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Failure of transversely isotropic rock under Brazilian test conditions

André Vervoort [a,*], Ki-Bok Min [b], Heinz Konietzky [c], Jung-Woo Cho [d], Bjorn Debecker [a], Quoc-Dan Dinh [c], Thomas Frühwirt [c], Abbass Tavallali [a]

[a] *Department of Civil Engineering, KU Leuven, Leuven, Belgium*
[b] *Department of Energy Resources Engineering, Seoul National University, Republic of Korea*
[c] *TU Bergakademie Freiberg, Freiberg, Germany*
[d] *Mechatronics Research Group, Korea Institute of Industrial Technology, Republic of Korea*

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ABSTRACT

The behavior of transversely isotropic rock material was studied under Brazilian test conditions for nine different rocks (two sandstones, one shale, two slates, one schist, and three gneiss). Both the variation of the strength and the final fracture patterns induced by testing were examined as a function of the inclination angle of the weak planes. The combination of the observations for both parameters illustrated clearly the complexity of the failure of such rocks, which was summarized by assuming four different trends. The four trends for the variation of the strength as a function of the inclination angles range from little or no variation (trend 1, i.e., isotropic behavior for strength) to a sharp decrease of the strength from very small angles onwards, followed by a leveling off (trend 4). Trend 2 is characterized by a constant value between 0° and about 45°, followed by a linear decrease, while trend 3 corresponds to a decrease of the strength over the entire interval, but a rather systematic decrease, approximating a linear variation. Different variations were observed among these four trends in terms of the relative lengths of the respective fractures along the weak planes and in any other direction. For the rocks investigated, there is a cross-over from dominant fractures in directions other than the weak planes to dominant fractures along the weak planes. For the four trends, there are systematic changes in the position of this cross-over point, i.e., on average, at about an inclination angle of 75° for trend 1 and at about 15° for trend 4. For inclination angles larger than the cross-over point, the rock specimens failed primarily by splitting between both loading lines.

1. Introduction

In recent years, there has been an increased interest in the behavior of transversely isotropic rock material [1–6]. The main reason for this is that numerous current applications deal with this type of rocks; e.g., exploitation of shale gas [7–9], drilling through shale formations in the overburden of oil and gas reservoirs [10,11], radioactive waste disposal in clay formations [12,13], development of excavation damage that occurs during underground construction [14,15], and rock-cutting performance in mechanized tunneling [16,17]. Another reason for the increased interest in transversely isotropic rock materials is that new techniques and methods have become available for conducting laboratory experiments and numerical simulations, and the behavior of these materials can be characterized more effectively than before. In recent years, several authors have successfully simulated individual fracture growth using discrete elements or other numerical codes [18–23].

The failure of transversely isotropic rock is more complex than is often assumed. First, this statement is valid for the variation of the strength as a function of the inclination angle of the plane normal to the plane of isotropy [3–5]. Second, the induced fracture patterns are complex [6,23,24]. Often, when studying failure, one considers the simplest form of transverse isotropy, i.e., planar anisotropy, in which the rock mass has a set of parallel planes of weakness [25]. In the cases of uniaxial and triaxial tests, failure occurs in the configuration along a weak plane for the interval of the weak planes angle between the friction angle and a value close to the vertical orientation of the weak planes. For this interval, the variation of the axial strength with inclination angle generally follows an upward, concave curve. For other angles, the rock fails in a different direction from that of the weak planes, and the axial strength is considered constant for these angles. A similar simple model can be considered for a Brazilian test, in which the axis of the disks is parallel to the strike of the weak planes. The specimen splits below a certain inclination angle, and thus, the fracture is independent of the weak planes. However, for

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* Corresponding author. Tel.: +32 16 321171; fax: +32 16 321976.
E-mail address: andre.vervoort@bwk.kuleuven.be (A. Vervoort).

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moderately-inclined angles, shear failure occurs along a weak plane and for very steep angles (close to 90°), the specimen splits again, but this time it splits along a weak plane. Third, the final fracture patterns are complex, both for isotropic and anisotropic rocks. This is often illustrated by recording acoustic emission during the loading and unloading of the specimen [26–29]. Development of failure in quasi-brittle materials is linked with the occurrence of micro-cracks, which release energy in the form of elastic waves (i.e., acoustic emission). At the start of the loading, the amount of hits is low and diffuse over a large part of the entire specimen. When the material's strength is approached, the acoustic emission activity increases and is mainly situated in critically stressed regions. As damage increases and peak stress is reached, a coalescence or localization of damage occurs. During unloading further damage may occur.

The objective of this paper is to report a systematic analysis on the anisotropic behaviors in strength and fracture patterns observed during Brazilian test of various rock types. In addition to compressive or shear strength, the tensile strength is a key parameter for determining, for example, the load-bearing capacity of rocks, their deformation, damage, and fracturing, and the crushing process of rocks. It is also used to analyze the stability and serviceability of rock structures. Tensile strength plays an important role because rocks are much weaker in tension than in compression. To address the complex behavior of transversely isotropic rock material, laboratory experiments were conducted with nine different rocks. The results were compared in a relatively extensive and uniform examination, even though the experiments were conducted by three different organizations. In addition to the variation of the strength, the emphasis was on the fracture patterns that were visible after loading. In this paper, the examples are limited to Brazilian tests, in which the axis of the disk was parallel to the strike of the weak planes; in other words, the specimens were tested at various angles of the plane normal to the plane of isotropy. This means that one can consider the failure as a pseudo two-dimensional process. The concept of a comparative study was developed after the three research groups had already completed their individual tests [3,4,6,23], so there are small differences in the test procedures; e.g., different diameters and different thickness-to-diameter ratios. However, in general, the ISRM suggested method [30] was followed. The dimensions of the specimens that were tested are provided in Table 1.

2. Rock materials studied

In total, nine rocks, which can be classified as transversely isotropic rock, were investigated. Each rock can be characterized by a certain degree of heterogeneity and anisotropy following its origin and geological history. Of the three basic rock classes, i.e., igneous, sedimentary, and metamorphic rocks, transverse isotropy is observed mainly among the two latter classes. Various origins of transverse isotropy are observed, including bedding, stratification, layering, foliation, fissuring, fracturing and jointing. For the class of sedimentary rocks, a layered structure is observed due to sequential sedimentation. When sedimentation takes place in distinct sequences, the layers can differ from each other in several aspects, including grain size, type of material, type of cementation, and degree of compaction [31]. The grain-size distribution mainly determines the difference between sandstone (between 0.0625 and 2 mm), siltstone (between 0.0039 and 0.0625 mm), and shale (less than 0.0039 mm). For the class of metamorphic rocks, the transversely isotropic character is caused by high stresses, often the weight of overburden. A typical example is slate or phyllite, which is formed by clay or shale being metamorphosed. In this rock, the layered structure is formed by the parallel rearrangement of the platy clay minerals so that they are orthogonal to the maximal stress direction [32]. The weak direction in such rock is called foliation, cleavage direction or schistosity. Other examples are schist and gneiss. For this class, it is typical for the material to be rather homogeneous, contrary to the heterogeneous nature of the first class. Bedding planes can still be seen in such a metamorphic layered rock. Bedding planes and schistosity can vary in direction when the bedding planes are folded due to tectonic activity, and, consequently, the orientation of the stress vector relative to the bedding plane changes. It is worthy of noting that rocks that have undergone several processes of formation may present more than one direction of planar anisotropy, as in foliation and bedding planes in slates. These directions may not necessarily be parallel to each other. In addition, linear features, such as lineations, can be superimposed on the planar features.

Table 1 lists the nine rocks under examination and gives the ratio of the strength or failure load when disk-shaped specimens were loaded both parallel to and perpendicular to the weak planes. Detailed information is provided below concerning the strength or failure loads of these rocks. Postaer Sandstone, Modave Sandstone, and Boryeong Shale belong to the class of sedimentary rocks; Mosel Slate, Herbeumont Slate, Yeoncheon Schist, Freiberger Gneiss, Leubsdorfer Gneiss, and Asan Gneiss belong to the class of metamorphic rock. A brief geological description of these nine rocks follows:

Postaer Sandstone: this is a homogeneous sandstone [33]. The fine-to-medium grains of sand have a rather uniform distribution and are bound by siliceous cement. The main constituents are quartz (about 80%) and siliceous binder (about 17%), accompanied by some accessory minerals; e.g., feldspar and heavy minerals (1–2%). Pores that have typical diameters of 0.1–0.4 mm cause their porosity to be about 2–3 vol%.

Modave Sandstone [24,34,35]: this is a typical layered sandstone. It consists predominantly of siliciclastic shelf sediments. This sandstone is characterized by numerous thin and parallel

Table 1
Brazilian type of loading: anisotropy ratio of failure load when disk was loaded parallel vs. perpendicular to weak planes (average over 3–5 specimens), arranged from large to small ratio. The dimensions of the disks are also given.

Rock	Anisotropy ratio	Average failure load for loading perpendicular to weak planes (MPa)	Average failure load for loading parallel to weak planes (MPa)	Diameter (mm)	Thickness to diameter ratio
Postaer Sandstone	1.04	3.4	3.5	50	0.5
Modave Sandstone	0.73	14.0	10.3	50	0.5
Boryeong Shale	0.66	11.4	7.5	18–22	1.0
Leubsdorfer Gneiss	0.49	17.7	8.7	50	0.5
Freiberger Gneiss	0.40	15.5	6.2	50	0.5
Asan Gneiss	0.38	22.2	8.5	18–22	1.0
Yeoncheon Schist	0.29	12.0	3.5	18–22	1.0
Mosel Slate	0.24	17.8	4.2	50	0.5
Herbeumont Slate	0.02	20.0	0.5	80 or 100	0.4