Osmotic consolidation of expansive soil

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ABSTRACT

The mechanical behavior of expansive soils is influenced by the concentration of salts in their pore water. Research has shown that volume change of soil can occur due to a difference in salt concentration in the pore water between different zones of the soil as a result of either osmotically-induced consolidation or osmotic consolidation. The effect of the salt concentration of the pore water in unsaturated soil mechanics can be expressed as osmotic suction. Very little work has been done to quantify the mechanical equivalence of osmotically-induced and osmotic consolidation. This study attempts to quantify the mechanical stress equivalence of consolidation of an expansive soil submerged in a salt solution. Two remoulded soil samples of kaolin - bentonite mixture in proportions of 70% – 30% and 90% - 10%, (kaolin – bentonite) by dry mass were submerged in different concentrated salt solutions to investigate the effect of osmotic suction. Results showed that osmotic suction caused an additional settlement over the consolidation settlement under a mechanical stress but does not affect the soil compressibility. The osmotic coefficient of volume change \( m_\pi \) is only a fraction of the coefficient of volume change \( m_v \).

Keywords: Osmotic consolidation, osmotic suction, mechanical stress, consolidation settlement

1 INTRODUCTION

Soil suction is widely accepted as one of the stress state variables of unsaturated soils which consists of matric and osmotic suctions (Edil and Motan, 1984; Fredlund, Rahardjo, and Fredlund, 2012; Krahn and Fredlund, 1972). In unsaturated soil mechanics, osmotic suction is attributed to the salt concentration of the pore water (Fredlund and Rahardjo, 1993) which affects the soil structure of clayey soils and does not act like matric suction (Leong and Abuel-Naga, 2017). Research has shown that the volume change of soil can occur due to a difference in salt concentration in the pore water between different zones of the soil (Barbour and Fredlund, 1989; Barbour, 1987; Di Maio, 1996; Rao and Thyagaraj, 2007; Thyagaraj and Rao, 2013). The resulting osmotic gradient causes water to move between zones and this is termed osmotically-induced consolidation (Barbour and Fredlund 1989). The pore water in a soil generally contains dissolved salts. Salt transportation into clay soils affects the double diffuse layer. This can result in reduced electrical repulsion forces between the clay platelets leading to a reduction in the void ratio and changes in effective stresses. Experimental results by Di Maio (1996) showed that exposure of specimens of Ponza bentonite to saturated salt solutions produced ion diffusion into the pore fluid causing large volume decreases and large residual shear strength increases. A volume reduction in soils translates into a void ratio reduction hence an increase in the effective stress. Rao and Thyagaraj (2007) showed that an additional stress component is created due to increase in osmotic suction in pore water. Barbour et al. (1992) explain that two stress state variables exist in saturated soils: the generally accepted effective stress and a physico-chemical stress state variable representing the net electrostatic repulsive stresses between the soil particles controlled by the osmotic pressure of the pore fluid. Osmotic consolidation occurs as a result of a change in the electrostatic repulsive-minus-attractive (R-A) stresses between clay particles. However, there are restrictions on the use of this stress state variable (R-A) because it cannot be experimentally quantified in the laboratory and occurs only under ideal conditions. For this reason, there is a need for a more easily measured quantity than (R-A). In this paper, both osmotic and osmotically-induced consolidation is not differentiated and only one term osmotic consolidation is used.

Volume change \( \Delta v \) can be caused by a change in mechanical stress, given as

\[
\frac{\Delta v}{V_0} = \frac{\Delta e}{(1 + e_0)} = \Delta(\sigma - u_f)m_v
\]

or, it can be caused by a change in osmotic pressure (Barbour et al., 1992) given as

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\[
\Delta V = \frac{\Delta e}{V_0} = m_\pi \Delta \pi 
\]  

(2)

Equating equations (1) and (2) give

\[
\Delta (\sigma - u_f)m_v = \Delta \pi m_\pi 
\]  

(3)

where; \(\Delta (\sigma - u_f)\) = change in effective mechanical stress, \(\sigma\) = vertical stress, \(u_f\) = pore-water pressure, \(\Delta \pi\) = change in osmotic pressure, \(m_v\) = coefficient of volume change, and \(m_\pi\) = osmotic coefficient of volume change. Very little work has been done to quantify the mechanical equivalence of osmotic consolidation. This study attempts to quantify the mechanical stress equivalence of osmotic consolidation of expansive soils submerged in a salt solution.

2 MATERIAL AND TEST PROCEDURE

In this study, two remoulded soil mixtures of kaolin - bentonite in proportions of 70% – 30% (KB30) and 90% - 10%, (KB10), by dry mass were used. The basic properties for the kaolin - bentonite mixtures are summarised in Table 2. The grain size distributions are shown in Figure 1.

2.1 Salt solutions

Saturated salt solutions of potassium sulphate (K₂SO₄), potassium chloride (KCl) and sodium chloride (NaCl) were prepared by addition of salt to distilled water until excess salt were observed. Table 2 shows a summary of the theoretical and measured osmotic suctions (pressures) for the salts. The osmotic suction was measured using a chilled mirror dew-point device, WP4 (Leong et al., 2003).

Table 2. Osmotic suction of the prepared salts

| Saturated Salt Solution | Measured using WP4 at 25°C | Theoretical at 25°C |
|-------------------------|-----------------------------|---------------------|
| Sodium Chloride, NaCl   | 38803                       | 38790 - 38972       |
| Potassium Chloride, KCl | 23368                       | 22975 – 23952       |
| Potassium Sulphate, K₂SO₄ | 3753                      | 3056 – 4468         |

2.2 Specimen preparation

Two series of soil specimens were prepared by mixing powdered kaolin and bentonite with water to form a slurry. Water corresponding to 1.5 times the liquid limit of KB30 and 0.63 times the liquid limit of bentonite of KB10 were used to form slurries of KB30 and KB10, respectively. The slurry was transferred to a mixer for further mixing to obtain a homogeneous slurry. The slurry was then transferred to a consolidation tank, 600 mm in diameter, and consolidated under a vertical pressure of 125 kPa. Settlement was observed on a regular basis until there was no more settlement which is about a week. After consolidation, the sample was extruded from the consolidation tank and cut into blocks of 70 x 70 x 50 mm. The blocks were wrapped with 3-5 layers of cling wrap followed by two layers of aluminum foil, waxed and placed into the humidity cabinet for later use.

2.3 Volume change tests

In this study, a conventional oedometer equipment with a load lever arm ratio of 1:10 was used to conduct the one-dimensional volume change tests following ASTM D2435/D2435M-11. Both KB30 and KB10 specimens were cut out from the blocks using the oedometer ring of 63.5 mm internal diameter and 20 mm height. Silicone grease was smeared on the inner surfaces of the oedometer ring to reduce friction between the specimen and the oedometer ring (Fang, Chen, Holtz, and Lee, 2004). For each kaolin-bentonite mixture (KB30 and KB10), two specimens were prepared. One specimen was consolidated from 32 to 2048 kPa in the oedometer, using load increment ratio of 1 for successive loads. This gives the usual e-log \(\sigma'\) curve. For the osmotic consolidation, the other specimen was first consolidated from 32 to 64 kPa. After which, the water in the oedometer cell was replaced with the saturated salt

\[
\frac{\Delta V}{V_0} = \frac{\Delta e}{(1 + e_0)} = m_\pi \Delta \pi 
\]  

(2)

Equating equations (1) and (2) give  

\[
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(3)

where; \(\Delta (\sigma - u_f)\) = change in effective mechanical stress, \(\sigma\) = vertical stress, \(u_f\) = pore-water pressure, \(\Delta \pi\) = change in osmotic pressure, \(m_v\) = coefficient of volume change, and \(m_\pi\) = osmotic coefficient of volume change. Very little work has been done to quantify the mechanical equivalence of osmotic consolidation. This study attempts to quantify the mechanical stress equivalence of osmotic consolidation of expansive soils submerged in a salt solution.

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![Grain size distribution](Fig. 1. Grain size distribution of the soil used in the study)

Table 1. Basic soil properties

| Soil Properties | Soil Type | Values |
|-----------------|-----------|--------|
|                 | Kaolin    | Bentonite | KB30 | KB10 |
| Specific Gravity, Gs | 2.66 | 2.60 | 2.63 | 2.65 |
| Liquid Limit, LL (%) | 49 | 210 | 78 | 51 |
| Plastic Limit, PL (%) | 34 | 44 | 40 | 35 |
| Plasticity Index, PI (%) | 15 | 166 | 38 | 16 |
| USCS classification | ML | CH | MH | MH |
solution and settlement was observed until no further settlement was observed. Mechanical consolidation then resumes and the specimen was consolidated up till 2048 kPa. This was repeated for each saturated salt solution (K₂SO₄, KCl and NaCl) and for each kaolin-bentonite mixture (KB10 and KB30).

3 RESULTS AND DISCUSSION

3.1 Osmotic consolidation

Figures 2 – 4 each shows two curves. The first curve shows the settlement curve with time due to a mechanical loading from 32 to 64 kPa. Subsequently, the water in the oedometer cell was drained and replaced with a saturated salt solution. The second curve shows the settlement curve with time due to the respective salt solutions. It was observed that the settlement caused by NaCl solution is much more significant than that caused by either K₂SO₄ or KCl solutions. Similar trends were observed with both kaolin-bentonite mixtures but KB10 specimens showed much lesser settlement than KB30 specimens (Table 3). This is attributed to the low bentonite content in the KB10 specimens.

A salt solution with higher osmotic pressure will result in a larger consolidation settlement. Besides that, the sodium cation entering the clay particles reduces the thickness of double diffuse layer and contributed to the consolidation settlement. Similar observations were made by Nara et al. (2014) who studied crack velocity with the stress intensity under variation of salt concentration. They concluded that electrolyte concentration decreases the thickness of the double diffuse layer as observed by the decrease in crack velocity and increase in stress intensity factor. Furthermore, in the interlayer spaces and regions where the individual montmorillonite stacks are in close proximity, double diffuse layer overlap will occur and anion exclusion effects will take place (Bradbury and Baeyens, 2002). However, the potassium cation will form a K-linkage between soil particles (Grim, 1953), which will reduce the osmotic consolidation effect. Therefore, the osmotic effect caused by potassium cation is not as significant as that caused by sodium cation. Table 3 shows a summary of the settlements caused by the different salt solutions.

| Salt solution | Osmotic pressure (kPa) | KB30 Settlement (mm) | KB10 Settlement (mm) |
|---------------|------------------------|----------------------|----------------------|
| K₂SO₄         | 3753                   | 0.38                 | 0.10                 |
| KCl           | 23368                  | 0.83                 | 0.14                 |
| NaCl          | 38803                  | 1.25                 | 0.16                 |
3.2 Equivalent mechanical stress

Figures 5 and 6 show the $e - \log \sigma'$ plots, for the cases of water, NaCl, KCl and K$_2$SO$_4$ of KB30 and KB10, respectively. The dotted line represents mechanical consolidation under water while the other curves represent the different salt solutions used in the experiments. Since the vertical stresses were kept constant during the exposure to the salt solution, the changes in void ratio is entirely attributed to the salt solution (osmotic consolidation). From Figures 5 and 6, the equivalent change in effective vertical stress $\Delta\sigma'$ to cause the same settlement is determined by drawing a horizontal line at the end of osmotic consolidation to the mechanical consolidation under water $e - \log \sigma'$ plot. The $\Delta\sigma'$ are summarized in Table 4.

Table 4. Equivalent mechanical stress of salt solutions.

| Soil specimen | Salt solution       | Change in equivalent vertical stress $\Delta\sigma'$ (kPa) |
|---------------|---------------------|---------------------------------------------------------|
| KB 30         | Sodium chloride (NaCl) | 41                                                      |
|               | Potassium chloride (KCl) | 25                                                      |
|               | Potassium sulphate (K$_2$SO$_4$) | 16                                                      |
| KB 10         | Sodium chloride (NaCl) | 36                                                      |
|               | Potassium chloride (KCl) | 23                                                      |
|               | Potassium sulphate (K$_2$SO$_4$) | 15                                                      |

Figures 5 and 6 show a general trend of reduction in the void ratio at the same vertical stress of 64 kPa on introduction of the salt solution. The behavior of KB30 and KB10 specimens when exposed to NaCl solution is different compared to that of the specimens exposed to KCl and K$_2$SO$_4$ solutions. Specimens exposed to KCl and K$_2$SO$_4$ solutions under additional vertical stress tend towards the mechanical consolidation line (dotted lines, tested only under water) whereas those exposed to NaCl solution remains almost parallel. It can be also observed that additional vertical stress after completion of osmotic consolidation resulted in a small decrease in the void ratio. This can be attributed to the change in the interparticle concentration due to the further loading since the concentration of the salt solution was not changed. According to Barbour (1987), the difference in stress from the void ratio at the completion of osmotic consolidation, to the stress level along the virgin branch at the same void ratio is taken as the net $(R-A)$. In this study, the difference is considered as a result of osmotic pressure. Specimens exposed to NaCl show the highest equivalent mechanical stress (Table 4) as a result of the highest deformation observed in Table 3. This is probably due to ion exchange and it is worth noting that the affinity of montmorillonite for K$^+$ is higher than Na$^+$ however ion exchange reaction depends on ion concentration (Di Maio, 1996).

3.3 Osmotic coefficient of volume change

Table 5 shows the osmotic coefficient of volume change, $m_v$ computed using Equation 3 and the coefficient of volume change ($m_\pi$) computed from the mechanical consolidation curve. From Figure 7, it can be observed that a plane where osmotic suction, $(\pi)$ is constant, the slope of the constitutive surface may be described by the coefficient of volume change, $m_v$ and where the effective mechanical stress, $(\sigma-\sigma_u)$, is constant, the slope can be defined by the osmotic coefficient of
It can be observed that a higher coefficient of volume change was registered with specimens of KB30 as compared to specimens of KB10.

| Soil Specimen | Solution | Coefficient of volume change, $m_v$ (m$^2$/kN) | Osmotic coefficient of volume change, $m_o$ (m$^2$/kN) |
|---------------|----------|---------------------------------|---------------------------------|
| KB30          | NaCl     | 0.162E-04                        | 1.707E-06                        |
|               | KCl      | 0.162E-04                        | 1.728E-06                        |
|               | K$_2$SO$_4$ | 0.162E-04                        | 6.886E-06                        |
| KB10          | NaCl     | 3.879E-04                        | 3.879E-04                        |
|               | KCl      | 3.879E-04                        | 3.879E-04                        |
|               | K$_2$SO$_4$ | 3.879E-04                        | 1.551E-06                        |

Fig. 7: Experimental Constitutive Surface for Na Montmorillonite during compression (From Barbour, 1987)

4 CONCLUSION

The effect of salt solution on the volume change behaviour of soil specimens of kaolin-bentonite mixtures was observed using a conventional oedometer. Saturated salt solutions of NaCl, KCl and K$_2$SO$_4$ were used in this study. Results showed that exposing the soil specimen to salt solution caused an additional settlement over the consolidation settlement under a constant vertical stress but did not affect the soil compressibility. The pore-water salt concentration affects the soil structure and induces additional settlement. It should further be noted that, the osmotic coefficient of volume change, ($m_o$) is only a fraction of the coefficient of volume change, ($m_v$). Therefore, a large osmotic suction is needed to cause an equivalent settlement under a vertical stress.

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