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# Swelling pressures and one-dimensional compressibility behaviour of bentonite at large pressures

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ABSTRACT

In this study, the swelling pressures and one-dimensional compressibility behaviour of several compacted saturated bentonite specimens were determined. Laboratory oedometer tests were carried out on a bentonite from Germany, using distilled water as the bulk fluid. A newly developed high pressure oedometer device was used that enabled measurement of swelling pressures of initially unsaturated compacted bentonite specimens (strain-controlled tests) and then facilitated subsequent loading the specimens up to 25 MPa. Several initial compaction conditions (i.e., dry density and water content) of the bentonite were considered. The test results showed that both initial water content and compaction dry density influenced the swelling pressure of the bentonite. For the range of void ratio considered in this study, the swelling pressures of compacted saturated specimens were found to be significantly smaller than the applied vertical pressures during the consolidation tests. Also, the compression paths of compacted saturated specimens remained distinctly below that of the compression path for the initially saturated bentonite specimen even at very large pressures. The initial compaction conditions affected the compression index of the bentonite, whereas the effects were found to be less significant on the decompression index. The effect of initial compaction conditions on the coefficient of consolidation was found to be significant at void ratios greater than 0.5. The variation of the coefficient of permeability with the void ratio was found to be distinctly bilinear for an initially saturated bentonite specimen, whereas the permeability varied linearly with the void ratio for compacted saturated specimens. In general, the compacted saturated bentonite specimens were found to be more permeable than the initially saturated bentonite.

## 1. Introduction

Compacted bentonites are known to meet several pre-requisite scientific and engineering characteristics for various important geotechnical engineering applications. Some of the important properties that the compacted saturated bentonites have to offer are: low permeability, high swelling capacity, and low ion diffusivity (Pusch, 1982). Upon imbibing water or electrolytes, compacted bentonites exhibit significant volume change. On the other hand, if the volume change is prevented, the clay exerts pressure (i.e., swelling pressure) on the adjacent restraint.

Compacted bentonites have been proposed as suitable barrier and backfilling materials for the underground storage of nuclear waste in many countries (Pusch, 1977; Dixon and Gray, 1985; Radhakrishna et al., 1989). Radioactive and toxic wastes of various degree of toxicity are planned to be stored below the ground level at depths ranging from 500 m to 1000 m surrounded by compacted bentonites. In the waste disposal repositories, the saturated host rock serves as the source for supplying fluid to the compacted bentonites and also acts as confinement against the volume increase. Considering the stress level at the location of the waste disposal repositories and the stress convergence of the host rock with the compacted saturated bentonites, it is necessary to study the compressibility behaviour of compacted saturated bentonites at very large pressures.

A number of laboratory studies reported in the literature focussed on studying the hydro-mechanical behaviour of bentonites by subjecting them to large pressures and suctions (Al-Mukhtar et al., 1999; Marcial et al., 2002; Fleureau et al., 2002). The studies on the volume change behaviour of bentonites due to the application of mechanical stresses mostly were for saturated condition with initial water content greater than the liquid limit. The compressibility behaviour of compacted bentonites after the swelling pressure is developed under confined conditions is a near field situation and has not been studied so far.

The bentonite used in this study was from Southern Germany and has been proposed to be used as the barrier and backfilling material in German concept of radioactive waste disposal (Herbert and Moog, 2002). A newly developed high pressure oedometer device was used to carry out swelling pressure tests on several compacted bentonite

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specimens under constant volume conditions. After the swelling pressure tests were completed, the specimens were subjected to pressures greater than the swelling pressures up to a vertical pressure of 25 MPa to determine the one-dimensional volume change behaviour. The void ratio-swelling pressure relationship and the compression–decompression behaviour of the compacted saturated bentonite specimens were compared with the compression–decompression behaviour of an initially saturated specimen subjected to a vertical pressure of 21 MPa. The effects of initial compaction conditions and the vertical pressure on the compression and decompression indices, the calculated coefficient of consolidation, and the saturated coefficient of permeability, are brought out in detail.

## 2. Background

One-dimensional compressibility behaviour of soils is commonly determined from laboratory oedometer tests using saturated soil specimens (either undisturbed or remoulded). In general, the initial water content chosen is greater than the liquid limit for the remoulded soils, referred to herein as the initially saturated bentonite. There have been substantial contributions on the study of the compressibility behaviour of bentonites by several researchers in the past (Bolt, 1956; Olson and Mesri, 1970; Mesri and Olson, 1971; Sridharan and Rao, 1973; Mitchell, 1993; Di Maio et al., 2004). The studies have emphasised the influence of physicochemical forces affecting the void ratio changes due to an increase in the applied stress. Volume change behaviour of bentonites is known to be influenced by several factors (Sridharan and Jayadeva, 1982; Chen, 1988; Gens and Alonso, 1992; Fredlund and Rahardjo, 1993): (a) compaction density, (b) type and amount of exchangeable cations, (c) specific surface area, (d) montmorillonite content, (d) temperature, (e) properties of the bulk fluid, (f) initial and final stress states (suction and net stress), and (h) stress history.

Reported studies on the compressibility behaviour of initially saturated bentonites at large pressures are limited. Bolt (1956), Warkentin et al. (1957), and Di Maio et al. (2004), carried out oedometer tests up to a vertical pressure of about 5 MPa. Mesri and Olson (1971) reported test results up to about 3 MPa, whereas Yong and Mohamed (1992) and Al-Mukhtar et al. (1999) presented experimental results up to 10 MPa. Marcial et al. (2002) showed that the $e$-log $p$ relationships (i.e., the void ratio versus log-vertical pressure relationships) of initially saturated bentonites for a large pressure range (up to 30 MPa) can be identified by two coefficients of compression; one in the initial pressure range and the other at large pressures. They showed that the transition from an initially steeper slope to a moderate slope occurs at different pressures depending upon the type of exchangeable cations present in the bentonite. The compressibility behaviour of the bentonites before the transition (in general, below a pressure of 1000 kPa) was attributed to two phenomena, such as: (i) the compression of a gel structure at very high void ratio, and subsequently, (ii) the compression of largest interaggregate voids. Beyond the transition and at pressures greater than about 1000 kPa, it was stated that the regular parallel arrangement of clay platelets seems to be reasonably valid. In this pressure range, the pressure–void ratio behaviour of bentonites is affected by the type of exchangeable cations and the number of water molecules contained in the hydration shells within the interlayer space.

Compacted bentonites are comprised of pores at different structural levels. (Gens and Alonso, 1992; Romero et al., 1999; Lloret et al., 2003; Delage et al., 2006). Pore size distribution studies for initially unsaturated compacted bentonites by Delage et al. (2006) showed that the total pore volume of compacted bentonites are comprised of the interlayer pores between the layers, the interparticle pores between the particles inside the aggregates, and the inter-aggregate pores between aggregates made up of clay mineral particles. With an increase in the water content, the swelling of bentonites is characterised by a division of the particles within the aggregate, thus increasing the interparticle spacing that is manifested on the reduction of the interaggregate pores (Saiyouri et al., 2004; Delage et al., 2006; Delage, 2007).

Swelling pressures of compacted expansive clays can be determined from several methods, such as the swell and load method, the load-swell method, and the no-swell method (Sridharan et al., 1986a; see ASTM D4546-96 (ASTM, 1998b). The latter test is known as the strain-controlled test where the volume change of the clay is not permitted (Chen, 1988). Considering the use of compacted bentonites as the sealing material in the access galleries, tunnels, and also as the buffer material in the vicinity of the waste canisters, the in situ condition suggests that strain-controlled tests are more useful than the other methods of determination of swelling pressures. Therefore, most studies in the past have focussed on the determination of swelling pressures from strain-controlled tests (Müller-Vonmoos and Kahr, 1982; Gray et al., 1984; Japan Nuclear Cycle Development Institute, 1999; ENRESA, 2000).

Several researchers in the past have emphasized the development of swelling pressure for compacted expansive soils during the water uptake process (Brackley, 1973; Pusch, 1982; Komine and Ogata, 1994; Imbert and Villar, 2006; Schanz and Tripathy, 2009). It was noted that the development of swelling pressures with elapsed time during the saturation process was influenced by the initial compaction conditions. For bentonite specimens with greater initial water contents, the increase in swelling pressure with an elapsed saturation time was found to be smooth, whereas for specimens with very low initial water contents a collapse followed by an increase in the swelling pressure was noted. Additionally, the development of swelling pressures for very high dry density clays was shown to exhibit multiple peaks.

## 3. New high pressure oedometer device

A review of literature on the oedometers designed for applying large pressures (>3 MPa) revealed that the existing devices are suitable either for measuring swelling pressures of clays using a force transducer for the strain-controlled condition or for applying large vertical pressures up to about 30 MPa to determine the consolidation behaviour (Romero, 1999; Marcial et al., 2002). However, measurements of the swelling pressure and further loading of clay specimens to very large pressures may not be possible using the available designs. Therefore, a new oedometer device was designed and fabricated to study the swelling pressure as well as the compressibility behaviour of compacted saturated bentonite specimens.

A schematic of the new high pressure oedometer device with detailed itemised components and a photograph of the test set up are shown in Fig. 1. In Fig. 1, a thick bottom stainless steel base (no. 3) houses a porous stainless steel plate (no. 7) and the bottom water chamber (no. 19). The central part of the device (no. 2) holds a thick-walled specimen ring of thickness 20 mm and 50 mm in diameter (no. 4) that accommodates a compacted clay specimen (no. 5), and a pressure pad with a porous stainless steel plate (no. 6). The top part carries the loading piston (no. 10) attached with a force transducer (no. 8). The force transducer used in this study had a maximum loading capacity of 50 kN with a precision of 0.001 kN. A strain gauge (no. 9) with a precision of 0.001 mm and a total run of 25 mm was connected directly to the loading piston to record the vertical deformation. The bottom and the central parts are connected with the help of heavy screws (no. 17), whereas the top part is directly screwed onto the central part. The force transducer together with the loading piston becomes fixed between the pressure pad (no. 6) and the upper restraint (no. 12). In case of compacted specimens, the top part of the device was rotated to apply a seating pressure of 10 kPa. The force transducer enabled measuring the swelling pressures and monitored the applied vertical pressures. The device was designed in such a way that upward vertical movement above the initial height of the specimen can be restricted, whereas the loading piston can move downwards. Hence, soil specimens can be loaded after the equilibrium swelling pressures are reached to study the compressibility