International Journal of Rock Mechanics and Mining Sciences 110 (2018) 210–217

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Laboratory study on the time-dependent behavior of intact and failed sandstone specimens under an unconfined condition with the relaxation test

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ARTICLE INFO

Keywords:
Relaxation
Sandstone
Radial strain
Failure condition

ABSTRACT

This research reports the laboratory relaxation tests investigating the time-dependent behavior of intact and failed sandstone specimens under unconfined condition. The results indicate that the stress relaxation curves show smooth relaxation behavior in the pre-failure region and show staircase type relaxation behavior in the post-failure region. The failed specimens experienced sudden and large stress drops after a stage of smooth relaxation and as a result, more stress is relaxed from the failed specimens than the intact ones. In addition, the radial-strain-time curve during a relaxation test shows similar trend as creep. No third stage was observed for the relaxation test in the pre-failure region while in the post-failure region, the radial strain accelerates to failure in a short time after a few cycles of jump and stabilization. The sudden changes in the radial strain are likely induced by the failure propagation or shear-off of asperities along the major shear failure plane. The radial strain is much larger than the inelastic axial strain, especially in the post-failure region, demonstrating that the time-dependent deformation concentrates in radial direction once the specimen fails. Furthermore, any change in the radial strain curve coincides with the change in the stress curve during a relaxation test, and the regression analyses show that they are linearly correlated. The sensitivity of stress to radial strain depends on the failure condition of the specimens.

1. Introduction

Extensive research on roof falls in underground coal mines has significantly reduced the occurrence of fatalities; however, roof falls are still recognized as a major safety hazard in US underground coal mines.[1] Many researchers have investigated various factors that contribute to roof falls.[2–6] The effect of time on roof falls, however, is rarely considered in coal mine design. Field observation demonstrates that the competent roof of a coal mine does not fail immediately after excavation; failure occurs sometime later depending on various geo-mechanical factors.[5,7] Therefore, it is necessary to study the roof behavior from a time-dependent point of view.

In the past, the time-dependent behavior of a mine roof was usually shown by a convergence curve. The relationship between cumulative roof convergence and time is similar to the creep curve with three stages. Convergence rate decreases rapidly at first, then remains constant, and finally accelerates to failure when the deformation exceeds a certain threshold value. The accelerating convergence in the third stage can be considered a sign of roof instability. The roof convergence curve shows the time-dependent deformation of a mine roof. However, the roof convergence is not merely the result of the creep of intact rock. Closure data for underground excavations has demonstrated that viscosity values determined from laboratory tests on intact specimens are much greater than those measured on field scale.[8,9] This indicates that, besides the creep of intact rock, other factors contribute to time-dependent deformation. These factors include the separation of bedding planes, rock layer bending, and concentrated failure. Malan et al.[9] studied the time-dependent behavior of deep-level stopes in gold mines with a boundary element code. The intact rock was simulated as Burgers material, and the fractures were treated as viscoplastic. The problem space was covered by a random mesh of potential fractures, which were initially intact with a prescribed strength. Once they failed, the potential fractures became viscous discontinuities. Good agreement between the numerical simulation result and field closure data was obtained. The simulation results indicate that time-dependent behavior of the stopes is governed mainly by the rheological behavior of the fracture zone and the time-dependent generation of new fractures. The fracture zone relaxes over time, transferring stress to the more solid rock. New fractures are generated in these positions with time. This shows the importance of the time-dependent behavior of failed rock and the failure process in the time-dependent closure of underground excavations. Bieniawski[10] also pointed out that the knowledge of the

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https://doi.org/10.1016/j.ijrmms.2018.08.011
Received 9 April 2018; Received in revised form 16 May 2018; Accepted 16 August 2018

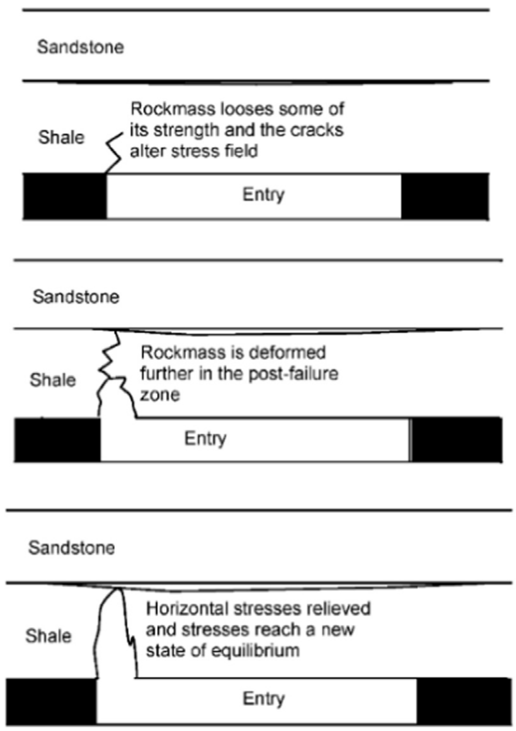

Fig. 1. Cutter failure development in underground coal mines.[4].

time-dependent behavior of fractured rock is particularly important in designing rock structures for long-term stability.

Fig. 1 shows the development of cutter-type failure in coal measure rocks overlying the Pittsburgh coal seam. Failure usually initiates on one side of the entry during development. The rock within this failed zone is in the post-failure region and loses some or all load-bearing capacity. This alters the stress field and deformability of the roof. As a result, failure can progressively propagate, eventually leading to roof collapse. The strain-softening model has been successfully used in simulating the gradual loss of load-bearing capacity in the fractured zone during mine development.[4,5] However, the cutter failure in underground mines is gradually developed with time. As shown in Fig. 1, intact rock, failed rock, and time-dependent failure propagation are involved in this process. If the time-dependent behavior of intact and failed rock can be determined, the time-dependent failure process can be numerically simulated. The purpose of this paper is to study the time-dependent behavior of intact and failed sandstone specimens.

Creep tests are commonly used to investigate the time-dependent behavior of intact rock. There are extensive studies reported on the time-dependent behavior of intact rocks. However, once the rock fails, it is extremely difficult to maintain a constant load.[11] As a result, limited information is available about the time-dependent property of failed rock. The relaxation test was used by various researchers to overcome the challenges posed in constant load tests. Relaxation tests have been successfully performed at different stages of a complete load-displacement curve.[11–13] At the same and even lower stress level, relaxation in the post-failure region is more pronounced than in the pre-failure region. However, these relaxation test results were only used to qualitatively describe the stress relaxed from the specimens; no information is available on using the relaxation test for understanding the time-dependent behavior of failed rock. In addition, previous studies with the relaxation test only focused on the load applied on the specimens in the axial direction. No data about the deformation in the lateral or radial direction is available. It has been demonstrated that the deformation in the radial direction is larger than in the axial direction during laboratory creep tests and that volumetric strain is a good indicator of the failure or damage development within specimens.[14] If the radial strain is monitored during relaxation tests, the volumetric strain can be calculated to interpret the failure development and stress relaxation inside the specimens. Therefore, it is necessary to monitor and study the radial deformation during relaxation tests.

In this paper, the relaxation test was used to investigate the time-dependent behavior of intact and failed sandstone under the unconfined condition. A few unconfined compression tests were first conducted to determine the mechanical properties of the sandstone specimens. The strength and lateral deformation at failure were summarized. This was the basis for determining the specific points to start the relaxation tests in the pre-failure region and post-failure region. Two groups of unconfined compression tests with relaxation tests in the pre-failure and post-failure region were then conducted to study the time-dependent behavior of intact and failed specimens. The test results were analyzed from failure condition, stress-strain curve, the relationship between stress and radial strain, and the inelastic axial strain.

2. Laboratory test

Berea sandstone was used in the laboratory test. Berea sandstone has excellent, uniform material properties. The mineral compositions of the sandstone were determined by XRD. The results show that Berea sandstone is composed mostly of pure quartz with slight amounts of feldspars, dolomite and kaolinite.

Cores were drilled from Berea sandstone blocks, and specimens with a 50.8 mm diameter were prepared in the rock mechanics laboratory at West Virginia University following the ASTM standard. An MTS servo-controlled compression testing system was used to perform the laboratory test (Fig. 2).

The mechanical behaviors of sandstone were determined from four unconfined compression tests. Stroke-control mode applied the load on the specimens with a displacement magnitude of 0.76 mm. A circumferential strain control mode was then used to control the failure of the specimens. The tests stopped when the circumferential deformation exceeded the 2.54 mm limit. Figs. 3–5 show the typical failure mode, stress-strain curves, and stress-lateral deformation curves for the

Fig. 2. MTS servo-controlled compression testing machine and its components: (1) Machine load, (2) Glass shield, (3) Hydraulic actuator, (4) Manual control system, (5) Strain gauge control panel, (6) Computer, (7) MTS data acquisition system.[15]