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Predicting time-to-failure of rocks based on secondary creep strain rate

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Abstract

The time-dependent deformation of rocks is important for evaluating the stability of rock engineering structures. The current study proposes the analysis of the time-dependent mechanical behaviour of Gosford sandstone using the creep testing method, focusing on long-term strength estimation and time-to-failure prediction. Six different creep stress ratios, ranging from 40% to 95% of the short-term strength, were adopted for conventional creep compression tests. Throughout the creep test, the creep stress ratio was kept constant until the sample reached failure. The results showed that the minimum strain rate is strongly dependent on the level of the applied stress. Only a 10% reduction in the applied creep stress ratios results in a decrease in the secondary strain rate of approximately 3 order of magnitude. Based on experimental results a novel methodology has been proposed to predict time-to-failure. The proposed approach involves the utilization of secondary strain rates as predictive indicators for time-to-failure and long-term strength in rocks, effectively addressing the inherent variability associated with time-to-failure predictions. Validation across various rock types demonstrates a consistent linear correlation between secondary strain rates and time-to-failure, regardless of creep stress ratios. This comprehensive approach provides a practical tool for engineers to predict the structural stability and engineering structures subjected to sustained loading.

Keywords

Time-dependent deformation, time-to-failure, long-term strength, creep strain rate.

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1 Introduction

Stability of rock structures is essential for sustainable operation of both surface and underground mining projects as well as safety of personnel. Such a stability is also important to prevent equipment entrapment, enable continuous access to future ore reserves and to mitigate any potential adverse environmental impacts (Brady and Brown, 2006). These rock structures usually experience complex stress conditions leading to continuous damage and failure after a long period. Time-dependent deformation under constant loading also known as “creep” is a fundamental mechanical characteristic of rocks which its characterisation is crucial, particularly in long term rock engineering projects (Atkinson, 1982, Brantut et al., 2013). Therefore, investigation of creep behaviour is of paramount importance in rock mechanics (Paraskevopoulou, 2016).

In general, an idealized creep deformation includes three distinct regions: a) primary phase or transient creep where the creep strain increases with a decrease in the rate, b) secondary phase or steady creep which can be characterized by a rise in the creep strain at a relatively constant rate and c) tertiary phase or unstable creep where the creep strain increases with an increase in the strain rate followed by the failure of sample (Brantut et al., 2013). The primary creep characterized by the rapid decrease in the strain rate versus time. During this stage, the behaviour of sample is mainly elastic due to the closure of pre-existing flaws according to Xu and Yang (2016). The creep curve then turns into the apparent secondary creep phase where the creep strain demonstrates relatively steady growth over an extended period. This stage can be described as the state of balance between two opposing mechanisms, microcracking and defects closure. While microcracking can lead to less elastic behaviour in rock, the defects closure can increase the strength and elasticity (Xu and Yang, 2016). Presence of this phase, especially in brittle rocks has been debated by scholars (Fabre and Pellet, 2006, Lockner, 1993, Amitrano and Helmstetter, 2006, Paraskevopoulou et al., 2018a). Some argued that the strain rate during the secondary phase is not constant (Brantut et al., 2014) and instead, it represents a transitional period from the primary phase directly to the unstable creep or the tertiary phase (Dusseault and Fordham, 1993). Finally, the last phase or the tertiary creep stage is marked by the deformation instability within a short period which can be attributed to occurrence of dilatant cracking followed by the coalescence of microcracks and then generation of macrocracks throughout the rock sample leading to localized shear failure (Heap et al., 2009). Creep damage in brittle rocks is primarily driven by the sub-critical growth of cracks, which can occur when the stress intensity at the crack tips is below the fracture toughness (Meredith and Atkinson, 1985). Under sub-critical crack growth conditions, cracks gradually propagate until they reach a critical length. At this point, the cracks attain critical dimensions, resulting in fracture growth and sudden failure. This process can be marked by the transition from stable to unstable cracking where the cracks grow rapidly leading to rock failure.

When the stress magnitude under creep loading is lower than a specific value or “threshold” (Schmidtke and Lajtai, 1985), the microcracks which are induced during the creep loading cannot spread throughout the tested sample to reach the critical damage point; however, if the magnitude of creep stress exceeds the threshold value, creep deformation can then develop rapidly due to progressive damage evolution in rock (Brantut et al., 2013). Such a stress threshold is usually defined as the long-term strength of rock and is considered as one of the significant parameters to predict long-term stability of underground structures (Fabre and Pellet, 2006). Therefore, it is important to estimate such a threshold as accurately as possible.

Several approaches were proposed for evaluating long-term strength of rocks and some studies specifically utilized time to failure data to predict long-term strength of various rocks (Lajtai and Schmidtke, 1986). In such methods, rock samples are commonly subjected to high creep compressive stresses until they fail. Then, time to failure data is plotted against applied stresses and a relationship is established through linear fit into the data on logarithmic scale. Innocente et al. (2021) successfully used this method to analyse the data obtained from laboratory tests on rock samples under creep loading. Schmidtke and Lajtai (1985) and Aydan and Ulusay (2013) also demonstrated that by plotting long-term strength data against driving stress ratio and natural logarithm of time to failure, a log-linear equation for the corresponding rock can be obtained through fitting a line to the lab data. Extrapolation of such a fit to extended durations allows the selection of stress magnitude that does not lead to failure of rock during the given lifetime. This is the most well-known approach to determine long-term strength of rock materials. However, such a method is strongly dependent on experimental condition even for a single material. Another factor that can impact on reliability of results is associated with intrinsic variability or heterogeneity of rock matrix. Definition of long-term strength is based on the magnitude of creep stress with respect to the uniaxial compressive strength (UCS) (Paraskevopoulou et al., 2018b). However, this strength may change significantly from one sample to another even under the same testing condition due to natural rock heterogeneity.

In this work, the creep behaviour of different rock types along with prediction of their long-term strength and time to failure were examined. A systematic laboratory analysis was carried out on Gosford sandstone to study its creep behaviour under different stress magnitudes. From the experimental results, a novel time-dependent failure model was introduced.

2 Experimental methodology

White Gosford sandstone from Gosford quarry in New South Wales, Australia was used for experimental study (Masoumi et al., 2014). To ensure consistency in the experiments, all the samples were obtained from a single block. The cylindrical samples were prepared as recommended by International Society for Rock Mechanics (ISRM) (ISRM, 1978, Fairhurst and Hudson, 1999). The upper and lower end surfaces of samples were grounded to achieve parallel and flat end surfaces within ± 0.02 mm tolerance in accordance with the suggested method by ISRM (ISRM, 1978, Fairhurst and Hudson, 1999). The samples were dried at 105 ± 1 ℃ followed by being left in the ambient temperature for 24 hours before the experiments.

A set of conventional uniaxial compressive tests were carried out on Gosford sandstone samples with different slenderness ratios following ISRM suggested method (ISRM, 1978, Fairhurst and Hudson, 1999) to benchmark their UCS, Young Modulus (E) and Poisson's ratio (ν) for the design of creep experiments. A servo-controlled loading frame (Instron 600DX) with 600 kN maximum loading capacity was utilised for the experiments as shown in Fig. 1. According to ISRM (Fairhurst and Hudson, 1999), the failure of a sample under uniaxial compressive loading should be between 5 and 10 minutes, thus, a constant strain rate of 10^{-6} s^{-1} was utilised for the quasi-static experiments. A linear variable differential transducer (LVDT) and a non-contact laser extensometer (model LX1500) with the resolution of 1 micrometre were used to record the axial deformation. The radial deformation was obtained using the circumferential LVDT and the radial strain was calculated through the correction proposed by Masoumi et al. (2015).

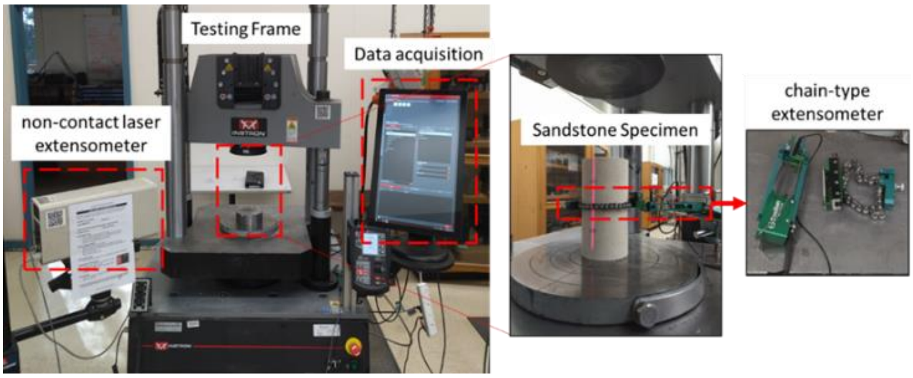

Fig. 1. Servo-type loading frame.

Based on the determined peak strength, six different stress levels are adopted for conventional creep compression tests. Creep experiments are performed using hydraulic creep loading frames which are located in the controlled temperature and humidity environment. Two linear displacement transducers (LVDT) were used to measure the axial strain of the specimens.

3 Creep strain evolution

In total 17 cylindrical samples were tested under creep loading. The applied creep stresses and their corresponding creep stress ratios are summarized in Table 1.

Base on the results provided in this table only a 10% reduction in the creep stress ratio results in a decrease in the secondary strain rate of approximately 3 order of magnitude. Fig. 2 shows the creep strain evolution for the sample that was under stress level 70%UCS. it is evident that the deformation behaviour of Gosford sandstone can be clearly marked by all the three main phases of creep at moderate to high creep stress ratios. During the first phase, gradual increase in the creep strain is recognisable which can be characterized by the rapid decrease in the strain rate versus time. Also, the elastic behaviour of rock increased during this stage as a result of pre-existing flaws closure (Xu and Yang, 2016). During the second phase, which is the longest stage of creep evolution, increase in the creep strain at constant rate is apparent. This stage can be described as the state of balance between two competing mechanisms, microcracking and defects closure. Microcracking can lead to decrease in rock elasticity while defects closure can result in the improvement in rock strength and subsequently its elasticity (Xu and Yang, 2016). During the final phase of creep process, there is a rapid increase in the creep strain over time, which can be attributed to occurrence of dilatant cracking followed by the coalescence of microcracks and then generation of macrocracks throughout rock sample leading to localized shear failure (Heap et al., 2009).

Table 1 Overview of creep tests conducted on Gosford sandstone

Test ID	Stress level (σ/σ_{UCS})	Creep strain rate (1/s)	Time-to-failure (s)
1	0.95	1.92E-05	36
2	0.95	2.50E-06	122
3	0.95	1.00E.06	449
4	0.95	1.19E-06	267
5	0.90	2.48E-06	268
6	0.90	1.08E-06	560
7	0.90	2.73E-07	1030
8	0.90	3.50E-07	1065
9	0.90	2.70E-07	1581
10	0.90	7.47E-07	777
11	0.85	9.47E-09	28464
12	0.85	4.00E-09	103082
13	0.85	2.36E-07	3400
14	0.85	2.24E-08	13240
15	0.85	3.10E-08	8299
16	0.80	1.22E-10	948782
17	0.70	4.41E-11	8020796

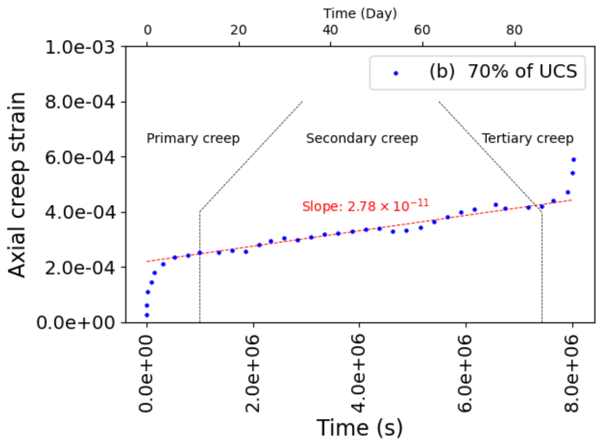

Fig. 2. Creep strain evolution at creep stress ratio of 70%UCS.

4 Time-dependent failure model

Predication of time to failure in rock materials under creep condition is important to ensure stability and sustainability of rock engineering projects particularly in mining industry. Time to failure results obtained from Gosford sandstone samples at different creep stress ratios are grouped in Fig. 3. It is evident that at ratios higher than 0.85, samples failed within an hour while at 0.7 and 0.8 creep stress ratios, failure occurred at longer periods, ranging from days to months. Such a significant time difference can be attributed to the critical role of stress intensity factor at microcrack tips in rocks where at high creep stress ratios, the intensity factor is greater leading to quicker failure of rock under constant loading (Atkinson, 1982, Amitrano and Helmstetter, 2006). Consequently, an increase in the creep stress ratio can trigger a considerable rise in the creep strain rate and decrease in the time to failure.

Recent studies indicated that the common approach for estimating time to failure of rock materials subjected to constant stress within the laboratory setting is to utilize the semi-log data where the applied stresses and the natural logarithm of time are incorporated (Innocente et al., 2021). However, there are still some limitations regarding the application of this model due to its time-consuming nature, particularly at low creep stress ratios. Also, due to intrinsic variability or heterogeneity in rocks, the average UCS used in this model may not necessarily reflect the real UCS of individual sample which is tested under creep loading condition. Therefore, the predicted long-term strength and time to failure can be adversely affected.

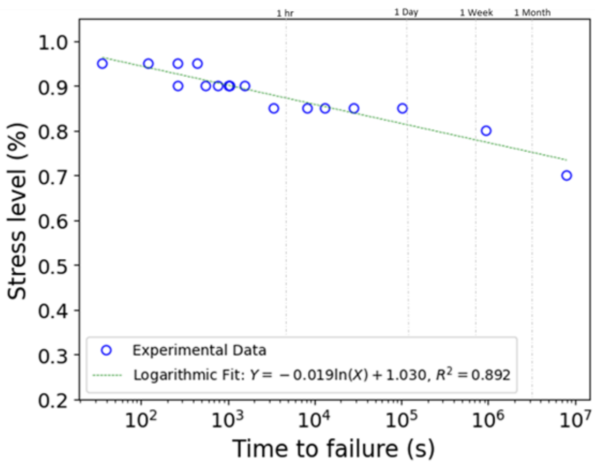

Fig. 3. The relationship between the applied stress levels and the Time to Failure.

As highlighted above, the earlier predictive models for rock media have been based on creep stress ratio while the intrinsic inhomogeneity in rock samples and variability in their static strength (e.g. UCS) can adversely affect the reliability of such a model. One technique to address such a limitation is through applying the time-dependent failure model that implicitly incorporates creep stress and rock strength. Such a model was originally developed by Monkman (1956) for metals. The earlier studies on metal, soil (Saito, 1961, Feda, 1992) and concrete (Cornelissen, 1984) indicated that time to failure is inversely proportional to the secondary creep strain rate and is uniquely valid irrespective of creep stress ratio. The model that was originally proposed by Monkman (1956) relies on the relationship between the creep failure time and the secondary creep strain rate according to:

$$\dot{\varepsilon}.t_f^n = C \qquad (1)$$

Where $\dot{\varepsilon}$ Minimum strain rate

t_f Failure time

C, n Material constants

It is noteworthy that the impact of rock intrinsic variability or heterogeneity can be eliminated in this method as the prediction process of time to failure does not depend on the creep stress ratio which is commonly estimated from the average of UCS values.

Fig. 4 demonstrates the relationship between the secondary creep strain rate and the time to failure for Gosford sandstone. The secondary creep strain rates were obtained directly from creep experiments was used to fit the data leading to a good agreement between predictions and experimental data as shown in Fig. 4. From this analysis, the value of C was determined to be 3.98×10^{-4} for shaly sandstone used in this study. Utilizing such a model enables the precise estimation of time to failure in rock materials and if the secondary creep strain rate is measured during the test, time to failure can also be estimated using Eq. 1.

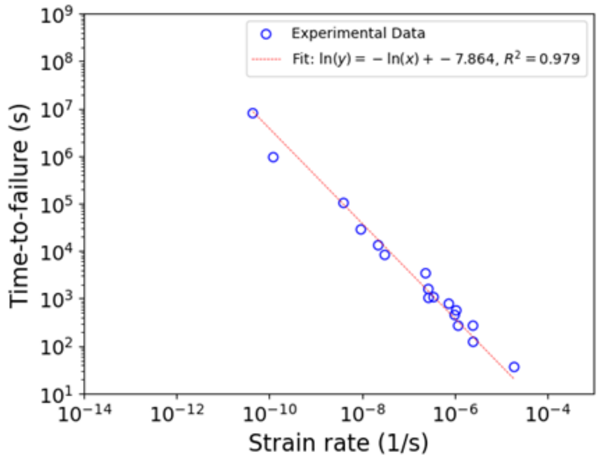

Fig. 4. Time-dependent failure criterion.

To further assess the applicability of such a model to a wide range of rock types, a set of time to failure data was collected from various rock types and then, they were calibrated using Eq. (1) as shown in Fig. 5 (Fujii et al., 1999, Heap et al., 2011, Rybacki et al., 2017, Adachi and Takase, 1981, Ohtsuki et al., 1981, Brantut et al., 2013, Wang et al., 2017). It is evident that a set of consistent linear relationships can be observed between the creep failure time and the secondary creep strain rate for different rock types with the identical slope while their intercepts are different due to type of rock.

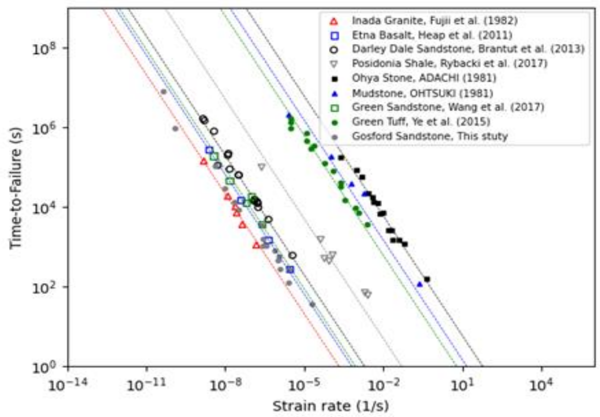

Fig. 5. Time-dependent failure criterion.

5 Conclusion

This study investigates a time-dependent criterion for rock materials, emphasizing the Gosford sandstone. The key finding is the successful prediction of failure time based on minimum creep rates derived from sustained load experiments. This predictive model demonstrates high accuracy, irrespective of loading level, and considers the logarithmic time scale typical of creep-related problems. Furthermore, the analysis of a diverse database reveals a consistent linear correlation between creep failure time and minimum axial strain rate across various rock types, suggesting a universal relationship independent of test conditions. However, further investigation is required to understand the relationship between rock type and a constant parameter in the model. These findings offer valuable insights into predicting failure time in rock materials, with implications for assessing structural integrity and long-term stability in geological and engineering contexts.

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