A STUDY ON THE COMBINED EFFECT OF SALT SOLUTIONS ON THE SWELLING AND HYDRAULIC BEHAVIOUR OF BENTONITES

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ABSTRACT: Study was carried out on two different types of bentonites, differ by their swelling characteristics, in the presence of various concentrations of mixtures of inorganic and heavy metals salt solutions. Bentonites were studied for their change in the Atterberg limits, swelling and hydraulic conductivity in the presence of the above solutions. Solutions of sodium chloride and calcium chloride 0 (i.e. De-ionized (DI) water), 0.1 and 1N concentration were prepared by dissolving salts of NaCl and $CaCl_2$ along with 100 ppm concentration of heavy metals such as zinc, lead and copper in DI water and used for the study. With increasing concentration, the liquid limit, swelling pressure decreased and hydraulic conductivity increased due to diffuse double layer related factors. Increase of concentration from 0 N to 1N $CaCl_2$ in the mixture solution of salt and heavy metals showed a maximum decrease in swelling pressure and swelling potential in case of high swelling bentonite. Increase in the cationic valency increases the inter-particle attractive forces which favors higher flocculation and resulting in contraction of aggregates. The divalent calcium ions by virtue of their high valency are strongly adsorbed by the clay surface and contribution to the double layer thickness is much less whereas monovalent ions like sodium ions are weakly held by the surface and readily dissociate to contribute significantly to the thickness of diffuse double layer. Mainly the salt concentration of NaCl and $CaCl_2$ dominated the above mentioned changes in comparison to the concentration of heavy metals. A comparison between the two bentonites showed that the salt and heavy metals has a significant effect on hydraulic conductivity of higher quality of bentonite which is characterized by a higher swelling and liquid limit.

Keywords: Bentonite, Atterberg limits, swelling, valency, hydraulic conductivity

1 Introduction

Clays are used as barriers in landfills, slurry walls and similar structures to slowdown the movement of contaminants. 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. Due to the higher swelling, low permeability and contaminants adsorption ability of the bentonite, it is widely used as a soil admixture for the construction of seepage barriers and waste containments (Daniel, 1984). Bentonite is naturally available clay, primarily consists of a mineral called montmorillonite, 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 higher swelling capacity and consequently the lower hydraulic conductivity of bentonite have been attributed to the formation of diffuse double layer with water (Mesri and Olsen, 1971). The swelling capacity of bentonite, which in turn controls its hydraulic conductivity, depends upon the various physico-chemical and mineralogical factors. 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.

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 (Madsen and Mitchell, 1989). Bentonite exposed to fluids varying in dielectric constant undergoes increase in hydraulic conductivity, although, the percentage of decrease depends on the type of fluids used, with highest being for the low dielectric constant and vice versa (Mesri and Olsen, 1971). Atterberg limits of bentonite is also controlled by cationic valency and hydrated ionic radius for constant valency. An increase in the valency of the adsorbed cation leads to higher hydraulic conductivity; while, for a constant valency, an increase in the hydrated radius of lower hydraulic conductivity (Sridharan et al., 1986). For engineered landfill sites, the performance of clay liner can be affected by the presence of cations like sodium ions (Na^+) and calcium ions (Ca^{2+}) in the fly ash and bottom ash (Ohtsubo et al., 2004). Presence of different salts in the leachate could affect the hydraulic conductivity of soil liner and reduce the sorption capacity of heavy metals onto the soil liner in turn reducing the usefulness of the liner. Presence of different salts in the leachate could affect the hydraulic conductivity of soil liner (Li and Frankly, 2001). In order to design a secure clay liner, it is important to have a better understanding of the effect of those cations of different concentration on the liner material.

The study was carried out to investigate the combined effect of salt solutions and heavy metals on the swelling and hydraulic conductivity of two bentonites varying in mineralogical composition. The two bentonites studied for their change in the behaviour such as Atterberg limits, swelling pressure, swelling potential and hydraulic conductivity in the presence of mixture of salt solutions and heavy metals.

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.

Table 1. Properties of bentonites used in the study

Property	Bentonite-A	Bentonite-B
Liquid limit	218%	560%
Plastic limit	35.5%	36%
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/cm3	1.23	1.28

The clay content of the bentonites was 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 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 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. Sodium (Na^+), calcium (Ca^{2+}), zinc (Zn^{2+}), lead (Pb^{2+}), and copper (Cu^{2+}) ions are commonly present in municipal solid waste (MSW) leachate.

Table 2. Salt combination used in the study

Permeant series	NaCl (N)	$CaCl_2$ (N)	Heavy metals (ppm)
0	0	0	0
1	0.1	0.1	100
2	1	0.1	100
3	0.1	1	100

Solutions of 0 (i.e. DI water), 0.1N and 1N concentration were prepared by dissolving salts of NaCl and $CaCl_2$ solution along with 100 ppm concentration prepared using heavy metals compound such as $ZnCl_2$, $Pb(NO_3)_2$ and $Cu(NO_3)_2$ in DI water and used for the study as shown in Table 2.

2.3 Determination of hydraulic conductivity

The bentonites were mixed with water at their respective optimum moisture content and kept in humidity controlled desiccators for 24 h to attain the moisture equilibrium. The moisture-equilibrated specimens were then statically compacted to its MDD in oedometer rings of a diameter of 60 mm to a thickness of 15mm. The entire assembly was then placed in the consolidation cell and positioned in the loading frame. The specimens were inundated in the DI water or the respective salt solutions under the nominal pressure of 4.9 kPa and allowed to swell. Once the swelling was completed then the samples were consolidated by increasing the pressure gradually by an increment ratio of 1 (i.e. increased by 4.9, 9.8, 19.6 kPa at each step) to a maximum pressure of 784.8 kPa. For each pressure increment the change in the thickness of soil sample was measured from the dial gauge readings. The change in the void ratio corresponding to the increase in the overburden pressure was calculated as

$\Delta e = \Delta H(1 + e_0)/H$ where, ΔH is the change in the thickness of sample due to increase in pressure; H is the initial thickness of the sample; e_0 is the initial void ratio.

From the consolidation test result, a time-settlement curve was obtained at each pressure increment. The coefficient of consolidation (c_v) was obtained using Taylor's square root time (√T) method (Taylor, 1948).

The coefficient of volume change was calculated as

$m_v = -\frac{\Delta\sigma}{\Delta e}(1 + e_0)$ where, $\Delta\sigma$ is the change in pressure and Δe is the change in void ratio.

Coefficient of consolidation (c_v) was determined by the square root of time fitting method given by Taylor (1948) (IS 2720 part XV). The hydraulic conductivity (k) was calculated by fitting Terzaghi's theory of consolidation (Terzaghi, 1943) for various pressure increments using the c_v and m_v as

$k = c_v m_v \gamma_w$, where γ_w is the unit weight of the pore fluid.

2.4. Determination of swelling potential and swelling pressure

A conventional oedometer apparatus was used for the determination of the swelling potential and swelling pressure of compacted bentonite sample. A surcharge load of 4.9 kPa was applied and then the compacted bentonite specimen was inundated with saturating liquid and the values of swelling with time were recorded. The measurements were continued until the swelling increment reached negligible values. At this point a standard consolidation test was conducted by applying incremental loads starting with 4.9 kPa and ending with 784.8 kPa. The pressure required to revert the specimen to its initial void ratio was determined as the swelling pressure, which is defined as the value of pressure required to keep the sample at zero swelling after saturating it with saturating fluid. The swelling potential is defined as the percentage swelling of the soil. The details of this method has been described by Sridharan et al. (1986) and Sridharan and Gurtug (2004).

3. Results and discussions

3.1. Atterberg limits

For any concentration, bentonite with 1N NaCl solution mix exhibited a higher value of liquid limit in comparison to 1N $CaCl_2$ solution. This can be attributed to the formation of a relatively large diffuse double layer thickness in the presence of NaCl solution in comparison with the same concentration of $CaCl_2$ solution. The liquid limit of the Bentonite-B decreased more significantly in comparison to the Bentonite-A. The liquid limit of Bentonite-B shown a maximum decrease of 83% compared to 54 % in case of Bentonite-B due to an increase in the concentration from 0 to 1 N of $CaCl_2$ in the mixture solution. $CaCl_2$ solution decreased the liquid limit of bentonite more significantly in comparison to NaCl solution. Since the increase in the salt concentration and the cation valency decreases the inter-particle repulsion which leads the particles to become free to move at lower water contents or lower inter-particle distances, resulting in a decrease in the liquid limit (Warkentin, 1961; Sridharan and Rao, 1975).

3.2 Swelling pressure and swelling potential

Table 3 shows that with increasing salt solution both swelling pressure and swelling potential decreases. Swelling pressure showed a maximum decrease with 1 N $CaCl_2$ salt solution of 62% with respect to water in case of Bentonite-B whereas in case of Bentonite-A maximum decrease of 31% was observed. Similarly, swelling potential decrease was higher in case of Bentonite-B i.e. about 62% when concentration increased from 0 to 1 N $CaCl_2$ in the mixture of salt and heavy metals solution (permeant series 3). Bentonite-A undergo a large change due to permeation of salt solution compared to Bentonite-B.

Table 3 Swelling pressure and swelling potential

Permeant Series	Swelling Pressure(kPa)		Swelling Potential (%)	
	Bentonite-A	Bentonite-B	Bentonite-A	Bentonite-B
0	267	697	21	48
1	196	392	20	31
2	194	294	15	19
3	183	267	14	18

For NaCl solutions osmotic as well as hydration swelling takes place, allowing the interlayer spacing to become large while for $CaCl_2$ solutions only hydration swelling takes place (Norrish and Quirk, 1954).

3.3 Hydraulic conductivity

Figure 3 plots the hydraulic conductivity versus void ratio relationships for different concentrations of permeating fluid. Each of the plot shows that the hydraulic conductivity (*k*) of the samples increases by adding salt to the pore fluid. This increase in the *k* with the increase in the concentration is due to a decrease in the diffuse double layer, resulting in a large intergranular pore and significant decrease in the swelling capacity of the clay particles causing a reduction in damages to the flowing channels. As a result, hydraulic conductivity for all the samples increased marginally due to permeation of NaCl and $CaCl_2$ solution along with heavy metals. At a given concentration, Bentonite-B exhibit higher *k* value than Bentonite-A. Mixture solution with 1N $CaCl_2$ solution exhibited higher *k* value than the mixture containing 1N NaCl solution. This is due to the increase in cationic valency and decrease in hydrated ionic radius (Sridharan et al., 1986).

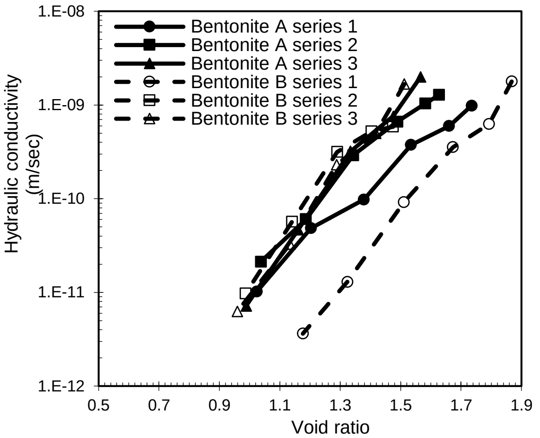

Fig 1 Hydraulic conductivity values of Bentonite A & B

4. Conclusions

Results showed that the liquid limit, swelling potential and swelling pressure of the bentonites decreased with an increase in the salt concentration. Bentonite with NaCl solution exhibited a higher of these values in comparison to the same concentration of $CaCl_2$ solution. The reduction in these parameters with increase in the salt attributed to the decrease in the diffuse double layer thickness. However, the hydraulic conductivity of the bentonite increased with an increase in the inorganic salt concentrations. It was observed that the effect due to increased concentration of $CaCl_2$ on the hydraulic conductivity was more significant than other permeant series. A comparison between the two bentonites showed that the salt and heavy metals has a significant effect on Bentonite-B. This study concludes that the effect of the salt on the properties of the bentonites depends on the salt type, salt concentration.

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