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How pore fluids shield crack growth: direct experimental evidence of hydro-mechanical couplings in tensile fracture

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Abstract

Fracture mechanics has been mostly developed for elastic, brittle, dry materials, yet many subsurface geo-engineering applications involve crack growth in porous rocks that are fluid-saturated. While the role of injected fluids in fracture propagation has been studied extensively, the contribution of pore fluids is still commonly treated indirectly. In most cases, pore fluid effects are ignored or absorbed into an apparent fracture resistance. In fluid-saturated conditions, tensile fracture generates a localized dilation of the pore space ahead of the crack tip, which draws fluid inward from the surrounding pores. This results in a drop of pore pressure in this region, which reduces the effective stress applied to the skeleton, modifies the near-tip failure micromechanisms, and ultimately leads to a change of apparent fracture energy at the macroscopic scale. Up to now, these phenomena have been mostly predicted rather than observed, largely because pore-pressure transients are difficult to resolve at the spatial and temporal scales of crack propagation in the laboratory. Here, we present a custom experimental platform designed to resolve pore-pressure transients during stable quasi-static crack propagation at prescribed velocity. We use a wedge splitting test (WST) in a water-filled triaxial pressurized cell. A miniature pressure sensor is embedded in the specimen provides real-time internal pore pressure measurements. Combining crack opening displacement, via digital image correlation, and applied force, using a force sensor, we infer the crack velocity and fracture energy throughout the test. We selected a class G oil well cement, with a homogeneous pore structure, low viscosity and well-controlled mechanical and hydraulic properties, as an analog material. In water-saturated conditions, its low permeability and high stiffness bring the characteristic poroelastic length scale ℓ_{pe} of pore-pressure variations into the micrometer-millimeter range for laboratory-accessible quasi-static crack speeds, for which spatiotemporal coupling becomes measurable. Our measurements reveal a transient pressure drop that develops ahead of the crack front, whose magnitude scales with the square root of crack speed, consistent with poroelastic predictions. This underpressure reduces the near-tip effective stress, producing a fluid-induced toughening effect: the apparent fracture energy increases by up to a factor ~2 at the highest tested velocities. This toughening can be attributed to the contraction of the process zone, which leaves a measurable imprint on the fracture surface, revealed by green-light interferometry. Together, these findings show how fluid–solid interactions reshape classical fracture mechanics and control the transition between drained and undrained regimes at the process zone scale. These insights provide a common basis for interpreting and modeling fracture in materials as diverse as cements, geomaterials, biological tissues, and hydrogels.

Keywords:

experimental fracture mechanics hydro-mechanical coupling tensile fracture fluid-saturated porous media