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Influence of Inorganic Salt Solutions on the Engineering Behavior of Black Cotton Soil

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Abstract. The key purpose of the clay liner in the landfilling system is to reduce or eliminate leachate interaction with groundwater. Bentonite clays and sand-bentonite mixtures are frequently used as bottom liners because of their significant swelling tendency and low permeability. However, in India, bentonite and sand are both expensive and scarce. It is necessary to get alternative liner material to replace costly bentonites and sands. On the other hand, almost 20% of India's land is covered with black cotton (BC) soil derived from basalt rock. As a result, the focus of this study was on the utilization of BC soil as a landfill liner. However, it is crucial to evaluate the properties of the liner material in the presence of chemicals that influence the actual engineering properties of the liner material. The main motive of this research is to examine BC soil's consistency limits, swelling, and volume change tendency under the impact of two inorganic salt solutions (NaCl and $CaCl_2$) at different concentrations (0, 0.1, & 1N). Test findings show that free swell index, consistency limits, coefficient of volume change, swelling strains, and compression ratio were decreased for a rise in cation valency and salt solution concentration.

Keywords: Black cotton soil, Salt solutions, Consistency limits, Swelling strains, Coefficient of volume change.

1 Introduction

Landfills are the most widely used engineered structures for the proper disposal of municipal solid waste worldwide (Bogner and Matthews, 2003). In landfills, clay liners are ordinarily positioned as barriers that avoid groundwater pollution owing to leachate interaction. A potential liner should satisfy important geotechnical characteristics such as high swelling, adequate shear strength, and low permeability to mitigate pollutants from leachate (Benson et al., 1999; Emmanuel et al., 2020). Because of the presence of the montmorillonite mineral, bentonite clays typically satisfy the standards for liner material (Mitchell and Soga, 2005). However, these bentonites are only available in a single Indian state, Rajasthan (Sivapullaiah and Baig, 2011). Despite the limited availability and high expense of bentonites, an alternate material should be identified for use in liner applications. Here, BC soil is determined to be a substitute and cost-effective material for bentonites because it occupies one-fifth of the Indian soil mass and consists of montmorillonite as its predominant mineral, which will work effectively for liner applications (Srivastava et al., 2014; Babu and Mishra, 2022). However, the chemical substances in leachate alter the geotechnical attributes of liner material, significantly lowering liner performance (Petrov and Rowe, 1997; Lee and Shackelford, 2005). Numerous studies have been done in the past to examine how chemicals affect liner material's geotechnical characteristics. Petrov and Rowe (1997) investigated the effect of monovalent salt and synthetic municipal solid waste permeants on the hydraulic property of geosynthetic clay liner and found a decrement in void ratio and increment in hydraulic conductivity values at higher concentrations of NaCl salt permeant. Mishra et al. (2009) looked at how inorganic salts affect bentonite-soil mixtures' index and engineering properties. They found that at 1N concentrations of NaCl and $CaCl_2$ salt permeants, the liquid limit and hydraulic conductivity values dropped by a lot. Rout and Singh (2020) evaluated the hydro-mechanical properties of bentonite-pond ash mixture (BPM) as a liner material in the chemical environment and found a considerable reduction in free swelling, volumetric shrinkage, and hydraulic conductivity of BPM with an upsurge in the cation valency and concentration of inorganic salt solutions. Hence, examining the integrity of liner inundated with chemicals that mimic the leachate effect is necessary. However, there is no proper literature on the swelling and volume change properties of BC soil for the application of landfill liner. In this research, the swelling and volume change behavior of BC soil was determined through monova-lent and divalent inorganic salt permeants at 0.1 and 1N concentrations.

2 Materials and Testing Methods

2.1 Materials

BC soil was used as a liner material in this work, which has been occupied around 20% of the Indian land mass. This soil was taken from the East Godavari district of Andhra Pradesh, India. The dry soil passed through a 425-micron sieve was utilised for the entire work, and its physical characteristics are presented in Table 1.
Two inorganic salts, monovalent and divalent (NaCl and $CaCl_2$), were used as salt permeants at 0.1 and 1N concentrations by dissolving them into 1 litre of distilled water. These inorganic salts and their concentrations were chosen based on the previous literature. The purity levels of these two salts are more than 99%.

2.2 Testing Methods

Free swell index (FSI) and consistency limits of BC soil were found according to IS 2720-40 (BIS 1977) and IS 2720-5 (BIS 1985b), respectively. According to IS 2720-4 (BIS 1985a), grain size analysis of BC soil was performed and determined the amount of clay, silt and sand contents in BC soil. The specific gravity of BC clay was found using IS 2720-3 (BIS 1980). The compaction parameters of BC soil were found according to IS 2720-7 (BIS 1980). In accordance with IS 2720-15 (BIS 1986), a 20 mm high by 60 mm in diameter consolidation ring was utilized to investigate BC soil's swelling and volume change characteristics under different pore fluids.

Table 1. BC soil's geotechnical properties.

Geotechnical Property	Black cotton soil
Specific gravity	2.59
Free swell (%)	196
Atterberg limits:	
Liquid limit (%)	84.8
Plastic limit (%)	38.1
Plasticity index	46.7
Grain size analysis:	
Clay content (%)	68.0
Silt content (%)	22.7
Sand content (%)	9.3
USCS classification	CH
Compaction parameters:	
Maximum dry density (g/cc)	1.44
Optimum moisture content (%)	27.7

2.3 Determination of Swelling and Coefficient of volume change (m_v)

To determine swelling and volume change behavior, soil samples were prepared at optimum moisture content and maximum dry density conditions of DI (Deionized) water. Then samples were packed in air-tightening polythene covers and put in a desiccator for one day to get an equilibrium water content for all samples. After one day, soil samples were taken out from the desiccator and compacted in the consolidation ring of 15 mm in height and 20 mm in diameter. Then consolidation ring was assembled in the consolidation cell by providing filter papers and porous stones on both sides of a cell, and the whole set-up was fixed on the consolidation stand with a seating load of 5 kPa. Finally, samples were allowed to saturate with the required pore fluid, and swelling readings were recorded using a dial gauge until their asymptotic values were reached. Once swelling was done, then gradual rise in load was applied to the sample for the determination of the mv and compression ratio. Here the loading was carried from 4.9 kPa to 784.5 kPa with a rise of one factor (4.9, 9.8, 19.6 kPa at each stage) for each sample, and variation in thickness values was evaluated by taking the dial gauge readings.

The variation in the void ratio due to the addition of load was calculated by using the below formula:

$$\Delta e = \frac{\Delta H(1 + e_0)}{H} \tag{1}$$

Where Δe is the change in void ratio; ΔH is the change in height
H is the initial height of the sample; e_0 is the initial void ratio of the sample

The coefficient of volume change was computed using the below equation:

$$m_v = \frac{\Delta e}{(1 + e_0)} \times \Delta\sigma' \quad (2)$$

Where e_0 is the initial void ratio; $\Delta\sigma'$ is the change in load

The compression index was computed from the straight-line portion of the void ratio curve using the below equation:

$$C_c = \frac{e_i - e_j}{log\left(\frac{P_i}{P_j}\right)} \quad (3)$$

Where, e_i and e_j are corresponding void ratios of equivalent loads p_i and p_j at i^{th} and j^{th} loading stages

The compression ratio (C_r) was computed by using the below equation:

$$C_r = \frac{C_c}{1 + e_0} \quad (4)$$

3 Result and Discussion

3.1 Free Swell Index (FSI)

FSI gives an idea about the change in soil volume due to water absorption without any external pressure. The free swell behavior of BC soil under the influence of different salts is shown in Fig.1. According to the obtained results, the FSI of BC soil decreased as the concentration of salt solution increased. FSI of BC soil with DI water was 196%, and it was decreased to 171 and 141% for 0.1 and 1N NaCl solution. For a rise in cation valency, the reduction in FSI was observed more. For divalent salt solution $CaCl_2$, this FSI was decreased from 196 to 155 and 132% with 0.1 and 1N concentrations, respectively. Generally, the swelling takes place in expansive soils due to inner-crystalline and double-layer/osmotic swelling (Zhang et al., 1995). Whenever high concentrations are added to soil, a significant decrease in double-layer swelling would occur, leading to a reduction in FSI values. This reduction in double-layer swelling would be more dominant for the divalent solution than the monovalent solution (Mishra et al., 2009). The findings of this study revealed that FSI values were reduced by 12.8 and 28.1% at 0.1 and 1N NaCl solutions, respectively, compared to DI water. This reduction was 20.9 and 32.7% for the identical $CaCl_2$ salt concentrations compared to Deioinized water.

3.2 Atterberg limits

The index properties of the soil will aid in determining the engineering properties of that specific soil. Atterberg limits also provide necessary information for soil engineers to get additional information on the other engineering properties of clay, like soil compressibility on the site.

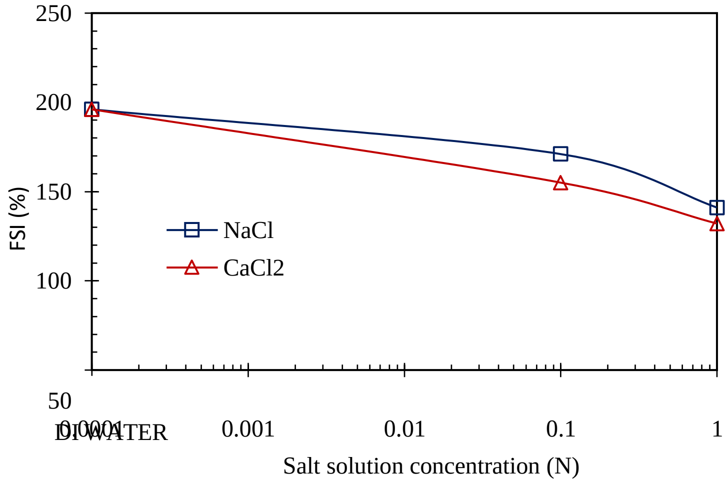

Fig. 1. Free Swell Index of BC soil with monovalent and divalent salt solutions.

The atteberg limits of BC soil mixed with different solutions are shown in Fig. 2. The liquid limit (LL) of BC soil with DI water was found as 84.8%, as shown in Fig. 2(a). This was reduced by about 6.3 and 13% with 0.1 and 1N NaCl, respectively. However, for a rise in cation valency, this reduction in LL was more predominant. The reduction in LL was about 8.5 and 17.6% with 0.1 and 1N divalent salt solution, respectively, compared to DI water. The lower inter-particle distance between the clay particles may be the reason for the reduction in LL at higher concentrations and cation valency of salt solutions (Sivapullaiah and Sridharan, 1985). At lower inter-particle distances, the clay particles tend to move freely, resulting in lower LL values at higher concentrations and cation valences. However, a similar kind of behavior was observed in the plastic limit (PL) and plasticity index (PI) of BC soil with the same type and concentration of salt solutions. As shown in Fig. 2(b), PL was marginally reduced by about 4.3 and 13.2% at 0.1 and 1N monovalent salt solution compared to DI water. This reduction was about 5.3 and 14.1% at similar concentrations of divalent salt solutions. The PI behavior of BC soil also follows a similar trend shown in Fig. 2(c).

3.3 Swelling Behavior

The swelling height of BC soil under various saturating permeants with respect to time is shown in Fig. 3. As shown in Fig.3. all swelling curves display an S-shape curve regardless of the type of pore fluid. Generally, the swelling phenomenon occurs in three different stages: initial, primary, and secondary (Rao et al., 2006). More than 70% swelling was observed in the primary swelling stage, and the minimum amount of swelling was observed in the initial and secondary swelling stages. However, according to Rao et al. 2006, macropores may be the reason for swelling in the initial stage, and-

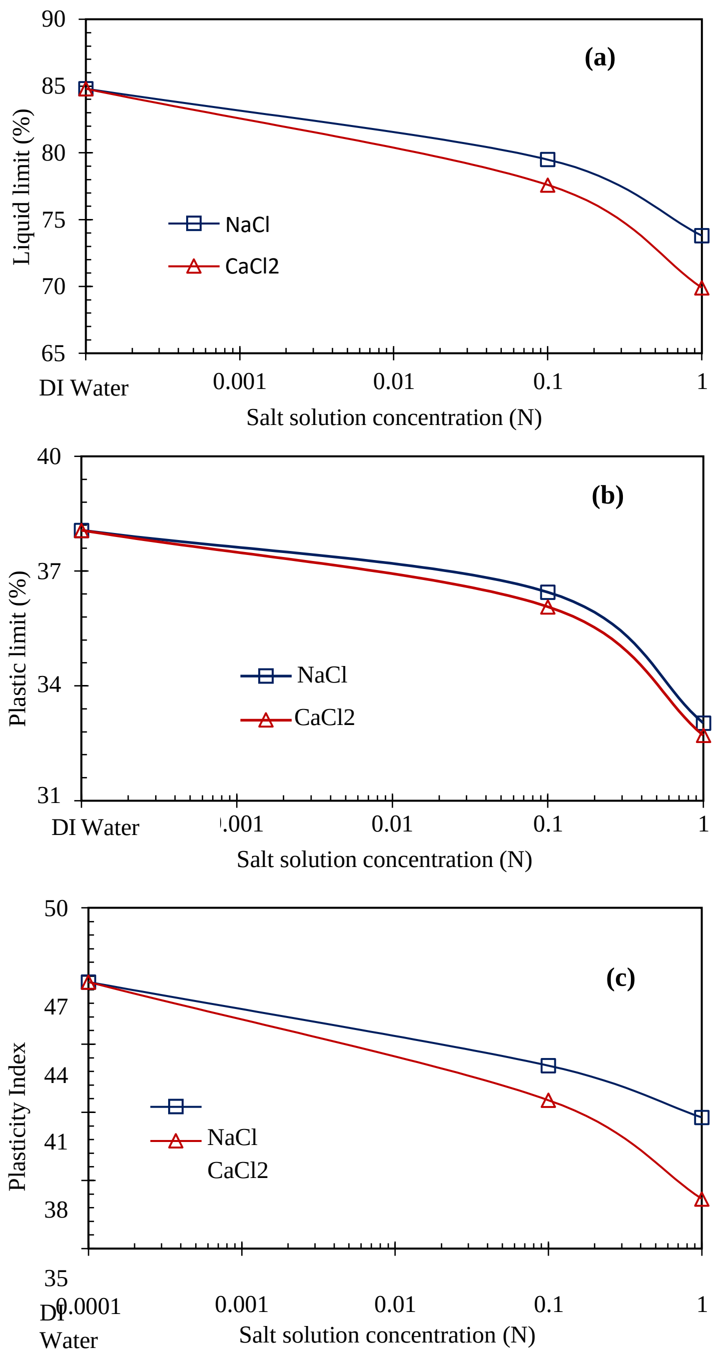

Fig. 2. Atterberg limits of BC soil with monovalent and divalent salt solutions, (a) Liquid limit, (b) Plastic limit, (c) Plasticity index.

-micropores may contribute to primary and secondary swelling phenomena. The swelling height of BC soil with DI water was 3.1 mm, as depicted in Fig.3. This height was decreased to 2.4 and 1.8 mm for saturating monovalent permeant at 0.1 and 1N, respectively. This height was reduced further to 2.1 and 1.6 mm for 0.1 and 1N divalent permeant, respectively. The reduction inter-particle distance and void ratio may be the reason for less swelling height at high concentrations and valencies. The coefficients of swelling strains mentioned in Table 2 were calculated according to the formulae mentioned by Soltani et al. 2019. It was identified from Table 2 that the coefficient of primary swelling was higher than the coefficient of secondary swelling, irrespective of all pore fluids. However, these coefficients were lowered with high pore fluid concentration and cation valency.

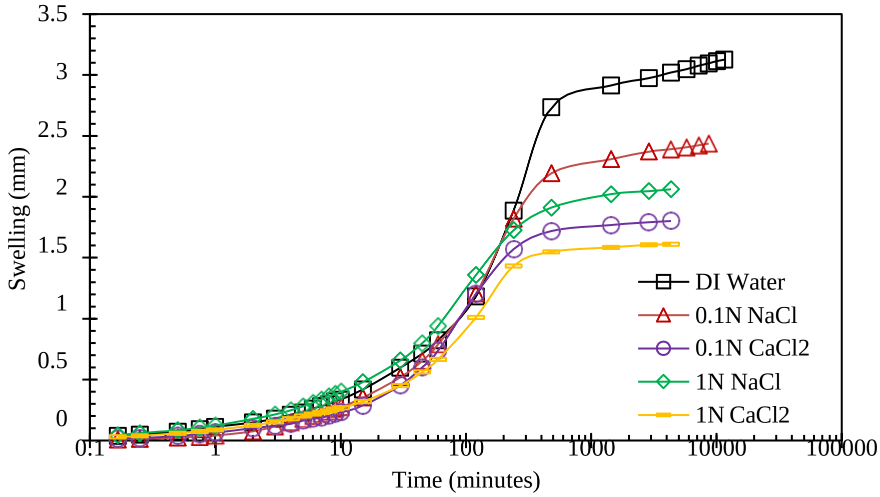

Fig. 3. Time vs swelling plot of BC soil with monovalent and divalent salt permeants.

Table 2. Swelling strains of BC soil with various inorganic salt permeants.

Salt permeant	Coefficient of Primary swelling	Coefficient of Secondary swelling
DI Water	0.104	0.019
0.1N NaCl	0.082	0.014
1N NaCl	0.065	0.012
0.1N $CaCl_2$	0.057	0.012
1N $CaCl_2$	0.049	0.011

3.4 Coefficient of volume compressibility (m_v)

Generally, m_v gives an idea about the volume change of soil with corresponding effective stress values, which will be calculated using equation (2). The coefficient of volume change behavior with corresponding external pressure was depicted in Fig.4. According to Fig.4, m_v was increased initially and then reduced at higher external pressures. Generally, the void ratio is higher at lower external pressures, which will be reduced more at higher external pressures that cause a significant reduction in mv values. However, this reduction in m_v values was more for high concentrations. For example, at the external pressure of 196.1 kPa, the mv value of BC soil was 0.053 for DI water as pore fluid. This m_v value reached 0.047 and 0.034 for 0.1 and 1N monovalent pore fluid, respectively. Usually, diffuse double-layer thickness will be more for the prominent montmorillonite mineral clays with DI water. This thickness will be reduced further by adding salt solution permeants due to the cations present in the salt solutions. However, this reduction in m_v was more dominant for higher cation valency also. It was recognized that the m_v value reached 0.039 and 0.033 for divalent salt permeant at 0.1 and 1N concentrations for the same external pressure, respectively. Another finding from the results is that the reduction mv value for both monovalent and divalent salt permeants is marginal at higher concentrations.

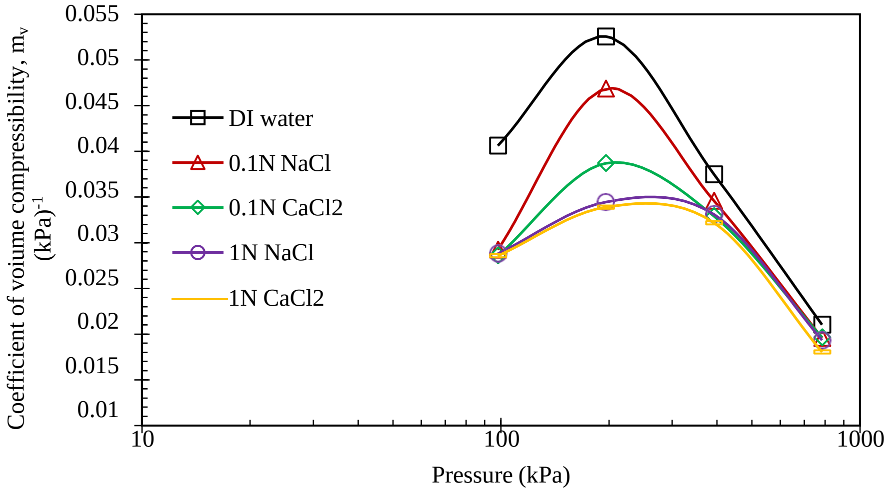

Fig. 4. Coefficient of volume compressibility vs pressure plot with monovalent and divalent salt permeants.

3.5 Compression ratio (C_r)

The compression ratio (C_r) of BC soil under different pore fluids was computed by using equation 4, and obtained values were plotted in Fig. 5. The observation made from Fig.5 is that the C_r value of BC soil was reduced for an increase in the salt permeants concentrations. The C_r value of BC soil with DI water was 0.283, which was reduced marginally to 0.28 and 0.242 for 0.1 and 1N monovalent salt permeant, respectively. This decrease in C_r is the result of a fall in the void ratio as pore fluid concentration increases. However, a further decrease in the void ratio occurs at higher cation valency of pore fluids leading to furthermore reduction in C_r values of BC soil. For divalent salt permeant, this C_r value became 0.259 and 0.235 at the same concentrations.

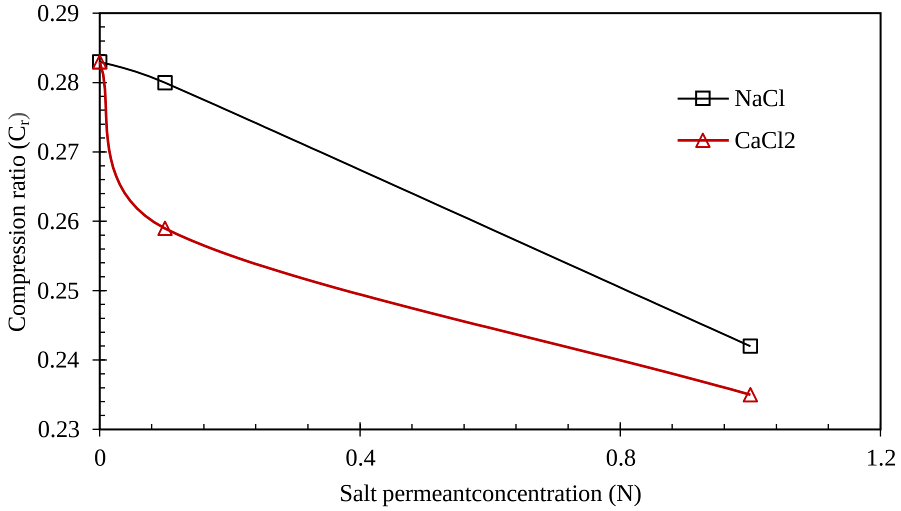

Fig. 5. Compression values of BC soil with monovalent and divalent salt permeants.

4 Conclusions

Clay liner in landfills plays an essential role in avoiding leachate mitigation into the groundwater by having a prominent swelling capacity and low hydraulic conductivity. In this research, significant laboratory tests were performed, which will give a detailed idea about the swelling and volume change behavior of BC soil for the utilization of landfill liner. The following conclusions have been derived from the outcomes of this study.

1. Free swelling and Atterberg limits of BC soil were decreased for an upsurge in the concentration of salt solutions. This decrement was more prominent with higher cation valency.
2. From time-swelling curves, it was identified that a considerable reduction in swelling height concerning an increase in pore fluid concentrations from 0.1 to 1N.
3. From time-swelling plots, the major part of swelling (more than 70%) occurred in the primary swelling stage rather than the initial and secondary swelling stages.
4. From obtained swelling strain values, a considerable decrement was noticed in the coefficient of primary swelling values with the high concentration of

pore fluids, whereas marginal reduction was noticed in the coefficient of secondary swelling values.

5. The m_v vs pressure plot showed that lower mv values were reported at higher external pressures irrespective of salt permeants. However, furthermore reduction in mv values was observed with monovalent and divalent salt permeants.
6. The marginal decrement in C_r values was found for both monovalent and divalent pore fluids owing to a reduction in void ratio with salt permeants.
7. Therefore, obtained results would be profitable to design engineers and other nations regarding the geotechnical behavior of BC soil under different pore fluids for liner utilization.

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