A look into time dependent behaviour of clays at macro and micro scale

Une étude du comportement dépendant du temps des argiles aux échelles micro et macro

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ABSTRACT: This paper aims to analyze and combine the mechanisms that occur at micro and macro scales during 1-D consolidation of clays. In this study, the approach by Yin (1999) was used to interpret time dependent action during creep phase of a specifically designed 1-D consolidation test program. This phase of the study gave a creep rate parameter, (ψ/v) which is itself a characteristic feature of time dependency and also well-accepted to carry the implications of micromechanical changes. In addition to obtaining the creep rate parameter, a quantification process was applied on micrographs that were taken at different consolidation stages and load increments of the 1-D consolidation test. This process was facilitated to find a micro-scale parameter defined as PF (Percent Finer). The possibility of existence of an interrelationship between ψ/v, and PF was then searched for as both of these parameters vary with respect to creep time. A strong correlation with a direction, either positive or negative, depending on the applied load increment was found. However, it should be noted that the number of data points are quite a few and a greater number of data points and data sets may be required to ascertain the validity and reliability of a correlation. Nevertheless the developed relation seems to be promising.

RÉSUMÉ : Le but de ce papier est d'analyser et de combiner les mécanismes de déformation qui se produisent pendant la consolidation 1-D des argiles aux échelles micro et macro. Dans cette étude, L'approche de Yin (1999) a été utilisé pour interpréter la réponse dépendant du temps des argiles lors de tests spécialement conçus de fluage-consolidation 1-D. Cette étude nous a fourni le paramètre (ψ/v) qui est une caractéristique de la réponse dépendant du temps des argilites et représentant, comme il est communément admis, les effets des changements de la microstructure. En plus, une analyse quantitative des micrographies, prises à différents niveaux de consolidation et de charges, a été menée qui a permis d'identifier un paramètre microstructural PF (Pourcentage de Fines). Une possible corrélation entre les deux paramètres ψ/v et PF qui évoluent au cours du fluage a été recherchée. On a trouvé une forte corrélation qui peut-être positive ou négative selon l'accroissement de la charge appliquée. Il faut noter que le nombre de points de donné n'est pas suffisant pour assurer la validité du résultat de manière fiable. Cependant, la relation trouvée entre ces deux paramètres paraît très prometteuse.

KEYWORDS: creep, time dependency, micromechanics, ESEM, micrographs, clay structure, consolidation.

1 INTRODUCTION. FIRST LEVEL HEADING

Research on the constitutive behavior of clays revealed the important influence of micromechanical processes on the stress strain behavior. Current studies mostly focus on either observing micromechanical processes such as anisotropic fabric orientation, structuring – destructuring - restructuring phenomena or using macro-mechanical measurements to search for the implications of micromechanical behavior.

Research on the microstructural changes during consolidation attracted special attention and most of these studies investigated the variation of fabric and/or structure with respect to the state of stress (Mitchell 1993, Collins and McGrown 1974, McConnochie 1974, Smart and Tovey 1982, Delage and Lefebvre 1984, Adamcewicz et al. 1997, Hicher et al. 2000). In these studies, internal fabric and/or structure were usually defined in terms of a parameter found through a quantification method based on image processing applied on micrographs. These parameters are then facilitated as the tools to interrelate micro and macro behavior. On the other hand, time effects on the stress-strain behavior of soils cannot be overlooked in a study concerning micromechanical changes occurring in connection with any type of stress path application.

Following Šukjle's study (1957), recent research provided significant scientific evidence on the time dependent behavior of soft clays and showed that the differences in the strain rates cause changed consolidation processes as an indication of time dependent behavior. Strain rates are high just after increasing the load but decreases with time and strain develops. This implies that as the rate changes fabric also shows variation. Although, time-dependent behavior is not specific for the secondary compression stage (Leroueil 2006) creep models are usually preferred, as, they reflect time dependency directly. In this context, Yin (1999) proposed a nonlinear creep function, which involves time dependent creep parameter and has a limit state at infinite creep time. This modified version of classical empirical approach is simple and can be used in advanced general time dependent constitutive models.

Although extensive research has been conducted and important achievements have been realized regarding time dependency, there is a lack of consistency in the studies that try to combine the micromechanical observations with macro-mechanical measurements. This paper aims to analyze and combine micro and macro structural mechanisms that occur during 1-D consolidation of clays. In this study, a new approach for interpretation of time dependent behavior of clays is introduced. This method incorporates fabric change due to creep process with creep rate parameter. In the context of the presented research 1-D consolidation tests were conducted during which micrographs were taken at different stages and load increments. The results of the 1-D consolidation tests were then analyzed in accordance with the purpose of this study. The analyses were carried out with a dual approach both by displaying the applicable time rates encountered during consolidation and also by quantifying the micrographs taken at some specific times and stages of consolidation.

2 EXPERIMENTAL METHOD

One dimensional consolidation tests were conducted with commercial kaolinite. Reconstituted kaolin clay slurry specimens were prepared at 26% water content, compared to the liquid limit of 22%. The test programme was composed of 15 consolidation tests. These fifteen tests can be grouped into five, according to the five different maximum stress levels that were applied at the end of the tests, which were 20, 50, 100, 200 and 400 kPa's. In addition to this grouping, three sub-groupings were defined according to the duration of application of maximum stress levels; which are 15, 1440 and 4320 minutes. In each of these tests, starting with an initial stress level of 2.5 kPa, loading increments were increased with a ratio of 2, and each was sustained for 24 hours. At the maximum vertical pressure stage specific to the group, (the tests were ended abruptly for sampling at different times (15, 1440 and 4320 minutes) for each of the five samples that constitute one test group. Dimensions of the samples extracted at the end of these durations is1cmx1cm. Retrieved vertical undisturbed specimens were used in the ESEM analyses. Thus, there were 15 specimens to be used for observation of the micro behavior, each having different "consolidation level-maximum consolidation pressure" combinations. Three photographs were taken from each of the specimens and thus in total there were 45 photographs to be analyzed. Image analyses were conducted to investigate the implications of the influence of both the load increments and consolidation degrees on the micromechanical behavior.

3 IMAGE ANALYSIS

3.1 *The Method*

Image processing was conducted using the open source program ImageJ (Rasband 2009). Isodata threshold algorithm of 256 grey level images was used to distinguish clay aggregates from inter-aggregate voids. Brightness value of pixels above the threshold was established as indicating clay aggregates. This image was then converted to a binary image in which black and white represents clay aggregates and inter-aggregate voids respectively. The pixel size in the ESEM micrographs was $8.47*10^{-2}$ µm which corresponds to a size in the range of large enclosed pores within groups (macro voids). Binary images were segmented by the watershed function. Using this analysis, particles of all recordable sizes can be detected (Yigit 2010, Yigit and Cinicioglu 2011). Photographs show the planes that have normal, orthogonal to the loading direction, therefore reflect the positioning of the particles on the vertical plane. A raw photograph and its processed version are shown in Fig.1.

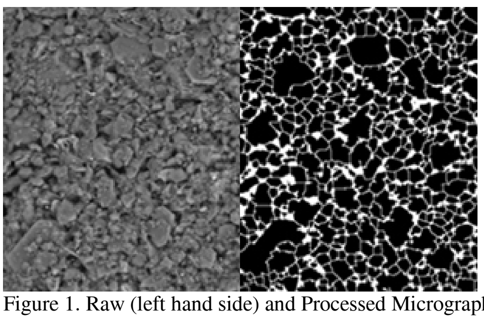

Figure 1. Raw (left hand side) and Processed Micrographs.

3.2 *Interpretation of structure in terms of clump sizes*

The gradation curves were found by applying a technique similar to that used in the presentation of sieve analyses results, but in this case the application was conducted on digitized micrographs. In this context, discrete clusters were detected and then grouped in the order of their areal sizes. The applied range for particle areas is between 0.1-100 μm^2. By dividing the total area of each size group to the total area of the entire clusters, "per cent retained" values were found and the cluster gradation curves were drawn in terms of per cent passing against area sizes in decreasing order, for a specific loading duration, as shown in Figs. 2.a and 2.b for load durations of 15, 1440 and 4320 minutes.

In order to analyze the gradation curves, in terms of degree of fineness, a threshold cluster size was chosen and the per cent passing value corresponding to the chosen clump size was defined as Per cent Finer (PF), to give the percentage of clusters finer than the threshold. Therefore increases in PF values are associated with disintegration into finer sizes and decreases are associated with clump formation into larger sizes. Fig. 2.a and 2.b give two different tendencies in cluster size variation. For load increment of 20 kPa in Fig. 2.a, clusters become finer with increasing load duration but in Fig. 2.b, for 100 kPa load increment, a reverse order is apparent; implying clump aggregation as the time proceeds. It can be argued that, the variation in cluster sizes is influenced by the stress state, time and the initial structural state respecting to the starting state of the current load increment.

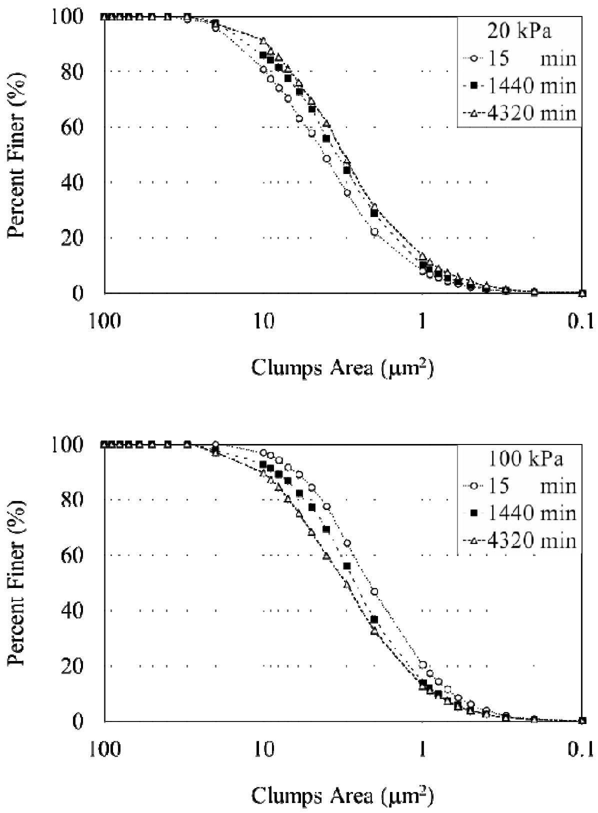

Figure 2. Variation of clump gradation curves for (a) 20 kPa and (b) 100 kPa load increments with loading duration.

4 TIME DEPENDENT BEHAVIOUR

Yin (1999), suggested a non-linear creep function with a limit creep strain. The function proposed by Yin (1999) and reproduced in Eq. 1 is advantageous due to its ability to represent nonlinear creep behavior of soils and its simplicity.

$$\Delta\varepsilon = \frac{\psi}{v} Ln \left[\frac{t + t_0}{t_0} \right] \quad (1)$$

where, $\Delta\varepsilon$ is the creep strain, t is the creep time for $\Delta\varepsilon$, t_0 is the reference time, ψ/v is the creep parameter used in the 1-D EVP models (Yin & Graham 1994) and v is the specific volume. From Eq. 1 ψ/v can be expressed as,

$$\frac{\psi}{v} = \frac{\psi_0^{'}}{1 + (\psi_0^{'} / \Delta\varepsilon_1) Ln[(t + t_0)/t_0]} \qquad (2)$$

Where $\Delta\varepsilon_1$ is the limit creep strain, $\psi_0^{'}$ is the value of ψ/v at the reference time. Eq. 2 dictates that ψ/v is not a constant and decreases with creep time, and also it can be stated that ψ/v is dependent on the stress level.

In this study, the creep function by Yin (1999) was used to interpret the time-dependent creep behavior, prevalent in the 1-D consolidation tests. Vertical strain-time relations were configured into time lines by applying Yin (1999) approach. An example of this application is given in Fig. 3 for the test conducted up to the 400 kPa stress level and this load was kept on the sample for 4320 minutes. Only creep phases of the consolidation tests were considered in this study and the results of the tests on the reconstituted kaolin clay specimens indicated that end of primary consolidation times correspond to approximately 15 minutes or less. The parameters, $\psi_0^{'}$ and $\Delta\varepsilon_1$, and thus the time lines were calculated for all the test groups with load applications up to 20, 50, 100 200 and 400 kPa stress levels and 15, 1440 and 4320 minutes of duration. In accordance with Yin (1999) approach, limit time lines were also determined and displayed on the graphs.

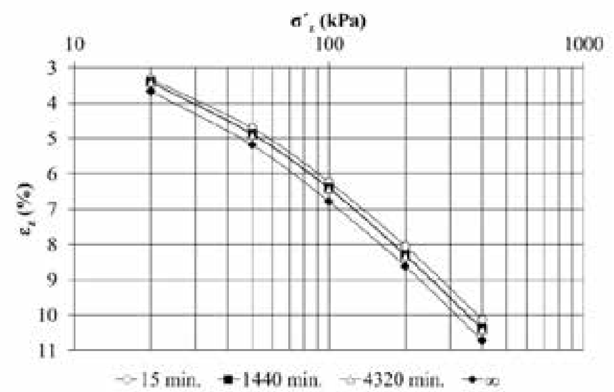

Figure 3. Time lines for the 400 kPa test.

5 Ψ/V AND PF RELATION

As stated before, Eq. 2 gives the creep parameter, ψ/v decreasing with time. In the same sense, the gradation curves given in Fig. 2 imply the variation of PF values with time, but the variation may change its direction either towards size enlargement or degradation. Therefore, it can be argued that a correlation between ψ/v and PF may exist. Such a correlation was searched for by comparing the results of the tests conducted in the scope of this research programme. Some examples of test results were presented in Figs. 2 and 3. The summary of the results obtained with this approach are given in Fig. 4 which shows ψ/v - PF relations for each load increment and all load durations. In Fig. 4, the symbols depicting the data points along a relationship corresponding to a load increment gets larger in size as load duration gets longer (e.g. the smallest size corresponds to 15 minutes and gets larger towards 1440 and 4320 minutes). The relationships displayed in Fig. 4 can be interpreted either in terms of the tendencies of clump formation or clump disintegration depending on the direction of variation in PF values. It can be seen in Fig. 4 that, at low stress levels, such as 20 and 50 kPa's, PF increases as load duration increases. As a matter of course, increases in PF correspond to clump disintegration. In the scope of the findings presented in Fig. 4 an opposite behavior seems to be present in case of higher stress application, 100, 200, 400 kPa stress states. In case of higher stress states PF values decrease as time proceeds; implying structure reconfiguration accompanied by clump formation. Referring to the creep rate parameter it can be stated that, ψ/v decreases with time at all the stress levels. The correlation between ψ/v and PF is negative at stress levels 20 and 50 kPa's, but positive at stress levels 100, 200 and 400 kPa's. If the variation of both of the parameters; ψ/v and PF with respect to time was considered, it seems that, both of these decreases as time proceeds. Moreover, ψ/v values are greater at high stress levels compared to low stress levels, provided that the load duration is the same for each test. In terms of the sign of correlation between ψ/v and PF it can be stated that, the stress level, 100 kPa acts as a threshold and at this stress state and towards higher stress states, the correlation changes sign from negative to positive. This argument is in accordance with the findings of McConnachie (1974) who studied the changes in the sizes of the domains against a large range of pressure; from 0.1 kPa to 100000 kPa's. McConnachie pointed out the possibility of occurrence of a fundamental change in the mechanism of consolidation between the pressures 10 and 100 kPa".

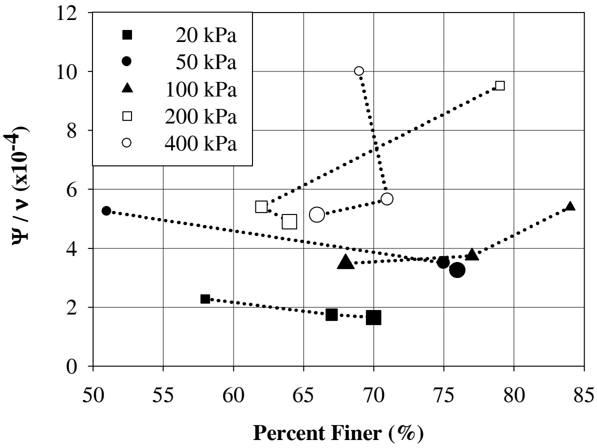

Figure 4. Relations obtained for the tests at different stress levels.

6 CONCLUSIONS

A specifically designed testing programme was conducted to investigate the interaction between macro and micro mechanisms that occur during time dependent consolidation process. The testing programme consisted five sets of 1-D oedometer tests; each with a different maximum stress level. Three duration periods were applied for each set of the tests. Micrographs were taken at the end of all of the fifteen tests and quantified in terms of the variation of clump sizes present at any stress level and time. The results were presented by using an approach similar to the construction of gradation curves. In order to analyze the gradation curves, in terms of degree of fineness, a parameter was defined which is called as Per cent Finer (PF), to give the percentage of clusters finer than a specific size that was chosen to act as a threshold. Macro measurements made during the application of the oedometer tests and micro measurements obtained through the quantification process applied on the micrographs provided two parameters; creep rate parameter, ψ/v and Per cent Finer, PF. The possibility of existence of an interrelationship between ψ/v, and PF was then searched for, as, both of these parameters vary with respect to creep time. The results can be interpreted in terms of the existence of a correlation. However, further evidence supported by larger sets of data is required. Current results can be summarized as; the creep rate parameter, ψ/v decreases with time at all the stress levels. The correlation between ψ/v and PF is negative at stress levels 20 and 50 kPa's, but positive at stress levels 100, 200 and 400 kPa's. Analyzing these results, it can be argued that, the mechanism of consolidation changes around 100 kPa stress range which is realized as the change of sign of the correlation found between ψ/v and PF. This finding complies with the argument put forward by McConnachie (1974) who pointed out the possibility of occurrence of a fundamental change in the mechanism of consolidation between the pressures 10 and 100 kPa. The results summarized here are part of an ongoing research. Further evidence is expected as the results of the new tests are released.

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