Experimental Determination of the Fracture Toughness and Ductility of the Mancos Shale, Utah.

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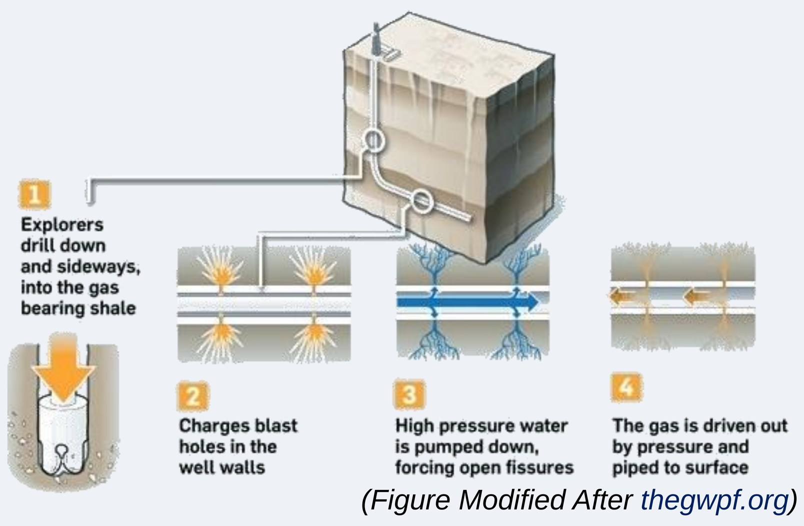
1. Hydraulic Fracture of Shale

Since the US "Shale Gas Revolution", interest in the mechanical properties of Shales has increased dramatically. Extraction of Shale Gas commonly involves drilling vertically and then horizontally into the Shale seam. The Shale is then hydraulically fractured, by injection of high pressure fluid. These fractures extend from the wellbore for a few hundred metres.

The mechanical properties of Shales remain poorly constrained, with a wide range of reported property values. Fracture Toughness is a significant control on hydraulic fracture propagation, but there is an extreme paucity of published data on the fracture toughness of soft sediments such as Shale *(Barpi et al., 2012)*.



(Figure Modified After thegwpf.org)

Shale is commonly a layered and strongly anisotropic material, which is often much weaker along the clay bedding planes. The stress field at depth is also anisotropic, with the vertical stress generally significantly higher than the horizontal stresses.

At great depth, where the magnitude of the stress anisotropy exceeds the strength anisotropy, fractures will therefore tend to propagate vertically. Conversely, at shallower depths where the strength anisotropy exceeds the stress anisotropy, fractures are more likely to propagate horizontally. As a result, it is important to measure the fracture toughness in different orientations

The Mancos Shale

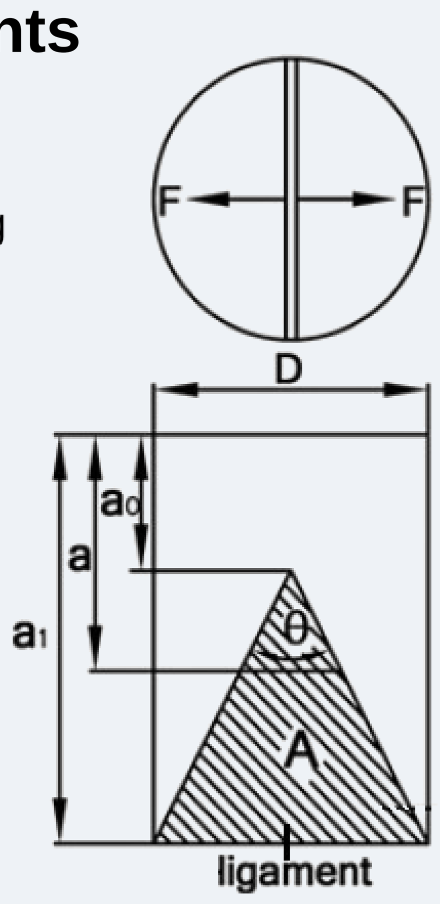
The Mancos Shale is an Upper Cretaceous Shale-Gas play deposited around 90-70 million years ago in the Rocky Mountain area of western Colorado and Eastern Utah. The Mancos is an unusually thick package (up to 1.1km) of Shale lithotypes including interbedded claystone, siltstone and very fine grained sandstone.

2. Fracture Toughness

Fracture toughness is a measure of a material's resistance to dynamic crack propagation. For linear elastic materials it is defined by the critical stress intensity factor, K_{Ic}, beyond which catastrophic crack growth occurs. For materials which deviate from linear elasticity, cyclic loading of the specimen can be used to calculate the ductility corrected Fracture toughness, K_{Ic}^c.

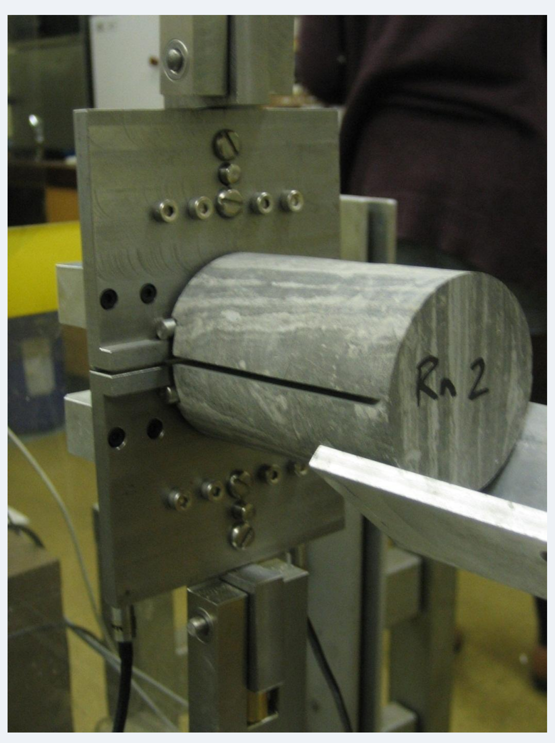
Short-Rod Fracture Toughness Experiments

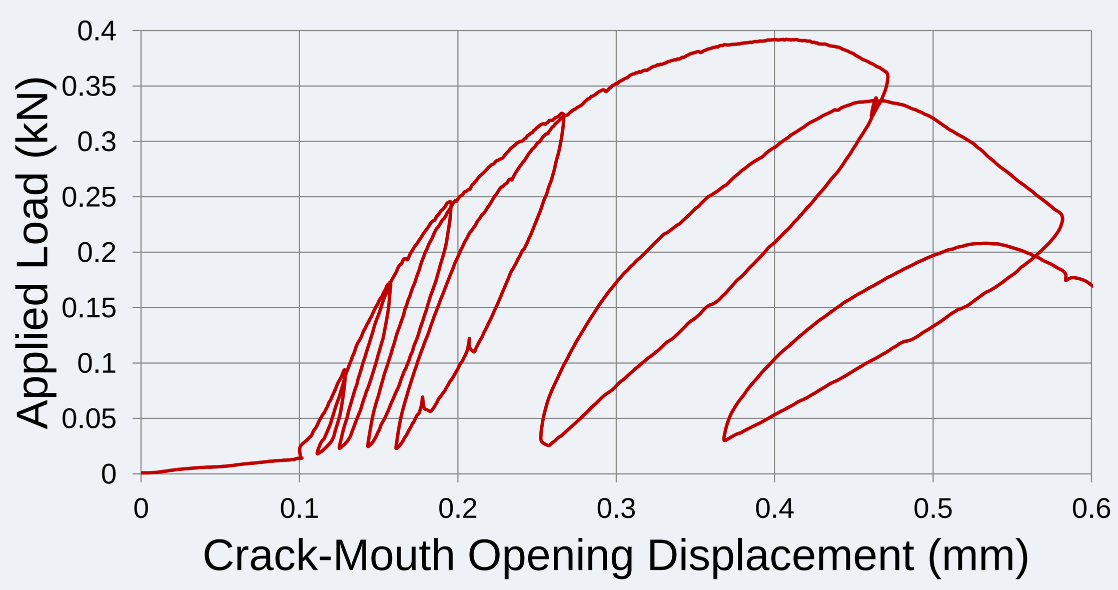
The Short-Rod Geometry for Fracture Toughness measurements involves a cylindrical sample containing a notch along the length of the cylinder. This notch is ground out, leaving a Chevron Ligament of rock material remaining (*Ouchterlony et al., 1988*).



The sample is loaded from the end of the cylinder, in a direction perpendicular to the plane of the chevron. At the same time, displacement between the two loading jaws is measured using LVDTs. K_{Ic} for brittle elastic materials can then be calculated directly from the maximum load. However, most soft rocks are only semi-brittle and in this case it is necessary to determine a ductility coefficient (m) from analysis of the cyclic loading curve. It is then possible to calculate a ductility corrected value; $K_{Ic}^c = m \times K_{Ic}$

Cyclic Loading of the rock samples was performed under displacement control using the uniaxial loading apparatus in the UCL Rock and Ice Physics Laboratory. The sample is suspended horizontally and a 20kN load cell is used to move the upper jaw, loading perpendicular to the plane of the chevron.



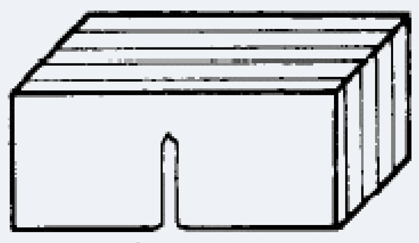


Cyclic Loading curve for Darley Dale Sandstone. Cycles become increasingly broad as the rock is damaged, due to deviation from linear elastic behaviour.

3. Anisotropic Fracture Toughness Results

The three principle Mode-I fracture orientations considered represent fractures propagating in different directions relative to the bedding planes.

Divider

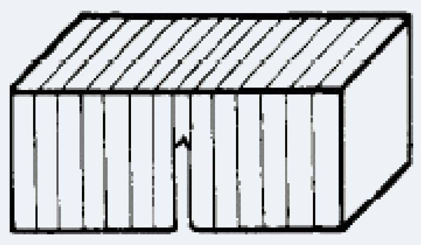


$K_{Ic} = 0.41 \pm 0.12\mathrm{MPa.m}^{\frac{1}{2}}$

$K_{Ic}^c = 0.81 \pm 0.13\mathrm{MPa.m}^{\frac{1}{2}}$

K_{Ic}, K_{Ic}^c and the loading curve are very repeatable. m is much higher than for other rocks in the published literature.

Short-Transverse

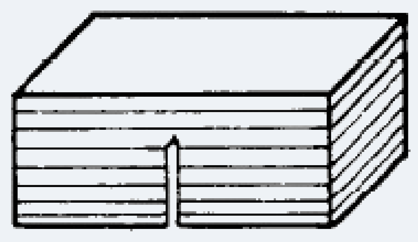


$K_{Ic} = 0.36 \pm 0.27\mathrm{MPa.m}^{\frac{1}{2}}$

$K_{Ic}^c = 0.65 \pm 0.37\mathrm{MPa.m}^{\frac{1}{2}}$

Large variations between values and loading curves depending on which bed the fracture propagates through.

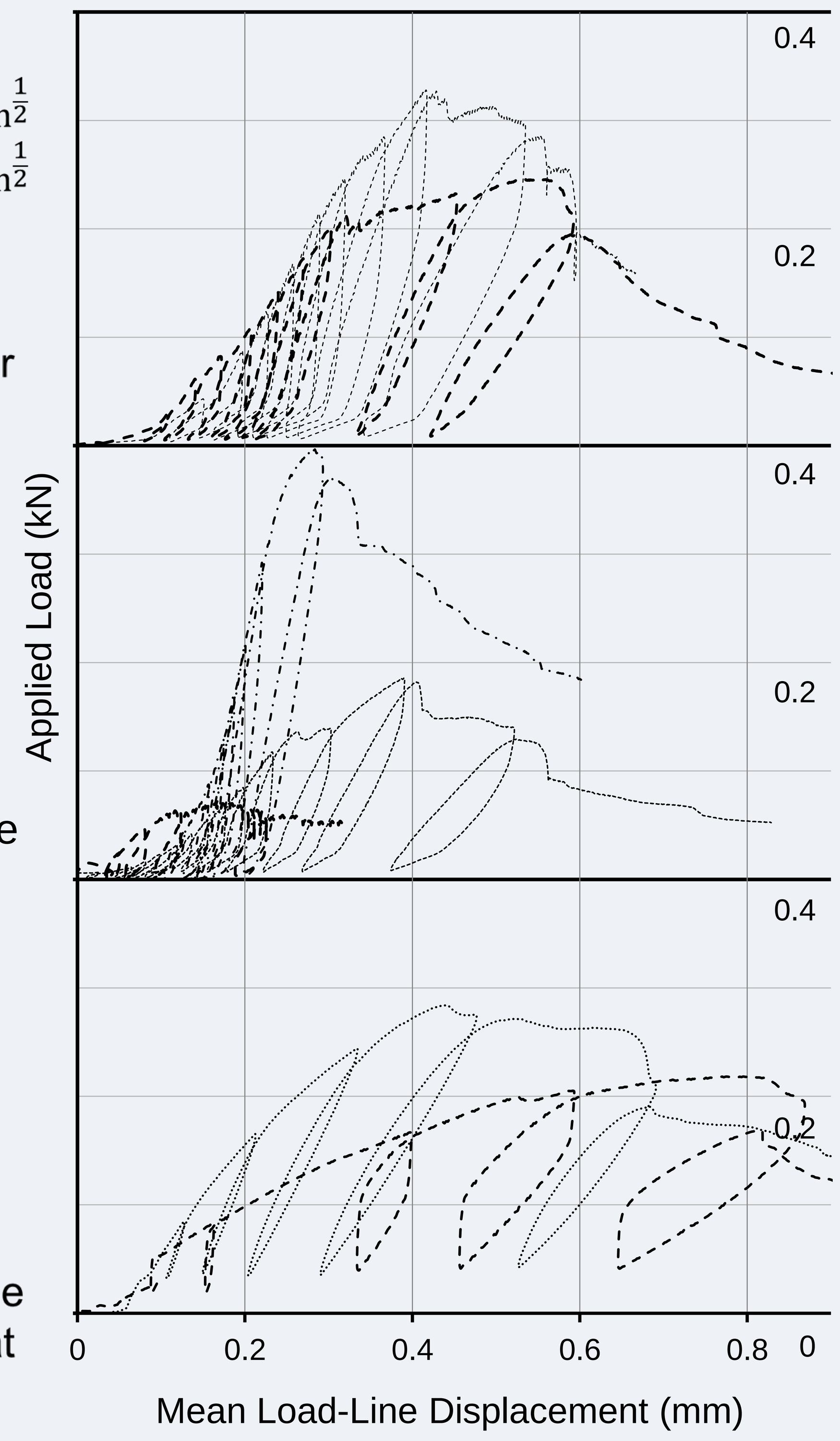
Arrester



$K_{Ic} = 0.44 \pm 0.07\mathrm{MPa.m}^{\frac{1}{2}}$

$K_{Ic}^c = 0.65 \pm 0.16\mathrm{MPa.m}^{\frac{1}{2}}$

Relatively constant maximum load and K_{Ic}values. Loading curves vary because the crack front is only acting against one bed at a time.



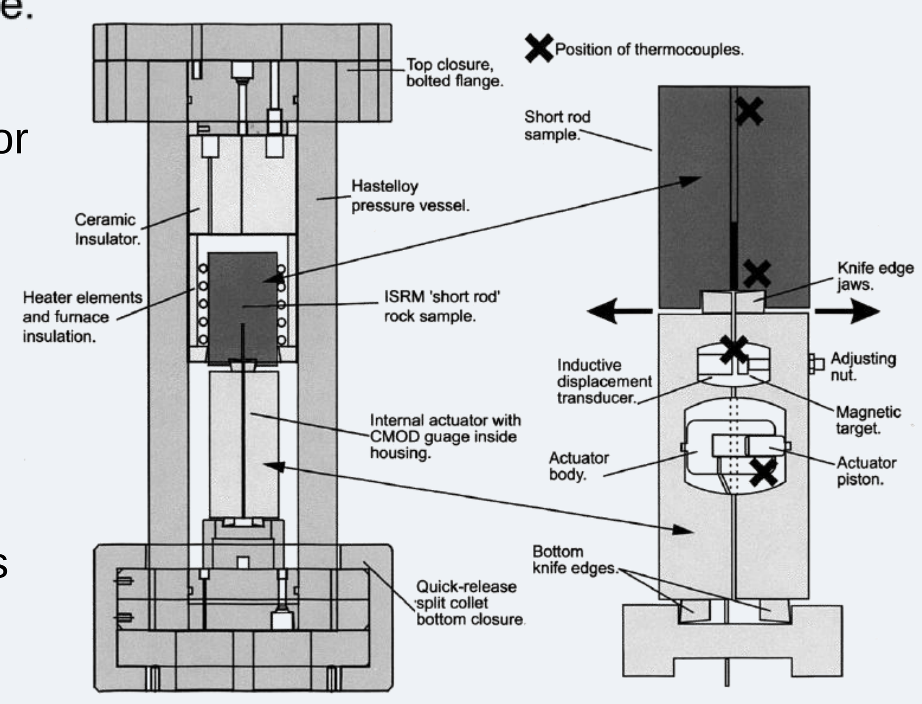
The consistently high m values across all orientations of the Mancos Shale imply an extremely non-linear material, but the K_{Ic}^c values themselves are not substantially lower than for many sandstone rocks. The anisotropy observed in K_{Ic}^c confirms that at ambient conditions, a fracture would be likely to propagate along the bedding planes in the Short-Transverse orientation.

4. Elevated Pressure Results

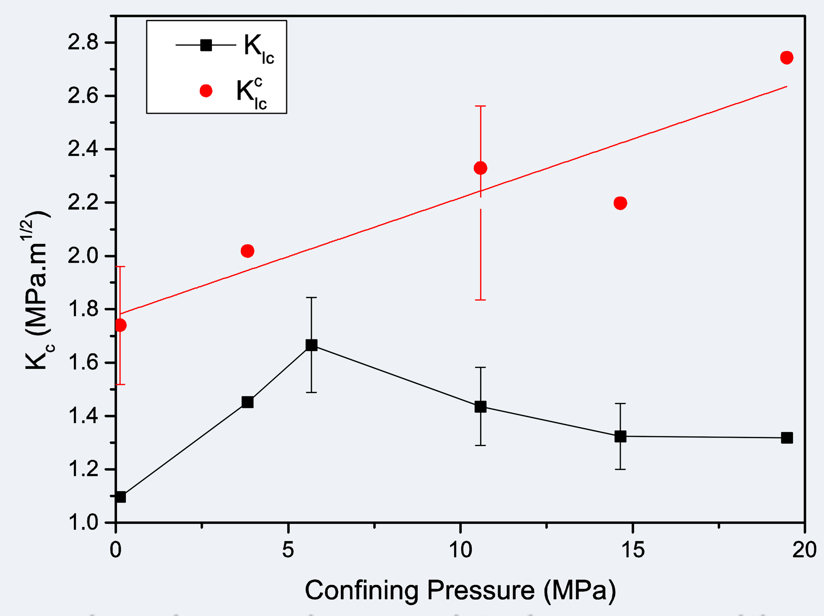
Initial measurements have been of K_{Ic} as a function of confining-pressure using UCL's High-Pressure Fracture Toughness Cell for Purbeck Limestone and Darley-Dale Sandstone. Confining Pressures up to 20MPa have been tested so far, with the intention of conducting further measurements up to 35MPa. The Short-Rod sample is coated in latex so that the confining fluid cannot access the crack itself, or equilibriate with the pore-pressure within the sample.

UCL's High-Pressure Fracture Toughness Cell uses an internal actuator within a split-cylinder housing, because an external load cannot be allowed to penetrate into the pressurised vessel. The actuator forces the cylinder apart, forcing knife-edges into the lips of the sample.

An inductive displacement transducer is used to monitor the crack-mouth opening displacement.



(Figure Modified After Balme et al., 2004)



For Purbeck Limestone, K_{Ic} is seen to increase by ~50% for even a very low applied confining pressure, before falling to around 130% of it's initial value and levelling off.

For Darley-Dale Sandstone, K_{Ic} is seen to increase by around 15% at a confining pressure of 10MPa.

K_{Ic} has been observed to increase with confining pressure by other authors, although in most cases the increase is seen to be linear with increasing pressure. A notable exception is the work of *Balme et al., 2004* who observed a similar initial increase followed by a plateau in heat-treated Icelandic Basalt.

The closure of naturally occurring microcracks is one suggested cause of the increase in K_{Ic} with confining pressure. This would suggest that by the confining pressure at which K_{Ic} begins to plateau, all microcracks have been closed.

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