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Research Paper

Effect of temperature on swelling pressure and compressibility characteristics of soil

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ABSTRACT

Clays are being used for several construction purposes particularly as waste isolation barrier and undergo several temperature and hydraulic condition during operational period. Clays may undergo large compression during the particular loading condition. Bentonite is highly swelling clay containing high amount of montmorillonite mineral is considered as barrier and backfilling material for high level radioactive waste disposal repositories. The present study investigates the effect of temperature on swelling pressure and compressibility behavior of divalent rich Indian bentonite (liquid limit = 139%) from Bikaner, Rajasthan and effect of temperature on compressibility behavior of local soil (liquid limit = 35%) from Rourkela. A new oedometer was designed and developed in-house to carry out consolidation and swelling pressure tests at various temperatures. Swelling pressures tests on compacted bentonite specimens of targeted dry density 1.6 Mg/m^3 were conducted under constant volume condition for the temperature range between 25 and 90 °C. Consolidation tests at various temperatures between 25 and 90 °C for both soils were carried out using distilled water as inundating fluid. The study revealed that with increase in temperature the swelling pressure and compressibility index of bentonite increased. However, effect of temperature on compressibility behavior of local soil was found to be minimum.

1. Introduction

Compacted bentonites upon saturation undergo large volume change. If the volume changes of the bentonite is prevented, they exert pressure on the restrained boundary known as swelling pressure. Compacted bentonites regarded as an important barrier and backfilling materials to be used for the underground storage of nuclear waste (Pusch, 1977) at great depths about 500 to 1000 m. The section of bentonite that is in contact with waste canisters is subjected to elevated temperature upon receiving heat from the radioactive waste, whereas the other section contact with saturated host rock may receive groundwater from the saturated host rock. In the restrained condition due to receiving ground water from host bentonite blocks would exert swelling pressure. Therefore, understanding the behavior of compacted bentonites under thermal and mechanical loading is necessary for the long-term safety assessment of the waste disposal repositories.

Out of the various methods available to measure swelling pressure of expansive soil (Sridharan et al., 1986), constant volume method or no swell method is mostly preferred in laboratory scale tests. Several researchers used strain controlled test for measurement of swelling pressure of bentonite in compacted condition (Madsen and Müller-vonmoos, 1985). Schanz and Tripathy (2009) used constant volume method to measure swelling pressure of bentonite at dry density range between 1.10 and 1.73 Mg/m^3 and found that development of swelling pressure mainly depends on the degree of saturation and the compacted dry density. The range of swelling pressure noted to vary between 200 kPa and 9.5 MPa. With increase in dry density the swelling pressure of compacted bentonite specimens were found to increase. In the past, a limited number of studied (Pusch, 1980, Villar and Lloret, 2004, Ye et al., 2013, Tripathy et al., 2015) have been conducted to understand the effect of temperature on swelling pressure and compressibility behavior of clays. Therefore, a detailed study was conducted to understand the temperature effect on swelling pressure of a bentonite and compressibility behavior of the bentonite and a local soil.

Conventional oedometers are suitable for measuring swelling pressure and compressibility characteristics of soil at ambient temperature, while, at elevated temperature measurement of the swelling pressure and compressibility characteristics may not be possible using the available design. Madsen and Müller-vonmoos (1985) used a modified oedometer to measure the swelling pressure of compacted bentonite at elevated temperature. Two dial gauges were used to monitor the deflection of the test specimen. The swelling pressure was measured using a pressure cell placed in between a loading plunger and a restrained bar. Romero (1999) also developed a device to measure swelling characteristics of saturated compacted bentonite using the strain controlled method. To measure swelling pressure a load cell installed in the device.

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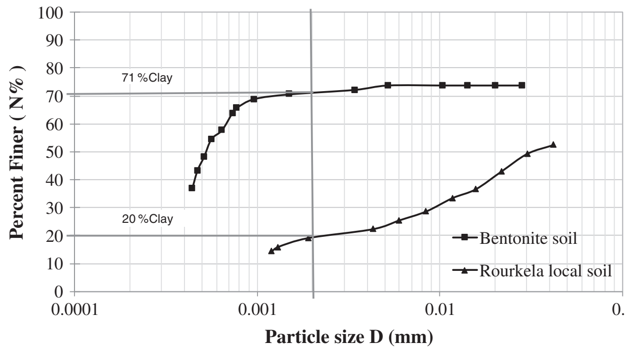

Fig. 1. Grain size distribution curve of the soils studied.

In order to hydrate the clay specimen fluid was circulated from both top and bottom using a burette and water reservoir. Similar device was used for measuring the swelling pressure of compacted bentonites under constant volume condition by several researchers (Schanz and Tripathy, 2009; Tripathy et al., 2014a, 2014b). A limited number of devices are available to measure the swelling pressures at elevated temperature (Agus, 2005). To conduct the swelling pressure tests at elevated temperature, a special arrangement and modification of the existing devices required. In this work, a new oedometer was designed and developed in-house to carry out consolidation and swelling pressure tests at higher temperatures.

Pusch (1980) measured the swelling pressures of compacted bentonite in saturated condition at temperatures of 20 °C and 90 °C and reported significantly lower swelling pressure at higher temperature i.e. at 90 °C. It was concluded that the decrease in swelling pressure was due to existence of less stable interlayer water at a higher temperature. Pusch et al. (1990) observed that as temperature increases swelling pressure of Ca bentonite decreases. Similar result was reported by Villar and Lloret (2004) for the FEBEX bentonite (i.e., bentonite having Ca and Mg predominant cation). On the other hand, Karnland et al. (1994) reported that as temperature increases swelling pressure of saponite and Na-montmorillonite also increases. Romero et al. (2003) studied the temperature effects on multi-step swelling pressure for compacted saturated Boom clay and reported that the swelling pressure at 22 °C was higher than those at 80 °C. Tripathy et al. (2015) observed a reduction in swelling pressure of compacted Na-rich bentonite with increase in temperature. It was stated that the temperature increase caused an increase in electric potentials at the Stern plane and in the mid-plane and hence the Gouy-layer charge, Stern-layer charge, non-dimensional mid-plane and the Debye length decreased.

Table 1
Properties of soils used in this study.

Property	Bikaner bentonite Soil	Rourkela local Soil
Liquid limit (%)	139	35
Plastic limit (%)	50	21
Shrinkage limit (%)	38	15
Plasticity index I_P (%)	89	14
Natural moisture content (%)	15	9
Linear shrinkage (%)	22	14
Differential free swell (%)	150	25
Specific gravity	2.65	2.67
Clay content (C %)	71	20
Activity = I_P/C %	1.17	0.7
Group symbol (IS Soil Classification System)	CH	CL
BET specific surface area (m^2/g)	70	21.7

Ye et al. (2013) reported an increase in swelling pressure of compacted bentonite with increase in temperature. Swelling pressure of bentonite primarily depends on type and amount of clay, type of exchangeable cation, pore fluid, dielectric constant and temperature. Soils enriched with montmorillonite mineral undergo a large volume change (Mitchell, 1993). Increase in ionic valence for a given concentration decreases the double-layer distance and there by aggregation of particles occur. In general, as the valence increases, the permeability increases, whereas, compressibility, swelling and plasticity characteristics decrease. In case of soils containing montmorillonite mineral, an increase in pore electrolyte concentration, decreases the plasticity, swelling and compressibility characteristic of the soils. Increase in the dielectric constant, increases the plasticity, swelling and compressibility. Increase in temperature increases the thickness of diffuse double layer. However, the dielectric constant of pore fluid decreases. These two effects have opposite influence on the properties of soils, and the net effect is dependent on the type of clay. Ye et al. (2013) concluded that the increase in swelling pressure due to increase in temperature was due to additional embedding of water molecules into the interlayers of expansive minerals and increase in repulsion between double layers.

The study on compressibility behavior of expansive clay has been carried out by several researchers, covering extensive void ratios range with large pressure changes (Sridharan et al., 1986; Tripathy and Schanz, 2007). The saturated condition having water content higher than the liquid limit of clay is considered as a reference state to study the behavior of clays. Fang and Daniels (2006) measured the compressibility and volume change at various temperatures and reported an increase in compressibility with increase in temperature. The compression index, c_c which is the slope of the linear portion of the pressure-voids ratio curve was reported to increase with increase in temperature. Depending on the magnitude of temperature change, the volume change of the specimen was noted. Romero et al. (2003) conducted tests on compressibility of compacted Boom clay at different temperatures and found that the compression index is larger at higher temperatures. Cui et al. (2000) described two phenomena during heating of expansive clay: (1) expansion of soil constituents (solid and water): (2) mechanical weakening of the contacts between soil aggregates. Saix et al. (2000) observed a contraction in volume during heating of the clayey soil under constant stress at 42, 160 and 800 kPa in oedometer. The main objectives of the current study was to develop an oedometer for conducting swelling pressure and consolidation test at elevated temperature and study the effect of temperature on those properties of soil.

2. Materials and methods

The soils used in this study were a commercial bentonite procured from Bikaner, Rajasthan and a local soil from Rourkela, Odisha, India. Grain size distribution curves for both the soils obtained by hydrometer analysis is shown in Fig. 1. The amount of clay size fraction present in the bentonite and Rourkela local soil was found to be 71% and 20%, respectively. Physical properties of soils are presented in Table 1. In all the tests distilled water was used to establish an apparent reference condition. Bentonite in dry powder form (initial moisture content = 15%) is chosen for this study and was stored in a plastic bag to maintain constant initial moisture content. Physical properties of soils were determined following Indian standard procedure (IS: 2720, 1992). The specific gravity of soil solids were determined in a volumetric flask was found to be 2.65 and 2.67 for bentonite and local soil, respectively.

The Brunauer, Emmett and Teller (BET) technique is the most common method for determining the external surface area of soil sample using gas adsorption analysis. In the current study, liquid nitrogen was used as adsorbent and the specific surface area was measured following ASTM procedure (ASTM D3663- 03, 2015). Total and fractional cation exchange capacity of the bentonite was determined using barium chloride solution (Hendershot and Duquette, 1985). The individual cation exchange capacities of Na, K, Ca and Mg were found to be 7.02, 0.94, 70.13 and 19.53,