Time-Dependent Softening of Rock Masses Can Alter Tunnel Lining Design Loads and Deformations

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Abstract: *The linings and support systems of underground structures such as tunnels and caverns are often designed using the deformation modulus reported from short-term laboratory compressive strength tests, leading to approximately constant loads over long periods of time. However, many rocks exhibit time-dependent strength and deformation behaviours. A sustained load of a fraction of the quick strength may lead to failure within a measurable time interval. Similarly, a rapid load up to a fraction of the ultimate strength will cause an initial elastic deformation, but continued (non-elastic) deformation thereafter: a phenomenon called "Creep". Therefore, the design of underground rock structures should be based on the long-term strength and deformation modulus, rather than the values determined by short-term laboratory tests. This paper presents some preliminary test results on long-term behaviour of Melbourne Formation mudstones, where strain/time relationships at different stress levels were measured, and the expected deformation modulus values over long-time intervals could be extrapolated. Numerical modelling demonstrates the predicted variations of tunnel loads, deformations and failure zones over different time intervals.*

Keywords: *Time-dependent deformation modulus, Mudstones, Lining deformations.*
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1. INTRODUCTION

Numerical parameters to predict rock behaviour over the life of an excavation are generally provided by laboratory or in situ rock test measurements which for practical considerations are usually completed in a relatively short time frame, orders of magnitude less than the design life of the project. Understanding the time-dependent behaviour of rocks involves conducting rock creep tests over time periods of the order of weeks or months, possibly leading to substantially increased costs. A principal who does not appreciate the possible significance of the time-dependent deformation data may be reluctant to authorize such spending. Hence, the effects of time-dependent behaviour of rocks on underground structures are seldom adequately studied while planning underground construction projects.

When a rock is subjected to a constant load over a period of time, it might fail at a stress much less than the compressive strength determined by the short-term lab tests due to the development of time-strain (1). This behaviour is attributed to the time dependant subcritical crack growth within the rock (2). The chemical reactions that take place between the atomic bonds of the rock substance and the geofluids, predominantly water increase the microcrack density causing rock failure without having to increase the applied stress (2). Therefore, creep phenomena may often or usually occur when deep underground openings are excavated, especially in soft rocks such as mudstones and siltstones.

Two major transportation tunnel projects are about to commence in Melbourne. The time-dependent deformation behaviour of the siltstones of the Dargile and Andersons Creek Formations should be taken into account in the design of tunnel linings for long-term stability. The effect of continued non-elastic deformation of a rock is to lower its effective modulus of deformation E. If this softening rock is in contact with a concrete lining, then the lining will be subjected to increasing loads with time. It is essential that the tunnel linings be designed with the long-term deformation modulus of the rock being used in the calculations, rather than the "quick" modulus determined in laboratory compression tests which are completed in a few minutes. The continued inwards convergence of tunnel walls and crowns, long after construction has been completed, may have important implications for the safety of the installations in the tunnel, and for the ground deformations outside the tunnel, possibly affecting the stability of nearby structures on the surface.

There have been a number of studies (2), (3), (4) conducted on developing constitutive equations to describe the phenomenon of rock creeping. When a rock sample is subjected to a stress which is less than its short-term failure stress it starts to deform. When this deformation is plotted against time, three main regions can be identified. These three main regions are known as primary creep, secondary creep and the tertiary creep. Primary creep includes the instantaneous deformation at the initial loading and the deformation that occurs shortly after the initial loading. If the applied stress is kept at a constant level, the strain rate during the secondary creep region remains steady. During tertiary creep, the rate of deformation gradually increases, eventually leading to failure.

2. TEST APPARATUS AND TESTING PROCEDURE

The Time Dependent Testing Laboratory (TDTL) at BRTS (Figure 1) is designed to conduct mechanical creep and swelling tests of Geomaterials, and the derivation of equations to describe deformation modulus as a function of time. In this study, uniaxial unconfined compression creep test was conducted following the standard procedure outlined in (5), on two Dargile Formation mudstone samples from Melbourne and one Ashfield Shale sample from Sydney.

Since temperature and humidity changes may affect the strain in both the rock specimen and the steel loading frames, the ambient temperatures and humidity should be kept constant during the tests. Any measured deformations attributable to thermal expansion or contraction of the steel loading frames, rather than to rock deformations, could be confusing, so this possibility must be eliminated by maintaining constant temperature in the lab, and reducing personnel entries by having remote logging of data.

Figure 1. BRTS Time Dependent Testing Laboratory

The samples used in this study were cylindrical in shape with a diameter of 52mm and kept saturated. The long-term loading apparatus consists of gas-hydraulic intensifiers, loading frames, electronic load cells and deformation transducers. During each test, the axial deformation of a sample was measured by two linear variable differential transformers (LVDT) and the readings were logged every one second during the first 15 minutes of the loading and every 10 seconds afterwards. The first stage stress applied on each sample was 15%-30% of the previously-measured UCS value and this was maintained for several days/weeks. The main aim of this was to observe if the applied stress was sufficient for the sample to commence creeping. The second stage was initiated by increasing the stress by another 15%-30% and this was maintained until the sample failed.

3. RESULTS AND ANALYSIS

3.1. Uniaxial Creep test results

The creep deformations of Melbourne Mudstone samples 1 & 2 and Sydney Ashfield shale are shown in Figure 2, Figure 3 and Figure 4 respectively.

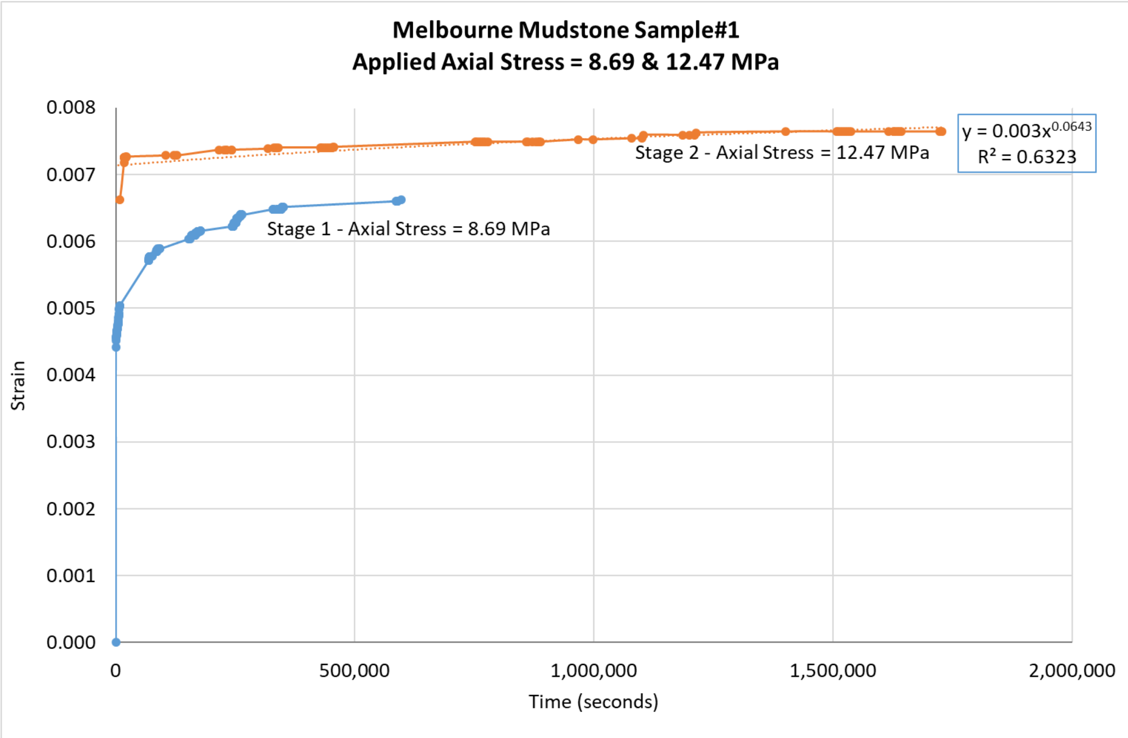

Figure 2. Melbourne Mudstone #1 creep deformation

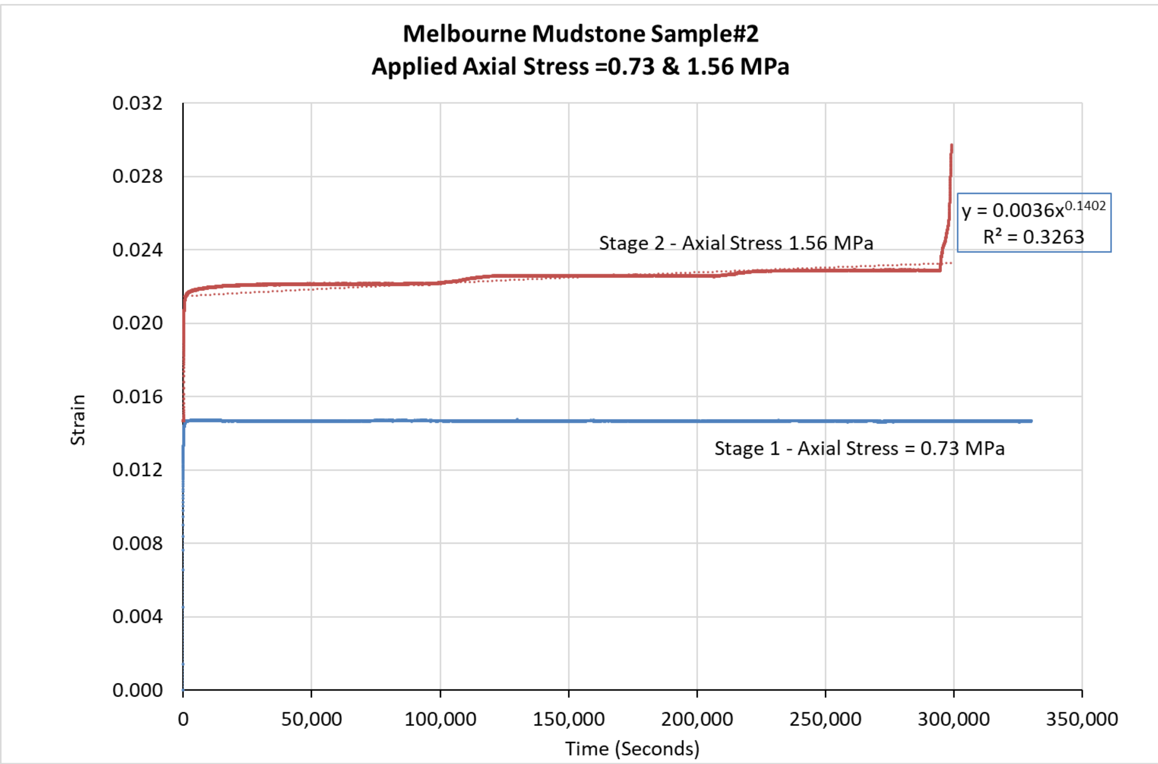

Figure 3. Melbourne Mudstone #2 creep deformation

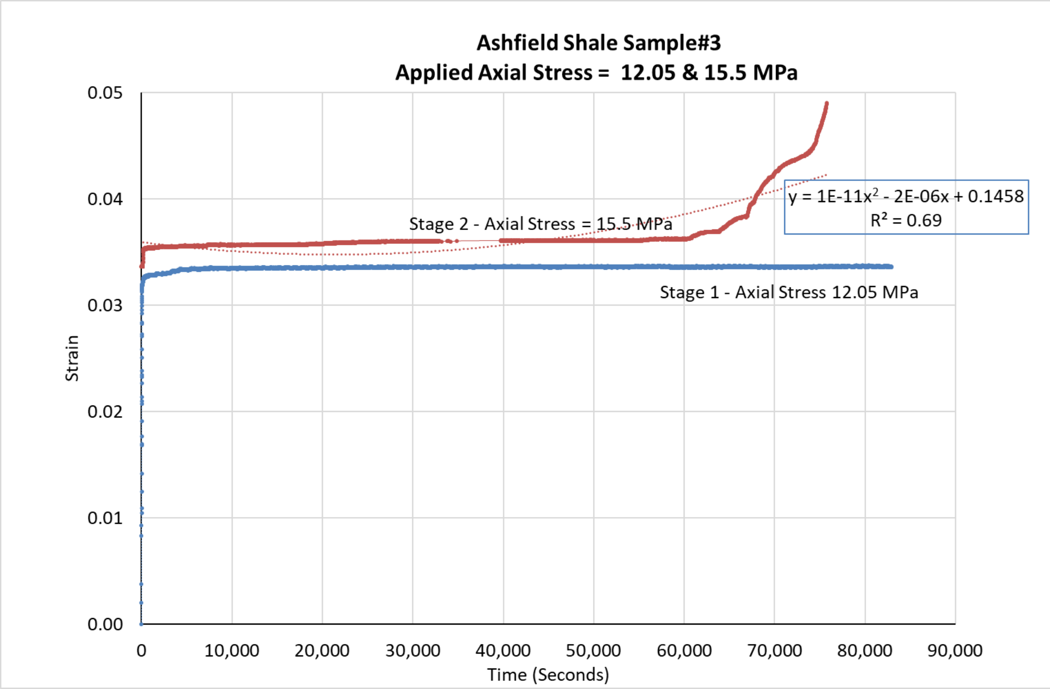

Figure 4. Ashfield Shale #3 creep deformation

The best-fit equation for strain as a function of time, from the second stage deformation observations, was used to calculate the incremental creep strain at any arbitrary time in the future. This was added to the initial elastic deformation to get a total strain, by which the constant stress was divided to calculate the apparent (time-dependent) deformation modulus E at that time, as illustrated in Figure 5 to Figure 7. Each creep curve was derived from a particular specimen, whose measured E value would not be expected to be truly representative of the entire rock mass, although the time-softening effect might be. So, the parameters of the equations were adjusted so that the curves had the same shapes, but now passed through the probable median E values for the entire rock unit.

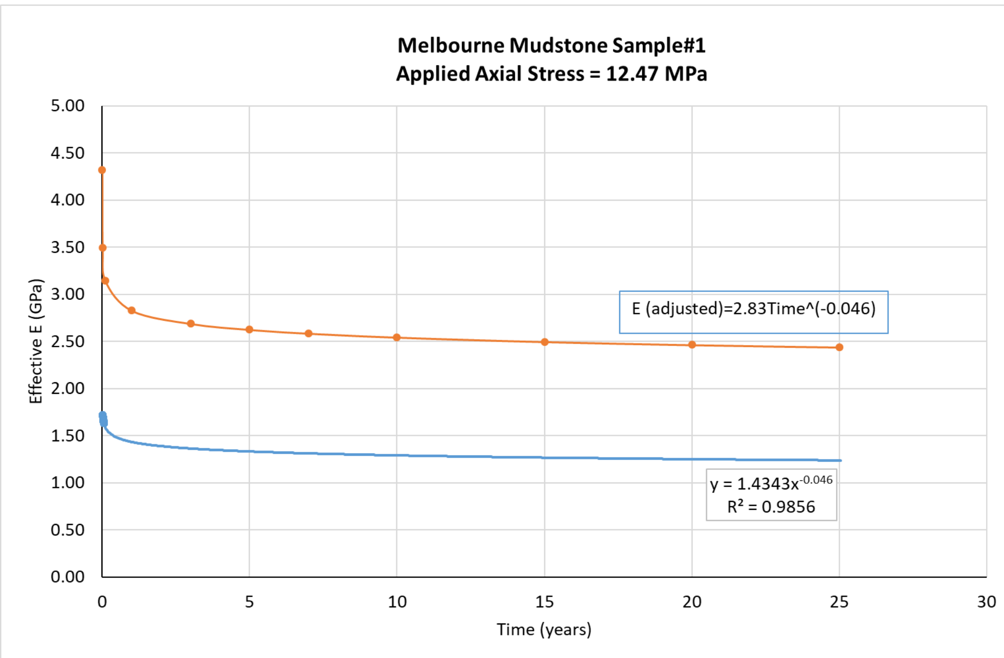

Figure 5. Melbourne Mudstone #1 Adjusted E

Figure 6. Melbourne Mudstone #2 Adjusted E

Figure 7. Ashfield Shale #3 Adjusted E

3.2. Rock Mass strength assessment

Previous testing in the BRTS lab had derived the median values of the measured strength and deformation parameters of the Melbourne Mudstone (UCS=12.34MPa, E=4.32GPa, Poisson's ratio=0.29) and the Ashfield Shale (UCS=28.29MPa, E=4.61GPa, Poisson's ratio=0.1)

Using the online tool ORMAS (6) which was developed based on the Generalized Hoek-Brown failure criterion, rock mass strength values (Rock Mass Young's Modulus, Cohesion, Friction Angle) were calculated for Melbourne Mudstone and Ashfield Shale. Rock Mass Cohesion and Friction angle of Melbourne Mudstone are 0.7439MPa and 23.85deg respectively. The Cohesion and Friction Angle of Ashfield Shale are 1.6676MPa and 29.31deg respectively. The variation of Poisson's ratio over a period of 25 years was estimated using the suggested methods in (7).

3.3. Deformation of tunnel lining

In order to analyse effects of the time-dependent softening of rocks on the tunnel lining, the online tool OTSA (8) was used. This tool was developed based on the simplified method using Mohr-Coulomb failure criterion outlined in (9).

The in-situ horizontal stress field in south-eastern Australia may be specified in terms of RSR (regime stress ratios) and the corresponding values for the vicinities of Melbourne and Sydney are shown to be 2.3 and 2.33 respectively (10). A back-analysis of RSR (a function of the assumed minimum stress (1MPa), intermediate principal stress (1.5MPa) and the observed faulting stress regime) was conducted and the probable magnitudes of the in-situ horizontal field stress around Melbourne and Sydney were calculated as 5MPa and 6MPa respectively.

The tunnel support analyses were conducted for a 7m radius tunnel with shotcrete (50mm, UCS=35MPa) and rock bolts (25mm) as supports. The tunnel wall displacements were calculated using the short-term lab results and the long-term creep results, and a comparison was made (Figure 8,Figure 9 and Figure 10).

Figure 8. Melbourne Mudstone#1 Tunnel Wall Displacement

These analyses were conducted considering the median values of strength and deformation parameters of Melbourne Mudstone and Ashfield Shale. However, a more conservative approach to study the wall displacements would be to use the lower quintile strength and deformation values in the calculations. For example, according to Figure 11, by the end of the 25th year the wall displacement values corresponding to the lower quintile material parameters of Ashfield Shale (UCS=12.22 MPa, E=2.04 GPa, Poisson's ratio=0.14) are around three times greater than that of the wall displacements calculated from median material parameters.

Figure 9. Melbourne Mudstone#2 Tunnel Wall Displacement

Figure 10. Ashfield Shale#3 Tunnel Wall Displacement, for median material properties.

Figure 11. Wall displacement with time considering lower quintile material properties of Ashfield Shale

4. SUMMARY AND CONCLUSIONS

The unconfined uniaxial creep tests conducted on the samples of Melbourne Mudstone and Sydney Ashfield Shale indicates that they exhibit time-dependent behaviour of rock creeping or time-softening of rocks when subject to a constant load over an extended period. All of the samples failed within 1 day to 3 weeks into the second stage of loading, with an applied stress equivalent to 42%-63% of the respective short-term UCS values. The estimated value of rock mass E at the end of 25 years is equivalent to 27%-57% of the E estimated from short-term lab tests. The calculated tunnel wall displacements at the end of 25 years are 8 to 18 times greater than the values obtained from the short-term lab test results. Simplified analyses have demonstrated that significant increases in the dimensions of the zones of deformation and failure around underground excavations, and the inwards closures of these excavations, should be expected to occur during their design life in any rocks, but particularly in mudrocks, mudstones, shales, siltstones. Even though design parameters can be adjusted arbitrarily to cater for the time dependent characteristics of rocks, comprehensive analyses based on laboratory creep tests are preferable to properly understand the phenomenon of time-softening of rocks in order to ensure long term stability of underground constructions. Techniques for quantifying and predicting these behaviours are available.

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