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Peeking Inside Rocks: Why Microstructures Matter When They Deform Under Stresses

Rocks are often perceived as strong, immovable masses, yet their stability is shaped by both what we observe at large scales and what is concealed in the interior [1]. At the macro-scale, discontinuities such as fractures, joints, and bedding planes have a potent effect on the deformation and fracturing of rocks [2]. Such characteristics form planes of weakness that can control the stability of rock masses. Even though rocks show no apparent cracks or joints at the macro-scale, their mechanical behavior is strongly governed by their complex internal microstructure. The resistance or vulnerability of a rock to stress depends on grain size, porosity, mineral composition and cementation nature [3]. Although macro-discontinuities precondition the stability on the large scale, the microstructure defines the ultimate way in which a rock actually behaves as the stresses accumulate.

To explore this hidden microstructure of rocks, researchers combine triaxial testing, a laboratory technique that simulates the stresses that rocks

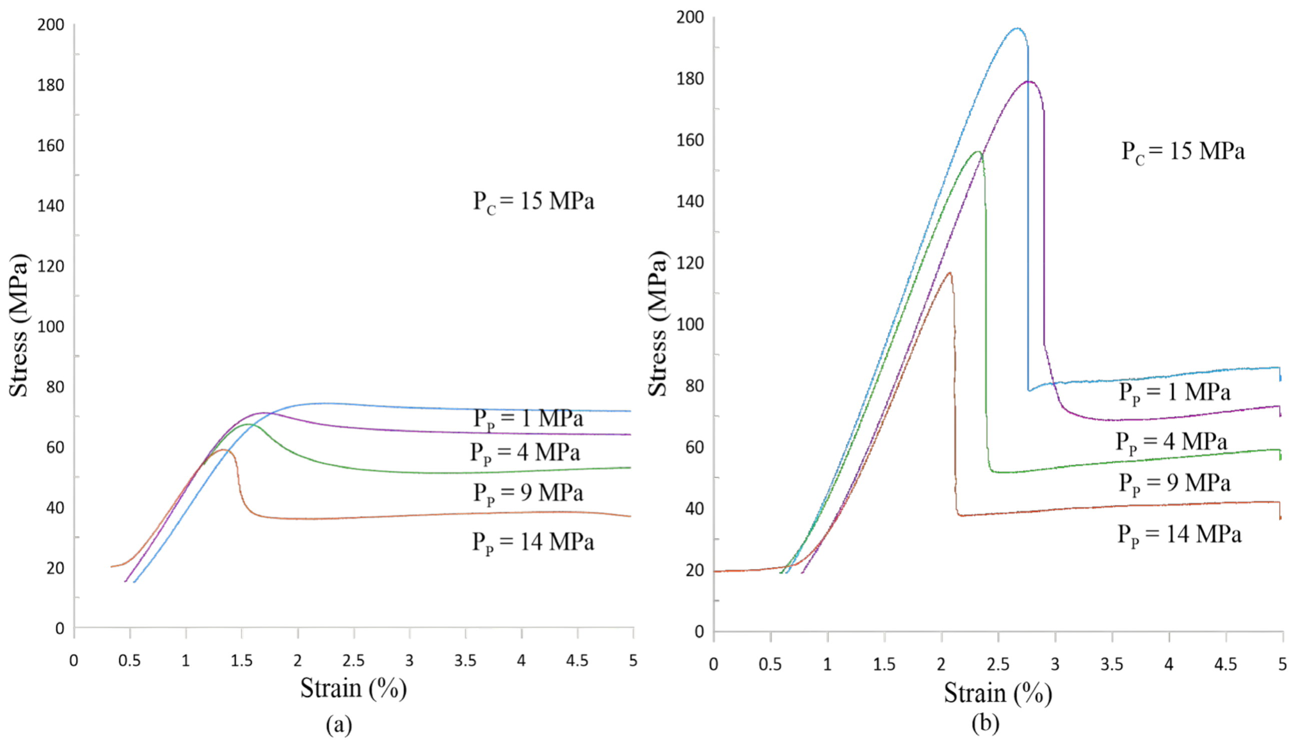

Figure 1: Stress-Strain distributions (a)for Kimachi sandstone (b)for Bibai sandstone [3]

experience deep underground, with imaging techniques. By compressing cylindrical rock samples under controlled conditions, it becomes possible to observe how they deform, compact, or fracture [3], [4]. When these mechanical tests are paired with thin-section microscopy and advanced imaging methods such as CT scanning, researchers can bridge the gap between microstructural observations and the mechanical behavior of the rock [3].

In our study, the focus was placed on two sandstones with contrasting characteristics: Kimachi sandstone, a medium-hard clastic rock with abundant cementing material, and Bibai sandstone, a hard clastic rock but with weaker grain bonding [3]. Despite being subjected to identical loading conditions, their responses showed the extent to which decisive microstructural differences can be (Figure 1). Kimachi sandstone shifted gradually from brittle cracking to ductile compacting as confining pressure increased. The strong cementing material binding to its grains facilitated compaction, making it less porous and less permeable at high levels of stress. This internal strengthening mechanism enabled the rock to sustain more load before failure. Bibai sandstone, on the contrary, did not lose its brittle nature despite high confinement. With less cement binding its grains, it developed shear planes and sub-ruptures (Figure 3), causing porosity and permeability to increase rather than decrease with the confinement.

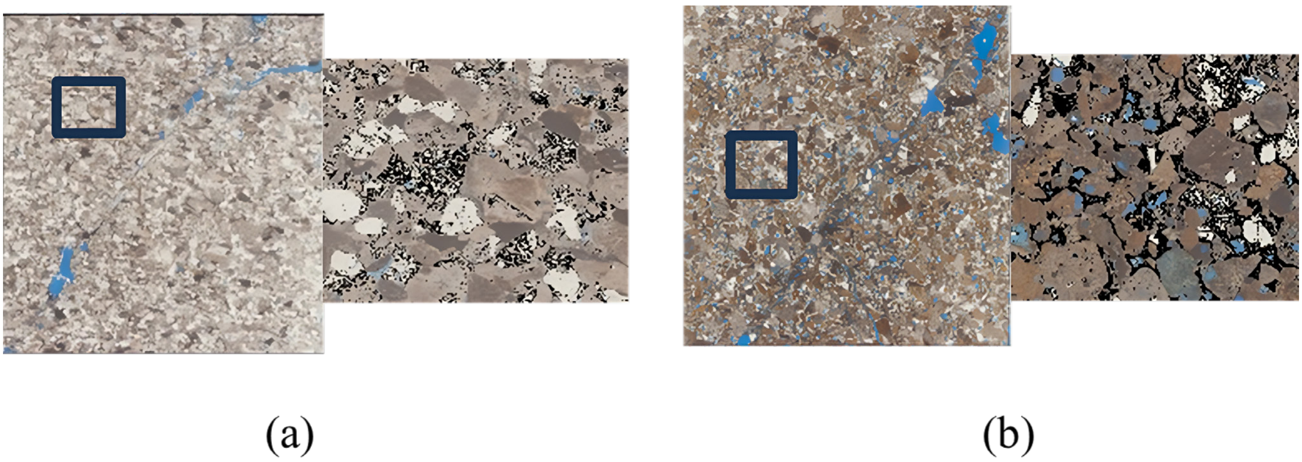

Figure 2: Segmented cementing material of the chosen areas on thin sections at a confining pressure of 2 MPa (a) for Bibai sandstone (b) for Kimachi sandstone [3]

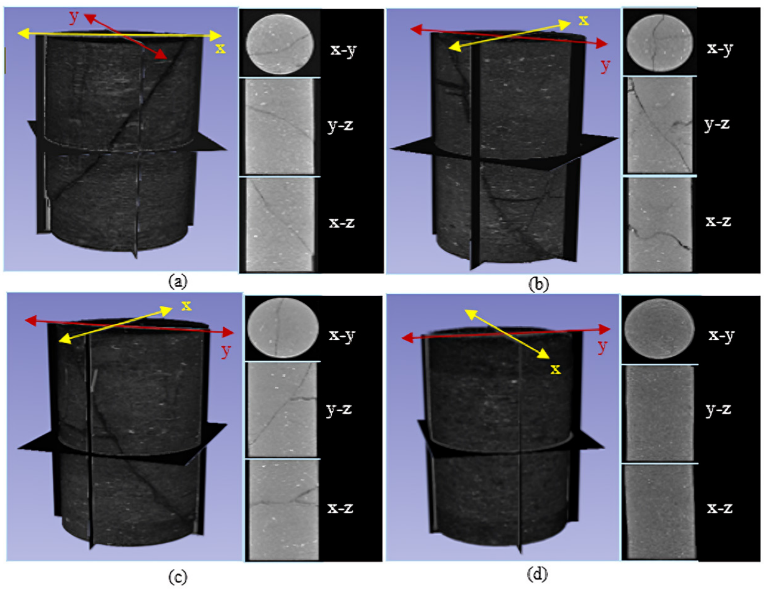

Figure 3: Reconstructed specimens (a), (b) under 15 MPa of confining pressure with 1 and 14 MPa of pore pressure for Bibai sandstone respectively (c), (d) under 5 and 15 MPa of confining pressure with 1 MPa of pore pressure for Kimachi sandstone respectively [3]

These contrasting behaviors emphasize that the strength and deformation of rocks cannot be understood by stress conditions alone. Although stress establishes a relationship that is external, the internal microstructure determines how stress is accommodated, whether by compaction and strengthening or by fracturing and weakening. This implies in practice that two rocks in the same environment can behave differently in terms of their stability, simply due to the differences at the microscopic level.

This observation has direct implications for engineering applications. In tunnelling, underground storage, and mining, to determine stability, it is necessary to go beyond mapping the discontinuities and calculating the stresses. A reliable assessment of rock stability requires explicit consideration of microstructural features, because they dictate the mechanisms of compaction, crack initiation, fracture propagation, and long-term deformation that cannot be inferred from stress analysis alone. Incorporating this microstructural analysis provides the predictive capability needed to evaluate rock performance in real underground settings.

Ultimately, rocks tell two intertwined stories. At the macro-scale, discontinuities dictate the broad outlines of stability, while at the micro-scale, grain arrangements and cementation decide the details of how stress is resisted or released. Together, these scales determine whether a rock mass endures or fails. By examining microstructural features, engineers can better assess how a rock will deform over time, a key factor needed for safer, more reliable, and more sustainable engineering solutions.

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