Laboratory measurement of time-dependent deformation properties of muddy siltstone

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ABSTRACT This paper investigates the time-dependent deformation of argillaceous rocks, drawing principally on laboratory experiments carried out on muddy siltstone recovered from an open pit mine located in the midlands, UK. A series of creep tests were conducted on both intact and fractured rock samples to cover the two ultimate structural conditions of rock mass. Based on the creep test results, the relationship between axial strain and time under different axial and deviatoric stresses was investigated. The creep data of both intact and fractured rock samples was successfully fitted to Burgers model to represent creep behaviours of pre and post failure. The study provides improved representation of the time-dependent deformation properties of rock mass, which is essential to enhance geomechanical modelling of long-term stability of abandoned mines and for the application of underground disposal of radioactive waste.

KEYWORDS

Time-dependent, Fractured rock, Argillaceous rocks, Burgers model

1 INTRODUCTION

1.1 Time-dependent observation in underground mine

Rock mass response may be time-*in*dependent or time-dependent and the material (whether it is intact or fractured) may behave elastically or may yield according to the confining pressure and the applied stress level (Kaiser and Morgenstein, 1981).

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 (e.g. Singh, 1975), and more recently it is becoming important for the application of underground disposal of radioactive waste (Liu et al., 2015).

In coal mines, it is generally accepted that after the initial excavation of an entry, most coal-measure rocks deform over time, even

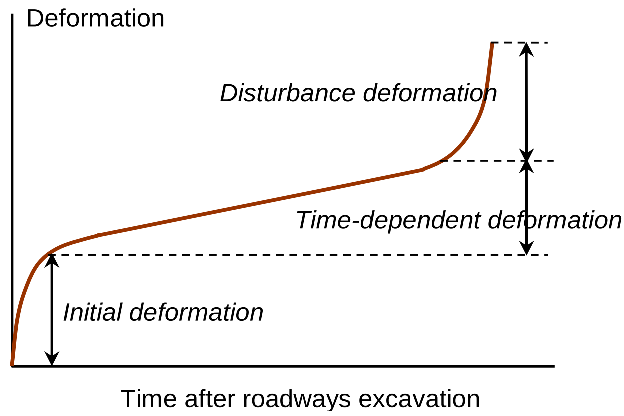

Figure 1. General components of deformation of underground roadways.

when no activity is taking place nearby. This deformation is most evident in the form of roof sag, floor heave, pillar dilation, or shearing along bedding planes and joints. Figure 1 presents graphically the deformation of underground roadways, which (generally) consists of three components. After the initial rapid deformation induced by the roadway excavation, a time-dependent deformation takes place. This rheological deformation might be followed by 'disturbance deformation', which is caused by stress changes due to mining activities in adjacent areas (e.g. Lu, 1984, cited by Wang et al., 2000). These physical events observed in underground excavation have been attributed to time-dependent characteristics, which can also be evident in a small rock sample tested in laboratories as discussed in next section.

1.2 Laboratory measurement of time-dependent behaviour

Laboratory experiments use three main 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 simply observed in much laboratory testing when 'relatively high' stress applied constantly on a cylindrical specimen for a period of time. Figure 3 shows idealised creep curve which exhibits three out of four principle phases of deformations as listed below:

a) Instantaneous elastic strain due to instantaneous load.
b) Primary or transient creep with rapid strain increments, but 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 (e.g. Jeremic, 1987).

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 (e.g. Munson, 1997; Günther et al., 2015) on the basis of empirically observed internal variables (e.g. Challamel et al., 2005) or the superposition of several viscous and elastic elements such as the Burgers body model (Cristescu, 2012).

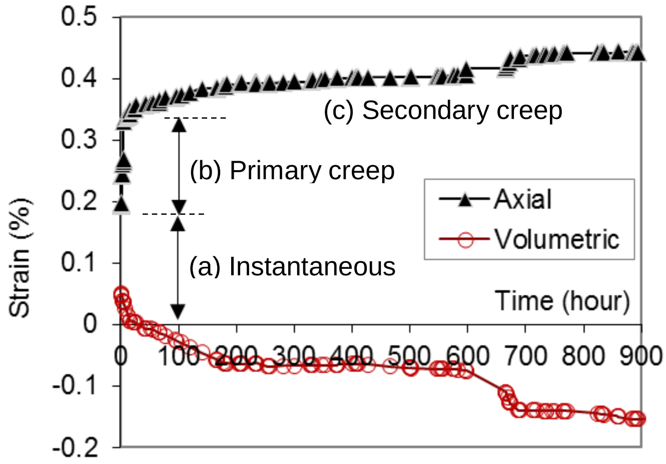

Figure 3. Axial and volumetric strain curves for Lea Hall Sandstone under 35.8 MPa uniaxial stress showing three stages of creep (after Hobbs, 1970).

Extensive creep testing has been conducted on coal-measure rocks around the mid of last century. In early stages (prior to 1964), the majority of the time-strain experiments have been carried out in uniaxial compression, at room temperature and, for periods of less than a week (e.g. Phillips 1930, 1931, 1954, Pomeroy, 1956 cited in Valsangkar, and Gokhale, 1972). These studies have been mostly carried out on intact rock samples. However, the time-dependent behaviour of fractured rock represents an important ultimate structural condition of the rock mass. Larson and Wade, 2000, indicated that creep in brittle coal measure rock occurs, likely, because of (i) microcracking 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, 1985, 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 (Wawersik, 1974). Creep of the rock was observed, particularly when water was present. The creep behaviour of jointed rock has the same character as that of the intact material, but with a larger amount of strain.

Larson and Wade, 2000, investigated friction and creep characteristics of weak planes in mudstone by conducting direct-shear creep tests; non-linear rheological model (Boukharov et al., 1995) was used to fit their experimental data.

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 (Lu et al., 2014). Although this model is an attractive solution to reproduce the macroscopic creep behaviour on the basis of the microscopic kinetics of microcrack growth, however the model requires suitable calibration in order to obtain reliable results. Therefore phenomenological and empirical approaches might still be a good alternative way to characterise rheological behaviour of both intact and fractured rock, i.e. representing the two ultimate structural conditions of rock mass.

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, conducted by Hamza et al., 2005, it has been found that creep strain rate of 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 (Hamza et al., 2005) to represent the effect of strain rate on strength and stiffness of both intact and fractured silty mudstone individually. It follows that other time-dependent behaviours such as creep of both intact and fractured rock can be modelled using a similar phenomenological approach such as the Burgers creep model. This paper investigates the creep properties of both intact and fractured rock using muddy siltstone. The study can assist in understanding the rheological properties of argillaceous rocks particularly under pre and post failure conditions, which are essential to enhance geomechanical modelling of long-term stability of mines.

2 CREEP TESTING ON MUDDY SILTSTONE

2.1 Materials and Apparatus

The tested rock material (muddy siltstone) was originally obtained from an open pit mine located at Arkwright in the midlands of the UK. The rock consisted 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 (shown in Figure 3) were cored from carefully selected similar blocks, which were mostly dominated by a similar angle of lamination (i.e. 0^o-7^o to the horizon of specimen flat surface). After coring, the rock, samples were left to dry out for 24 hours at 100^{o}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.

Figure 3. Intact samples of the muddy siltstone.

The tests were conducted at room temperature (about 23^{o}C) on cylindrical dry samples of 74mm in height and 36mm in diameter, which were prepared in accordance with the procedure outlined by ISRM (1981).

A total of 14 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 uniaxial/ triaxial strength and Young`s modulus of the intact and fractured rock at different confining pressures. The remaining eight rock samples were used for the creep tests, where a constant axial stress σ_1 was applied and maintained by a servo-controlled rig machine (shown in Figure 4). The equipment can be used to carry out conventional compression tests and rheological tests such as uniaxial creep. However the required triaxial loading condition was achieved by confining the rock sample using a Hoek cell connected to a manual pump, which can provide 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 effect of 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 were noticed in which samples developed a major shear plane at about 45° from horizontal. The failed (fractured) specimens were then used to carry out multi-stage creep testing with the prescribed confining pressure σ_3 (ranging between 1 and 6 MPa). Larger values of confining pressure would have allowed better investigation of triaxial creep behaviour, however the chosen pressure range was based on the best performance of the equipment used in the experimental programme.

2.2 Secondary creep strain rate

Secondary or Steady State (SS) creep strain rate (see Figure 2) is probably the most important parameter as far as the time-dependent deformation is concerned. Several research studies (e.g. Hobbs, 1970; Munson 1979; Yang et al., 1999; Cristescu and Hunsche, 1998) conducted over a number of rocks and hard soils have shown that steady-state creep strains are almost independent of the loading history and are a function of the current stress state only. It is important for many engineering applications to know when a steady state (SS) 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 time scale required to establish the steady state creep for the muddy siltstone used in this study. Figure 5 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 1300 minutes (almost 1 day). Therefore, in planning for our experiments, the rock samples were given at least double this time (about 2 days) to creep

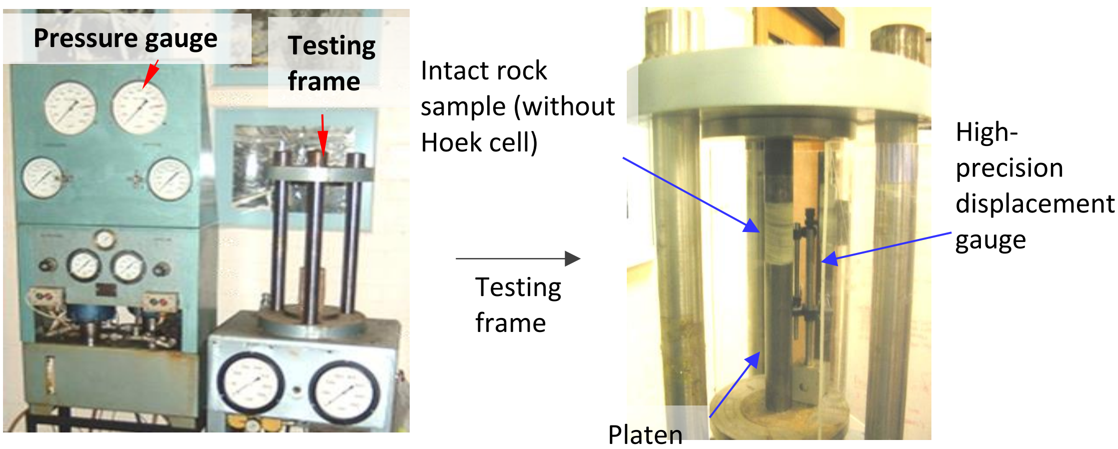

Figure 4. Testing Rig with servo-controlled hydraulic pressure cell system used for conducting the creep tests.

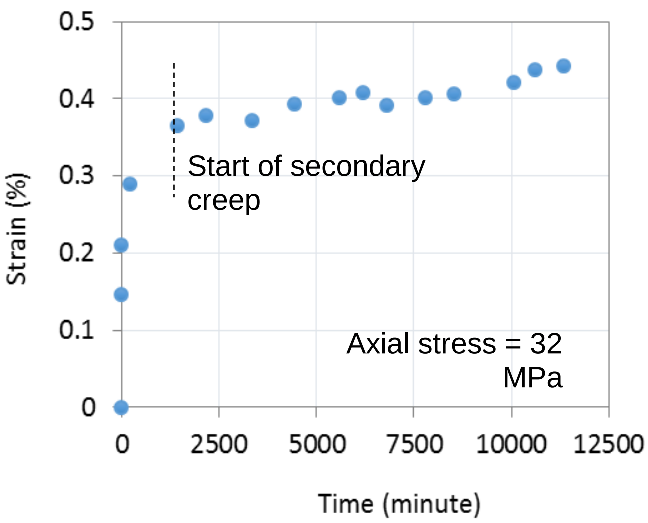

Figure 5. Creep test showing the period required to obtain secondary creep in intact muddy siltstone sample.

for each stress increment. This procedure allowed the steady state strain rate (SS) to be obtained, which is of great importance for modelling and characterising time-dependent behaviour.

2.3 Experimental results

2.3.1 *Uniaxial/ triaxial strength and stiffness*

Prior to conducting any creep experiment, six samples were initially tested to obtain the uniaxial/ triaxial strength and stiffness of the intact and fractured rock. The unconfined compression strength (UCS) and Young's modulus, (E) of the intact samples were found to be approximately 56MPa and 11GPa respectively. However it was not possible to conduct similar (unconfined) testing on any fractured rock sample without confinement. The results of the uniaxial compression tests are summarised in Table 1 and 2, where average Young`s modulus (E) and average peak strength (σ_p) are presented for each confining pressure.

2.3.2 *Creep experiments on intact rock samples*

Figure 6 shows results of multi-stage creep tests conducted on four intact rock samples at four different confining pressure σ_3 (0, 2, 4, and 6 MPa). For each sample, a constant confining pressure was applied, while the axial stress was increased in three stages: σ_1= 31.2, 39.1, and 46.8MPa; these values are approximately equivalent to 40%, 50%, and 60% of the average axial peak strength σ_p of the intact rock at confining pressure σ_3 = 2 MPa. Summary of stresses applied on the intact rock samples is presented in Table 3.

Table 1. Results of uniaxial/triaxial compression tests on intact rock samples

σ_3 (MPa)	0	2	4	6
E (GPa)	11.1	12.6	12.8	14.5
σ_p (MPa)	57.2	78.7	95.4	104.0

Table 2. Results of uniaxial/ triaxial compression tests on fractured rock samples

σ_3 (MPa)	1*	2	4	6
E (GPa)	2.8	3.7	4.2	5.8
σ_p (MPa)	11.7	23.4	37.4	46.0

* Sample is not stable under σ_3 less than 1MPa

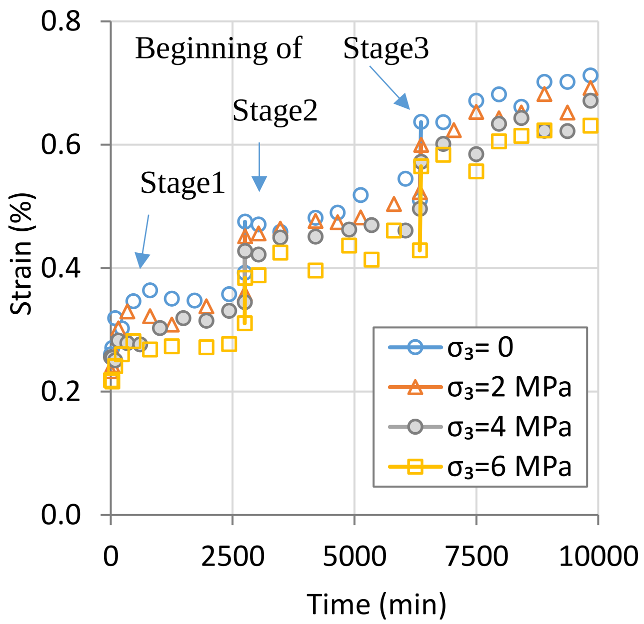

Figure 6. Creep strain obtained from four *intact* rock samples of muddy siltstone.

Table 3. Stresses used for creep experiments on intact rock samples

Test ID		**Test 1**	**Test 2**	**Test 3**	**Test 4**
σ_3 (MPa)		0	2	4	6
q= σ_1- σ_3	**Stage1**	31.1	29.3	27.2	25.2
	Stage2	39.1	37.1	35.2	33.1
	Stage3	46.8	44.7	42.8	40.6

2.3.3 *Creep experiments on fractured rock samples*

Table 4 presents stresses applied on the fractured rock samples, where typical confining pressures σ_3 (0, 2, 4, and 6 MPa) were used. However smaller values of axial stress were applied because the fractured rock samples are much weaker than the intact samples (according to the uniaxial/ triaxial properties of both rocks).

Four creep tests on were conducted, in each test, the axial stress was increased in three stages: σ_1= 10.35, 12.8, and 15.10 MPa; these values are approximately equivalent to 40%, 50%, and 60% of the uniaxial/ triaxial peak strength at confining pressure of 2MPa, respectively. The creep results of the fractured rock samples are shown in Figure 7.

Table 4. Stresses used for creep experiments on fractured rock samples

Test ID		Test 1	Test 2	Test 3	Test 4
σ_3 (MPa)		1*	2	4	6
q= σ_1- σ_3	Stage1	9.35	7.39	5.36	3.37
	Stage2	11.8	9.7	7.6	5.7
	Stage3	14.10	12.04	10.08	8.04

* Sample is not stable under σ_3 less than 1 MPa

3 DISCUSSION

3.1 General observation on creep behaviour

The most noticeable finding to emerge from the experimental data is that all stain curves (Figure 6 and 7) showed an initial instantaneous strain followed by two phases of time-dependent strain including transient creep phase (particularly for the first loading stage) and a steady creep phase. Accelerated or tertiary creep was not considered as part of this study because the applied stresses were moderately less than the compressive strength of the rock.

The results also indicate that the instantaneous and creep strain are proportional to the deviatoric stress. This is clearly shown in fractured rock samples

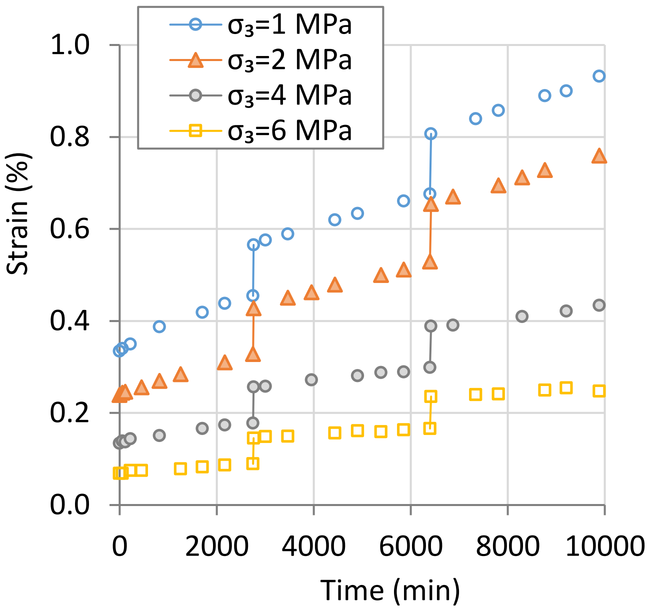

Figure 7. Creep strain obtained from four *fractured* rock samples of muddy siltstone.

where larger deviatoric stress resulted in increased creep strain and strain rate.

3.2 The effect of confinement on creep

The experiment conducted on intact rock samples shows that rock exhibit larger creep strain at larger deviatoric stress at almost similar rate regardless of confining pressure. Unlike the results from fractured rock samples where these showed that the creep strain is not only proportional to deviatoric stress but also to the level of confining pressure, where the temptation for creep in the fractured rock decreased with the increase of confinement. This was not clearly shown in the intact rock samples, possibly because of the low level of confining pressure (less than 6 MPa) in comparison with the high strength of intact rock (UCS=56 MPa).

To investigate the effect of confinement on creep behaviour of both intact and fractured rock samples, a further attempt of analysis was carried out, in which the recorded creep strains at 2 days are plotted against deviatoric stress, as shown in Figure 8. From this figure, it is possible to assess the tendency of creep in relation to deviatoric stress for all rock samples. The intact rock samples shows an average value of creep strain of 0.02% per MPa. On contrary the fractured rock samples

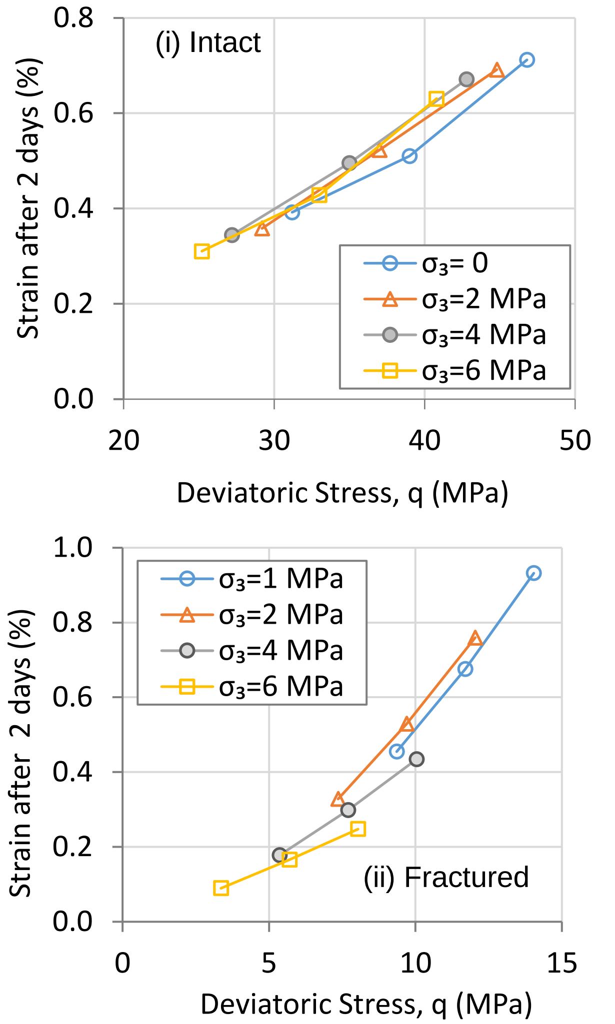

Figure 7. Creep strain recorded after approximately 2 days from the start of each loading stage. (i) Intact rock samples, (ii) Fractured rock samples.

showed large variation: from 0.09 to 0.03% of strain per MPa for confining pressure ranging from 1 to 6 MPa, respectively. The average steady state (SS) creep rate was approximately 0.023% per day for the intact rock, and between 0.05% to 0.01% per day for the fractured rock (corresponding to the increase of confining pressure).

3.3 **Analysis of creep model**

The experimental data obtained were analysed and fitted to the best mathematical expressions or *models*. These models with representative material properties are highly required to predict the geotechnical performance and also for the design applications.

Many constitutive laws (models) considering the effect of time have been developed using (i) Experimental/empirical fitting, (ii) Mechanical models and (iii) Phenomenological models based on physical process theories.

Burgers model is one of the most successful constitutive laws that have been used to model instantaneous and time-dependent deformation. Burgers model possesses instantaneous deformation properties, the primary creep, and steady creep. The constitutive equation of this model can be expressed as:

$$\varepsilon = \sigma\left[\frac{1}{E_m} + \frac{t}{\eta_m} + \frac{1}{E_k}\left(1 - e^{-\frac{E_k t}{\eta_k}}\right)\right] \qquad (1)$$

where ε = strain, σ = stress, t = time, and the rest are the model's parameters. In general, the parameters required for Burgers model are:

- Kelvin Parameters: Kelvin modulus (E_k) and Kelvin viscosity (η_k);
- Maxwell parameters: Maxwell modulus (E_m) and Maxwell viscosity (η_m).

In the current study, these parameters were determined through a non-linear, least squares regression analysis using Matlab software package (Mathworks, 2016). The values of parameters obtained for the creep tests are presented in Table 5. The model was found to be suitable to describe the experimental data with good accuracy (R^2 = 0.87 - 0.93).

From Table 5, the fractured rock has generally smaller parameters, thus allowing larger magnitude of creep deformation in comparison with the intact rock. These factors may explain the relatively good correlation between rock strength and its tendency for creep as previously reported by several authors (Parsons and Hedley, 1966; Hobbs, 1970).

The confining pressure has almost similar effect on creep parameters where their numerical values generally increase with the increase of confinement (up to confining pressure of 6MPa). Further studies, which investigate these variables for, will need to be undertaken.

Table 5. Creep parameters of the intact and fractured rock samples under different confining pressures

σ_3 (MPa)	E_m (GPa)	η_m (GPa.d)	E_k (GPa)	η_k (GPa.d)
Intact				
0	11.2	150.3	50.1	50.4
2	11.9	162.4	52.3	52.2
4	12.5	171.5	49.8	53.1
6	13.4	169.8	58.4	52.9
Fractured				
1	2.8	60.5	15.2	23.3
2	3.1	72.4	16.0	23.1
4	4.0	94.8	19.6	28.9
6	4.5	101.4	30.2	30.6

4 CONCLUSION

To understand the long-term stability of underground opening it is important to describe time-dependent behaviour for the entire strain range of rock, i.e. up to and beyond the yield point, where rock is expected to be fractured.

The creep behaviour muddy siltstone has been investigated in this study to determine and compare the time-dependent properties of intact and fractured rock samples.

Within the tested range of stresses used in this study, the confining pressure did not induce any significant changes in the creep properties of intact samples. On the contrary, the creep curves showed that the fractured samples experienced larger variation in stain influenced by the variation of confining pressure. A possible explanation for this might be that confinement plays important role in closing up the rock joints and stiffening up the rock specimen.

It is expected that in fractured rock samples the time-dependent process is largely influenced by the structure and degree of fracturing of the rock materials. However, in this study, no systematic investigation was carried out to assess the level of fragmentation of the fractured samples. The experiments would have been also benefited from measuring the volume and lateral strain.

The experimental data describing the creep of the intact and fractured muddy siltstone under various deviatoric stresses was successfully fitted to Burgers model, adopting elasto-viscoplastic properties. The application of this model to other type of argillaceous rock, with wider range of confining pressures, can be part of a future investigation. Moreover, applying the results to a case study would validate this approach and improve the geomechanical modelling of long-term stability of mines.

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