Compressibility and Strength of Active Clays: Influence of Pore Fluid Dielectric Constant

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Abstract

This paper reports experimental results relative to the influence of pore fluid composition on liquid limit, intrinsic compressibility, permeability and residual shear strength of some smectitic soils. The soils were reconstituted with distilled water, aqueous ionic solutions at various concentrations and organic fluids with different dielectric constants. The reconstitution procedure of the materials that underwent compression tests was such as to make compressive the results relative to so different fluids. All the tests were analysed with reference to the static dielectric constant of the pore fluid. As D increases from 2 (cyclohexane) to 80 (water), liquid limit and compression index increase, whereas permeability and residual shear strength decrease. Formamide (D=110) has effects similar to those of water in the case of fluid adsorption properties, volume change behaviour and permeability, whereas it causes a noticeable increase in residual shear strength. The maximum of liquid limit and compression index, and the minimum of permeability fall in the range 80<D<110 (maximizing water-formamide).

Keywords: clays, compressibility, strength, pore fluid, dielectric constant

I Introduction

It is well known that pore fluid composition influences both volume change behaviour and shear strength of clays. The type of influence depends on the type of clay. This paper deals with smectitic soils. The influence on their behaviour of salt solutions and organic fluids has been studied by many authors (among others: Janssen Salas and Serravalle, 1972; Boll, 1976; Kemery, 1967; Meaci and Gloan, 1970; 1971; Strizhans and Veshkalappa Rao, 1973; Barbour and Fredlund, 1989; Di Maio, 1996a; 1996b; Anon and Harakz, 1998; Di Maio et al., 2004; Calvello et al., 2005). Generally, experimental results relative to the effects of ionic aqueous solutions and those of organic fluids are investigated separately. In particular, results relative to materials prepared with ionic aqueous solutions are analyzed with reference to ion concentration - or to pH - and to the dielectric constant of the solvent, whereas the effects of organic fluids are analyzed with reference to their dielectric constant. According to such kind of analyses on smectitic clays, as ion concentration increases or the dielectric constant of organic solvents decreases, liquid limit and compressibility decrease, whereas shear strength
increases. Recently, Calvello et al. (2005) compared the effects of salt solutions to those of organic fluids referring to the fluid static dielectric constant $D$ also in the case of salt solutions. This paper adds new results to the above study and reports the effects of exposure of the considered soils to fluids different from the pore fluid. The influence of pore fluid composition has been evaluated on liquid limit, compressibility and permeability of the materials prepared with a procedure which makes the results comparable. The influence on shear strength was evaluated with reference to the residual shear strength which is known to be independent of initial conditions.

2 Materials

The experimentation was carried out on three saturated soils: the Ponza bentonite, the Bisaccia clay and a commercial bentonite provided by Laviosa Chimica Mineraria S.p.A. (Lavorno, Italy). The values of clay fraction, $C_{fr}$, was evaluated to be 70%, 60% and 82% for the three materials respectively. X-ray diffraction analysis showed that the two bentonites are almost pure smectites, whereas the Bisaccia clay contains about 30% montmorillonite (Di Maio et al., 2004; Calvello et al., 2005).

The liquid limit was evaluated with a number of different fluids by means of the fall cone test. Figure 1 reports the results obtained with NaCl solutions at various concentrations, a HCl solution at $pH = 1$, some organic fluids and mixtures distilled water-formamide. As $D$ increases from 2 up to 70, $w_l$ varies negligibly. In particular, it is worth noting that the value of $w_l$ of the Bisaccia clay reconstituted with saturated NaCl solution is very close to that of the material prepared with distilled water, an organic fluid whose dielectric constant is equal to that of the solution ($D=47$). For $D=80$, $w_l$ increases dramatically and in this range the differences among different clays increase. The value of $w_l$ obtained with formamide ($D=110$) are very close to those obtained with distilled water. First results relative to mixtures formamide-water show that the maximum value of $w_l$ falls in the range $80<D<110$. The unit weight of formamide is $13.3$ kN/m$^3$, so, also the void ratio at the liquid limit for the mixture 50% by weight water-formamide is higher than that obtained with distilled water.

![Figure 1. Liquid limit against pore fluid static dielectric constant $D$.](image)

3 Compressibility

Compressibility was evaluated by means of fixed-ring oedometer tests. The specimens - 2 cm thick - were loaded and subsequently unloaded by steps. The materials were reconstituted by mixing the air-dried powders with different fluids at about the corresponding liquid limit, following Burland (1990). The compression curve of these reconstituted materials should represent a "reference state": an upper bound of possible equilibrium conditions. As a matter of fact, in the case of salt solutions, water and formamide, the results relative to specimens prepared with various initial fluid contents higher than the liquid limit showed that the compression curves converge at about $o_{cr} = 150 - 200$ kPa. In the case of fluids with very low dielectric constant, the materials were prepared with the maximum fluid content for which they did not undergo self-weight consolidation. Some tests were carried out also on materials dried at 105°C. The dry specimens were prepared at an initial void ratio close to that of the materials prepared with cyclohexane.

The comparison of the effects of different types of pore fluids is reported for the Bisaccia clay in Figure 2 in terms of $e-log\sigma$. The figure shows that the behaviour of the material prepared with cyclohexane ($D=2$) is very similar to that of the dry material ($D=1$). The compressibility of the material prepared with formamide is similar to that of the material prepared with distilled water for $o_{cr} < 100$ kPa, it is lower for higher stress values. The compression curves of both cyclohexane-saturated and dry materials intersect the normal compression lines of the material reconstituted with the other fluids, clearly indicating an increase in shear strength at the particles' contacts. Swelling is noticeable for water and formamide, it is practically null for cyclohexane.

![Figure 2. Compression and swelling curves of the Bisaccia clay reconstituted with several different fluids.](image)
4 Hydraulic Conductivity

The rate of consolidation is strongly influenced by pore fluid composition (Calvello et al., 2005). Under the hypothesis of the Terzaghi model of one-dimensional consolidation, a first approximate value of the hydraulic conductivity $k$ in the axial direction was obtained. Figure 5 reports the results relative to the Bisaccia clay at a void ratio $e$ of about 1.4, reconstituted with various fluids. It can be observed that, consistently with the results relative to liquid limit and compression index, the hydraulic conductivity exhibits a minimum in the range 80 < D < 110.

It is worth to note that the observed strong variability of $k$ with $D$ cannot be explained with the different viscosity of the "free" fluids; in fact this latter varies less than 20% for the used fluids. A new experimentation is now in progress in which the hydraulic conductivity is determined by falling head permeability tests in flexible wall permeameters. The first results yield values of hydraulic conductivity similar to those obtained by consolidation tests.

5 Residual Shear Strength

The residual shear strength was determined by using the conventional Casagrande box and the Bishop ring shear apparatus. In the first case, for each value of axial stress, the specimens were sheared back and forth until the minimum strength was obtained. Rates of displacement in the range 0.001 - 0.005 mm/min were adopted. Various pore fluids were used: water, salt solutions at various concentrations and organic fluids with different dielectric constants, both
lower and higher than that of distilled water. Dry materials were also sheared. In the case of low dielectric constant fluids, the shear surface was often very irregular. So, frequently during the tests, the specimens were cut manually in order to ensure the flatness of the shear surface.

Figure 6, which reports some results relative to the Bisaccia clay in terms of $\sigma_0 - \sigma$, shows that the cohesion intercept is null. So, it is possible to compare the results in terms of $\sigma_0$ (Figure 7). As $D$ increases from 1 to 80, the residual shear strength decreases in a non-linear manner. The highest gradients are registered at about $D=2$ and $D=80$. For $D=110$ (formamide), the value of $\sigma_0$ is much higher than for water and very close to the value obtained with the concentrated NaCl solutions. This result is apparently in contrast with those relative to $w$, $C_t$, and $k$ which have similar values in water and in formamide. So, in order to verify this result further, the effects of water and formamide were observed on the very same specimen of the Bisaccia clay. The material was reconstituted with formamide, consolidated to a $c_h$ of about 208 kPa and initially sheared while immersed in the same fluid. Subsequently, it was exposed to distilled water after a displacement of about 80 mm. The exposure caused a noticeable decrease in strength (Figure 8), consistently with the results of Figures 6 and 7.

Figure 6. Residual shear strength of the Bisaccia clay reconstituted with various fluids.

6 Conclusions

This paper reports experimental results relative to the influence of pore fluid composition on liquid limit, compression index and residual shear strength of three smectitic clays. Some results relative to hydraulic conductivity derived from consolidation curves are also reported. Ionic aqueous solutions, acid solutions and organic fluids were used. The results have been analysed with reference to the static dielectric constant of the pore fluid, even in the case of ionic aqueous solutions. In order to investigate the range 80-D=110, some mixture water-formamide were also used.

The results show that in the range 2-D=110, $w$ and $C_t$ vary of an order of magnitude and the hydraulic conductivity $k$ of three orders of magnitude. The maximum of liquid limit and compressibility and the minimum of hydraulic conductivity are obtained for the materials prepared with a mixture water-formamide. So, the behaviour of smectic clays reconstituted with distilled water is not "the extreme behaviour". For 2-D=80, the residual friction angle $\phi'$ varies from about 30° (cyclohexane) to about 37° (distilled water), it is about 17° in the case of formamide (D=110). So, differently from $w$, $C_t$, and $k$, the strength parameter increases noticeably in formamide with respect to that in distilled water. The evaluation of $\phi'$ in the range 80-D=110 and the way by which the physico-chemical interparticle forces influence the observed behaviour are currently under study.

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References


The Influence of Ionic Diffusion on the Physical and Mechanical Properties of a Natural Marine Clay

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Abstract

This paper describes the results of a wide investigation on a marine clay outcropping in the southern Italy. The soil was exposed to saline-water solution in the laboratory and in situ, in a trial plot, where salt had been added to the groundwater. The aim of the research was to investigate the changes in soil mechanical properties as a consequence of ionic diffusion. Shear strength increase, due to ionic diffusion, is known to be accompanied by a decrease in liquid limit. Therefore, the experimentation consisted of laboratory tests to determine the liquid limit and the shear strength of the clay in its natural condition and after exposure to potassium chloride. Our results showed a considerable decrease in the liquid limit and an increase in shear strength as a consequent of the treatment. This observation suggests the desirability of adopting the described chemical treatment as a control work against landslides despite the long times involved in ionic diffusion in large volumes.

Keywords: natural marine clay, salt diffusion, potassium chloride, shear strength, liquid limit

1 Introduction

In the field of classical Geotechnics, the first studies of the effects of the physico-chemical interaction between pore water pressure and clayey particles and as the influence of theses phenomena on the mechanical behaviour of clays were developed at the Norwegian Geotechnical Institute, where Bjerrum and his researchers experimented on the quick clay. They had the intuition that the instability of a marine clay could be due to the washing away of the native pore water (saline concentration equal to 35g/l of NaCl) and the substitution with less saline water (only 2-3 g/l).

Also for the clay examined in this paper (a very active and plastic clay of marine origin, of Miocene age, sampled in Bisaccia, on the southern Italian Apennines) the described mechanism could have occurred. Reduction of mechanical properties, often observed in superficial clayey soils exposed to rainfall and climatic events, could be due to the chemical variation of the pore water. These layers of weathered soil, some metres thick, cover the original marine formations in several valleys where the slopes are not too steep.