



Research paper

Volume change behaviour of swelling and non-swelling clays upon inundation with water and a low dielectric constant fluid

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ABSTRACT

Studies of the volume change behaviour of saturated and unsaturated fine-grained soils upon exposure to various types of fluid are of significant interest while dealing with contaminated soils. In this study, the one-dimensional volume change behaviour of two clays (Spergau kaolin and Calcigel bentonite) with dominant minerals as kaolinite and montmorillonite was studied by inundating several initially unsaturated and saturated clay specimens with water and a non-polar organic liquid (heptane). For both cases, applied vertical pressures of 25 and 100 kPa were considered under oedometric conditions. The magnitude of compression and swelling deformations of the clays were found to be strongly dependent upon the mineralogy of clays, dielectric properties of the pore-fluid, initial compaction conditions, and applied stress during the wetting process. The test results indicated distinct interactions between unsaturated clays and water. Specimens of Spergau kaolin exhibited compression with water, whereas specimens of Calcigel bentonite exhibited swelling. Compression and swelling deformations of the clays with heptane as the inundating liquid remained within about $\pm 1.0\%$ for both clays indicating a very minor interaction between unsaturated clays and molecules of this non-polar organic liquid. The test results emphasized the significance of attractive and repulsive forces and their impact on the volume change behaviour of clays of different mineralogy.

1. Introduction

Studies of the volume change behaviour of fine-grained soils upon exposure to various types of fluid are of great interest, particularly while dealing with contaminated soils. Contamination of soils in vadose zone may occur due to industrial activity, agricultural chemicals, gasoline spillage, and improper disposal of waste. Similarly, mitigation strategies adopted for soils contaminated with various organic contaminants demands understanding of the soil-contaminant interaction at various stress states of soils.

The physico-chemical interaction between soil particles and their influence on the volume change behaviour of fine grained soils depends upon the clay mineralogy and the pore fluid characteristics (e.g., Sridharan and Rao, 1973; Lagaly, 1989; Mitchell and Soga, 2005). Organic fluids, chemicals, and petroleum products usually possess dielectric constant values far lower than that of water. A review of the literature suggests that the influence of organic fluids on the plasticity properties, compressibility, shear strength, and hydraulic conductivity

of saturated clays has been studied in detail by several researchers in the past (Mesri and Olson, 1971; Sridharan and Rao, 1973, 1979; Fernandez and Quigley, 1985; Lagaly, 1989; Shang et al., 1994; Kaya and de Brito Galvao, 1998; Kaya and Fang, 2005). However, studies concerning the volume change behaviour of compacted unsaturated clays upon exposure to organic fluids, particularly in the context of the influence of mineralogy, compaction conditions, and applied external stress are scarce in the literature. In this study, laboratory one-dimensional swell or compression tests were carried out on two clays with two types of fluid and at two different stress levels for studying the impacts of polar and non-polar fluids, the magnitude of an applied stress, and initial compaction conditions on the volume change behaviour of clays.

2. Background

During the wetting process and under a constant applied stress, the volume change of unsaturated fine-grained soils is accompanied by a decrease in the shearing resistance at inter-particle level brought about

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by a reduction in the soil suction, and by the changes in the magnitude of the physico-chemical forces. As a result, a soil may exhibit swelling or compression, or even the volume change may not occur under specific stress and hydraulic boundary conditions. The physico-chemical forces are comprised of the electrical attractive and the repulsive forces (Verwey and Overbeek, 1948; Bolt, 1956; van Olphen, 1977; Sridharan and Jayadeva, 1982; Heuckel, 1992; Mitchell and Soga, 2005). The repulsive forces that may get generated within clay-fluid systems are due to the interaction of electrical double layers around the clay particles and hydration of ions and surfaces of clay particles (Madsen and Müller-Vonmoos, 1989; Laird, 2006; Baille et al., 2010). These forces tend to cause an increase in the volume of clays. The interaction between the edges of clay particles with the negatively charged surfaces are electrostatic (Columbic) in nature. The primary and secondary bonding (hydrogen bond and van der Waals bond) are the other possible sources of attractive force that govern the shearing resistance at inter-particle level. The short range inter-particle force exists at very close spacing, whereas the long-range attractive forces (van der Waals force) are considered to be sensitive to applied force and pore fluid properties.

The mobilised physico-chemical forces within clay systems to a great extent depend upon the physical and chemical properties of the clays (i.e., specific surface area and type and amount of exchangeable cations present in the clay), the bulk fluid properties (i.e., solvent type, concentration, dielectric properties, and pH), the applied external stress, the soil suction, the initial compaction conditions of the clay (i.e., dry density and water content), and the temperature (Sridharan and Jayadeva, 1982). The physico-chemical forces influence the fabric in fine-grained soils, which in turn regulates the hydraulic conductivity, compressibility, stiffness, and shear strength (Sridharan, 1991; Sridharan and Rao, 1979; Fernandez and Quigley, 1985; Chen et al., 2000; Santamarina et al., 2001; Mitchell and Soga, 2005; Wang and Siu, 2006). The fine-grained soil system is complex and the individual effects of various parameters influencing the repulsive and attractive pressures cannot be readily separated. However, it has been brought out in the literature that the dielectric constant of the pore medium plays an important role in that, the attractive force varies inversely and the repulsive force varies directly with the dielectric constant of the pore medium (Verwey and Overbeek, 1948; van Olphen, 1977; Sridharan and Rao, 1973, 1979).

Adsorption of water molecules in the silicate layers of clay minerals tends to eliminate the attractive pressure at the edge-face contacts in flocculated clay structure. Development of the repulsive pressure during the wetting process causes further decrease in the attractive pressure between the clay particles. A decrease in the attractive pressure gets manifested on a reduction in the shearing resistance due to a reduction in effective contact stress. Both the mobilized repulsive and attractive pressures are strongly dependent upon the characteristics of the hydrating fluid. Partially saturated and fully saturated clay systems possess attractive pressures lower than that occur in dry clays due to a partial or completion of the surface and ion hydration processes (Sridharan, 1968).

The exchangeable cations in clay are soluble in polar fluids (e.g., water and polar organic liquids); however, are insoluble in non-polar organic liquids (e.g., heptane, toluene etc.). The adsorption of polar organic liquid molecules in the interlayers occurs either as replacement to water molecules in partially saturated clay systems or via the exchangeable cations in fully dry clays (Grim, 1968; Theng, 1974; van Olphen, 1977). Sorption of non-polar organic molecules in the interlayers of dry clays is usually insignificant, whereas the process can be very slow or only limited adsorption may take place in the interlayers of partially saturated clays (Grim, 1968; Theng, 1974; Amarasinghe et al., 2009).

Table 1
Properties of the clays used in the study.

Properties	Spergau kaolin	Calcigel bentonite
Specific gravity of soil solids, G_s	2.62	2.80
Liquid limit, w_L (%)	53.4	178.0
Plastic limit, w_p (%)	30.1	56.0
Shrinkage limit, w_s (%)	22.3	8.8
Specific surface area, S (m^2/g)	14.0	650.0
Base exchange capacity, B (meq/100 g)	8.0	74.0

3. Materials and methods

Spergau kaolin and Calcigel bentonite, both clays from Germany, were used in this investigation. The properties of the clays are given in Table 1. The chosen clays possess a wide range of physical and chemical properties. X-ray diffraction studies indicated that about 60% of the minerals in Calcigel bentonite were montmorillonite, whereas the remaining were quartz, feldspar, dolomite, and calcite. Spergau kaolin was found to contain about 72% kaolinite, 16% quartz, and 10% muscovite. Studies of the cation exchange complexes of the clays indicated that more than 85% of the exchangeable cations in Calcigel bentonite were Ca^{+2} and Mg^{+2} with small fractions of Na^+ and other ions (Schanz and Tripathy, 2009). Spergau kaolin was found to contain Ca^{+2} , Mg^{+2} , and K^+ .

One-dimensional swell and compression tests (American Society for Testing and Materials (ASTM), 1986) were carried out in conventional oedometers. All tests were carried out at a temperature of $20 \pm 2^\circ C$. Compacted clay specimens were prepared at various water contents including from oven-dried clay powder. Distilled water was used for preparing the clay-water mixtures. The clay-water mixtures were stored in air-tight plastic bags for about a week in the laboratory for moisture equilibration to take place. Compacted clay specimens were prepared corresponding to predetermined dry densities with gentle tamping on the clay-water mixtures within the oedometer rings. Extreme precautions were exercised in order to minimize the errors due to side friction by lubricating the specimen rings with technical grade silicon grease. Filter papers were used at the top and bottom of the specimens.

The details of the specimens tested for Spergau kaolin and Calcigel bentonite are given in Tables 2 and 3, respectively. For both clays and for each combination of water content-dry density, two different vertical pressures levels were considered, such as 25 and 100 kPa. For the clay specimens that were prepared from oven dried clay powder and at low initial water contents (i.e., 0 and 12% for Spergau kaolin and 0 and 9.0% for Calcigel bentonite), the targeted external loads were applied in a single step loading process, whereas for the specimens that were prepared at higher water contents (61.5% for Spergau kaolin and 55.2 and 64.3% for Calcigel bentonite), a load increment ratio of one was adopted to attain the required vertical pressure levels. The incremental loads were applied after an elapsed time of more than three hours or upon completion of the primary consolidation phase, which ever occurred earlier. Following the loading process, the specimens were inundated either with water or heptane (C_7H_{16}). For every applied vertical stress, time-vertical deformation readings were monitored using dial gauges of sensitivity of 0.001 mm and a total run of 25 mm. Similarly, the time-deformation readings (compression or swelling) were monitored until the equilibrium conditions were attained. At each compaction conditions (see Tables 2 and 3), four specimens were tested. In total, thirty-six clay specimens were tested, sixteen for Spergau kaolin and twenty for Calcigel bentonite.

The dielectric constant of water is 80.4, whereas that of heptane is 1.92 as against the dielectric constant of air of 1.0. Additionally, water is a polar liquid, whereas heptane is a non-polar organic liquid. Heptane is a highly flammable solvent. Extreme care was exercised while handling the solvent by wearing gloves and a medical mask. The oedometer tests were carried out in an isolated room with appropriate

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