# Effect of Induced Osmotic Suction and Bentonite Content on Swell Behavior and Hydraulic Conductivity of Compacted Red Soil

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**Abstract.** Clay liners are integral part of both hazardous and municipal waste landfills that prevent leachate from percolating into the soil beneath and polluting it. Hence the compacted soils must have very low hydraulic conductivity (< $10^{-7}$ cm/s) to act as effective clay liners. Locally available red soil may be used as a liner material as it satisfies the design criteria. To meet the hydraulic conductivity requirement, the locally available red soil was modified by adding 10% and 20% bentonite by dry weight. Multiple identical compacted specimens were set-up in oedometric assemblies under a surcharge pressure of 12.5 kPa and were inundated with distilled water, 0.4M $CaCl_2$ and 0.4M NaCl solutions to study the swelling behaviour of red soil and red soil modified with different bentonite contents. The specimens were compacted at their respective optimum moisture content values to their maximum dry unit weights. Falling head permeability tests were conducted to measure hydraulic conductivity using the rigid wall permeameters at a hydraulic gradient of 20 and surcharge pressure of 12.5 kPa. The nature of the inundating fluid and the bentonite content is seen to greatly affect the swelling behaviour and the hydraulic conductivity of the compacted red soil.

**Keywords:** Compacted Soil, Modified Clay, Clay Liners, Swell-Shrink Paths, Hydraulic Conductivity

## 1 Introduction

Clay liners are integral part of both hazardous and municipal waste landfills. They are compacted using clay soils of very low permeability so that the leachate does not percolate into the underlying ground and pollute it. Different environment Protection Agencies specify that the soils used for clay liners should have a hydraulic conductivity value as low as $10^{-7}$cm/s [US EPA 2009, UK EA 2011]. Bentonite is commonly mixed with locally available in-situ soils when they do not have the required hydraulic conductivity characteristics as the bentonite is known to possess high specific surface area and sealing characteristics [Kumar and Yong, 2002; Sallfors and Oberg-Hogsta, 2002; Sivapullaiah and Lakshmikantha, 2004]. In addition to the hydraulic conductivity characteristics, the swell-shrink behaviour of the compacted clay liners is also of importance. Daniel and Wu [1993] recommended a maximum volumetric shrinkage of 4% for soils to be used as clay liners. The extent of volume change depends on the type and amount of the clay mineral, soil structure, compaction conditions, physico-chemical factors and environmental factors [Yong and Warkentin, 1975].

In the field, constant leachate interactions occur with the compacted soil, which causes the physico-chemical changes in the soil. Because of the difference in dissolved salt concentration between the soil and leachate, an osmotic gradient is developed, which in turn causes diffusion of salt into the soil, and thereby a reduction in the diffused double layer thickness [Di Maio, 1996; Rao and Thyagaraj, 2007]. Previous studies show that the swell potential decreases with the reduction in the diffused double layer thickness [Thyagaraj and Rao, 2010]. The increase in osmotic gradient also causes an increase in the hydraulic conductivity. Further, the divalent cations impart higher osmotic suction, and cause greater increase in hydraulic conductivity than with the monovalent cations [Mishra et al., 2005]

This paper presents the effect of bentonite content and induced osmotic suction on the swell and hydraulic conductivity of compacted red soil. To study the swelling behaviour, series of one dimensional oedometric swell tests were conducted on identical soil specimens prepared using distilled water and inundating them with distilled water, 0.4M NaCl and 0.4M $CaCl_2$ solutions. After complete swelling, the hydraulic conductivity was determined for each specimen by conducting falling head permeability tests.

## 2 Material Properties

Red soil used for the present study was collected from IIT Madras campus, Chennai, Tamil Nadu. It was air dried, passed through 2 mm sieve (No.10 sieve), and mixed thoroughly for homogenous base material and stored in containers. Commercially available sodium bentonite was procured and used for the study. Red soil-bentonite mixtures were prepared in two proportions: 10% and 20% bentonite by dry weight, and they were designated as B1 and B2, respectively (Table 1). Characteristics of the red soil, bentonite and red soil-bentonite mixtures are presented in Table 2. Figs. 1 and 2 show the grain size distribution and the compaction curves of the soils used for the present study. Laboratory grade NaCl and $CaCl_2$ dehydrate were used for the preparation of solutions.

**Table 1.** Soils used for the present study

| Soil | Soil designation | Proportions of soils | |
|---|---|---|---|
| | | Red soil (%) | Bentonite (%) |
| Red soil | A | 100 | 0 |
| Red soil-bentonite mixture-1 | B1 | 90 | 10 |
| Red soil-bentonite mixture-2 | B2 | 80 | 20 |

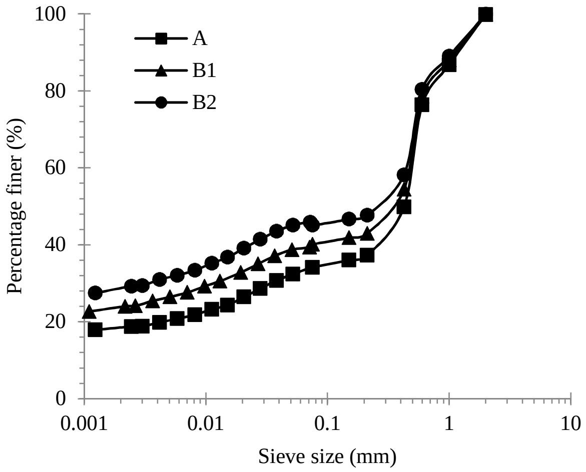


**Fig. 1.** Grain size distribution curves

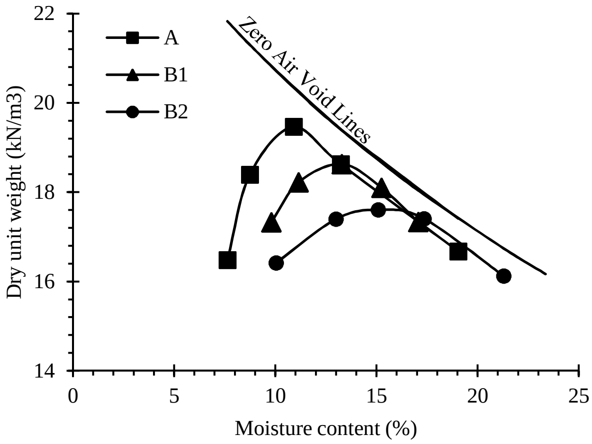


**Fig. 2.** Compaction curves

**Table 2.** Characteristics of red soil, bentonite and red soil-bentonite mixtures

| Property | Soil designation | | | |
|---|---|---|---|---|
| | A | Bentonite | B1 | B2 |
| Liquid limit (%) | 34 | 224 | 86 | 113 |
| Plastic limit (%) | 20 | 48 | 27 | 35 |
| Shrinkage limit (%) | 15 | 8.4 | 15 | 13 |
| Plasticity index (%) | 14 | 176 | 59 | 78 |
| Specific gravity | 2.68 | 2.92 | 2.70 | 2.73 |
| Soil classification | SC | CH | SC | SC |
| Maximum dry unit weight ($kN/m^3$) | 19.4 | - | 18.75 | 17.6 |
| Optimum moisture content, OMC (%) | 11 | - | 12.5 | 15 |
| Unconfined compressive strength (kPa) | 212 | - | 230 | 251 |

# 3 Experimental Programme

## 3.1 Preparation of Soil Specimens

Red Soil, A and red soil-bentonite mixtures, B1 and B2, were pre-wetted with desired volume of water corresponding to their respective OMC values and stored in plastic covers for 48 h in the desiccator for moisture equilibration. The water content was then measured to ensure that the target water contents were achieved. Identical samples were prepared using these prewetted soils by statically compacting them in oedometer rings of height 30 mm and diameter 75 mm, to an initial height of 20 mm such that their respective standard Proctor maximum dry unit weight values were attained.

## 3.2 One Dimensional Oedometer Swell Tests

The identical soil specimens were placed between two porous stones and filter papers and were assembled in the test set-ups under a surcharge pressure of 12.5 kPa. The identical soil specimens were then inundated with distilled water, 0.4M NaCl solution and 0.4M $CaCl_2$ solutions separately. The details of the compacted specimens and inundating fluids are given in Table 3. The vertical deformations were noted using dial gauge of 0.002 mm least count till the vertical deformations became constant and the swell potential was calculated using equation 1.

$$Swell\ (\%) = \frac{\Delta H}{H} \times 100 \tag{1}$$

Where $\Delta H$ is the increase in height of soil specimen during swelling and $H$ is the initial as compacted height of soil specimen.

The induced osmotic suction is calculated using the van’t Hoff equation (equation 2)

$$\pi = iMRT \quad (2)$$

Where, M is the maximum dissolved salt concentration of the inundating fluid (mol/L), R is the universal gas constant, T is the absolute temperature (K) and i is the van’t Hoff factor ( i = 2 for NaCl solution and i =3 for $CaCl_2$ solution)

**Table 3.** Details of compacted specimens and inundating fluids

| Soil specimen | Inundating fluid | Osmotic suction induced (kPa) |
|---|---|---|
| A | DW | 100 |
| B1 | DW | 100 |
| | 0.4M NaCl solution | 1,951 |
| | 0.4M $CaCl_2$ solution | 2,927 |
| B2 | DW | 100 |
| | 0.4M NaCl solution | 1,951 |
| | 0.4M $CaCl_2$ solution | 2,927 |

### 3.3 Rigid Wall Hydraulic Conductivity Tests

After the completion of swelling, the hydraulic conductivity of the saturated specimens was determined using falling head method in rigid wall permeameters in accordance with ASTM D 5856-15. The tests were conducted using the same inundating fluid used for swelling under a hydraulic gradient of 20 and a surcharge pressure of 12.5 kPa.

## 4 Results and Discussions

### 4.1 Effect of Bentonite Content on Swell and Hydraulic Conductivity

Fig. 3 presents the time-swell plots of compacted red soil and red soil-bentonite mixtures. The swell curves are S shaped curves with three distinctive phases: i) initial swelling, ii) primary swelling and iii) secondary swelling. The initial swell takes more time to finish in B1 than in B2 owing to its lesser bentonite content, resulting in larger voids, and hence longer intervoid swelling [Sivapullaiah et al., 1996]. Fig. 3 shows that the compacted red soil showed no swell when inundated with distilled water, whereas red soil containing bentonite swelled. As the bentonite content increased, the magnitude of swell also increased. By adding bentonite to the red soil, a fraction of non-swelling red soil was replaced by a fine-grained soil with high swelling potential, which absorbs water into its crystal lattice. Thus, the diffused double layers around the soil particles expanded, and hence the swell potential is higher.

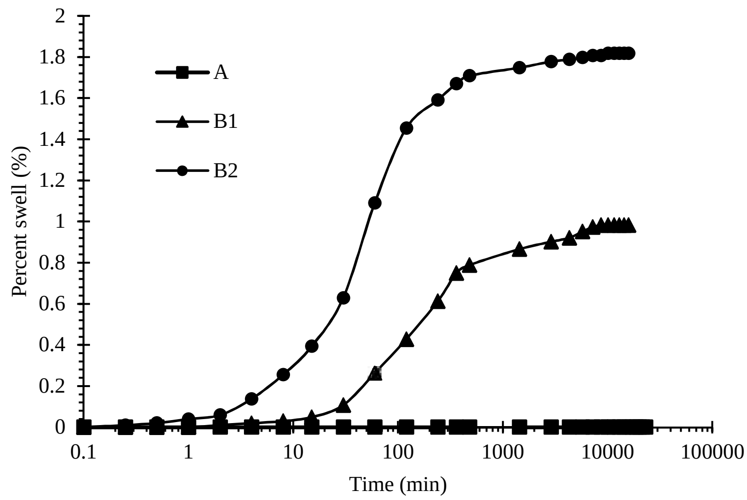


**Fig. 3.** Time-swell plots of compacted red soil and red soil-bentonite mixtures inundated with distilled water

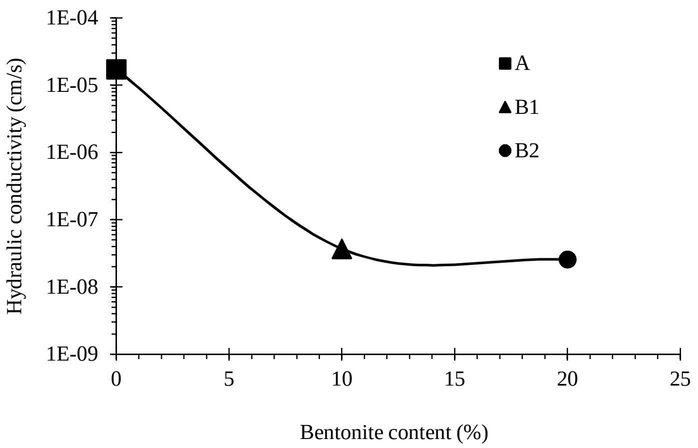


**Fig. 4.** Effect of bentonite content on hydraulic conductivity of red soil using distilled water as inundating fluid

Fig. 4 brings out the effect of bentonite content on hydraulic conductivity of compacted red soil. It can be seen that the addition of bentonite to the red soil reduces the hydraulic conductivity values. This is because of the high specific area and high swelling potential of bentonite which absorbs more water into its crystal lattice and expands its double layers, thereby reducing the macropores in the soil specimen and thus the hydraulic conductivity [Kumar and Yong, 2002].

### 4.2 Effect of Osmotic Suction on Swell Potential and Hydraulic Conductivity

Figs. 5a and 5b bring out the effect of osmotic suction on compacted red soil with 10% and 20% bentonite contents, respectively. The figures clearly show that the specimens inundated with salt solutions show a reduction in swell potential than the specimens inundated with distilled water. The reduction in swell is more for specimen inundated with divalent $Ca^{2+}$ cations than monovalent $Na^{+}$ cations. When the soil specimen is inundated by salt solutions, it is being subjected to an osmotic gradient because of the difference in dissolved salt concentration in the soil pore water and the external reservoir solution. Soil being an imperfect semi-permeable membrane allows the transfer of salt through diffusion. This diffusion of salts results in the reduction of diffused double layer thickness, which in turn reduces the swell potential [Rao and Thyagaraj, 2007]. In Fig. 5b all the three plots of B2 are S shaped. However, there is a delay in the beginning of primary swelling of soil inundated with $CaCl_2$ solutions. Fig. 5a shows that soil specimen B1 inundated by $CaCl_2$ solution shows no swell. $CaCl_2$ solution induces higher osmotic suction, resulting in a larger reduction of double layer, and hence the swelling occurs only in the intervoid space.

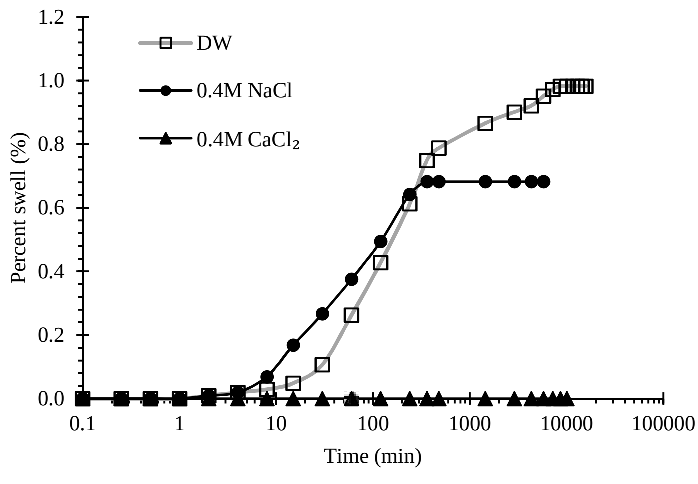


**Fig. 5.** a. Effect of salt concentration on time-swell plots of compacted red soil-bentonite specimen B1

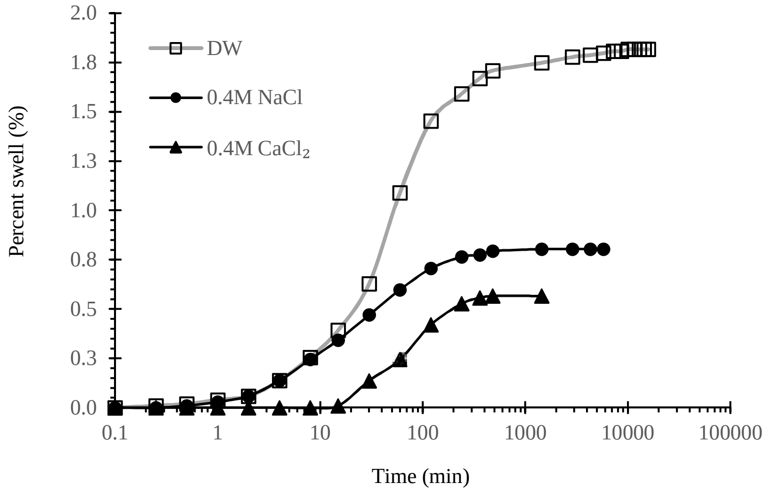


**Fig. 5.** b. Effect of salt concentration on time-swell plots of compacted red soil-bentonite specimen B2

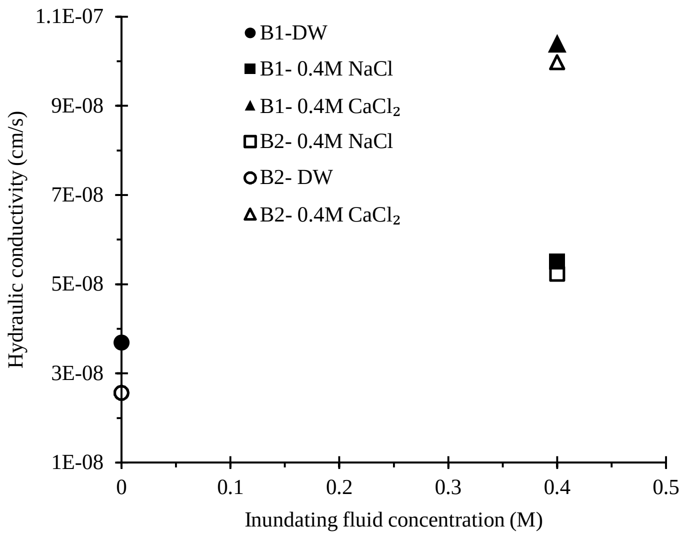


**Fig. 6.** a. Variation of hydraulic conductivity with inundating fluid concentration

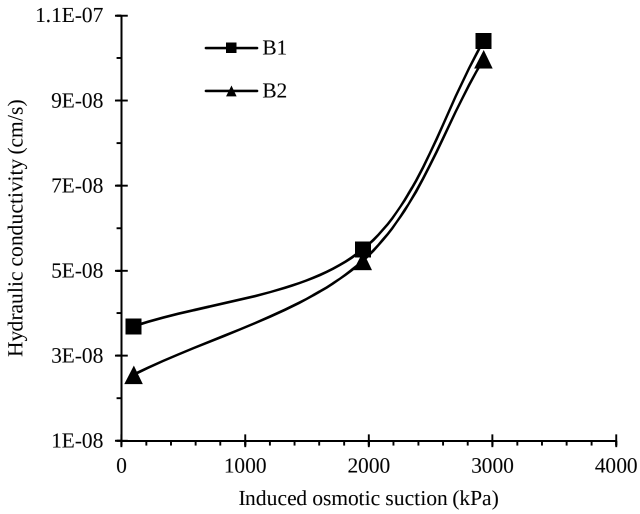


**Fig. 6.** b. Effect of induced osmotic suction on hydraulic conductivity of red soil-bentonite mixtures

Figs. 6a and 6b bring out the effect of salt concentration and induced osmotic suction on the hydraulic conductivity of the red soil-bentonite mixtures, respectively. The hydraulic conductivity increased with inundating fluid concentration and osmotic suction. When the soil is inundated with salt solution, because of the concentration gradient between the soil pore water and the external reservoir solution, the induced osmotic suction develops in the soil. This increase in suction is dissipated by absorbing salt solution into the partially saturated soil pores [Rao and Thyagaraj, 2007]. The diffusion of salt into the soil causes a reduction in the diffused double layer thickness which decreases the volume of micropores and increases the volume of macropores in the soil, which in turn results in a higher hydraulic conductivity in specimens inundated with salt solution. Higher the salt concentration and the valency of the ions, higher will be the induced osmotic suction.

## 5 Conclusions

Based on the above study, the following conclusions can be drawn.

- Addition of bentonite to the red soil increases the swell potential of the soil due to the expansion of diffused double layers. The hydraulic conductivity of soil which is largely dependent on macropores in the soil reduces due to the closing of macropores when the double layers expand.
- Exposure of compacted red soil-bentonite specimens to salt solutions has significant effect on the swell potential and hydraulic conductivity as well. The swell potential decreases and hydraulic conductivity increases when the compacted

soil is inundated with solutions, rather than with distilled water. This effect is more with divalent $Ca^{2+}$cations than with monovalent $Na^{+}$ cations.

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