Determination of the fracture toughness of a saturated soft rock

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Although the literature provides a reasonable range of information concerning the fracture toughness of relatively hard rocks, there is virtually no data for saturated soft rocks of uniaxial compressive strengths less than about 10 MPa. To gain some insight into the plane strain fracture toughness of such a soft rock for use in the numerical modelling of crack propagation during pressuremeter testing, a large number of laboratory tests were conducted. The material used in these tests was a synthetic soft rock that modelled soft mudstone rocks reasonably accurately. This paper describes the test techniques adopted and the results obtained. The variation of fracture toughness with loading rate and with size and shape of the test specimens is presented and discussed. On the basis of these results, guidelines are suggested for the determination of plane strain fracture toughness of a soft rock.

Key words: fracture mechanics, fracture toughness, laboratory testing, soft rock, weak rock.

Quoique la littérature fournisse une quantité raisonnable d'information concernant la tenacité de fracture des roches relativement dures il n'existe à toute fin utile aucune donnée pour les roches molles saturées ayant des résistances en compression uniaxiale inférieures à environ 10 MPa. Afin d'avoir un aperçu de la dureté de fracture en déformation plane de telles roches molles pour les fins d'un modèle numérique de propagation des fissures dans l'essai au pressiomètre, un grand nombre d'essais de laboratoire a été réalisé. Le matériau utilisé dans ces essais était une roche molle synthétique modelant les mudstones de façon raisonnablement exacte. Cet article décrit les techniques adoptées et les résultats obtenus. La variation de la tenacité de fracture avec la vitesse de chargement et avec la dimension et la forme des spécimens d'essais est présentée et discutée. En partant des résultats, des règles sont suggérées pour la détermination de la tenacité de fracture en déformation plane de la roche molle.

Mots clés : mécanique des fractures, tenacité de fracture, essai de laboratoire, roche molle, roche de faible résistance.

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Introduction

Recent studies into the performance of the pressuremeter test in soft rock of uniaxial compressive strengths of less than 10 MPa (Haberfield and Johnston 1986, 1989; Haberfield 1987) have revealed that an extensive pattern of radial cracking may form at the borehole wall and propagate into the body of the soft rock. These radial cracks are a direct consequence of the relatively high tensile circumferential stresses induced around the pressuremeter probe as it is expanded. As these radial cracks can dramatically influence the pressure–expansion response curves, it was concluded that the effects of cracking must be included in the analysis of the pressuremeter if relevant engineering properties are to be derived. However, because of the complexity of the boundary conditions and failure mechanisms involved with the expansion of a pressuremeter in soft rock, it was necessary to adopt a numerical technique, such as the finite element method, to obtain a satisfactory model for the solution of the problem.

In the past, geotechnical engineers have employed the rather simplistic approach of incorporating a limited tension formulation (i.e., a tension cut-off model) similar to that suggested by Zienkiewicz *et al.* (1968) to model tensile failure. Although this approach may simplify programming, it fails to provide an accurate model of crack propagation (Haberfield 1987). Such a model is only capable of predicting the onset of catastrophic tensile failure, such as occurs during direct tensile strength tests, and cannot model the gradual propagation of tensile cracks and their influence on the pressure–expansion response of a pressuremeter. A more appropriate approach for the modelling of crack propagation may be obtained with fracture mechanics theory and, in particular, linear elastic fracture mechanics (LEFM) (e.g., Ingraffea 1985).

To apply these methods to a particular material, it is necessary to define the fracture toughness of the material. Unfortunately, although there is a range of published data concerning the fracture toughness of relatively hard rocks (e.g., in Atkinson 1987), there is virtually no data available for saturated soft rocks, particularly those with a uniaxial compressive strength less than about 10 MPa. Therefore, since it is these types of rock that were of particular interest to the authors and their investigation into pressuremeter behaviour, a series of tests were carried out to quantify the mode 1 fracture toughness of a saturated soft rock under drained conditions, with particular reference to strain rate dependency and specimen size and shape. It should be noted that the tests were conducted under fully drained conditions in order to be representative of the behaviour of a soft rock when it is tested by a pressuremeter (Ameratunga 1986; Haberfield 1987).

Application of LEFM to geomaterials

Although fracture mechanics theory has been used extensively in hard rock mechanics, it is only recently that it has gained some acceptance in the soft rock and soil mechanics fields. Therefore, to ensure that the reader has at least a basic knowledge of fracture mechanics theory, a short, simplified description of the application of LEFM to geomaterials is included below. A much more detailed insight into fracture mechanics theory may be found in works such as Atkinson (1987).

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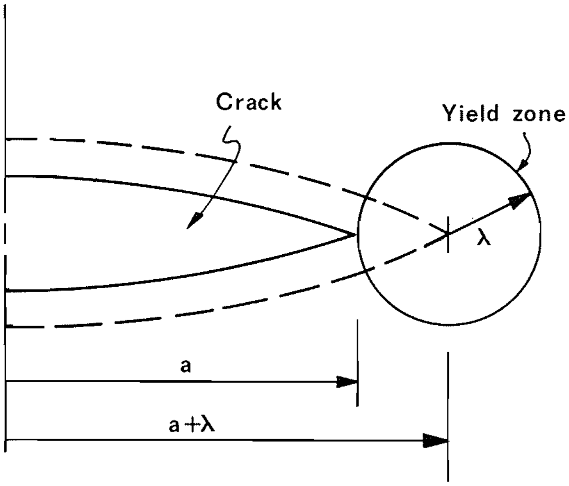

FIG. 1. Crack tip yield zone.

LEFM basically involves the determination of the magnitude of the singularity at a crack tip in an elastic body. This value is called the stress intensity factor and is usually denoted by K. The stress intensity factor is a function of the mode of stress application, the crack and body geometry, and the stress in the vicinity of the crack tip. If the stress intensity factor is larger than a critical stress intensity factor, K_C, then the crack will propagate.

This critical stress intensity factor is a property of the intact material and is a measure of the material's resistance to fracture. This property is also referred to as the fracture toughness of the material. Clearly, then, to model crack propagation it is necessary to determine the fracture toughness of the material. This can be achieved by conducting tests on initially cracked specimens and deriving the critical stress intensity factor or fracture toughness from the point at which the specimen fails.

A significant problem associated with the application of LEFM to rock (as well as other materials) arises from the inability of the rock to remain elastic throughout loading. The very high stresses that occur at the crack tip cause the rock to yield locally to form a crack tip yield zone. Figure 1 shows this yield zone as a circular area of radius λ. The performance of a cracked specimen depends on the size and shape of this crack tip yield zone with respect to the overall dimensions of the specimen. If the yield zone is small compared with the size of the specimen, then the effect of a yield zone is also small and the specimen may be considered as behaving elastically. However, as the crack tip yield zone increases in size, relative to the size of the specimen, more of the specimen will be behaving inelastically, and the assumption of linear elasticity becomes increasingly questionable.

A direct implication of the above is that fracture toughness tests can be size dependent. Therefore, it is important to test specimens of size sufficiently large that mainly elastic behaviour is involved and a reasonably constant fracture toughness is measured. This constant value of fracture toughness is called the plane strain fracture toughness, K_{IC}, and it is this value that is applicable to LEFM as it applies to modelling pressuremeter response.

Although the form of the crack tip yield zone is unknown, several models have been suggested, for example, Irwin (1958), Dugdale (1960), and Barenblatt (1962) for metals, and Schmidt (1980) and Labuz *et al.* (1985) for rocks. All these models postulate that the size and shape of the yield zone depend on the magnitude of the stress intensity factor at the crack tip and the tensile strength of the material. In particular, they all propose that the size of the crack tip yield zone, defined as radius λ in Fig. 1, is directly proportional to the square of the ratio of the plane strain fracture toughness to the tensile strength, that is

$$[1] \quad \lambda \propto \left(\frac{K_{IC}}{\sigma_t}\right)^2$$

These models also propose that the formation of the crack tip yield zone effectively increases the crack length from a to $a + \lambda$ as shown in Fig. 1. The influence of this crack length extension on the results of fracture toughness tests will be discussed later.

TABLE 1. Typical properties of the synthetic soft rock

Property	Saturated water content (%): 11	15	21
Uniaxial compressive strength (MPa)	8	4	1.5
Young's modulus (MPa)	800	400	100
Poisson's ratio	0.25	0.25	0.35
Cohesion (MPa)	2.0	1.0	0.5
Peak friction angle (deg)	36	32	28
Residual friction angle (deg)	23	23	23
Peak dilation angle (deg)	12	9	6
Tensile strength (MPa)	0.9	0.6	0.3

Test material

The authors and their colleagues have been investigating the behaviour of soft rocks for several years. The early experimental studies carried out on naturally occurring rock, although very useful for establishing general patterns of behaviour, produced results that displayed a significant scatter This scatter complicated the interpretation of the results and, consequently, it was often very difficult to obtain sufficiently accurate or reliable data with which to validate analytical or numerical models. To overcome the problems of inherent variability, a synthetic soft rock was developed. This material is homogeneous and isotropic, and may be reproduced simply and reliably with a range of selected properties. These properties are similar to those of naturally occurring soft mudstone rocks, and can be controlled and accurately determined. In addition, the synthetic rock can be cast or machined into a wide variety of shapes and sizes to suit specific applications.

The synthetic rock is formed from a specific mixture of mudstone powder of a prescribed grain-size distribution and a small quantity of cement, water, and set accelerator. The mixture is placed in a mould and is compressed under load allowing full dissipation of excess pore-water pressures. Once equilibrium is attained, the load is removed and the mould is stripped. The resulting specimen is then allowed to cure for at least 3 weeks, after which the material properties become constant.

The stress applied during the compression process determines the final properties of the synthetic rock, with the