AN APPROACH TO THE INTERPRETATION OF THE MECHANICAL BEHAVIOUR OF INTENSELY FISSURED CLAYS

C. VITONEi), F. COTECCHIAi), J. DESRUESii) and G. VIGGIANIii)

ABSTRACT

The paper discusses the intrinsic properties, the geological history, the natural structure and the mechanical behaviour of intensely fissured clays from Santa Croce di Magliano, a site located within the East-side border of the Apennine chain (southern Italy). The clays were originally deposited elsewhere and subsequently moved and largely deformed during the Apennine orogenesis, so that their structure appears severely disturbed and fissured. The applicability of a continuum-based approach to describe the mechanical behaviour of a Representative Element Volume (REV, hereafter) of the natural, fissured clay is experimentally investigated by analysing the clay specimen deformation under plane strain compression by means of False Relief Stereophotogrammetry. The results of such analysis show that, despite the intense network of pre-existing fissures, the patterns of deformation – including the eventual development of shear bands within the REV of the natural clay – are similar to those observed for unfissured clays. Triaxial tests were carried out on both natural and reconstituted clay samples and the results were compared with those recognised in the literature to be typical of unfissured clays. Based on such comparisons, the study provides a few essential elements that are useful to define a general framework for the mechanical behaviour of intensely fissured clays.

Key words: fissured clays, mechanical behaviour, plane strain tests, stereophotogrammetry, triaxial tests (IGC: D0)

INTRODUCTION

Fissuring makes a clay significantly weaker than the original unfissured one (Terzaghi, 1936), so that engineering problems such as, for example, slope instability problems (e.g., Esu, 1977; AGI, 1985; Picarelli et al., 2003; Cotecchia et al., 2006) or bulging of tunnel lining, are frequently encountered when constructing within fissured clay masses (e.g., Cotecchia and Valentini, 1973). Therefore, the understanding of the effects of fissuring on the mechanical behaviour of clays is of important practical relevance.

In the scientific literature, fissured soils are recognised as being part of the so-called structurally complex formations (Croce, 1971), which generally include lithological heterogeneities. In fact, discontinuities and fissuring can be seen as particular forms of non-homogeneity. However, the literature does not report any conclusive interpretation of the general influence of fissuring on the soil mechanical behaviour. Rather, previous research studies have investigated either the behaviour of intensely fissured clays (e.g., AGI, 1979; Airo Farulla and La Rosa, 1977; Picarelli and Olivares, 1998), or that of medium fissured clays (e.g., Lo, 1970; Marsland, 1971; Petley, 1984), with little focus on the comparison between the responses for different levels of fissuring. Starting from this background, a large experimental research programme is on-going at the Technical University of Bari with the aim of assessing the influence of different levels of fissuring intensity on the mechanical behaviour of clays. In the research, a continuum mechanics approach is adopted to interpret the mechanical behaviour of the REV of the fissured clay. Accordingly, fissuring is dealt with as an internal state variable that, together with void ratio and clay microstructure, controls the clay behaviour.

This paper studies an intensely fissured clay from Santa Croce di Magliano (Southern Italy). The fissuring features of the material are first discussed, and classified using a chart recently introduced by the authors (Vitone et al., 2005). Then, the applicability of a continuum-based approach to describe the mechanical behaviour of a REV of the natural, fissured clay is experimentally investigated by analysing the clay specimen deformation under plane strain compression by means of stereophotogrammetry. Finally, the paper discusses a few selected results from an extensive triaxial testing programme on the Santa Croce di Magliano clay, both natural and reconstituted in the laboratory. Based on these results, a general framework for the mechanical behaviour of the clay is briefly discussed.

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THE DAUNIA SCALY CLAYS

The clays being investigated outcrop at Santa Croce di Magliano (SCM, hereafter), a site located in the Daunia region (Southern Apennines, Fig. 1). The clays possess an intensely fissured mesostructure, defined as scaly mesostructure, as it is often the case for clays outcropping in the Southern Apennines. The fissuring network crossing the scaly clays is the result of extremely high shearing deformation experienced by the soil during its tectonic history. In particular, these clays are allochthonous, since they were originally deposited several hundreds kilometres away from their current location and were subsequently subjected to large displacements during the Apennine orogenesis. Such displacements are responsible for the intense straining and consequent disturbance that the soils have been subjected to. Figure 2 shows a Scanning Electron Microscope (SEM) picture at low enlargement of the scaly clay mesofabric in its natural state. A sketch of the same mesofabric is reported in Fig. 3. The clay mesofabric appears to be crossed by an intense network of fissures confining strongly bonded lens-shaped fragments of clay, of millimetre size, called scales due to their platy-like shape. Each scale is in turn characterised by a “scale-in-scale” fabric (see Fig. 3). The scales are not bonded between each other, but strong bonding exists inside them (intra-scale bonding), due to the diagenetic phenomena resulting from tectonic loading.

It is important to note that the scales of SCM clay appear to be iso-oriented. Such peculiar mesostructure makes the soil strength very low, as demonstrated by the widespread instability processes taking place within the scaly clay deposits in Daunia. As an example, Fig. 4 shows one of the typical soil slips taking place in Daunia scaly clay slopes.

The SCM scaly clays are part of the Daunia Unit, which outcrops along the outer margin of the southern Apennines (see Fig. 1). In particular, they form the upper part of the Red Flysch Formation (Dazzaro and Rapisardi, 1996), an Oligocene-Miocene succession of clayey and calcareous strata, at the base of the Daunia Unit.

Block sampling for this study was carried out at SCM within the Red Flysch outcropping shown in Fig. 5, about 3 m below the ground level, after removal of a thick stratum of soil.

Table 1 reports the mineralogical composition of the clays, measured using X-ray diffraction. The clay is grey-green to red in colour and has a high content of phyllosilicates, represented mainly by mixed-layer clay minerals (i.e., illite interlayered with smectite). The mixed-layer clay minerals have low content of illite and high content of smectite. Hematite is ubiquitous in the red scaly clays whereas it is absent in the green ones.

The clay fraction (CF) is equal to 91% and the soil plasticity index (PI) is about 52%, so that the clay appears to be of medium activity (A = 0.57). However, it is worth noting that several authors (Cotecchia, 1971; Airò Farulla and La Rosa, 1977; Rippa and Picarelli, 1977) have demonstrated that the Atterberg limits and the clay...
fraction measured for scaly clays increase significantly with the energy used in remoulding; therefore, the aforementioned parameter values are probably an underestimation of the real values. In particular, Fearon and Coop (2000) demonstrated that the plasticity index of scaly clays can increase by more than 15% if measured after mincing the clay by means of a food mincer. This is due to the strong diagenetic intra-scale bonding which is not fully degraded by standard remoulding. The underestimation of the clay PI may be the reason for the relatively low value of the activity index measured for SCM clay, which is in contradiction with the high content of swelling minerals found by means of the mineralogical analyses (see Table 1).

Both the void ratio and the saturation degree of the clay have been found to be highly non-uniform within the blocks, due to the variability of the fissure opening; on average they are equal to 0.88 and 77% respectively.

**CLASSIFICATION OF THE FISSURED MESOSTRUCTURE**

In order to compare the mesostructures of different fissured clays, the fissuring features have been classified using the classification chart recently proposed by the authors (Vitone et al., 2005), which is reported in Fig. 6. This classification takes into account all the parameters that are considered useful according to the most relevant contributions to the characterisation of fissured soils reported in the literature (e.g., Fookes and Denness, 1969; Walker et al., 1987; ISRM, 1993).

The classification applies solely to homogeneous fine-grained soils (i.e., soils belonging to category A in the classification for structural complexities proposed by Esu, 1977) and it refers to both the lithology and consistency of the soil matrix, and to the discontinuity fea-

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**Table 1.** Mineralogical composition (weight %) of the bulk sample and of the clay fraction. Key. Bulk sample: phyllosilicate (ΣPh), quartz (Q), feldspars (F), calcite (Cc), hematite (Hm), chlorite (Ch), dolomite (Dol), gypsum (Gy); clay fraction: mixed-layers illite/smectite (I/S), illite (I), kaolinite (K), chlorite (Ch), nd = not detected, tr = in trace

<table>
<thead>
<tr>
<th>Sample</th>
<th>ΣPh</th>
<th>Q</th>
<th>F</th>
<th>Cc</th>
<th>Hm</th>
<th>Ch</th>
<th>Dol</th>
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<th>I/S</th>
<th>I</th>
<th>K</th>
<th>Ch</th>
<th>1 in I/S</th>
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<tr>
<td>Block (green scaly clay)</td>
<td>94</td>
<td>5</td>
<td>tr</td>
<td>—</td>
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<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>80</td>
<td>1</td>
<td>17</td>
<td>2</td>
<td>30</td>
</tr>
<tr>
<td>Block (red scaly clay)</td>
<td>92</td>
<td>4</td>
<td>tr</td>
<td>tr</td>
<td>3</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>80</td>
<td>2</td>
<td>16</td>
<td>2</td>
<td>30–35</td>
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tues. In particular, in the first part the classification refers to the intact soil (categories A and B) and in the second part to the discontinuities (fissuring nature, orientation and geometry: categories C-I). The most important feature is the intensity of fissuring (category I), which is defined by both the average volume of the clay element between the fissures and its average specific surface. The classification can be used for soils from rarely fissured (I1) at the macroscale (i.e., in-situ scale), for which the clay element can have volume larger than 1 m$^3$ and specific surface smaller than 3 m$^2$/m$^3$, to highly fissured soils (I6) whose clay element is on average smaller than 1 cm$^3$ and has specific surface higher than 300 m$^2$/m$^3$.

According to a procedure referred to as filling up the chart in Fig. 6, the SCM scaly clays are characterised as A1, B3–B4 being the clay element from soft to firm, with discontinuities that are shear induced, C3, with a smooth to slickensided surface, D3–D6, often fresh to weathered, E1–E4. The fissure planes are mainly normal to a single direction, F1, planar to folded, G1–G4, with many intersections, H2.

The fissuring intensity (category I) of SCM scaly clays is very high, I6, since the maximum volume of each scale is very small (about 0.3 cm$^3$) and the specific surface is very high (about 1000 m$^2$/m$^3$).

### PLANE STRAIN COMPRESSION

#### Experimental Device, Sampling and Testing Procedures

A total of five plain strain compression tests on SCM scaly clays were performed in the plane strain (baxial, hereafter) apparatus at the Laboratoire 3S-R of Grenoble (Desrues, 1984; Desrues and Viggiani, 2004). Within this device, a 35 mm thick prismatic specimen is mounted between two rigid walls inducing plane strain conditions. The initial height and width of the specimen in the plane of deformation were either 80 mm and 40 mm, or 150 mm and 70 mm, respectively. The side walls are glass plates which allow photographs to be taken of the in-plane deformation of a specimen during the test. The top plate is free to slide horizontally in the plane of deformation, which allows free lateral displacement of the upper portion of the specimen when a shear band forms due to deviatoric loading. All surfaces in contact with the specimen are lubricated with silicone grease to minimize friction.

Undisturbed prismatic specimens of SCM scaly clays for plane strain testing were taken by means of an unconventional sampling technique. On-purpose designed C-shaped steel samplers of slightly bigger dimensions than the biaxial specimens were inserted into the soil as shown in Fig. 7 (the sampling site is the outcropping already shown in Fig. 5). The inner surface of the samplers was lubricated with silicon oil before the insertion. Their extraction was carried out after having removed the surrounding soil (Fig. 8). Thereafter, each full sampler was wrapped in cling film and waxed in-situ, in order to minimize the loss of water content. The clay was pulled out from the samplers just before testing. The saturation degree of the specimens ranged between 70 and 88%.

All SCM clay specimens were tested at zero confining pressure, i.e., the minor principal total stress ($\sigma_3$) was kept to zero throughout the test. The material was there-
for tested from the *in-situ*, unsaturated state, with the total mean stress being zero at the beginning of a test. Loading was performed under displacement control with a rate of applied displacement of 0.003 mm/min. Note that the loading direction (i.e., major principal stress direction) was always normal to the orientation of the scales in the clay specimen.

**False Relief Stereophotogrammetry**

In all the experiments on SCM scaly clay, the deformation of the specimens was characterized throughout the test by using stereophotogrammetry. First applied to soil mechanics experiments by Butterfield et al. (1970), this method has been further developed and extensively used in Grenoble starting from the early 1980s' (Desrues, 1984) to capture non-homogeneous deformation throughout a test under plane strain conditions (Desrues and Viggiani, 2004). 'False Relief Stereophotogrammetry' (FRS, hereafter) is based on the photogrammetric analysis of photographs taken from a fixed viewpoint at different times during the loading process. In this application of FRS, the photographed image is the side of a SCM clay specimen deforming under load, and the source of the differences between successive images is the deformation process undergone by the specimen.

To obtain a clear stereoscopic effect, the photographed surface must be textured. In this application, this was achieved by projecting fine, highly contrasting paint drops on the specimen side prior to the test. High resolution photographs were obtained by using an optical-mechanical large format camera with 6×6 cm negative film. See Desrues and Duthilleul (1984) for further details.

Stereo comparison was then used to obtain the displacement field associated with any two photographs. Displacements were measured using a stereocomparator, a tool originally developed for topographic and other 3D-photogrammetric measurements. A stereocomparator has two (negative) photograph holders and allows for measuring the displacement between the two configurations considered. Essentially, the coordinates of homologous points of the left and right images are measured. Adequate transformations allow to express the coordinates of both sets of points in the same reference frame, and finally to get the displacements (with an accuracy of about 10 μm at the scale of the photograph). The scale of the photograph is determined from six or more reference marks placed on the specimen side of the glass sidewall (in the plane of deformation). Points where measurements are taken define a triangular partition covering the photographed side of the whole specimen. A continuous, piece-wise linear displacement function is then defined by linear interpolation of the displacements measured at all apices of the triangles. Finally, a regular mesh is defined and, for each quadrilateral element of the mesh, the spatial derivatives are obtained numerically at the element centre, which allows for determining the deformation gradient and hence all components of the (finite) strain tensor. See Desrues and Viggiani (2004) for further details.

For each test on SCM scaly clay, a set of displacement measurements was obtained by following, throughout the entire set of photographs, several points sprayed on the photographed side of the specimen. Denser measurements were taken in the zones where large displacement gradients were detected in the stereoscopic view. Typically, the number of measurements for a test ranged from 250 up to 500, when complex patterns of localized deformation appeared. Strain fields were calculated using the code ANADEF (Desrues, 2002).

It should be noted that in the plane strain testing carried out on SCM clay, distinct cracks, i.e., discontinuities of the displacement field, were often observed. In this case, interpreting the deformation in terms of strain can be inappropriate. Therefore, a specific module of...
Results

Figure 9 shows the stress-strain response obtained from test BX1 on a 40 × 80 mm specimen of SCM clay. The numbers noted on the curve are the photograph numbers.

The use of stereophotogrammetry as a quantitative tool allows for representing the evolution of localized deformation in terms of (incremental) strain fields. Figures 10(a)–(g) show, for each photographic increment, FRS-based shear strain intensity, \( \varepsilon_s = (\varepsilon_1 - \varepsilon_3)/2 \), and volumetric strain, \( \varepsilon_v = (\varepsilon_1 + \varepsilon_3) \). The size of the symbols is proportional to the value of the relevant quantity (note that symbol scale, reported on the top left of each figure, is different for each increment). As far as volumetric strain is concerned, square symbols are for dilatancy and hexagons for contractancy. Starting with increment 3–4 (Fig. 10(b)), the figure also shows the displacement jumps across all visible discontinuities.

Although no bands of localization were observed before photograph 3, some non-homogeneous deformation existed in the specimen already during strain increment 2–3 (Fig. 10(a)). During strain increment 3–4 (Fig. 10(b)), i.e., shortly before the peak stress (see Fig. 9), two parallel shear bands appeared and a fissure formed in the top right portion of the specimen. Significant dilation (square marks in Fig. 10(b)) occurs in the less extended shear band, where the shear strains are more significant. Thus, the onset of strain localization occurred shortly before the peak of axial stress, as previously observed for other geomaterials, e.g., stiff clays (Viggiani, 1994; Viggiani and Desrues, 2004; Marello et al., 2004) and sands (Desrues, 1984; Desrues and Viggiani, 2004).

During increment 4–5 (Fig. 10(c)), i.e., immediately post-peak, the shear strain intensity starts decreasing within the shear band which had become more extended till then, whereas it keeps increasing in the other shear band, which had previously experienced the largest shear strains. The fissure onset follows the development of this shear band which remains active post-peak and that finally crosses the entire specimen during increment 7–8, i.e., post-peak (Fig. 10(f)). A sliding mechanism on a single surface through this shear band takes place at increment 8–9 (Fig. 10(g)). During post-peak increment 5–6 (Fig. 10(d)), shear strain intensity starts increasing again in the shear band where it had reduced previously (i.e., near the top of the specimen), and such reactivation is followed by the onset of a second fissure, at increment 6–7 (Fig. 10(e)).

As soon as sliding occurs, at increment 8–9, the gradient of the stress-strain curve in Fig. 9 reduces significantly. Therefore, despite the pre-existing intense fissuring network characterising the natural clay mesostructure, it is only far after the peak stress that the specimen ‘deformation’ mechanism consists in the sliding of two nearly rigid clay blocks. A similar finding resulted also from the analysis of the strain fields for unsaturated clay specimens (e.g., Viggiani, 1994; Viggiani and Desrues, 2004; Marello et al., 2004). Thus, the pre-existing fissuring does not seem to modify significantly the evolution of straining during shear within a REV. It is worth noting that the biaxial tests being discussed were carried out on partially saturated specimens at zero confinement stress, within which the fissure opening was significant, such as to cause bulk unsaturated conditions for the specimens. It is expected that the findings about the strain field characteristics discussed above would apply also to re-saturated specimens subject to shear with confining stresses above zero, within which the fissure opening would be more limited. Figure 11 shows specimen BX1 after the test. The failure mode can be characterised as complex according to Irwin (1958) because two modes of failure appear to have taken place. The opening mode (mode I) is evident at the top of the specimen (circled area in Fig. 11), whereas both the opening (mode I) and the sliding (mode II) modes can be detected in the central part of the specimen. The occurrence of relative sliding (square area in the figure) is also confirmed by visual inspection of the failure surface (see Fig. 12).

Figure 13 shows the stress-strain response obtained from test BX2. The dimensions of the specimen were the same as for test BX1. Again, the numbers noted on the curve are the photograph numbers (a high resolution digital camera, Kodak DCS Pro 14N 13.8MPixels, was used in this case). Note that while the values of axial strain at the peak are similar in tests BX1 and BX2 (6.3 % and 7.0 %, respectively), a significantly lower peak strength is obtained in test BX2. This is likely to depend on the heterogeneity characterising the state, nature and structure of the clay outcropping (Cotecchia et al., 2006), due to which specimen BX2 appears to be made of a locally more plastic clay than BX1. In addition, the saturation degree of specimen BX1, \( S_r = 73\% \), is lower than for specimen BX2, \( S_r = 88\% \). Hence, higher suctions are
Fig. 10. Test BX1: stereophotogrammetry based incremental fields of shear strain intensity (1), volumetric strain intensity (2) and the fissure development (3). The numbers refer to stress-strain states in Fig. 9. At the top left of each box the symbol scale is reported.

Figures 14(a)-(i) show that the onset of relative sliding occurred largely after the peak stress (increment 6–7, Figs. 14(f) and (g)). Large discontinuities developed through the specimen and sliding occurred during increment 7–8, which corresponds to the maximum rate in stress decrease. Mode I (circled areas in Fig. 14(i)) seems

present in specimen BX1, which are likely to give rise to a higher strength.
to have dominated the fissure development both at the top and in the centre-base of specimen BX2, whereas a sliding mode (mode II) appears to have occurred along the fissure crossing the left side of the specimen (square symbol in Fig. 14(i)). It follows that the analysis of digital photographs in Fig. 14 appears to confirm the FRS results on test BX1, despite the differences in nature and saturation degree of the two specimens. In conclusion, the FRS analysis of the strain fields suggests that within the clay of fissuring intensity I6 (Fig. 6), shearing induces the development of strain fields very similar to those observed within unfissured clays (e.g., Viggiani, 1994; Viggiani and Desrues, 2004; Marello et al., 2004). In particular, the onset of shear bands occurs just before peak strength, which develops further post-peak but a fully developed relative sliding occurs only far after peak; about the stage defined as post-rupture by Burland (1990). Such a finding confirms that for clays characterised by fissuring
Fig. 10. (continued)

Fig. 11. Specimen BX1 after the test. Circle and square symbols refer to failure modes I and II respectively

Fig. 12. The sliding surface of specimen BX1 after the test

intensity I6, continuum mechanics can still be used in the interpretation of the results of representative element volume testing. Therefore, such approach has been adopted in the analysis of the results of triaxial testing on scaly clay specimens from SCM, as discussed in the following.

TRIAXIAL TESTING

Consolidated undrained shear tests were performed in the triaxial apparatus (axial displacement rate: 0.003 mm/min) on natural SCM clay specimens as well as on specimens of the same clay reconstituted in the laboratory. In the following, the symbol * refers to reconstituted clay parameters.

The natural specimens were trimmed with vertical axis (i.e., the direction of loading) normal to the orientation of the scales. They were saturated at constant effective stress prior to isotropic compression by the application of back pressures as high as 300 kPa. The $p'$ value kept constant during resaturation was equal to about 400 kPa, that is the average ‘suction’ measured (in the triaxial apparatus) for the natural specimens. The isotropic compression was started only after the measurement of a $B$ parameter value (Skempton, 1954) higher than 96%.

In Fig. 15 the specific volume, $\nu$, mean effective stress, $p'$, state paths followed by five standard specimens (38 mm in diameter and 76 mm in height) size and by one specimen of $70 \times 140$ mm size (SC6) during isotropic compression and undrained shear are reported, together
Fig. 14. High resolution photographs taken during test BX2. Numbers 1 to 9 refer to the stress-strain states in Fig. 13. In Fig. 14(i), circle and square symbols refer to failure modes I and II respectively.
Fig. 15. State paths followed by the natural and the reconstituted clay specimens during isotropic compression and undrained shearing. Thick horizontal paths refer to contractive specimens in undrained shearing and the thin ones to dilative specimens. The arrows (Y) identify the gross yield states

with the state paths followed by the reconstituted clay specimens (SC1* and SC2*).

Fearon and Coop (2000) and Cotecchia and Santaloia (2003) have shown that relics of the natural scales can be present in the clay after the standard reconstitution procedure. Nonetheless, the behaviour of such reconstituted clay has been found to comply with the relationships between the clay index properties (representative of the clay nature) and the clay mechanical properties (Cotecchia and Santaloia, 2003), which generally apply to reconstituted soils according to Critical State Soil Mechanics (Schofield and Wroth, 1968). Therefore, the clay resulting from standard reconstitution of a scaly clay can be considered representative of the reconstituted clay for reference in the comparison with the natural clay. The validity of this assumption has also been checked for another scaly clay, the Senerchia clay, by Cotecchia and Santaloia (2003).

Behaviour upon Isotropic Compression

During isotropic compression at pressures below 1000 kPa, the standard specimens SC1 and SC5, as well as the larger specimen SC6 exhibit a slightly stiffer response than at higher pressures (Fig. 15). The limited increase in curvature of the compression curve makes it difficult to deduce the value of the isotropic gross yield stress of the clay from the investigation of its compression behaviour. However, the contractive response (that is, positive excess pore water pressure) obtained upon undrained shearing of specimen SC6 suggests that isotropic gross yielding of SCM clay is likely to occur at about 1000 kPa mean effective stress (Y1 in Fig. 15). Therefore, the compression curves of specimens SC1 and SC5 post-gross yield define the isotropic normal compression line (INCL) of the natural clay. This is found to be located on the left of the isotropic normal compression line of the same clay when reconstituted (INCL*). Also, the data demonstrate that there is no specimen size effect on the clay compressibility, when considering the response of specimens of size either equal to or larger than the standard one (38 × 76 mm).

Plastic yielding of the natural clay during compression along the INCL shown in Fig. 15 is confirmed by the non-reversibility of large part of the volumetric strain accumulated by specimen SC5 during compression. Upon unloading, specimen SC5 follows a swelling line located far below the INCL. The compressibility of the clay along the INCL is characterised by a compression index \( \lambda = 0.14 \) for 1400 kPa < \( p' < 1800 \) kPa, whereas, during swelling, \( \kappa = 0.038 \) for 650 kPa < \( p' < 1100 \) kPa. The swelling index increases significantly with unloading to low pressures (Fig. 15).

Specimens SC3, SC4 and SC5 are characterised by values of the overconsolidation ratio, \( R = p'_{oc}/p'_{cl} \), approximately equal to 3.3, 2.1 and 2.5 respectively (according to the INCL of Fig. 15).

Note that these specimens exhibit a dilative response (i.e., negative excess pore water pressure) upon undrained shearing, which seems to confirm the location of the INCL of the natural clay shown in Fig. 15.

Figure 16 sketches a possible general framework that can be conjectured from these data for the isotropic compression behaviour of SCM clay. In such a sketch, the fissured clay reaches compression states on the left of the INCL* of the reconstituted clay up to high pressures. Therefore, its compression behaviour differs significantly from that found in sensitive un fissured soils (also shown in the figure), which gross yield on the right of the
INCL*. In particular, the fissured clay is less compressible than the reconstituted clay and far less compressible than the sensitive (structured) unfissured clay post-gross yield. The scaly clay does not enter the so-called structure permitted space (Leroueil and Vaughan, 1990) and its Stress Sensitivity ratio $S_e$ (Cotecchia and Chandler, 2000), defined as $p_e^0/p_s^0$ (where $p_s^0$ is the equivalent pressure on the INCL*), is lower than one, against $S_e > 1$ characterising unfissured sensitive clays. It is worth noting that such results confirm those found by Cotecchia and Santalola (2003) for Senerchia scaly clays during one-dimensional compression and are consistent with the isotropic compression data of Senerchia scaly clays discussed by Vitone and Cotecchia (sub.). Since the Senerchia scaly clays are deep, with scales from firm to stiff (B2-B3 in Fig. 6) and randomly oriented (F3 in Fig. 6), whereas the SCM clay scales are soft-firm (B4-B3) and oriented (F1) normally to the direction of loading, one might be tempted to conclude that the framework of compression behaviour sketched in Fig. 16 represents the general behaviour of 16 clays, regardless of the differences in consistency, orientation and state of the clay scales.

**Behaviour upon Undrained Shearing**

Figures 17 and 18 show the $q/p^*-e_s$ curves and the normalised stress paths corresponding to the undrained state reported in Fig. 15 respectively. Effective stresses in Fig. 18 have been normalised for the specific volume by means of the equivalent pressure $p_s^e$, that is the mean effective stress on the INCL* for current specific volume. A sliding mechanism on a single failure surface was eventually observed for all specimens, generally at large strains. In Figs. 17 and 18, the states corresponding to the onset of the sliding mechanism have been indicated with the symbol +. The failure surface was visible with the naked eye from shear strains of about 4 to 5% for all natural specimens, except for specimens SC2 and SC5 for which sliding started at $e_s$ of about 2.5 to 3.5%. A sliding mechanism took place also within the reconstituted clay specimen SC2* at $e_s = 11\%$.

Figure 17 shows that all the highly overconsolidated specimens (i.e., SC3, SC4 and SC5) exhibit a dilative behaviour, whereas a clearly contractive response is shown by the normally consolidated specimens SC1 and SC6-70 up to the stress state corresponding to the failure surface formation. The negative hardening of specimen SC5 ($R = 1.7$) upon undrained shear has to be ascribed to the onset of the premature sled movement.

Figure 18 shows that the normalised stress paths of the natural clay specimens SC3, SC4 and SC6, which were consolidated either to states pre-gross yield or to gross yield (Fig. 15), join a single state boundary curve (SBC1, hereafter) that passes through the isotropic gross yield state of the natural clay ($Y_1$, Fig. 15). The normalised stress path of the $70 \times 140 \text{ mm}$ specimen, SC6, consolidated to gross yield ($R = 1$), appears to exhibit a strength compatible with the SBC reached at peak by the smaller specimens SC3 and SC4. At the same time, only the $38 \times 76 \text{ mm}$ specimen SC2, consolidated pre-gross yield ($R = 1.67$), appears to exhibit a peak strength state below the SBC1, thus it does not join the same state boundary curve.

The above results suggest that the standard specimen dimension (38 mm diameter) may be used for reference to assess the shear response of highly fissured SCM clay. However, the specimen strength may happen to be lower, as observed for specimen SC2, most probably due to the coalescence of pre-existing fissures at lower deviatoric stresses. It follows that, for I6 clays, the $38 \times 76 \text{ mm}$ size specimen either exhibits the strength of soil REV, or exhibits a slightly lower strength (Vitone, 2005). Such finding is consistent with what is reported in the literature for other highly fissured clays (e.g., AGI, 1985; Bilotta, 1987; Fearon, 1998; Picarelli and Olivares, 1998).

Specimen SC1 was consolidated beyond gross-yield before shear. Its normalised stress path defines the wet side of another state boundary curve of the clay, SBC2 (Fig. 18), which relates to an isotropic gross yield pressure higher than the original value for the undisturbed clay ($Y_2$ in Fig. 15). The size of SBC2 is larger than the normalised state boundary curve for the clay consolidated pre-gross yield, SBC1. This finding demonstrates that the state boundary surface (SBS) of SCM clay cannot be normalised accounting solely for the effect of volume and that the rate of increase in size of this SBS with compression post-gross yield is larger than the rate characterising
the variation in size with compression of the SBS* of the reconstituted clay. Specimen SC5, which was compressed to the same $p'$ as specimen SC1, but was unloaded thereafter to $R = 2.5$, exhibits a dilative behaviour during shearing, as expected according to critical state soil mechanics (Fig. 17). However, its effective stress path appears not to join the same SBC as specimen SC1. This discrepancy (about 7.5% in normalized strength) is partly due to the occurrence, at about 3% shear strain, of a sliding mechanism for specimen SC5. However, the lower strength of specimen SC5 with respect to what is expected according to the SBCs, might also be ascribed to structure degradation, which is known to occur with large swelling for scaly clays (Vitone and Cotecchia, sub.).

The normalised stress path of the reconstituted clay specimen in Fig. 18 identifies the wet side of the state boundary surface of the reconstituted SCM clay, SBS*. The state boundary curves of the natural clay, both the SBC1 and SBC2, are found to be inside the SBS*. Therefore, the very high fissuring intensity of the natural clay seems to cause a reduction in size of the entire state boundary surface of the soil with respect to that of the same soil when reconstituted.

Figure 19 reports a sketch of the framework of shearing behaviour followed by clay of very high intensity of fissuring (I6) by comparison with the behaviour of both the reconstituted clay and the un fissured structured clay. In summary, intense fissuring is shown to degrade the mechanical properties of the clay not only with respect to the un fissured material, but also to the same soil when reconstituted, giving rise to the smallest state boundary surface. Such finding is consistent with the $S_\alpha$ value (Cotecchia and Chandler, 2000) below unity found for the scaly clays in isotropic compression. The friction angles corresponding to the stress states of the natural clay at the apex of the state boundary curves, $\phi^*_{\text{spec}} = 13.5^\circ$ and $11.5^\circ$, confirm the very poor strength properties of the scaly clay. The value of $\phi^*_{\text{spec}}$ is even lower than the critical state friction angle of the reconstituted clay ($\phi^*_{\text{spec}} = 18^\circ$). The residual friction angle of the clay, $\phi^*$, is lower than $9^\circ$. The circumstance that the SBS of the natural fissured clay cannot be normalised solely for volume and that the size of the normalised state boundary curves (SBC) increases with compression post-gross yield (Fig. 18), suggests that the hardening of the scaly clay depends not only on the volumetric plastic strains, but also on the structural changes occurring during post-gross yield compression, which are likely to be mainly changes in the clay mesostructure associated with the closure and eventual sealing of fissures.

CONCLUSIONS

The stereophotogrammetric analysis of the deformation field within a specimen of SCM scaly clay sheared in plane strain has confirmed the applicability of a continuum-based approach to the interpretation and modelling of the mechanical behaviour of such an intensely fissured soil. The analysis of the results of triaxial testing on SCM scaly clay specimens confirmed that for I6 clays, 38 x 76 mm size is the minimum specimen size to be used in triaxial testing for a reliable estimation of the clay strength parameters.

The mechanical response of the REV of SCM scaly clay, from low to medium shear strains, fits the critical state framework despite the fissured mesostructure of the clay. However, the intense fissuring causes a significant decay of the soil mechanical properties, not only with respect to the un fissured clay, but also to the same clay when reconstituted. These mesostructural effects are reflected in values of $S_\alpha$ that are below unity, whereas values above one are typical of sensitive un fissured clays.

The fact that the SBS of the natural fissured clay cannot be normalised solely with respect to volume and that its size increases with compression post-gross yield suggests that the hardening of the fissured clay depends not only on volumetric plastic straining, but also on the structural changes taking place at the meso-level. These changes are probably associated with the closure and eventual sealing of fissures due to post-gross yield compression.

It is worth noting that such findings refer to a loading direction which is always normal to the orientation of the scales in the SCM scaly clay specimen. However, according to both oedometer and triaxial testing results on other scaly clays reported in the literature (e.g., Cotecchia and Santaloia, 2003; Vitone et al., 2005) it is expected that a similar finding would apply also to clays characterised by randomly oriented scales. Nonetheless, the research is now on-going making use of more recent techniques, such as digital image analysis (i.e., Digital Image Correlation methods; e.g., Viggiani and Hall, 2008) with the aim of better focusing on the influence of the orientation of the scales on the validity of the adopted approach.

REFERENCES


45) Vitone, C. and Coteccia, F. Sub. The influence of intense fissuring on the mechanical behaviour of clays, Submitted to *Géotechnique*.