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Consolidation behaviour of bentonites in the presence of salt solutions

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ABSTRACT

Due to its high swelling capacity and lower value of hydraulic conductivity, compacted bentonite is used as a liner material at the waste disposal site. Salts presents in landfill leachates may cause the diffuse double layer of bentonite to shrink which in turn affects its swelling and compressibility behaviour. Consolidation is among important properties of the liner material which need to be studied for settlement analysis. This study was carried out to investigate the effect of NaCl and $CaCl_2$ solutions of varying concentrations, on the consolidation behaviour of two compacted bentonites having different mineralogical composition. The bentonites were studied in terms of changes in the mechanical parameters including the coefficient of volume change (m_v), coefficient of consolidation (c_v), compression index (C_c) and time taken to complete 90% of consolidation (t_{90}) in the presence of the salt solutions. The results showed that the C_c, m_v and t_{90} of the bentonites decreased, whereas, c_v increased with the increase in salt concentration. Bentonite of higher quality defined by having a higher cation exchange capacity, exchangeable sodium percentage and swelling capacity, exhibited higher values for C_c, m_v and t_{90} in comparison to lower quality bentonite. Results also showed that irrespective of the salt solution present c_v decreased, whereas, t_{90} increased with increase in the consolidation pressure. However, with increasing in the pressure, m_v increased initially and after reaching a peak value it decreased. A higher value of theoretical void ratio was obtained from diffuse double layer theory for both the bentonites at lower overburden pressure and water as pore fluid. However, with increase in the consolidation pressure the theoretically obtained void ratio–pressure curve converged towards the experimentally obtained curve and crossed it at certain pressure and diverged again. However, with salt as a pore fluid a higher value of experimentally obtained void ratio was observed.

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1. Introduction

Compacted clay liners are generally provided as a barrier to separates the waste from the groundwater system. Due to its higher swelling capacity, low hydraulic conductivity and contaminant adsorption ability, bentonite is used as a barrier material in landfills as a means of controlling migration of contaminants leachate into the surrounding environment (Daniel, 1984). The higher swelling capacity and consequently the lower hydraulic conductivity of bentonite have been attributed to the formation of diffuse double layer with water (Norrish and Quirk, 1954; Olson and Mesri, 1970). However, the contaminants present in the leachate suppress the thickness of the diffuse double layer; which in turn, shrinks the bentonite resulting in a reduction in the swelling capacity (Norrish, 1954).

Similar to the hydraulic conductivity, compressibility is one of the important properties which help in evaluating the settlement of the liner material due to the weight of the waste at the waste disposal site (Mishra et al., 2010). Volume changes in soils are important because of their consequences in terms of settlement due to compression which leads to changes in strength and deformation properties, which

in turn influence stability (Mitchell and Soga, 2005). Since the bentonite is a highly compressible material, the liner becomes compressed due to the increase in the weight of the waste. Consolidation is the compression that results when a load that is applied to saturated clay gives rise to a settlement, the magnitude of which is determined when the generated pore pressures are fully dissipated (Yong and Warkentin, 1975).

The compressibility behaviour of the bentonite is controlled by both mechanical and physico-chemical factors (Bolt, 1956). The short-range particle interaction controlled by the physical properties such bending, sliding, rolling, and crushing of soil particles controls the mechanical effect of the compressibility of bentonite, whereas, physico-chemical interactions between particles depend on long-range interaction between the particles through the diffuse double layer (Sridharan and Rao, 1973; Sridharan and Jayadeva, 1982; Mitchell and Soga, 2005).

Due to their importance on the compressibility behaviour various parameters such as compression index (C_c), coefficient of volume change (m_v), coefficient of consolidation (c_v) and time to complete 90% of the consolidation (t_{90}) has attracted much attention among researchers. Compression index (C_c) is defined as the slope of the straight line portion of the virgin void ratio–pressure (e–log P) curve. The C_c of a sample gives an indication about its compressibility and is used to determine the settlement of the sample due to the application of a vertical

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consolidation pressure. The coefficient of volume change (m_v) is defined as the volume change per unit volume per unit increase in load, and it depends on the stress range over which it is determined. The coefficient of consolidation (c_v) signifies the rate at which a saturated soil sample undergoes one-dimensional consolidation when subjected to an increase in the vertical consolidation pressure, which in turn, directly depends on the hydraulic conductivity of the soil medium undergoing compression. It is essential to know the c_v value of soil to determine its rate of settlement and hydraulic conductivity. A higher value of c_v indicates a faster rate of consolidation, whereas, a lower value indicates a slower rate of consolidation. Similarly, the t_{90} value of a sample indicates the time required to complete 90% of the consolidation under a given consolidation pressure.

Since the factors such as clay mineralogy, type of exchangeable cations and pore water chemistry influences the diffuse double layer thickness (Bolt, 1956; Olson and Mesri, 1970; Sridharan and Rao, 1973; Sridharan and Jayadeva, 1982; Mitchell and Soga, 2005, Dutta and Mishra, 2015) and consequently can produce a significance influence on C_c, m_v, c_v, and t_{90} (Salas and Serratosa, 1953; Robinson and Allam, 1998). Ouhadi et al. (2006) investigated bentonite–contaminant interaction at different pH levels and heavy metal ion concentrations and observed a definite influence of pH and heavy metals on the consolidation behaviour of bentonite.

Limited studies have been carried out in the past to investigate the effect of mineralogical and chemicals factors on the compressibility and consolidation behaviour of bentonite. From a series of experiments Salas and Serratosa (1953) concluded that the compressibility of monovalent bentonites decreases in the order lithium bentonite > sodium bentonite > potassium bentonite. Sridharan et al. (1986a) studied the compressibility characteristics of bentonites homoionized with a series of monovalent, divalent and trivalent cations and concluded that a decrease in the cation valence and increase in hydrated cationic radius increases the compressibility. They also showed that the size of the hydrated cation was more pronounced for monovalent cations in comparison to a divalent and trivalent cation. A study by Di Maio (1996) concluded that the exposure to the NaCl, CaCl$_2$ and KCl solutions to the bentonite produce a significant amount of osmotic consolidation and large increase in residual shear strength.

A study by Robinson and Allam (1998) on kaolinite, illite, montmorillonite clay concluded that the mineralogy of clay plays a significant role in consolidation behaviour and showed that with water as the pore fluid with an increase in the consolidation pressure the c_v of the montmorillonite decreases, whereas, it increases for illite and kaolinite. They also observed that the m_v for all the three clays decreases with increase in the consolidation pressure. Mishra et al. (2011) observed the influence of NaCl and CaCl$_2$ at various concentrations on the compressibility of mixtures of soil and bentonite and reported that the compressibility reduced with increasing salt concentration of the pore fluid. Mishra et al. (2010) studied the influence of bentonite on the consolidation behaviour of soil–bentonite mixtures and observed that C_c of the mixtures was increased with the increase in the liquid limit, free swelling and clay fraction of the bentonites and the c_v increases with the increase in the consolidating pressure. Shariatmadari et al. (2011) studied the effect of three inorganic salts i.e. NaCl, CaCl$_2$, and MgCl$_2$ on compressibility behaviour of mixtures of clay and bentonite and observed that C_c of the mixtures decreased with the increase in the salt concentration. From their experiments on the mixture of sand and polymerized bentonites mixed in various proportions Bohnhoff and Shackelford (2014) concluded that with the increase in the pressure m_v decreases and c_v increases.

Since the thickness of the diffuse double layer influences the compressibility behaviour of the bentonite (Bolt, 1956; Sridharan and Rao, 1973) and as the thickness of the diffuse double layer depends upon many factors such as mineralogical composition of the clay, valency of cation and concentration of salt solutions in the pores (Yong and Warkentin, 1975; Mitchell and Soga, 2005), these same factors may also influence C_c, m_v, c_v and t_{90} of the bentonite. Hence, the main purpose of this study to bring out the significance of the mineralogical as well as chemical composition of the pore fluid on the various consolidation parameters such as C_c, m_v, c_v and t_{90}. This work was carried out to study the effect of inorganic salts NaCl and CaCl$_2$ at varying concentrations, on the consolidation behaviour bentonites. Two bentonites with different mineralogical composition, which was reflected in their different liquid limit and free swelling value, were evaluated for C_c, m_v, c_v and t_{90} in the presence of various concentrations of NaCl and CaCl$_2$ solutions.

2. Materials and methods

2.1. Bentonite

Two bentonites of different mineralogical composition and swelling properties used for the studies were procured from Rajasthan state of India. These bentonites are named as Bentonite-A and Bentonite-B in the further discussion for brevity. The physical and chemical properties of the bentonites are listed in Table 1. The clay content of the bentonites were determined by hydrometer test as per as ASTM D422 (2002). Atterberg limits were determined according to ASTM D4318 (2000). The cation exchange capacity (CEC) and exchangeable cations of the bentonites were determined by the ammonium acetate method as described by Chapman (1965) and Pratt (1965), respectively. The specific surface area (SSA) of the bentonites was determined by the method described by Cerato and Lutenegger (2002). The free swelling test for the bentonites was conducted as per ASTM D5890 (2001) in which 2 g of oven dried powdered bentonite was added into a 100 mL graduated cylinder containing deionized (DI) water or salt solution gradually in 0.1 g increments. The free swelling value of the bentonite was determined by measuring the swollen volume of the bentonite after 24 h of exposure. The data in Table 1 shows that the Bentonite-B, which has a higher liquid limit, plasticity index, clay content, CEC, exchangeable sodium percentage (ESP), and SSA, swells more in comparison to Bentonite-A and termed as a high quality bentonite (Mishra et al., 2011). The compaction characteristic of bentonites, i.e. maximum dry density (MDD) and optimum moisture content (OMC), were determined as per as ASTM D698 (2012).

2.2. Permeant liquids

Since the leachate of the fly ash and bottom ash, which are dumped in the landfill site, mostly contains ions of Na$^+$ and Ca^{2+} (Ohtsubo et al., 2004), solutions of NaCl and CaCl$_2$ were chosen for this study. Solutions of 0 (i.e. DI water), 0.01, 0.1 and 1 N concentrations were prepared by dissolving salts of NaCl and CaCl$_2$ (powdered with purity grade greater than 95%) in 1 L of DI water.

Table 1
Properties of bentonites used in this study.

Property	Bentonite-A	Bentonite-B
Liquid limit	218%	560%
Plastic limit	35.5%	36%
Plasticity index	182.5	524
Shrinkage limit	16.3%	19.7%
Specific gravity	2.8	2.82
Clay content	57%	68%
Silt content	43%	32%
Cation exchange capacity (CEC) (meq/100 g)	27.2	44.6
Na$^+$	10.5	24.2
K$^+$	3.4	1.9
Ca^{2+}	10.8	16.9
Mg^{2+}	2.5	1.6
Exchangeable sodium percentage (ESP)	38.8%	54.2%
Specific surface area (m^2/g)	339	456
Optimum moisture content (OMC)	33%	32%
Maximum dry density (MDD) g/cm^3	1.23	1.28