Long-term behavior of different rock types based on laboratory testing

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ABSTRACT
Over the past few decades' significant interest from rock engineers has been given to the understanding of the long-term strength and the susceptibility to damage of different rock types. The long-term behavior of underground works, in general, is usually associated with time-dependent deformations. Tunnel construction can be very challenging due to the difficulties in making reliable predictions at the preliminary stages of the design of a project. It is necessary to understand the time-dependent mechanisms of the host rock and the gradual development of the irreversible deformations around underground openings, as they will have a direct impact on the excavation damage zones. Excessive deformations can take place and cause severe damage both to the support system that can result to timeline delays and cost overruns. The latter could be more challenging in the case of the design and construction of nuclear waste repositories where the generally accepted time frame such engineering projects is in the order of one million years during which creep and strength degradation phenomena can take place and govern the materials behavior. This study tries to give more insight of the long-term behavior of brittle rocks through a series of unconfined static load tests (constant loading) performed on Jura Limestone. The results are compared to reported data on literature review of different rock types as an attempt to create and establish a database, which can be used from researches and engineers as a preliminary tool to determine the long-term behavior of various rock types.

RÉSUMÉ
Au cours des dernières décennies, un intérêt considérable des ingénieurs des roches a été appliqué à la compréhension de la résistance à long terme et à la susceptibilité aux dommages de différents types de roches. En général, le comportement à long terme des ouvrages souterrains est associé à des déformations qui sont dépendantes du temps. La construction de tunnels peut être très difficile en raison de la difficulté à faire des prévisions fiables aux étapes préliminaires de la conception d'un projet. Il est nécessaire de comprendre les mécanismes qui dépendent du facteur temps de la roche hôte et du développement progressif des déformations irréversibles autour d'ouvertures souterraines, car ils auront un impact direct sur les zones de dégâts des excavations. Des déformations excessives peuvent avoir lieu et causer de graves dommages au système de soutien qui peuvent entraîner, à la fois, des retards à l'échéancier et des dépassements de coûts. Ce système pourrait être plus difficile dans le cas de la conception et de la construction des dépôts de déchets nucléaires, où le délai généralement accepté pour de tels projets d'ingénierie est de l'ordre d'un million d'années, pendant lesquelles les phénomènes de fluage et de réduction de la résistance peuvent avoir lieu et régir le comportement des matériaux. Cette étude tente de donner une meilleure compréhension du comportement à long terme des roches fragiles à travers une série d'essais de chargement statique à l'état non confiné (chargement constant) réalisés sur le calcaire du Jura. Les résultats sont comparés aux données provenant de la revue de littérature pour différents types de roche dans une démarche pour créer et établir une base de données, qui pourra être utilisée en recherche et pour les ingénieurs comme un outil préliminaire pour déterminer le comportement à long terme de divers types de roche.

1 INTRODUCTION

As discussed in the literature (time-dependent behavior usually refers to the rate-dependent behavior, creep or delayed fracturing and long-term strength reduction (Malan 2002) which commonly occur in clay-rich and argillaceous rock materials and salt cavities (Cidivini et al. 1979, Ottosen 1986). However, time-dependnet deformations have been reported in the last century in tunnels and underground works excavated in rockmasses that are present in high in situ stressed environments usually in great depths or heavily sheared weak rockmasses (Barla 1995, Bhasin and Grimstad 1996). Time-dependent strength degradation and creep behavior can be observed in stronger (brittle) rocks as well and in general, this phenomenon warrants further investigation for rock and understanding of its characteristics.

According to Aristorenas (1992) there are two distinct types of deformation: a) immediate, and, b) time-dependent. Immediate deformations may be caused due to the undrained elastic response of the rock mass to the excavation process and may also include elasto-plastic elements. However, rocks do not uniquely follow the laws of elasticity, plasticity or viscoplasticity. It is still important to determine the stress–strain relationship associated with rocks and the time-dependent strain in order to predict the mechanical behaviour of the rock types of interest. Several mechanical models have been suggested that may have a direct or indirect application to the description of the behaviour of the rock (Lama and Vutukuri, 1978). The numerical and analytical methods employed to define and predict time-dependent behaviour also warrant further investigation and improvements (Paraskevopoulou and Diederichs 2013a).

The primary focus in excavation design lies on the short-term behavior of rocks in association with the support performance; consequently, the engineering practice is commonly related with the short-term material properties. However, challenges may arise when dealing with complex in-situ stress conditions. The latter can be present during numerical analysis and simulations of the long-term behavior of underground excavations where time-dependency issues such as swelling, squeezing or creep take place. For instance, multiple mechanisms that occur simultaneously or empirically derived constitutive models that can be mechanistically unsound and/or impractical testing requirements for numerical modelling can lead to engineering challenges, yield incorrect results of the support system and false cost estimates of the project (Paraskevopoulou et al. 2015).

The purpose of this paper is to give an insight for the long-term behavior of brittle rocks that can be applied to engineering projects such as nuclear waste repositories with an emphasis on time-dependency. According to Damjanac and Fairhurst (2010) a better understanding of the rock deformability in the design and construction of nuclear waste repositories can aid to predict the ability of the rock to isolate the waste from the biosphere.

2 BACKGROUND

Time-dependent phenomena can be defined as mechanisms acting and weakening on the rockmass over time (Paraskevopoulou and Diederichs, 2013b). In the literature, the most widely discussed time-dependent mechanisms associated with tunneling are squeezing, swelling and creep. According to Barla (2001), squeezing is synonymous with yielding and time-dependence; it is closely related to the excavation and support techniques, which are adopted. This definition can lead to confusion (Paraskevopoulou and Diederichs, 2013a) and that it is important to note that a component of squeezing is a function of excavation staging (distance from the face), while another component is a function of time. As true time-dependent behavior may involve components of swelling, rock deforms with or without tunnel advance. If the support installation is delayed, the rockmass moves into the tunnel and stress redistribution takes place around it. On the contrary, if deformation is restrained through support, squeezing will lead to long-term load build-up acting on the rock support system.

Moreover, during the life span of an underground project other mechanisms of time-related effects may take place and influence and disturb the excavation damage zone (EDZ). Strength corrosion where the surface energy of a crack is reduced by atmospheric absorption and the stress propagating though a crack is reduced; visco-elastic reorganization where time-dependent (or anelastic) strains and ‘indefinite’ deformation is present and visco-platic yield during which time-dependent plastic strains take place that lead to permanent deformation and sometimes failure. The main characteristics that govern these mechanisms are consolidation, crystal rheology, internal slip, fracture growth, crystal weakening and damage propagation and require further investigation. Figure 1 summarizes three of the main time-dependent phenomena that influence the long-term behavior of rockmass around an underground opening. Creep is usually related with the closure of underground cavern whereas relaxation refers to the reduction of the stress with time and is controlled by the internal creep – deformation (transient creep under decreasing stress) and is driven by the stored elastic energy (Lin, 2006).

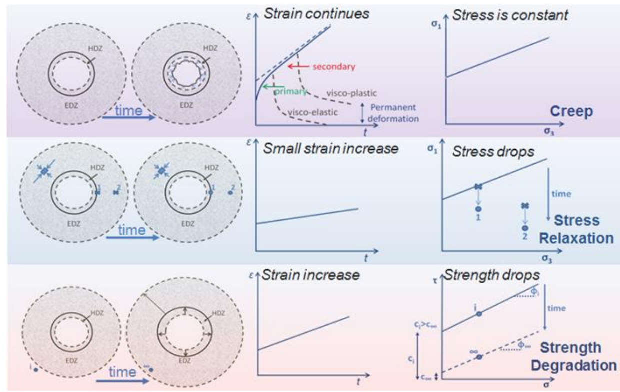

Figure 1. Three fundamental long-term effects (creep, stress relaxation, strength degradation) of the EDZ expressed in stain-time and stress space.

The analysis presented herein focus on the long-term response of rocks under constant loading or creep.

2.1 Creep of rocks

Creep is defined as the time-dependent distortion of rock under a sustained load that is less than the short-term strength of the rock or the irreversible deformation under constant stress over time or “flow”. Creep strain can seldom be recovered fully when loads are removed, and as such, it is largely plastic deformation that defines such behavior (Glamheden and Hokmark, 2010). The shape of the creep curve is typical and similar for all rock types (Figure 2).

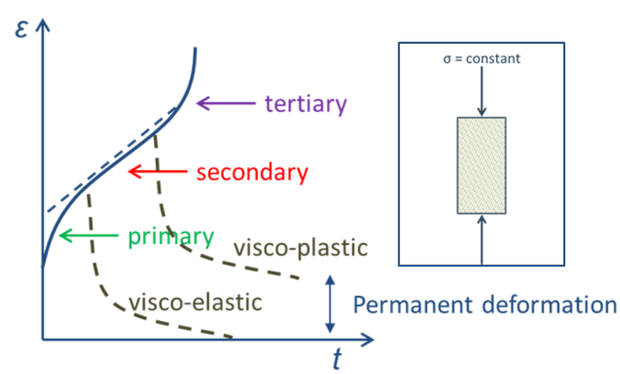

Figure 2. The three stages of creep (primary, secondary, tertiary) of a material subjected under constant load.

At the beginning, the elastic strain occurs instantaneously, as the load is being applied. Then, the applied load is kept constant and the rate of strain decreases; this period is called primary creep (or transient). It is worth noted that in certain types of rock, primary creep approaches a constant strain rate (almost steady rate), which determines the transition to the secondary creep (or steady). At the end of this stage, the material rapidly fails as the strain rate starts to accelerate which is called tertiary creep (or accelerated) and it is a characteristic for each rock type.

According to Hoek and Brown (1980) all materials will creep when subjected to the appropriate long-term loading conditions. Brittle rocks behave differently than softer rocks, where brittle rocks can support substantial deviatoric stresses more or less indefinitely at shallow depth. Hence, for brittle rocks, the creep processes are extremely slow or do not occur at the deviatoric stress magnitudes common for a shallow excavation. According to Glamheden and Hokmark, (2010) creep strain in intact brittle rock gives modest net deformations even after very long loading periods. Brittle rocks usually fail due to both the propagation and the coalescence of microcracks (Damjanac and Fairhurst, 2010). Shao et al. 2005 stated that the growth of microcracks affects the short – term strength of the rock but it can also lead or contribute to the time-dependent creep deformation and failure. Rheological models combined with the viscoplasticity theory describe time-dependent creep deformation as these models provide a mathematical framework; however, they do not take into account physical mechanisms related to microcrack initiation and propagation (Paraskevopoulou et al. 2015).

The degradation of the mechanical properties over time for various brittle rocks has been discussed in literature by many researchers (Bieniawski, 1967; Schmidtke and Lajtai, 1985; Kranz and Scholz, 1977; Lau et al. 2000). Therefore, the analysis herein aims to give more insight into the time-dependent behavior of rocks by presenting and discussing the results of a series of static load (constant) tests on limestone to improve the capability to estimate representative long-term strengths as the results are related to reported data on literature as an attempt to create and establish a database which can be used from researches and engineers.

3 DAMAGE EVOLUTION AND FAILURE OF BRITTLE ROCKS

Brittle failure process refers to loss of cohesion as friction is mobilized. Stress-strain curves for brittle rocks give information for crack initiation (CI), long-term strength and peak strength. The last two are sensitive to the amount of induced damage since the greater the amount of damage, the lower the long-term and peak strengths (Martin, 1997).

It is generally accepted that a progressive process governs the failure on brittle materials and is dominated by the growth of small cracks in the direction of maximum load. The stages of the failure process include at least four distinct stages that can be identified if the stress-strain response is monitored during a compressive loading process as shown in Figure 3, i.) crack closure; ii) linear elasticity; iii) stable crack growth; and iv) unstable crack growth and peak strength (the point of maximum stress).

Many researchers have performed experimental investigation and numerical simulation of crack propagation. Bieniawski (1967) reported that the main fracture was formed by the coalescence of favorably oriented microcracks induced by local tensile stress concentration. Lajtai (1998) studied the microscopic fracture processes. Eberhardt et al. (1999) investigated the effects of grain size on the initiation and propagation thresholds of stress-induced brittle fractures in crystalline rocks. Most of the studies however are constrained by the increasing loading experiments, and further analysis is required in understanding the damage evolution under constant loading conditions, which can be crucial during the design of an underground repository.

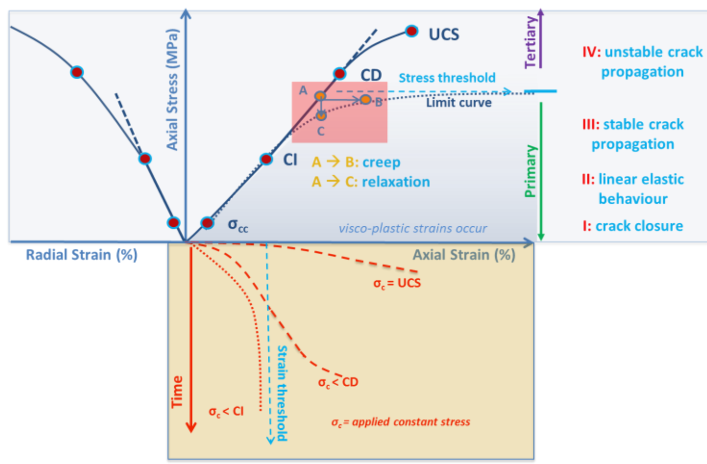

Figure 3. Schematic of the stress- strain response and stages of brittle rock fracture and onset of accelerating creep after a critical strain, (where: σ_{cc} – stress level during crack closure, CI – crack initiation, CD – crack damage, UCS – unconfined compressive strength).

Crack initiation (CI)) is noted at the beginning of the stage iii) during the stress-induced damage process in low porosity rocks, the cracks growing in a stable manner as an increase to loading do not trigger time-dependent crack growth under constant loading. The crack damage (CD) indicates that the formation and growth of cracks exceeds the elastic compression. Loading a sample above the crack damage threshold could initiate time-dependent deformation, lead to creep and result to sudden failure if the load is sustained. In addition, Cruden (1974) also showed that a critical strain could be related to the critical crack density of brittle rock due to the coalescence of cracks.

4 TIME-DEPENDING WEAKENING OF JURA LIMESTONE

According to Damjanac and Fairhurst (2010) specimens of crystalline rock subject to creep tests (sustained constant loading that is below the instantaneous compressive strength) — are found to collapse after a period of time. This study aims to examine the long-term behavior of Jura limestone by conducting a series of static load (constant) tests (Figure 4) and investigate if a stress threshold exists below which the rock will cease to deform.

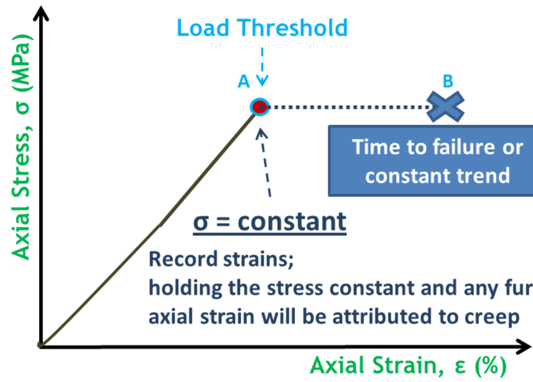

Figure 4. Static load (constant stress) test is used to examine the long-term (creep) behavior of Jura limestone while recoding the strain response.

4.1 Sample Description

The material selected comes from a quarry north of Zurich, Switzerland, in the tabular Jura Limestone (Figure 5). The samples are a fossile rich packstone, following the classification system of Dunham (1962), with variable sized vugs ranging from 0.1 – 3 mm and pyrite rich crystal patches. There are also lime-mudstone blebs ranging from 5 – 30 mm in diameter, mixed within the packstone framework. 55.6 mm diameter samples were cored from a block measuring 500 x 500 x 150 mm, such that the cores long axes (before grinding) were 150 mm long. All the samples were prepared according to the ISRM (1979) requirements.

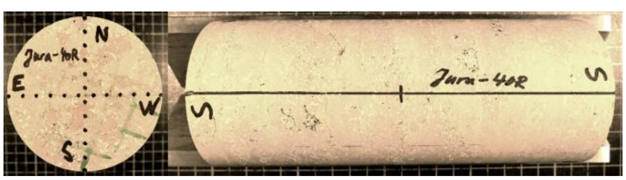

Figure 5. Jura Limestone samples.

4.2 Baseline Testing

Baseline unconfined compressive strength (UCS) testing was conducted on 10 cylindrical samples to establish the peak strength and other damage thresholds. The testing was conducted according to the ISRM guideline (1979).

The volumetric strain approach was used to determine the damage thresholds. CI was determined according to Martin and Chandler's (1994) approach where CI was determined as the reversal point of the crack volumetric strain. The crack volumetric strain is determined by subtracting the elastic volumetric strain from the volumetric strain. The Crack Initiation (CI) threshold varies typically between 30 to 50 % of the UCS for different rocks (Brace et al. 1966). Critical Damage (CD), the crack coalescence and interaction threshold; was determine as the axial load at the volumetric strain reversal point when subjected to compression. Bieniawski (1967) stated that it is the point of unstable crack growth, typically occurring between 70 and 85% of the peak strength. The results in stress – strain space from the 10 UCS tests are shown in Figure 6.

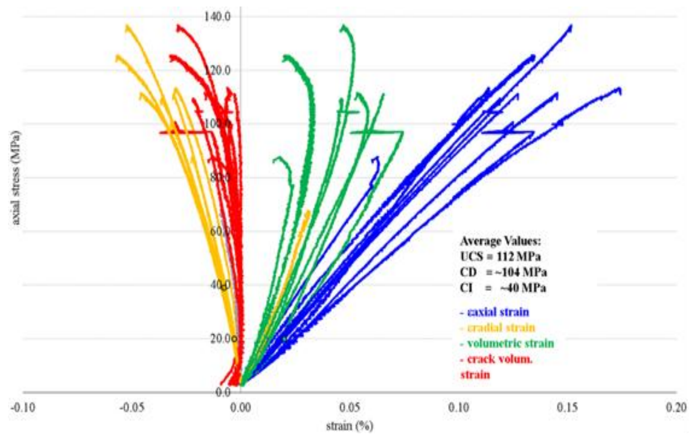

Figure 6. Stress-strain response of 10 Jura Samples tested in Unconfined Compressive Strength conditions.

4.3 Static Load Testing

Eight static load tests were conducted on Jura Limestone at different stress levels; the strains and the time to failure (how long the material is subjected to a static load until it fails) were monitored. Figure 7 shows the results of the testing results and the stress level for each test was normalized to the average UCS from the Baseline testing defined as the driving stress-ratio.

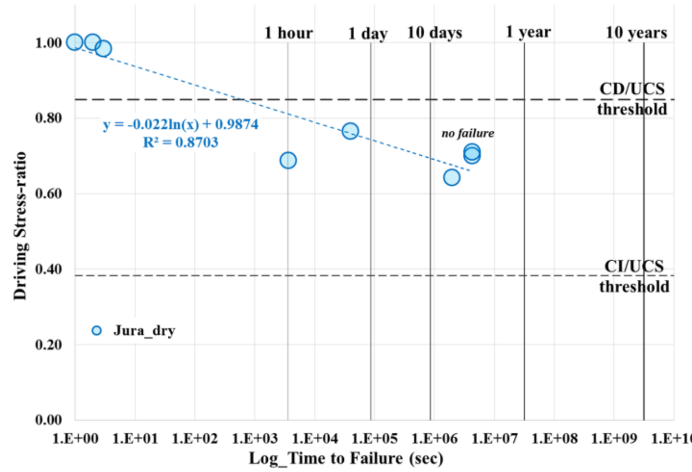

Figure 7. Creep test data for Jura Limestone performed at room temperature and dry conditions (where the driving stress-ratio is the stress level at failure to unconfined compressive strength of the material).

It should be sated that the tests performed and the data presented refer to unconfined conditions. For the dry samples: if the applied axial stress is higher than the 0.8σc, failure occurs within the first hour and if the applied axial stress ranges from 0.8 to 0.6 σc failure occurs during the first hours to a day. Schmidtke and Lajtai (1985) reported similar findings. Interesting is however the fact that current tests at a stress level of 0.7σc have not reached failure even after 50 days of constant loading.

5 DISCUSSION

These results are compared to other data from static load tests performed on brittle rocks in relation to the failure time, how long the material is subjected to a static load until it fails. Figure 8 illustrates that Jura limestone shows a similar trend with the other data and more specifically of LdB granite when it is subjected to similar stress conditions, which can be extrapolated to a million year life span. However, further testing and analysis is required to support the findings presented herein. Interesting is the fact that no test presented herein is performed below 0.6σc stress level.

Figure 9 shows the data from different types of granite reported in the literature.

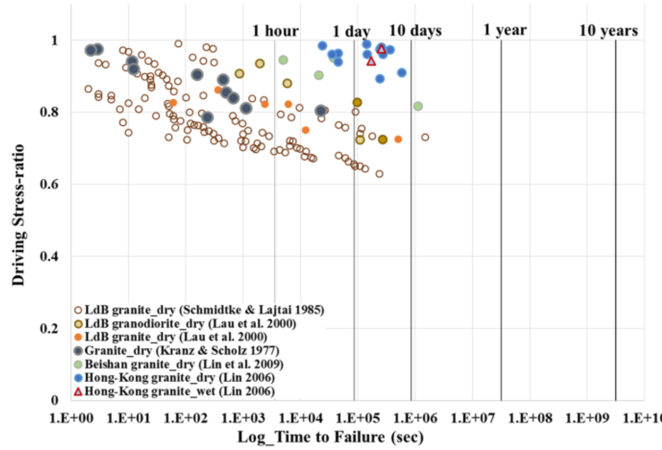

Figure 9. Creep test data for different types of granite performed at room temperature (where the driving stress-ratio is the stress level at failure to unconfined compressive strength of the material).

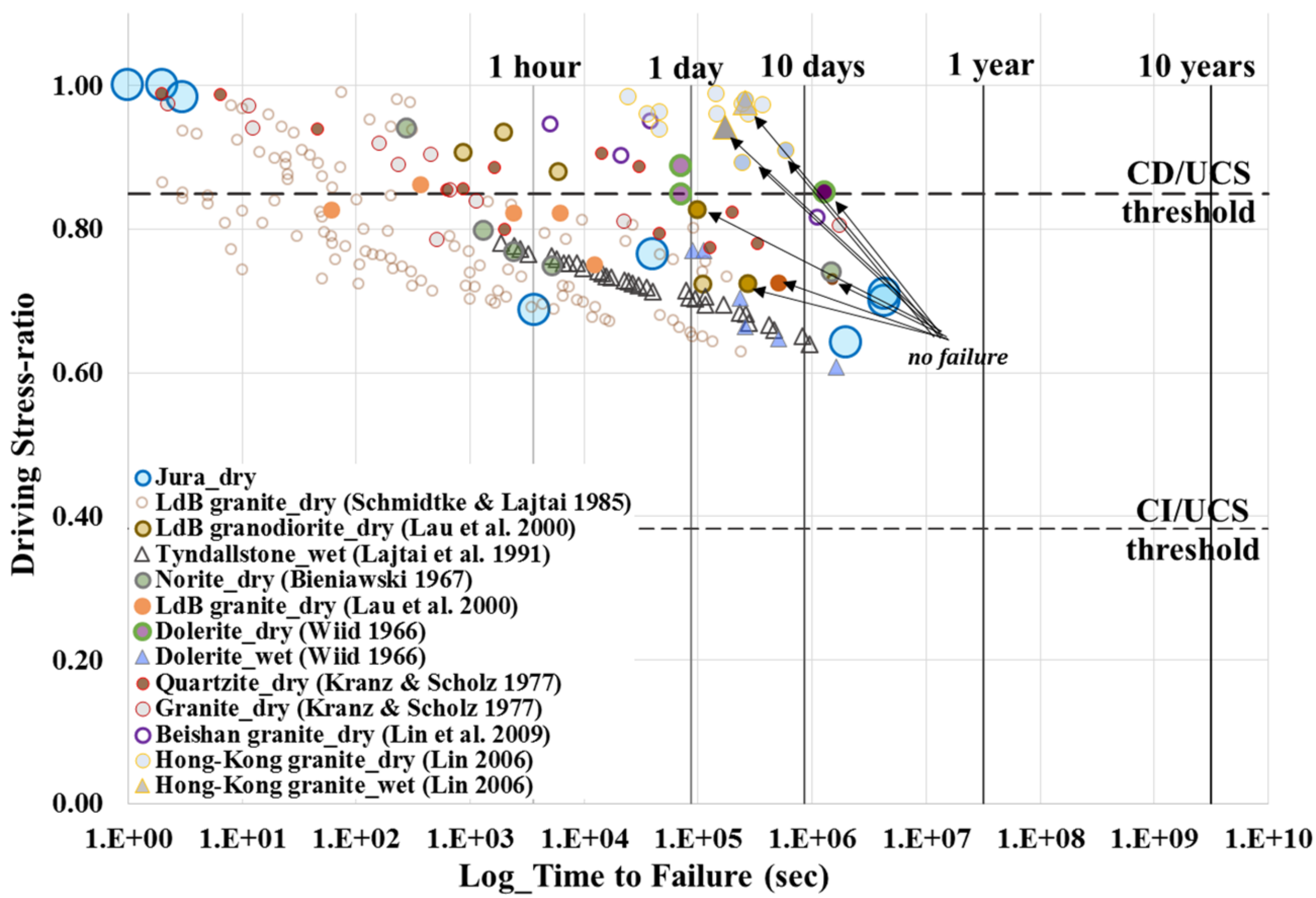

Figure 8. Creep test data for brittle performed at room temperature in wet or dry conditions (where the driving stress-ratio is the stress level at failure to unconfined compressive strength of the material).

The influence of moisture in the long-term strength of brittle rocks is shown in Figure 10 a. & b. For the wet samples: the failure occurs at stress level below 0.8σc and the lowest stress which failure occurs was at 0.60σc.

Wiid (1966) reported the water aids the failure process and moisture affects the time-dependent aspects of the long-term strength, as moisture lowers the surface free energy in the path of the growing cracks Colback and Wiid (1965). However, if the loading rate is too fast, moisture will not have time to migrate to the crack tips and will not affect the rock' strength. As Widd (1970) reported moisture increase leads to strength reduction reflecting the primarily decrease in the molecular cohesive strength of the material.

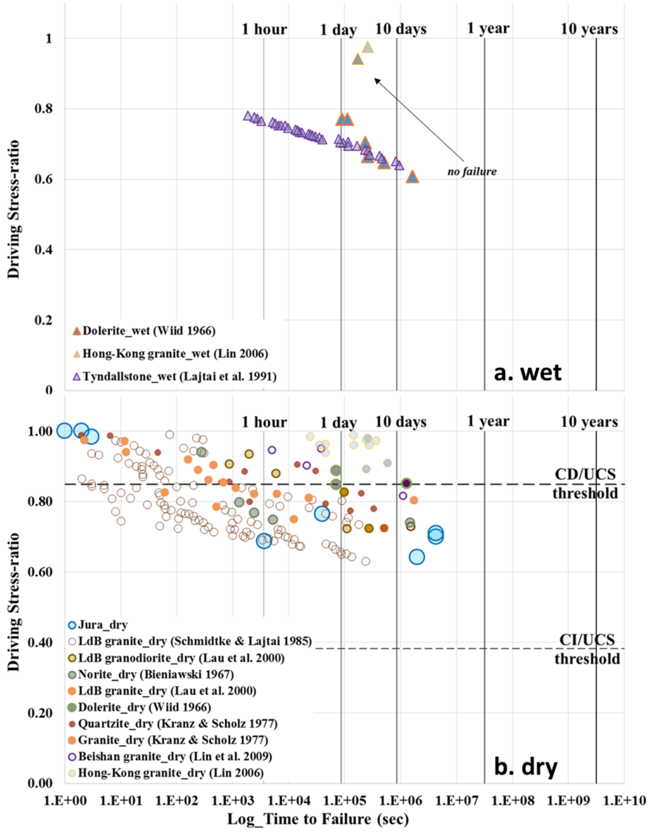

Figure 10. Creep test data for brittle performed at room temperature a.) in wet and b.) dry conditions (where the driving stress-ratio is the stress level at failure to unconfined compressive strength of the material).

6 CONCLUDING REMARKS

The analysis presented herein aimed to show the existence of time-dependent phenomena with emphasis to creep in brittle rocks. This paper also examined the existence of a stress threshold below which the rock deformation will be terminated. Evidence of such possibility is presented in this paper; however, further analysis is needed for more reliable conclusions to be made.

From the data presented the following should be highlighted; for the dry samples: if the applied axial stress is higher than the 0.8σc, failure occurs within the first hour and if the applied axial stress ranges from 0.8 to 0.6 σc failure may occur during the first hours to a day and for the wet samples: the failure occurs at stress level below 0.8σc and the lowest stress which failure occurs was at 0.60σc as moisture and water presence affects the long-term strength.

Finally, this study tries to give more insight of the long-term behavior of brittle rocks as an attempt to create and establish a database, which can be used from researches and engineers as a preliminary tool to determine the long-term behavior of various rock types.

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