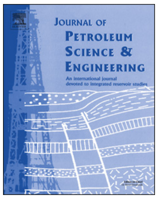
Journal of Petroleum Science and Engineering 143 (2016) 158–170

Contents lists available at ScienceDirect

Journal of Petroleum Science and Engineering

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



The brittleness indices used in rock mechanics and their application in shale hydraulic fracturing: A review

Decheng Zhang, P.G. Ranjith*, M.S.A. Perera

Deep Earth Energy Laboratory, Department of Civil Engineering, Monash University, Building 60, Melbourne, Victoria 3800, Australia

A R T I C L E I N F O

Article history:
Received 30 June 2015
Received in revised form
4 February 2016
Accepted 16 February 2016
Available online 17 February 2016

Keywords:
Shale gas recovery
Hydraulic fracking
Brittleness index
Field application

A B S T R A C T

Brittleness is commonly used to characterize the possible failure features in rocks, quantified by the brittleness index (*BI*(26)*BIs*, the applicability of each *BI* should be well understood to enable the selection of the most suitable for each application. This study reports on a detailed review of existing *BI* definitions in the rock mechanics field, the transition from brittle to ductile and the application of *BIs* to shale fracturing.

The success of shale gas recovery using hydraulic fracking is greatly dependent on the shale's brittleness, since brittle shales have many pre-existing fractures and are easy to fracture in tensile and shear modes. A combination of laboratory and geophysical approaches are recommended for shale brittleness quantification. Precise quantification of brittleness is important, both in the laboratory and the field. Brittleness indices based on the elastic moduli (Young's modulus and Poisson's ratio) and mineral composition are common in field applications, and can be derived from both laboratory tests and field log data.

1. Introduction

Brittleness is a term commonly used in rock engineering applications to identify the possible failure characteristics of the rock mass. To date, different researchers have proposed various expressions to quantify rock brittleness based on various concepts, taking different influencing factors into consideration, including mineral composition, in-situ stress, and strength parameters. The reliability of each index is dependent on the use of the appropriate approach for the required purpose. Researchers have defined brittleness in various ways, including lack of ductility (Morley, 1944; Hetényi, 1950), destruction of internal cohesion (Ramsey, 1968), fracture failure at or slightly beyond the yield stress (Obert and Duvall, 1967), rock material rupture/fracture with small/no plastic flow (Howell, 1960), or a self-sustaining failure process (Tarasov and Potvin, 2013). In general, brittle rocks are subjected to sudden failure with the occurrence of tensile/shear fractures, creating a large strength drop with small inelastic strain. In contrast, ductile rocks undergo a large inelastic deformation before failure. According to existing studies (Hucka and Das, 1974; Hajiabdolmajid and Kaiser, 2003; Nygård et al., 2006; Jarvie et al., 2007; Rickman et al., 2008; Tarasov and Potvin, 2013; Jin et al., 2014a, 2014b), brittle rocks commonly exhibit certain unique characteristics including: (1) low elongation upon load application, (2) fracture failure, where distinct failure fracture surfaces can be seen during brittle failure and such surfaces cannot be seen in ductile rocks upon failure, (3) comparatively greater fine particle and crack formation under load application due to cohesion loss, (4) higher resilience resulting from the larger elastic proportion, (5) higher ratio of compressive strength to tensile strength, (6) higher internal friction angles (since the internal friction angle exhibits slipping ability of fractures, high friction-angled brittle rocks have less possibility to slip along the fracture), (7) greater percentages of brittle minerals like quartz and minimal amounts of ductile minerals like clay minerals, (8) higher Young's modulus and lower Poisson's ratio values, where these terms describe the rock's ability to fail and to maintain induced fracture, respectively, (9) huge strength reduction occurs with failure, and a large gap between the peak strength and the residual strength can be seen in brittle rocks, (10) intensive failure process, where brittle rocks fail suddenly in an intensive and self-sustaining way.

Correct identification of the brittleness characteristics of the rock mass is important in many field applications, including shale gas recovery through hydraulic fracturing. The successful shale exploration experience in North America has led to a shale gas revolution in the world in recent years. However, organic-rich and fine-grained shale formations have extremely low porosity and permeability values. Therefore, the use of an appropriate permeability enhancement technique is necessary to harvest an economically viable amount of gas. Hydraulic fracturing is one such

---

* Corresponding author.
E-mail address: ranjith.pg@monash.edu (P.G. Ranjith).

http://dx.doi.org/10.1016/j.petrol.2016.02.011
0920-4105/© 2016 Elsevier B.V. All rights reserved.

technique. During the hydraulic fracturing process, a pressure fluid is injected into the shale formation to create a network of fractures, which creates connectivity among micro-pores by reopening the natural fractures and offering an easy pathway for the shale gas to move towards the wellbore. However, the possibility of creating an effective fracture network is dependent on many factors, among which the shale formation's brittleness plays a major role. This is because brittle shales can be easily fractured through tensile or shear failure modes and the induced fractures have greater potential to be kept open by proppants, which does not happen in ductile shales due to their plastic deformation characteristic that causes the fractures to heal after pressure release. This implies the importance of correct identification of the brittleness of the shale rock mass to screen fracturable candidatures.

2. Quantification of brittleness

The brittleness index (*BI*) is a term that is usually used to quantify the brittleness of rock mass. To date, many different expressions for *BI* have been proposed using various approaches and considering different characteristics of brittle performance (Hucka and Das, 1974; Altindag, 2002; Hajiabdolmajid et al., 2003; Nygård et al., 2006; Rickman et al., 2008; Yagiz, 2009; Holt et al., 2011; Tarasov and Potvin, 2013; Jin et al., 2014a, 2014b). This study considers the *BI* definitions that have been proposed based on the following approaches: stress–strain curve; unconfined compressive strength and Brazilian tensile strength; penetration, impact or hardness tests; mineral composition, porosity and grain size; and geophysical method.

2.1. Stress–strain curve parameters approach

2.1.1. Stress- or strain-based analysis

The use of stress–strain curves to determine strength parameters is common in rock mechanics. The approach can be applied to quantify the brittleness of any rock mass, because the brittle behaviour of any rock mass is exhibited by its strength and deformation performance under stress. The *BI* can be easily derived from the shape of these stress–strain curves. Brittle rocks fail generating only a small strain, mostly in the elastic region, while ductile rocks undergo a large inelastic (plastic) strain without losing their bearing capability before failure. Careful consideration of these two kinds of failures shows the possibility of using the ratio of elastic strain to total strain ratio as an indicator to quantify rock brittleness (Eq. (1)), where a higher ratio corresponds to a greater *BI*.

$$BI_1 = \varepsilon_{el}/\varepsilon_{tot} \tag{1}$$

where ε_{el} is the elastic (recoverable) strain and ε_{tot} is the total strain at failure. This ratio can be easily predicted using the stress–strain curve (Fig. 1). If a line (CE) is drawn through the failure or peak point (C) parallel to the linear part of the stress–strain curve (AB), the BI_1 ratio will be equal to the horizontal projections of that line (EF) and the curve up to peak load (OF), as these will be equal to the elastic and total strain at failure, respectively.

If the energy aspects at failure are considered, *BI* can be given as a ratio between elastic energy and total energy at failure (Hucka and Das, 1974), which is equal to the area ratio between the CEF and OABCF in Fig. 1. This definition can be used to identify the energy aspects of elastic and inelastic deformation. For example, ductile rocks have smaller BI_2 values as they continuously absorb energy in their long plastic deformation before failure.

$$BI_2 = W_{el}/W_{tot} \tag{2}$$

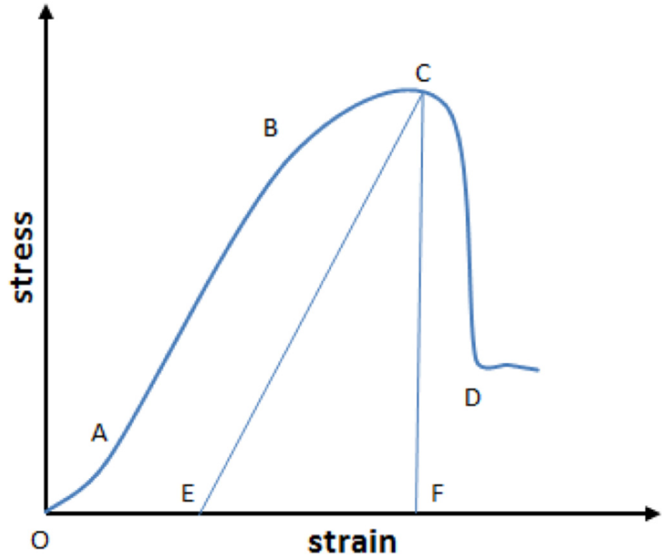


Fig. 1. Typical stress–strain curve for brittle rocks.

where W_{el} is the elastic energy at failure, and W_{tot} is the total energy at failure.

When rocks are subjected to axial loads, inelastic or plastic deformation is characterised by irreversible longitudinal strain, which can be used to quantify the brittleness (Andreev, 1995). According to Andreev, absolute irreversible longitudinal strain can be used to identify the brittleness of rock, as brittle rocks have $\varepsilon_{li} < 3\%$, ductile rocks have $\varepsilon_{li} > 5\%$ and rocks in the brittle-ductile transition stage have $3\% < \varepsilon_{li} < 5\%$.

$$BI_3 = \varepsilon_{li} * 100 \tag{3}$$

Bishop (1967) proposed an equation for the brittleness index (Eq. (4)) considering the nature of possible shear failures in brittle and ductile rocks upon load application, because shear–dominant failure is very common in rock failure under triaxial stress conditions. Brittle rock usually fails suddenly with a significant reduction in its shear strength (this is indicated by the large gap between rock strength at points C and D in Fig. 1), and ductile rocks exhibit much gentler strength reduction upon load application.

$$BI_4 = \frac{\tau_p - \tau_r}{\tau_p} \tag{4}$$

where BI_4 is the shear strength-based brittleness index, τ_p is the peak shear strength and τ_r is the residual shear strength.

Although brittle materials are generally subjected to macro-scale failure due to their sudden and huge strength reduction beyond the peak strength, this is entirely dependent on the applied confining stress condition, because this sudden strength reduction is reduced with the increasing confining stress and therefore even brittle rocks can exhibit ductile failure under high confinements (Holt et al., 2011; Yang et al., 2013). Such rock behaviours indicate the importance of considering the confining stress effect when quantifying their brittleness, possibly by incorporating the strain performance during load application. Although Eq. (4) reflects a post-failure behaviour, it considers only the strength behaviour and the corresponding strain performance is ignored. Such a relationship does not really show the stress path effect or the strains at corresponding strength points (Hajiabdolmajid and Kaiser, 2003). For example, although the two rocks shown in Fig. 2 have the same BI_4 values as they have the same peak and residual stresses, the shapes of the stress paths are quite different, due to their distinguishing pre- and post-peak stress–strain processes.