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Creep properties of intact and fractured muddy siltstone

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1. Introduction

In deep underground excavation, rock mass response may be classified as time-*in*dependent or time-dependent and the material (whether it is intact or fractured) may behave elastically or may yield according to the applied stress level.[1] An understanding of the time-dependent behaviour has been considered essential for further development in the field of underground mine design and long-term strata control,[2] and more recently it has become important for the application of underground disposal of radioactive waste.[3–5]

It is generally believed in coal mines that after the initial excavation of an entry, most coal-measure rocks show time-dependent deformation, even when no activity is taking place nearby.[6] This deformation usually appears in different forms[7,8] such as roof sag, floor heave, pillar dilation, or shearing along bedding planes and joints. This rheological deformation might be followed by 'disturbance deformation', which is caused by stress changes due to mining activities in adjacent areas.[9] These physical events (observed in underground excavation) have been attributed to time-dependent characteristics, which can also be measured in a small rock sample tested in laboratory.

Conventional laboratory experiments have used three testing methods to investigate time-dependent behaviour; these are: (i) creep, (ii) relaxation and (iii) loading tests at different stress or strain rates. Creep in particular can be observed in laboratory testing when *relatively high* stress is constantly applied on a cylindrical specimen over a period of time. Fig. 1 shows an idealised creep curve which exhibits three out of four principal phases of deformations: (a) Instantaneous elastic strain due to instantaneous load; (b) Primary or transient creep with rapid strain increments, however at a decelerating strain rate; (c) Secondary creep at low, or near constant strain rate; (d) Possible tertiary creep accelerating strain increment to failure, which might take much longer time than in the lab studies.[10]

If the specimen is unloaded during the primary creep stage, the deformation can be recovered. However, permanent deformation is resulted if the secondary creep is dominated. To represent such time-dependent behaviour of rocks in mathematical form, mechanical, phenomenological or rheological models are commonly developed by fitting the experimental data[11,12] on the basis of empirically observed internal variables[13] or the superposition of several vicious and elastic elements such as the Burgers body model.[14]

Extensive creep testing has been conducted on coal-measure rocks around the mid of last century. In early studies (prior to 1964), the majority of the time-strain experiments were carried out in uniaxial compression, at room temperature and, for periods of less than a week.[15–18] These studies have been mostly carried out on intact rock samples. However, the time-dependent behaviour of fractured rock represents an important condition of rock mass. Larson and Wade[19] indicated that creep in brittle coal measure rock occurs, likely, because of (i) micro-cracking along weak bedding planes and (ii) weakening of asperities of joints. Therefore creep along bedding plan and pre-existed joints is also important. This has been investigated in a number of studies as explained below. Höwing and Kutter[20] conducted direct-shear tests to investigate the effects of joint filler on creep behaviour. In this study, creep velocity during the primary phase has followed a power law, up to the point where creep progressed from the primary to the tertiary phase.

Clean joints have been investigated in uniaxial and triaxial compression tests on intact and jointed rock specimens of Westerly Granite and Navaho Sandstone.[21] The study has shown that creep behaviour of jointed rock has a similar character as that of the intact material, but with a larger amount of strain. Larson and Wade[19] investigated friction and creep characteristics of weak planes in mudstone by conducting direct-shear creep tests; non-linear rheological model[22] has been used to fit their experimental data.

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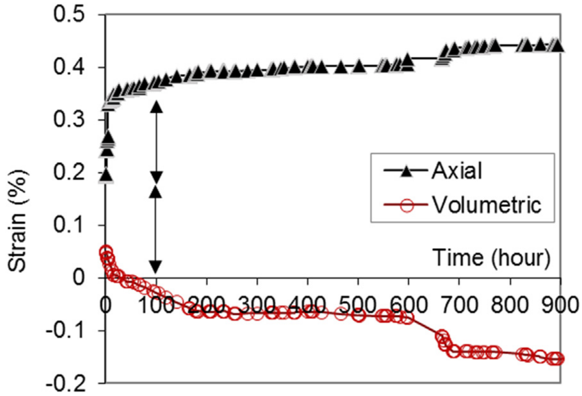

Fig. 1. Axial and volumetric strain curves for Lea Hall Sandstone under 35.8 MPa uniaxial stress showing three stages of creep (after Hobbs[25]).

More recently, a microcrack-based damage constitutive law, established at the elemental scale, has been used to directly link the time-dependent degradation of elastic stiffness and the induced anisotropy to microcrack propagation.[23] Although this model is an attractive solution to reproduce the macroscopic creep behaviour on the basis of the microscopic kinetics of microcrack growth, the model requires proper calibration in order to obtain reliable results. Therefore, it appears that phenomenological and empirical approaches might still be good alternative ways and therefore they were adopted in this study to characterise and compare the rheological behaviour of all rock samples tested.

Although extensive research has been conducted on creep of intact as well as jointed rocks, very limited studies exist which investigate both conditions for the same type of rock. In a previous laboratory work,[24] it has been found that the effect of strain rate on broken rock samples can be significantly greater than that of the intact rock samples (depending on the confinement), indicating that the ability of rock to relax or creep considerably increases in fractured rocks. Despite this difference, a similar phenomenological model has been successfully used[24] to represent the effect of strain rate on strength and stiffness of both intact and fractured silty mudstone. It follows that other time-dependent behaviours such as creep can be modelled for both intact and fractured rock using a similar phenomenological approach such as the Burgers creep model. Furthermore, the creep model parameters might have a certain pattern of correlation between the intact and fractured rocks. These aspects were investigated in this paper using laboratory experiments conducted on small-scale samples of intact and fractured muddy siltstone. The study can improve our understanding of the rheological properties of argillaceous rocks particularly at pre and post-failure conditions generated by mining activities; it also provides a good basis to enhance geotechnical modelling of long-term stability of deep underground openings, which is significant for many engineering applications such as mining and petroleum engineering, and safety assessment of radioactive waste disposal.

2. Experimental method

2.1. Materials and apparatus

The rock material selected for the laboratory experiments was obtained from an open pit mine located at Arkwright in the Midlands of the UK. The recovered rock consists of laminated muddy siltstone (also described as silty mudstone in places) which is grey in colour with darker bands. The rock has a dry density of 2.48 ± 0.01 g/cm^3 and specific gravity of approximately 2.75. To reduce any possible variability in the mechanical properties, the samples were cored from carefully selected similar blocks, which were mostly dominated by a similar angle of lamination (i.e. 0–7° to the horizon of specimen flat surface). After coring, the rock samples were left to dry out for 24 h at 100 °C and then coated with a very thin layer of flexible varnish to eliminate the effect of humidity so that the unweathered condition of the material would be maintained over the storing and testing periods.

The tests were conducted at room temperature (20 ± 1.5 °C) on cylindrical dry samples of 74 mm in height and 36 mm in diameter, which were prepared following the procedures outlined by ISRM (1981). A total of 14 out of 16 samples of the muddy siltstone were successfully tested and reported in this paper.

Before conducting the creep experiments, six samples were initially tested to obtain the instantaneous strength and stiffness of the intact and fractured rock at different confining pressures. The experiments were conducted using uniaxial compression test as well as multistage triaxial testing technique (MSTT). The MSTT technique enables experimenters to conserve samples and to obtain more consistent strength and stiffness data by eliminating sample variability. Loading on samples was carried out at a strain rate equal to approximately 10^{-5} s^{-1}.

The remaining eight rock samples (i.e. four intact and four fractured) were used for creep tests conducted under uniaxial and multistage triaxial loading conditions, where a constant axial stress σ_1 was applied and maintained by a servo-controlled rig machine. The equipment is perfectly suitable for conducting uniaxial creep compression tests; however, the required triaxial loading condition was achieved by confining the sample using a Hoek cell connected to a manual pump. This equipment can maintain constant confining pressure throughout the test. The axial displacement was measured by a high precision displacement gauge, and the recorded deformation was corrected for the stress effect on the steel Platens used for the application of axial stress.

The fractured rock samples were produced from the intact rock samples after bringing them to failure in conventional triaxial compression tests. A similar pattern of fractures was noticed in which rock samples developed a major shear plane at about 45° from horizontal. It is important to clarify that the fractures considered in the study are limited to shear failure surface generated by compression effect. A future study might be conducted on rock fractures generated by tensile failure.

After creating the failed (fractured) specimens, they were then used to carry out multistage creep testing with the prescribed confining pressure σ_3 (ranging between 1 and 6 MPa). Larger values of confining pressure would have allowed a better investigation of the triaxial creep behaviour. However, the chosen range was based on the best performance of the equipment used in the experimental programme.

2.2. Secondary creep strain

Secondary or Steady State (SS) creep strain rate (see Fig. 1) is an important parameter and several research studies[11,25–27] conducted over a number of rocks and hard soils have shown that the steady-state creep strains are almost independent of the loading history and are a function of the current stress state only. For many engineering applications, it is essential to know when a steady state (SS) condition is reached and what magnitude it can be at a certain level of stress.

This was investigated at an early stage of our experimental programme to determine the likely timescale required to obtain steady-state creep for the intact muddy siltstone. Fig. 2 shows a typical creep curve conducted at constant axial stress σ_1 = 32 MPa (≈57% of UCS); as expected the secondary creep did not start before some time i.e. approximately 1200 min (less than one day). Previous research[26,28] conducted on rock salt has shown that time required to reach SS strain increases as deviatoric stress increases. Therefore, in planning for our experiments, the rock samples were given approximately two days to creep for each stress increment (stage). This procedure was found to be adequate to allow the steady state (SS) strain rate to be obtained, which is of great importance for modelling and characterising time-dependent behaviour.