk had a diameter of 11 mm and was 5 mm thick. The rough workpieces to make specimens were drilled from parallel planes under water with a hollow diamond drill; the planes had a thickness not less than 5 diameters of a future specimen. The cylindrical rough workpieces were cut by a small-size diamond saw 45 mm in diameter and 0.1 mm thick under continuous spraying by water. Then, the side surfaces of the specimens were polished up to flatness on a tool-grinding diamond wheel. The indirect tensile tests (Brazilian tests) were carried out under room temperature on Shimadzu AG-50K XD tension test frame (crosshead speed of 0.1 mm/min). The testing was terminated when the stress–strain curve acquired a dog-leg reflective of initiation of a critical fracture in a specimen. For each type of rocks, two groups of 10 specimens each were tested. The first group was the specimens in the initial state, and the second group was the specimens held in tape water for a day. The test data processing used materials testing software Trapezium of Shimadzu. The surfaces of the specimens before and after the tests were examined using Epson Perfection V750 Pro scanner (augmentation ×10) and MIM-8M metallographic microscope with Canon high-resolution camera (augmentation ×100). Using the microscopic images and Adobe Photoshop, topograms of the fractured surfaces of the specimens were plotted. In the topograms, the shape, length, width and number of fractures were determined and statistically processed using a standard program. The array data characteristics were chose the arithmetical average and standard deviation.

The stress–strain curves were plotted for each type of rocks. The curves of initial specimens and specimens held in water exhibited the same behavior. Unexceptionally, deformation endured by the specimens down to failure was of the order of 1%. It can be concluded that the specimens subjected to the tensile load behaved as a brittle material irrespective of being held in water or not. The only difference lied in the quantitative characteristics of such parameters as ultimate stress limit and deformation to failure. The data on the mechanical properties of the test rocks are given in Table 1. Evidently, the strength characteristics of the test rocks after the day-long water storage reduced.

Table 1. Mechanical properties of model materials.

Index	Coaly quartzite		Serpentinite		Artificial sandstone	
	air	water	air	water	air	water
σ, MPa	32	25	23	18	6	4
δ, %	1.3	0.9	1.3	0.9	0.6	0.6

After the tests, the untreated quartzite specimens came apart while the untreated specimens of serpentinite and sandstone preserved integrity. This suggests two competing mechanisms of stress relaxation in a material subjected to tensile loading: initiation–growth of fractures and deformation (reversible and irreversible). In serpentinite, which like all rocks is incapable for macroscopic irreversible deformation, the mechanism to compete with failure will be reversible or elastic deformation. In sandstone, due to high porosity, the contribution of irreversible deformation to stress relaxation cannot be neglected as some pores can collapse under loading. In quartzite, the main relaxation mechanism is fracturing while the part of deformation is insignificant.

Although the ultimate strength and deformation to failure decreased in the specimens after water storage, only a half of the quartzite specimens came apart after the tests whereas the specimens made of serpentine and sandstone preserved integrity. This means that the both mechanisms of stress relaxation, i.e. fracturing and deformation, are active in serpentinite and sandstone, while in quartzite the initiation and growth of fractures is competed by the deformation mechanism.

The microscopic studies of the fractures showed that their tips were sharp irrespective of the type of rock a specimen was made of, and the trajectories of the fractures were oriented along the load application axis (Figs. 1a and 1c, Figs. 2a and 2c). The length of the main fracture was different in the treated and untreated specimens. In the dry specimens, the length of the main fracture was comparable with the specimen diameter; in the specimens after water storage, it was smaller (Table 2). The microscopic examination revealed that the main fracture was composed of fine lens-shaped fractures tending to coalescence (Figs. 1b and 1dm Figs. 2b and 2d). Most fractures had blunt tips though there were sharp tip fractures. Fractures in the dry specimens were 2–3 times wider than in the wet specimens (Table 2). An inclusion on the pathway of the main fracture could deflect the fracture from the initial trajectory.

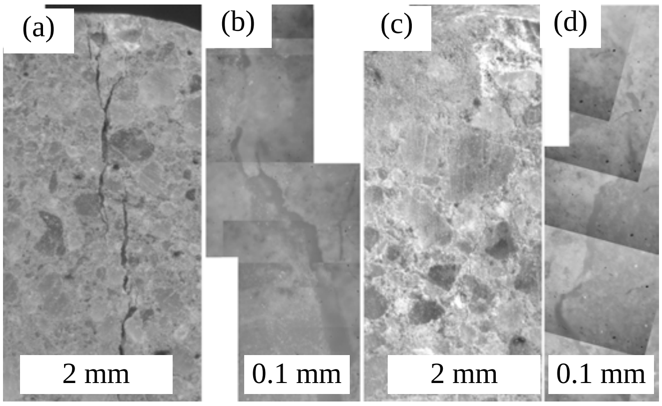

Figure 1. Failure of initial sandstone specimen and after water storage on a macroscale (a), (c) and on a microscale (b), (d).

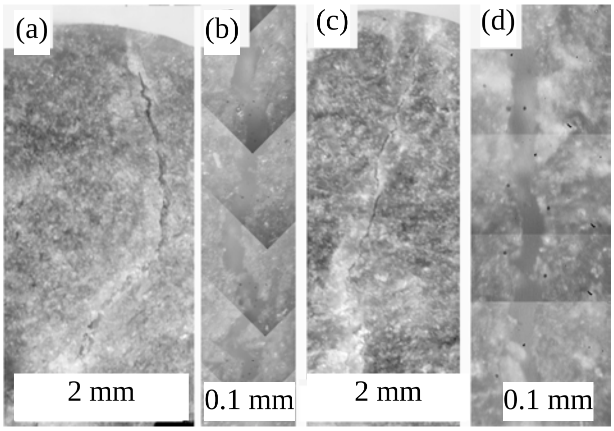

Figure 2. Failure of initial serpentinite specimen and after water storage on a macroscale (a), (c) and on a microscale (b), (d).

Table 2. Fracturing of model materials.

Specimen		Coaly quartzite		Serpentinite		Artificial sandstone	
		air	water	air	water	air	water
Diameter, mm		6	6	6	6	10	10
Total length of fractures, mm		3.98±0.12	4.18±0.04	3.86±0.16	3.42± 0.07	8.20±0.24	7.21±0.07
Number of fractures		2	6	3	4	3	14
Fracture length, mm	Left side	2.09±0.01	0.30±0.03	1.92±0.07	0.48±0.03	2.17±0.15	0.56±0.04
	Center	–	1.72±0.04	0.88±0.24	1.79±0.08	5.33±0.27	0.07±0.02
	Right side	1.89±0.15	0.16±0.01	0.43±0.09	0.13±0.04	0.70±0.08	1.17±0.09
Fracture width, mm	Left side	0.03±0.02	0.01±0.00	0.04±0.01	0.03±0.01	0.04±0.04	0.02±0.01
	Center	–	0.01±0.00	0.03±0.01	0.04±0.01	0.10±0.04	0.01±0.00
	Right side	0.03±0.01	0.01±0.00	0.03±0.01	0.02±0.01	0.02±0.01	0.02±0.01

The macro-level analysis of deformation behavior of the specimens proves the brittle behavior of rocks under tensile loading irrespective of the rock type. The presence of water unalters the brittle deformation behavior but reduces the strength characteristics of the specimens. The data on fractures on the macroscale conform with the inference on the brittle failure of the specimens: the main fractures have sharp tips and straight profile. The analysis of the microscale failure yields that the main fracture results from the coalescence of lens-shaped fractures with blunt tips, and the width of the fractures is governed by the presence of water in the specimen. The failure mode described above suggests two mechanisms of elastic energy relaxation in the specimens: fracture growth and deformation. Consequently, the microscale mode of failure can be characterized as viscoplasticity. The reduction in the ultimate strength limit and deformation to failure, as well as the decrease in the width of fractures under action of water is the effect of Rebinder [7].

It is noteworthy that according to the test data on water-saturate granite specimens [8], the mode of failure changes during deformation. In case of dry specimens, failure follows the two-stage mechanism: disperse accumulation of defects and localization and growth of a single failure source, as a rule; in water-saturated specimens, chaotic failure and high-rate damage embrace the whole volume of the material.

Conclusion

The studies have shown that the test rock materials under tensile loading exhibit brittle behavior on macroscale and viscoelastic behavior on microscale. The influence of water on deformation behavior of specimens can be explained by the Rebinder effect. The mechanism of the water effect on strength needs further analysis.

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Corrigendum: Effect of water on fracture of rocks under diametral compression

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Description of corrigendum e,g,

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Acknowledgements section should be added as follows:

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