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Crack initiation stress in low porosity crystalline and sedimentary rocks

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ABSTRACT

The stress–strain data from 376 laboratory tests carried out on samples of igneous, sedimentary and metamorphic rocks were analyzed to establish the onset of microcracking in compression, referred to as the Crack Initiation (CI) stress. A statistical approach was used to find the geological parameters influencing crack initiation stress. Among various rock properties such as grain size and mineralogy, the proportion of the hardest constituent mineral were found to correlate with CI stress. Foliation induced anisotropy was found to affect the peak strength but its effect on CI stress was less pronounced. The CI stress to peak stress ratio ranged from 0.42 to 0.47 regardless of the material properties in uniaxial compression whereas this ratio ranged from 0.50 to 0.54 when confined. The crack initiation parameters for the Hoek–Brown spalling criterion for igneous rocks can be expressed in terms of the CI stress ratio and the tensile strength. A comparison of tensile strength from the Brazilian and Direct tension tests showed that the Direct tensile strength was approximately 0.77 of the Brazilian tensile strength.

1. Introduction

It is well known that the operational strengths of soils and rocks that are back calculated from case histories seldom match laboratory peak strength values. The reasons put forward for this discrepancy vary from (1) rate effects, i.e., loading rate in the laboratory is different from that in situ (Lavrov, 2001), (2) scale effects, i.e., the strength in-situ decreases with increasing scale, with the lab strength representing the maximum strength (Hoek and Brown, 1980), and (3) process effects, i.e., the laboratory sample is tested using loading conditions that do not reflect the loading process followed in-situ (Holcomb, 1993). In brittle rock, the failure process in laboratory samples is a progressive process requiring the initiation, growth and coalescence of cracks (Lockner, 1993; Thompson et al., 2006). This process has also been observed in-situ around underground excavations using microseismic monitoring systems (Collins and Young, 2000). Several researchers have suggested that the crack initiation observed in laboratory compression tests provides a good estimate of the operational spalling strength observed in hard brittle rocks around underground openings (Martin, 1997; Diederichs, 2007; Andersson and Martin, 2009; Martin and Christiansson, 2009; Rojat et al., 2009). More recently Damjanac and Fairhurst (2010) suggested that crack initiation may also be used as a lower bound estimate for the long-term strength threshold of crystalline rocks. Other researchers suggest that crack initiation related to the Kaiser effect can be used to establish the in-situ state of stress. Hence there is ample evidence that crack initiation in compression testing may be an important parameter.

The early work of Brace et al. (1966) showed that crack initiation in laboratory samples was coincident with dilatancy measured using volumetric strain and that the crack initiation for granite, marble and aplite occurred between 0.3 and 0.7 of the peak strength. Brace et al. (1966) also compiled results for dolomite, soapstone, diabase, olivine basalt, quartzite and concrete, and found similar crack initiation values ranging from 0.35 to 0.6 of the peak strength. The ratio of crack initiation stress to peak strength appeared narrowly constrained despite the range in rock types. Despite this early work determination of crack initiation from laboratory tests is seldom reported in the literature. In this paper we examine crack initiation in uniaxial compression and triaxial compressions tests in igneous, metamorphic and sedimentary rocks. A total of 336 tests were evaluated and used to examine the effect of mineralogy, anisotropy, grain size and confinement on crack initiation. The Griffith criterion is often considered as a crack initiation criterion (Hoek and Bieniawski, 1966). The tensile strength measured on a suite of Lac du Bonnet samples is used to examine if the Griffith or Hoek–Brown criteria can be used to predict crack initiation over a confining stress ranging up to 60 MPa.

2. Sample description

2.1. Igneous rocks

The igneous samples were obtained by the Swedish Nuclear Fuel and Waste Management Co. (SKB) during their site investigation of the Forsmark and Laxemar–Simpevarp area between 2002 and 2007. All samples were obtained using triple tube core barrels, which produced a 50.6-mm-diameter core. The Forsmark site is located within the municipality of Östhammar about 150 km north of Stockholm, Sweden (Stephen, 2010) while Laxemar–Simpevarp is situated in Småland in

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the south-eastern part of Sweden and 230 km south of Stockholm. Both sites are located in geology that is considered typical of the Precambrian Scandinavian Shield. In summary, Forsmark site rock types are meta-intrusive bodies that are located at the south-western part of Fennoscandian Shield. The bedrock is classified into four rock units based on their mineralogy, grain size and relative age that ranged from meta-granite or meta-granodiorite to tonalite. More detailed description of the bedrock geology can be found in Stephen et al. (2007).

The bedrock at the Laxemar–Simpevarp site was dated at 1.8–1.9 Ga (Wahlgren, 2010). The petrology includes intrusive rocks of quartz monzodiorite, granodiorite or granite with a range of grain size and texture. The dominant rock types are medium-grained porphyritic Ävrö granite and medium grained equigranular quartz monzodiorite (Wahlgren, 2010). The modal analysis of the samples with measured uniaxial compressive strength data has been used for classification according to Quartz-Alkali Feldspar-Plagioclase (QAP) diagram (Streckeisen, 1976) and presented in Fig. 1. Based on grain size, almost all the samples that are used in this study are from fine grained to medium grained, Table 1.

The next group of samples was obtained from the site investigations for the Deep Underground Science and Engineering Laboratory (DUSEL) at the former Homestake mine in northern Black Hills of South Dakota, USA. The unconfined compression tests were performed on 50 mm diameter samples of rhyolite. The grain size data of rhyolite samples based on visual examination are considered as very fine grained which is consistent with common geological description of rhyolite (RESPEC Co, 2010). An overview of geological description of available igneous specimens is presented in Table 2.

2.2. Sedimentary rocks

The sedimentary samples have been obtained by the Nuclear Waste Management Organization (NWMO) during their site investigations for a low- to intermediate- level radioactive waste Deep Geological Repository, known as Bruce site, located near Tiverton, Ontario, Canada. The 75 mm-diameter samples were obtained from the Palaeozoic stratigraphy typical of southern Ontario (Frizzel et al., 2008). The samples tested in this paper range in lithology from shale to limestone/dolomite with various amounts of clay (mainly illite) and carbonate. The samples are very fine to fine grained according to Schandl (2009). The mineralogical descriptions of the sedimentary specimens are presented in Table 3. Samples were jacketed with heat-shrink tubing before the sample preparation to minimize the change in water content (Gorski et al., 2009a).

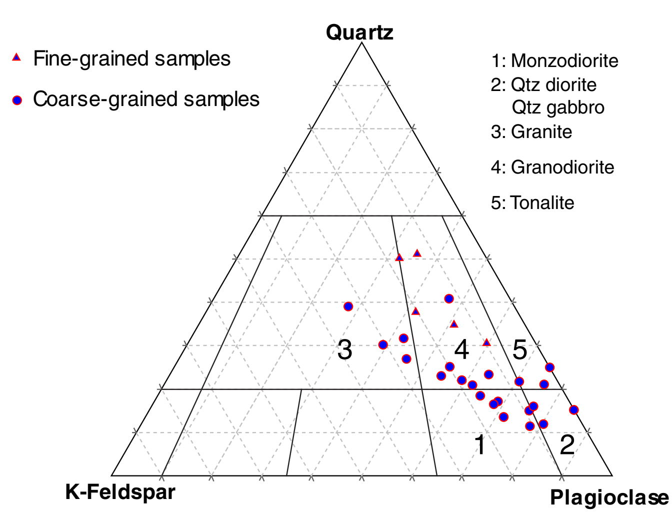

Fig. 1. Classification of igneous samples based on modal analysis.

Table 1
Grain size classification system of igneous rock samples (Strahle, 2001).

Class	Grain size (mm)
Very fine grained	0.05–0.5
Fine grained	0.5–1
Fine to medium grained	1–1.5
Medium grained	1.5–3
Medium to coarse grained	3–5
Coarse grained	>5

2.3. Metamorphic rocks

Also tested from Homestake and Forsmark were samples of amphibolite and metagranites, respectively (Table 4). The remaining metamorphic specimens tested were obtained by Posiva Oy during the site investigation at the Olkiluoto site in Finland, Posiva. The Olkiluoto site is located on the Gulf of Bothnia coast in the municipality of Eurakoki in western Finland within the Fennoscandian Shield. The study area is within the Precambrian crystalline rocks known as Svecofennian domain (Saari, 2008). The lithology of Olkiluoto is divided into two groups: (1) high-grade metamorphic rocks that are classified according to their major mineral composition, texture and migmatitic structure that was metamorphosed at 1.8 Ga, and (2) igneous rocks which are mostly diabase dykes (Lahti et al., 2010). The 57-mm diameter samples belong to the first group and include migmatite gneisses, quartz gneisses and mica gneiss. The modal analysis of metamorphic specimens is presented in Table 4.

3. Testing methodology

3.1. Testing procedure

The uniaxial compressive strength of almost all samples was measured following the ISRM Suggested Methods (Brown, 1981). The igneous rock samples from Sweden were stored in water 20 to 60 days prior to performing the test. The axial load was recorded by a load cell and the axial and circumferential deformations were recorded by displacement transducers (Jacobsson, 2006a). All tests were data logged and these stress–strain responses were used for the results discussed in this paper.

3.2. Crack initiation stress measurement

Brace et al. (1966) and Bieniawski (1967) demonstrated that the stress–strain response in both unconfined and confined tests for low porosity rocks displays four important inflections: (1) crack closure, observed in the axial strain; (2) crack initiation, observed in the lateral strain; (3) unstable crack growth, observed in the volumetric strain; and (4) peak, observed in the axial strain (see Figure 2).

The methods that researchers have used to establish the load associated with the onset of crack initiation during laboratory compression loading have relied primarily on the measured strains. The methods utilized either the volumetric strain or the lateral strain (Brace et al, 1966; Bieniawski, 1967; Lajtai, 1974; Stacey, 1981), and have been modified by various researchers (Martin and Chandler, 1994; Diederichs, 2007) and at times augmented by acoustic emission techniques (Eberhardt et al, 1998). More recently, a new technique was introduced by Nicksiar and Martin (2012) that relies on the Lateral Strain Response (LSR). Briefly, in the LSR method the change in recorded lateral strain relative to a reference line is used to calculate lateral strain difference value. The crack initiation stress is determined by fitting a best-fitted parabola and selecting the stress associated with maximum strain difference (Figure 3). All the previous methods were reviewed by Nicksiar and Martin (2012) who showed using 10 samples of Äspö diorite that any of the strain methods provided statistically accurate results.