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Creep and time-dependent damage in argillaceous rocks

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Abstract

This paper presents the results of laboratory tests on the time-dependent behaviour of three rocks characterized by a high proportion of clay particles. The viscosity of these sedimentary rocks was studied under different loading conditions in uniaxial compression: static or cyclic creep tests and quasistatic tests (low-loading strain rate) were performed across various orientations of fabric planes.

The quasistatic tests showed similarities in the mechanical response of these three argillaceous rocks: a late phase of dilation and a linear development of volumetric deformation before the beginning of unstable crack propagation. The development of secondary and tertiary creep phases during the creep tests highlighted the existence of a deviatoric stress threshold, below which only primary creep is observed. Long-term creep tests also showed that the volumetric variation is not constant during the development of viscoplastic deformations.

A microstructural analysis of thin sections extracted from specimens after the tests, gave evidence of cataclastic and granular creep. Damage to the argillaceous matrix occurs and no cracks were observed in the quartz and carbonate grains. This evidence was also demonstrated for tests with loading at a high strain rate.

Finally, this study highlights the significant viscoplasticity of argillaceous rocks. The mechanical properties deteriorate rapidly when crack propagation becomes unstable and the viscoplastic strains seem to be due to clay particle slips, known as granular creep.

Keywords: Creep; Damage; Viscoplasticity; Time-dependent behaviour; Argillite; Clays

1. Introduction

The rock mass behaviour observed in underground structures occasionally shows large delayed displacements that could lead to failure. This phenomenon illustrates the long-term viscous behaviour of rocks and the progressive damage that occurs after stress redistribution around the excavated opening. Delayed failure can occur several hours or several years after the excavation. Typical storage periods of underground radioactive wastes far exceed the service life of most civil engineering underground structures. Therefore, repository projects require prediction of irreversible deformations over a large time scale (several centuries) in order to assess the extension and evolution of the Excavation Damage Zone (EDZ) around the cavity. Moreover, damage leads to a change in permeability, which may result in fluid leakage and ground contamination. In such projects, it is essential to take into account the time-dependent behaviour of the surrounding rock.

Argillaceous rocks possess some of the physical characteristics and mechanical properties essential for the formation of a natural barrier: low permeability, high creep potential and good adsorption capacity for radioactive ions. They are therefore studied as possible host layers for radioactive waste disposals. Due to their mode of formation, these sedimentary rocks also exhibit anisotropic properties that influence their deformation, strength, damage and failure behaviour.

The purpose of this experimental study is to clarify the mechanisms governing the development of delayed deformation and damage in argillaceous rocks. First, previous observations concerning time-dependent behaviour of rock are reviewed. Then, the physical properties of the rocks, the specific instrumentation of the specimens and the experimental programme are described and observations on the

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stress–strain and creep curves are presented. Finally, the change in microstructure and the development of damage are investigated.

2. Overview of previous studies

The amplitude of delayed strains depends on the material and the test conditions. More precisely, several intrinsic parameters such as mineralogy, porosity and water content, and extrinsic parameters such as deviatoric stress, strain rate, temperature and hygrometry, influence the time-dependent behaviour of rocks. Indeed, during laboratory tests on rock specimens, an increase in temperature, hygrometry or deviatoric stress increases the viscoplastic deformation amplitude [1,2].

Earlier research has shown that time-dependent behaviour of argillaceous rocks could be attributed to creep, pore-pressure dissipation, swelling and possibly electrochemical effects. Delayed deformations resulting from mechanical loading are principally studied through creep tests (deviatoric stress maintained constant over a long time period), relaxation tests (strain maintained constant with time) and monotonic quasistatic compression tests (loading at a very low strain rate).

During a constant stress test, three phases can be observed: (1) a primary creep phase, also known as transient creep, during which the strain rate decreases and the delayed deformation stabilises over a long period, (2) a secondary creep phase, or steady-state creep, during which the strain rate remains constant, and finally, (3) a tertiary creep phase characterised by an increase in strain rate due to the occurrence of progressive rock damage.

Secondary creep, which is often observed on ice, salt or metallic alloys, is rarely observed during tests on polycrystalline rocks. Some authors [3,4] have even expressed doubts as to its existence. For example, during tests performed on brittle rock, they observed a transition from primary creep to tertiary creep without any stabilisation of the strain rate.

However, results obtained from tests on other rocks have shown that the strain rate rises with the deviatoric stress [5]. A stress threshold should therefore exist below which only primary creep would develop and viscoplastic deformation would stabilise over a long time.

On the other hand, if loading is applied at a very low strain rate, the limit curve of the rock is obtained. This concept of the limit curve was first proposed by Bérest et al. [6]. It assumes that the loading strain rate is slow enough to allow the development of viscoplastic strains in real time. Theoretically, this curve is defined by the points reached at the end of creep or relaxation tests (Fig. 1). As a consequence, for low levels of deviatoric stress, the delayed deformation stabilises asymptotically to a maximum value corresponding to the deformation reached at the same level of stress on the limit curve.

For a deviatoric stress above the long-term rock strength but in very slow compression, the long-term change in

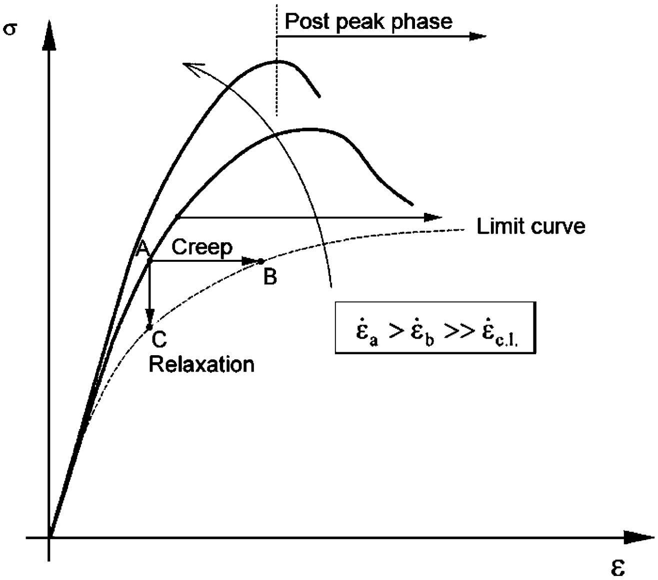

Fig. 1. The limit curve and its links with the creep path (AB) and relaxation path (AC).

deformation is no longer determined by the limit curve. This strength thus defines the stress threshold below which only the primary creep can be observed. As a first approximation, it can be assumed to be the same as the stress at the maximum contraction, σ_{cd}. Indeed, during a uniaxial compression test, σ_{cd} is defined as the stress above which the growth, coalescence and interaction of microcracks become unstable [7,8]. Martin and Chandler [9] highlighted a good correspondence between the tertiary creep threshold and the stress at maximum contraction for granite. However, this comparison does not hold true for porous rocks such as sandstone [10].

The consequence of this limit curve theory is that, in order to reach the tertiary creep phase, a high level of deviatoric stress must be applied. Some authors have shown that delayed failure can occur under lower deviatoric stress if a cyclic load is superimposed. Under cyclic loading, strain versus time curves present the same three phases of a static creep test, although failure occurs in a shorter time under the same maximum deviatoric stress [11–13]. These studies of material behaviour under cyclic loading also showed that low frequency and high amplitude cycles accelerate the development of viscoplastic strains. Moreover, Graiss et al. [14] measured a linear increase in strain rate with amplitude of the load cycles. But Scholz and Koczynski [12] concluded that the results of cyclic creep tests and static creep tests are difficult to compare as the deformation and microcracking mechanisms are different. More recently, Delfosse et al. [15] managed to obtain a quantitative correlation between the creep rate and the limit load from cyclic and static creep tests performed on grouted sand.

On an atomic scale, viscoplastic deformations are due to irreversible displacements of crystalline defects, known as dislocations [16,17]. But at ambient temperature,