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A study on the influence of inorganic salts on the behaviour of compacted bentonites

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ABSTRACT

Clay liners are frequently installed at waste disposal sites as a means of preventing pollutant migration and minimizing or eliminating the potential for ground water contamination. Because of their low hydraulic conductivity and high contaminant adsorption capacity, bentonite is used as a liner material to prevent subsurface contamination. However, presence of various chemicals in waste could affect the hydraulic and contamination adsorption capacity of bentonite and in turn reduce its usefulness as barrier material. In addition to the salt solution, a change in the mineralogical composition such as montmorillonite content, cation exchange capacity, specific surface area, exchangeable sodium percentage of the bentonite also significantly influences its swelling and hydraulic behaviour. This study was carried out to study the effect of salt solution and mineralogical composition on the behaviour of compacted bentonite. Two bentonites with varying mineralogical composition, which was reflected in their different liquid limit and free swelling value, were evaluated for their free swelling, Atterberg limits, swelling potential, swelling pressure, and hydraulic conductivity in the presence of various concentrations of NaCl and $CaCl_2$ solution. To study the effect of initial compaction conditions on swelling and hydraulic behaviour in presence of salt solution, studies were also carried out on samples compacted at optimum moisture content (OMC)–maximum dry density (MDD) and 5% dry of OMC–MDD. The result shows that the liquid limit, swelling volume, swelling pressure of the compacted bentonites decreased, whereas, plastic limit and hydraulic conductivity increased with increase in the salt concentration. The results also show that the effect of the salt on the properties of the bentonites depends on the salt type, salt concentration and initial compaction condition of the bentonite. The effects due to salt concentration were found to be more pronounced for the bentonite of higher quality which is marked by a higher swelling capacity, liquid limit, cation exchange capacity, exchangeable sodium percentage and specific surface area.

1. Introduction

With rapid increase in the population and standard of living the total amount of municipal solid waste (MSW) that has been generated has increased by many folds and become one of the serious environmental issue in both developed and developing countries (Beede and Bloom, 1995; Suocheng et al., 2001). Landfill is one of the most widely employed methods for the disposal of these MSW (Rowe et al., 1995; Qian et al., 2002). However, these wastes undergo physico-chemical and biological changes with time and produce leachates which are toxic in nature (Kjeldsen et al., 2002). When these leachates mixed with the percolating rain water, it moves towards the groundwater and contaminates it. In order to prevent the groundwater from being contaminated from these leachates, a very low permeable clay liner is provided at the bottom of the landfill which acts as a barrier between leachate and ground water (Daniel, 1984).

Due to its high swelling capacity and low hydraulic conductivity, bentonite is widely used as a liner material (Daniel, 1984). Bentonite is a naturally available clay, generated from the deposition and alteration of volcanic ash which contains high amount of swelling clay minerals and has highly plastic characteristics (Mitchell and Soga, 2005). The swelling capacity of bentonite, which in turn controls its hydraulic conductivity, depends upon the various physico-chemical and mineralogical factors. Bentonite primarily consists of a mineral called montmorillonite (Mitchell and Soga, 2005) and when it interacts with water, it forms diffuse double layer resulting in the swelling of bentonite (Norrish, 1954; Norrish and Quirk, 1954; Madsen and Vonmoos, 1989). As the bentonite swells it fills the pore spaces present between the solid particles in a soil matrix and provide a lower value of hydraulic conductivity (Howell and Shackelford, 1997; Komine, 2008). However, chemicals present in the leachate suppress the thickness of diffuse double layer which in turn shrinks the swollen bentonite (Norrish and Quirk, 1954). As the bentonite shrink, the flow path becomes open and the hydraulic conductivity increases (Quirk and Schofield, 1955; Madsen and Mitchell, 1989). Hence, in order to design a clay liner it is

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quite essential to study the behaviour of bentonite in the presence of various chemicals present in the leachate.

Many studies have been carried out in the past to study the effect of chemicals on the behaviour of bentonite. Mesri and Olsen (1971a, b) studied the hydraulic characteristics by performing consolidation tests on sodium and calcium montmorillonite with different fluids and found that the hydraulic conductivity is largest for nonpolar fluids (carbon tetrachloride), smaller for polar fluids with low dielectric constant (ethyl alcohol) and lowest for water, which is polar and has a high dielectric constant. Shackelford et al. (2000) evaluated the hydraulic conductivity of geosynthetic clay liners (GCL) permeated with non-standard liquids like NaCl, $ZnCl_2$, $CaCl_2$ and reported that permeants containing high concentration of monovalent cations as well as low concentration of divalent cations causes significant increases in hydraulic. Jo et al. (2004) investigated the long term effect of inorganic salt solutions (i.e. NaCl, KCl and $CaCl_2$) on the hydraulic conductivity of GCL and observed that the hydraulic conductivity of GCL increased twice as much as in comparison with water due to permeation of 100 Mm NaCl and KCl solution. Thammathiwat and Chimoye (2010) investigated the effect of monovalent (i.e. LiCl, NaCl and KCl), divalent (i.e. $CaCl_2$, $MgCl_2$ and $CuCl_2$) and trivalent ($FeCl_3$) salt solutions on swelling and hydraulic conductivity of GCLs and observed that at similar concentration, swelling was larger with monovalent cations than with divalent and trivalent cation solutions. GCLs permeated with solutions containing divalent or trivalent cations had exhibited higher hydraulic conductivity than GCLs permeated with monovalent or distilled water. Shirazi et al. (2011) investigated the salinity effect on swelling characteristics of compacted bentonite and observed that swelling rate depends on the concentration of NaCl more than on initial dry density and loading effect. Liquid limit of bentonite remarkably decreased from 497% to 112% when the test liquid changed from distilled water to 0.5 M NaCl solution, while the plastic limit is increased.

Xue et al. (2012) studied the impact of high concentration solution (i.e. $MgCl_2$, $CaCl_2$, NaCl and KCl) on hydraulic properties of GCL materials and reported that the hydraulic conductivity of GCL increased several times or exceeded two orders of magnitude when soaked and permeated with high concentration chemical solutions as compared with the permeation that used water as the permeant liquid. The chemical attack effect on GCL hydraulic conductivity was $CaCl_2 > MgCl_2 > KCl > NaCl$. Ouhadi et al. (2006) investigated bentonite–contaminant interaction at different pH levels and heavy metal ion concentrations and observed that pH and heavy metals has a definite effect on the behaviour of bentonite.

In addition to the salt solution, a change in the mineralogical composition such as montmorillonite content, cation exchange capacity, specific surface area, exchangeable sodium percentage of the bentonite also significantly influences its swelling and consequently the hydraulic conductivity. Since bentonite is a naturally occurring material, these mineralogical properties may vary to a great extent depending upon the source of its origin. However, very few of the previous studies have focused on the effect of the mineralogical parameters on the swelling and consequently on the hydraulic conductivity of bentonite. Quirk and Schofield (1955) concluded that the hydraulic conductivity of soil decreases with increasing the exchangeable sodium percentage (ESP), whereas, Martin et al. (1964) had shown that the hydraulic conductivity of soil has a definite relationship with the ESP at different pH levels.

Since bentonites with different mineralogical composition may behave differently in the presence of salt solution, it is quite essential to compare the behaviour of different bentonite in the presence of salt solution. Lee and Shackelford (2005) studied the differences in hydraulic conductivity for two GCLs containing different qualities of bentonite. The GCL with the higher quality bentonite (GCL-HQB) was characterized by a greater content of sodium montmorillonite, a higher plasticity index relative to the GCL with the lower quality bentonite (GCL-LQB). They concluded that GCL-HQB was more susceptible to chemical attack than the GCL with the lower quality bentonite. Permeation with $CaCl_2$ resulted in an increase in hydraulic conductivity of both GCLs relative to that based on water, with greater increases in hydraulic conductivity occurring for GCL-HQB relative to GCL-LQB. Mishra et al. (2009) studied the effect of salts (NaCl and $CaCl_2$) of various concentrations on liquid limit and hydraulic conductivity of four different mixtures of soil and bentonite and observed that the effect of salt concentration on the hydraulic conductivity of the mixture depended on the type of bentonite present in the mixture and concluded that the salt affect significantly the hydraulic conductivity of the mixture containing a higher quality of bentonite which is characterized by a higher ESP, swelling and liquid limit.

Since most of the previous studies mostly focused only on the study of the hydraulic conductivity of various bentonite (Quirk and Schofield, 1955; Martin et al., 1964; Lee and Shackelford, 2005) or soil–bentonite mixtures (Stewart et al., 2003; Mishra et al., 2009), the main purpose of this study was carried out to bring out the significance of mineralogical properties of bentonites on the swelling as well as hydraulic behaviour of bentonite in the presence of salt solution. In addition to this, to study the effect of initial compaction conditions on swelling and hydraulic behaviour in presence of salt solution, studies were also carried out on samples compacted at optimum moisture content (OMC)–maximum dry density (MDD) and 5% dry of OMC–MDD. Two bentonites with varying mineralogical composition, which was reflected in their different liquid limit and free swelling value, were evaluated for their free swelling, Atterberg limits, hydraulic conductivity, swelling potential, swelling pressure in the presence of various concentrations of NaCl and $CaCl_2$ solution.

2. Materials and methods

2.1. Bentonite

Bentonites used in this study were procured from Rajasthan state of India and in powdered form. Various physical and chemical properties of both the bentonites are listed in Table 1. Hydrometer test was carried out according to ASTM D 422 (2002) to determine the total clay content of the bentonites. Atterberg limits were determined according to ASTM D 4318 (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 swell test for the bentonite was conducted as per ASTM D5890 (2001). The consolidation test, swelling and swelling pressure was carried out in a standard consolidometer of 60 mm in diameter and 15 mm in thickness sample according to ASTM D 2435 (1996). The data in the Table 1

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) gm/cm^3	1.23	1.28