Long-term stress-strain response of chalk: a micro-mechanical interpretation

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ABSTRACT A long-term laboratory test programme of conventional compression and extension tests was carried out with test durations from 8 to 22-months, in a purpose built environmentally controlled facility, with specially designed loading frames and modified triaxial cells. In addition, Scanning Electron Microscope (SEM) techniques were employed in an effort to investigate the micro-mechanical response. Creep strains appeared to trigger an ageing process that produces elevated post-creep strength and stiffness irrespective of the applied stress path.

1 INTRODUCTION

There has been, and continues to be, extensive infrastructure development in the chalk of the Anglo-Paris Basin (e.g. Channel Tunnel, Channel Tunnel Rail Link, Thames Tideway, Lower Thames Crossing). These large civil engineering projects have highlighted the need for a comprehensive understanding of the material behaviour, and in particular the requirement to predict the time-dependent response (or creep) of the chalk (see Watson et al., 1999 and 2001). Within the time frame of large civil engineering projects, it is not always possible to evaluate the creep aspects of chalk. Consequently, prediction of the long-term response is usually based on data obtained under relatively short-term testing (of the order of a few months) that may not accurately reflect chalk's rheological behaviour. It is also well known that the behaviour of geomaterials is governed by their initial state as well as their loading history. Consequently, in any laboratory study it is desirable to replicate conditions in the test samples that match as closely as possible those experienced *in situ*.

Several studies have examined both the short and long-term behaviour of chalk, but generally concentrated on the effects of high confining stress levels, more relevant to hydrocarbon reservoir conditions (investigating the subsidence of North Sea oil fields; see De Gennaro et al., 2003; Hickman, 2004). There remains less information on the behaviour of chalk at lower stresses which are relevant to many civil engineering projects, such as tunnels, foundations and slopes.

Chalk is a frictional cohesive material with a complex overall mechanical behaviour primarily attributed to its sedimentary anisotropic nature, and controlled by the applied stress regime. Many researchers proposed that chalk displays three 'macroscopically independent' yield mechanisms, namely shear failure, pore collapse, and tensile failure. The shear failure is active at relatively low mean stress and high deviator stress. Pore collapse at relatively high mean stress and low deviator stress. Tensile failure occurs when one of the normal stress components becomes sufficiently small or tensile. The term 'macroscopically independent' is used because other workers (e.g. Risnes, 2001) suggested that all three yield mechanisms are fundamentally the same and triggered by shearing between the chalk grains in the microscopic level.

In order to investigate the micro-mechanical behaviour of chalk Scanning Electron Microscope (SEM) studies have been reported by several researchers (Mortimore & Fielding 1990; Petley et al 1993; Kågeson-Loe et. al 1993; Powell & Lovell 1994). In these studies, the fabric evolution under a variety of short-term loading conditions, was examined and correlated to the macroscopic response. A generalised conclusion to these studies is that the rearrangement of the chalk fabric constituents is a precursor of the macroscopic material deformation, which is evidently only possible if grain bond strength reduction or failure occurs beforehand.

The research presented here aims to investigate chalk behavior, and in particular the long-term response at stress levels typically encountered in civil engineering projects (σ_3<1MPa). An attempt is made to interpret the experimental results within a micromechanical framework (Bolton et al 2008).

2 EXPERIMENTAL STUDIES

Both short and long-term drained stress path tests were conducted on 38 mm diameter chalk cores. The response of geomechanics materials is known to be different under conditions of uniaxial compression and tension, and thus the specimen will be dependent, at least in part, on the stress path experienced. In particular the stress paths associated with reduction in confining stress are particularly relevant to the in-situ conditions in the vicinity of tunnels, underground constructions and natural or engineered slopes (Stone et al. 2003).

Table 1. Stress paths applied in experimental study.

Type of test	Confining stress	Axial Stress
1 - Axial Compression	Constant	Increasing
2 - Lateral Compression	Increasing	Constant
3 - Lateral Extension	Decreasing	Constant
4 - Axial extension	Constant	Decreasing

In the test programme reported here, stress path tests were carried out using a range of stress paths to simulate a variety of in situ situations associated with loading and unloading of the ground, for example the material immediately adjacent to the side of a tunnel will experience a reduction in lateral stress with a fairly constant axial stress. A summary of the applied stress paths used in the study is presented in Table 1 above.

The short-term test programme was undertaken using a conventional triaxial apparatus capable of applying only axial compression and extension tests (i.e. test type 1 and 4 in Table 1)

The long-term tests were conducted in a modified 'balanced ram' triaxial apparatus (Stone & Katsaros 2008) with axial loads applied via a cantilever loading frame.

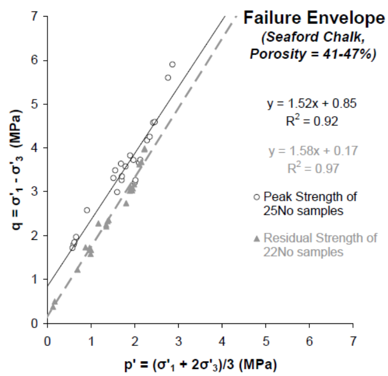


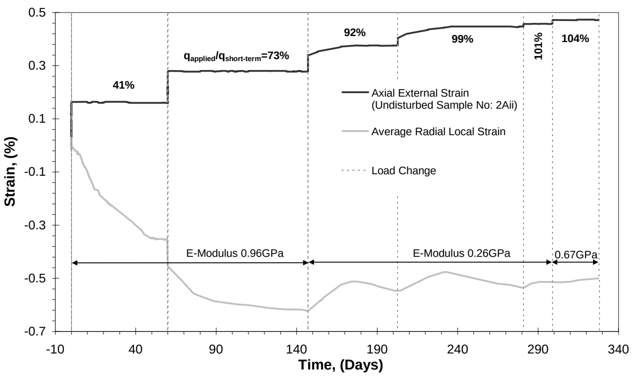
Figure 1. Short-term peak and residual strength envelopes as derived from conventional triaxial compression tests.

2.1 Short term tests

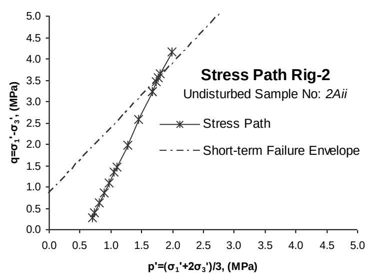
The short-term test results were undertaken to benchmark the strength of the chalk used in the long-term test programme. In the following plots, presenting the long-term material response, the applied load at any time is related to the ultimate short-term strength of the material derived from conventional triaxial compression tests. Although the long-term tests followed a variety of stress paths, failure was ultimately induced in all tests while the sample was following a conventional compressive stress path. Consequently the conventional compressive failure envelop is used to relate the stress state at any point in the long-term test to the predicted ultimate peak strength as determined by the short-term failure envelope, refer to Figure 1. Furthermore the strength of the samples obtained at the end of the long-term testing can be compared to the strength of the short-term tests to establish any increase or decrease in strength as the result of the creep process.

2.2 Long term tests

An overview of two long-term tests conducted on Seaford Chalk are presented below, full details of the complete test programme can be found in Katsaros (2008).



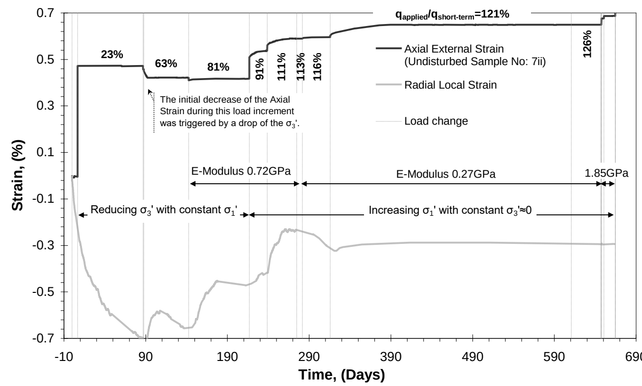
a)



b)

Figure 2a. Overview of long-term conventional compression test and b) associated stress path.

Figures 2a and 3a show the long term response in terms of axial and radial strain for the duration of the test. The stress path followed in each test is shown in the corresponding Figures 2b and 3b. The test presented in Figure 2 followed a conventional compression stress path and lasted for a total of 340 days. The post-test strength of the sample was seen to be greater than the predicted strength based on the short-term failure envelope. The test presented in Figure 3 initially followed a lateral extension stress path for approximately 214 days and then a conventional compression stage for 450 days with the sample under test for a total of some 665 days. In this test the post-test strength was significantly greater than the short term predicted strength based on the intersection of the final stress path stage with the short-term strength envelope, refer to Figure 3b.



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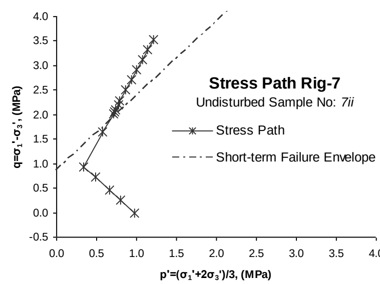

b)

Figure 3a. Overview of long-term extension/compression test and b) associated stress path.

A total of 8 long-term tests were conducted from which the following general observations regarding the long-term response of chalk at relatively low stress can be made:

i. It was generally observed that radial dilatant strains were exhibited during the early phases of loading where little or no axial creep strains were observed. The onset of axial creep strains was seen to be co-incident with a significant reduction or cessation of radial creep strains. After completion of the axial creep strains, radial creep strains were again observed in most cases (see Figures 2 and 3).
ii. Axial expansion was observed in specimens that were subjected to lateral extension and axial compression stress paths.

iii. Discernable axial creep strains were observed at 90% or higher of the expected short-term peak strength.
iv. Negligible axial macroscopic creep strains were observed for samples subjected to axial extension stress paths, and only very small axial creep strains were observed at ~80% of the short-term peak strength under lateral extension.
v. The axial creep strains were small. The maximum creep strain observed being 0.065% (under conventional axial compression).
vi. As specimens approached failure lateral displacement of the samples ceased and no radial strains were recorded.
vii. Higher post-creep strengths (ageing) are attained for longer test periods irrespective of the applied stress path.
viii. Higher deviatoric stresses result in increasing creep rates.

3 SEM ANALYSIS

A comprehensive Scanning Electron Microscope (SEM) study of the chalk fabric was undertaken both before and after the short and long term testing. This examination has been used to present a qualitative micro-mechanical model with which to interpret the macro-behaviour observed in the long-term tests. The initial phase of the SEM study was to characterise the fabric of the chalk prior to testing so that the effects, if any, of the testing regime could be identified. Figure 4 shows typical SEM images of unsheared material and sheared material. These images illustrate that the fabric texture away from the macroscopic shear planes (Figure 4a) that developed in the long-term compressive test is similar to that for an untested 'control' sample extracted from the same block of chalk adjacent to the source of the test sample (Figure 4b).

The fabric of the short and long-term shear planes is shown in Figures 4c and 4d respectively, and reveal a loose amorphous arrangement with the pore space partly occupied by the segregated and recompacted grains that tend to overlie each other. The long-term test appears to show some evidence of recementing, and in both cases it is noted that some coccoliths remain intact, suggesting that their different types exhibit varying grain bond strengths (Mortimore & Fielding, 1990), such that the stronger ones remain undamaged even after the sample failure.

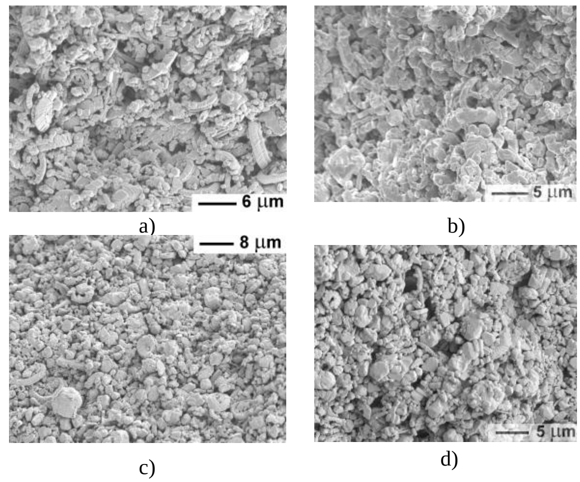

Figure 4a). Fabric in untested control sample and b) post long-term test away from shear zone and on shear zone in c) short-term and d) long-term test.

The SEM study also revealed the presence of clusters of grains in sphere-like or flaky forms of approximately 1-6µm in size (Figure 5). The cause of these is not readily apparent, though it can be postulated that given a large enough time scale (geological timescale) high stress concentration and consequent reduction of the overall pore space may have resulted in grains merging and cementing/welding to form clusters (see also Mortimore & Fielding, 1990).

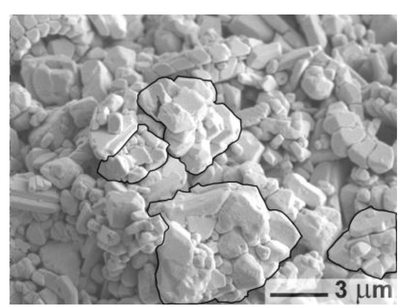

Figure 5. SEM image of typical 'cluster' features in fabric.

A similar effect is observed in aged sands that have the innate tendency to cluster with time, and thus improve their shear connections without necessarily any grain-to-grain cementing taking place (Bowman, 2002).

Clustering is observed in both intact and post-tested material. It is possible that the testing conditions could influence/alter or even induce further clustering. Since clusters are present in the pre-tested natural fabric then it is likely that the weakest clusters disintegrate during stress application, whilst the strongest ones remain bound in the post-tested state.

The SEM study was extensively reported in Katasaros 2008, with some very limited images being presented here. However based on the complete study the following observations can be made which are further utilised in the simple qualitative micro-mechanical model presented in the following section.

i. The higher the post-creep strength the higher the tendency for clustering. This suggests that clustering is somehow associated with the creep and ageing of chalk.
ii. It is possible that long-term testing is accompanied by dissolution and re-cementing. However, it was only observed within small vicinities (roughly less than 5% of the total surface investigated) under SEM, and thus would be of minor significance to the overall creep/ageing effect.
iii. More pervasive fabric transformation is noted for samples with higher post-creep strengths. It is suggested that this general response is probably affected by the duration of creep testing and/or the applied stress state, and may contribute to a potential strengthening mechanism.
iv. The individual grains, nannofossils, and grain clusters are all considered as chalk ‘particles’. The particle cataclasis contributes towards the overall chalk deformation mechanism. The individual calcite grains can be regarded as the strongest particles that do not break down under low confining stress regimes.

4 MICRO-MECHANICAL INTEPRETATION

One approach to developing constitutive relationships that describe the behaviour of a material is to link the macroscopic response to the microscopic deformation mechanisms that are ultimately responsible for the material behaviour. Combining the results and observations from the experimental programme, with observations of the SEM study, it is possible to postulate a qualitative micro-mechanical interpretation of the macroscopic response of chalk.

Essentially the deformation of chalk consists of consecutive stages (controlled by the externally applied stresses) of grain bond strength reduction followed by friction-limited mechanical rearrangement of the loose disaggregated particles that infill the pore space until stress redistribution reaches an equilibrium (Andersen et al., 1992; Monjoie et al., 1991). This mechanism eventually reduces the size of the weaker chalk particles, such as clusters and nannofossils, resulting in a material that tends towards a cohesionless/particulate state, which in the limit, would consist primarily of unbonded Calcite grains. This general response is confirmed through the SEM observations, on and adjacent to, the zones of localised deformation that develop in chalk samples at failure.

In Figure 6 the matrix of an area of undisturbed chalk is digitally manipulated to demonstrate a stochastic micro-mechanical deformation (Figures 6b and 6c) that visualises the sequence of grain bond strength reduction followed by the frictional rearrangement of the calcite grains with compaction occurring in the direction of the arrows.

In Figure 6a, the fabric is an open pore structure of limited grain boundary contacts and insignificant interpenetration. Figure 6b demonstrates the initial cataclasis of some of the coccoliths and subsequent pore infilling through frictional sliding and rotating of calcite particles. The total deformation applied in Figure 6b is roughly 1μm which corresponds to approximately to 8.7% strain. This is far greater than the overall external strain observed during short and long-term loading (typically less than 1%).

It is apparent that the pre- and post-tested fabric away from the shear plane is similar, and thus the externally measured strain is concentrated in the vicinity of the shear plane. The local strain associated with the degree of compaction observed on shear planes is of the order of 8-9% according to the scaled vectors of Figure 6.

Figure 6c illustrates the fabric change associated with further deformation in the vicinity of a zone of localised deformation leading to complete particulation. Stronger nannofossils remain intact, as shown in the top right and left corners. Furthermore, the development of numerous contact points and high interpenetration leads to particle clustering with enhanced frictional interlock.

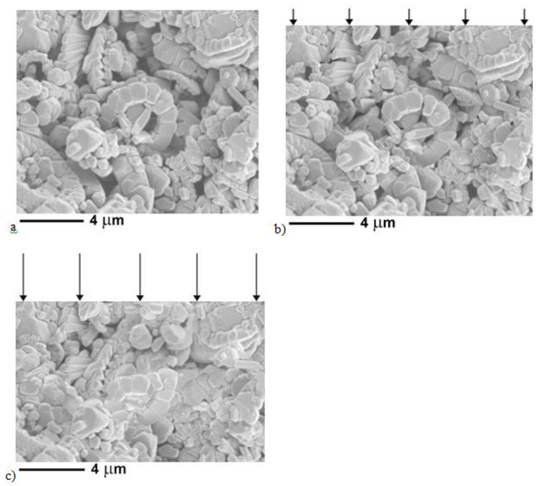

Figure 6. Stochastic fabric evolution. a) Undisturbed fabric state, b) fabric subsequent to load application, c) failed sample. Arrows represent the load application and overall deformation.

The fabric condition shown in Figure 6c is similar to that observed on highly compacted shear planes of long-term samples that failed at peak strengths above the short-term failure envelope. The total deformation applied in the simulation of Figure 6c is approximately 3 μm and corresponds to a normal strain of about 24.8%.

The stochastic simulation of fabric evolution of Figure 6 illustrates the deformation required at a micro scale to achieve certain fabric states within a chalk which are responsible for observed macroscopic strains.

4.1 Long-term test; micro-mechanical interpretation

With reference to Figure 2a a qualitative micro-mechanical interpretation of the creep mechanism of granular materials described by Bowman (2002) and the strong and weak force networks described for example (Bolton 2000; Potyondy & Cundall 2004), refer to figure 7, are used to interpret the long-term deformation mechanism of chalk.

In the long-term tests the increments of constant load application allow the gradual development and evolution of the contact force network. The gradual time dependent and friction limited rearrangement of 'loose' particles, will take place driven by the weak contact force network. This rearrangement continues until a structural equilibrium is attained, and the strong network columns gain adequate propping to stop them from further buckling.

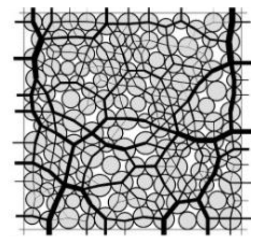

Figure 7. Schematic representation of contact force network after Potyondy and Cundall 2004 (thick lines represent strong network columns)

The macroscopic outcome of this response is depicted in the early load increments (at 41% and 73%) shown in Figure 2, and manifests itself through the observed dilation indicated by the radial strain measurements. The dilation rate is at a maximum at the onset of each load increment where rearrangement of the contact force network and opening of voids takes place. This is followed by the gradual re-propping of the strong network columns and the return of structural equilibrium that causes the reduction and eventual cessation of the dilation as seen at the end of the 73% load increment.

However, if a load increment exceeds the buckling capacity of the archaic strong network columns, it will trigger their localised failure. Although it is possible that most of the strain energy stored within the grain bonds of the buckling columns has already been released during the gradual reduction of the buckling (dilation) rate as observed at the 92% load increment. At the same time, the neighbouring particles that resumed increasingly locked positions provide lateral propping to the buckling columns. Consequently, when localised buckling failure of the strong columns occurs under long-term loading it is followed by caving and filling of the dilatant voids. This is observed as lateral contraction noted when the locally buckled columns release their energy by 'springing back' during the 92% load increment of Figure 2.

At the same time as lateral contraction, the segregated loose particles within the failed areas around the strong network columns may also exhibit a tendency to cluster, and the space freed is filled, triggering some localised compaction in the major principal stress direction (axial) around the failed areas of the archaic strong network columns. This rearrangement and compaction process is responsible for the small creep strains that develop at high load increments (92% and 99%).

The proposed long-term micro-mechanical creep deformation mechanism is associated with the fundamental tendency for the material entropy to increase through clustering. This is in agreement with the SEM study which reported that post-creep samples exhibited notably more clustered particle arrangements in comparison to those tested under short-term conditions.

Creep deformation will gradually subside as the open voids are occupied, and stabilise when a frictional equilibrium is attained through increased particle interlock. Higher post-creep strengths result from greater particle interlock triggered by the creep process.

5 CONCLUSIONS

Using the suggested mechanism of deformation for granular mediums (Bowman, 2002; Bolton, 2000; Monjoie et al., 1991) a qualitative stochastic model of micro-mechanical deformation of chalk, where particles are composed of clusters, intact/overgrown nannofossils and individual calcite grains, has been presented and applied to the interpretation of the long-term response of chalk. The dilation, creep and ageing of chalk observed macroscopically are related to the microstructure evolution based on supporting evidence from SEM observations.

It was established that failure is localised near the shear zones during standard short-term tests with low or no confining stress, but is somewhat more pervasive during long-term creep tests. This is related to the network of contact forces between the chalk fabric constituents (particles) that are responsible for the strain accumulation and overall deformation. Grain bond strength reduction was acknowledged as the prerequisite for creep to take place, and creep was associated with changes in the material entropy, and was identified as an ageing effect for chalk.

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