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ORIGINAL PAPER

Potassium Chloride Treatment to Control Alkali Induced Heave in Black Cotton Soil

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Abstract The results presented in this paper shows that high concentrations of sodium hydroxide causes abnormal changes on the volume change behaviour of illite–smectite (interstratified mineral) soil due to mineralogical changes. The higher swell that occurs is shown in the form of a new second stage of swelling. Increase in negative charges on soil particles and mineralogical changes after interaction with soil, respectively, are responsible for the swelling in these two stages. However, potassium hydroxide does not induce such high swelling in soils. This is mainly due to the fixation of potassium ions. Hence an attempt has been made to control the swelling induced by sodium hydroxide by making used of potassium chloride as an additive. Potassium fixation which is not substantial at neutral pH is favoured at higher pH Addition of potassium chloride salt solution (as 2 and 5% solution) can reduce only the first stage of swelling by linking the unit layers of mineral by reducing development diffuse double layer near clay surface. Potassium chloride is unable to prevent the formation of mineralogical alteration due to soil alkali interaction and hence the swelling associated with mineralogical changes. X-ray diffraction studies have revealed that mineralogical changes leading to formation of zeolite by soil alkali interaction is not inhibited by potassium ions. Morphological changes studied by scanning electron microscope corroborate these observations. Also the compressibility of soil which is increased in alkali solution is reduced in the presence of potassium salts. This reduction is due to reduction in the first stage of swelling.

Keywords Interstratified mineral · Alkali · Potassium chloride · Volume changes · X-ray diffraction · Scanning electron microscope

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1 Introduction

Soil pollution leading to any chemical or biological alteration of soil can have direct bearing on their geotechnical properties and can trigger failure structures founded on them. It is thus necessary to study the effects of soil pollutant interaction on foundation soils and to understand the mechanism of soil pollutant interaction to plan for remedial measures. The alterations in the foundation soils are caused mainly by volume changes and strength variations. Volume changes in soils are common because of their relation to settlements due to compression, heave due to expansion, and their contribution to deformations caused by shear stresses. Large volume changes in soils results in extensive structural damage, which often reflects as progressive failures.

One important pollutant that can have considerable effect is the alkali contamination of the soil. Hydroxides are released into the soil environment from varies industries such as paint and dyes, paper and pulp industries, cotton mills and aluminium industries and so on. When highly alkaline solutions contact clay minerals, mineral dissolution and precipitation may occur. The effect of alkaline solutions on the transformation of clay minerals has been the subject of many studies (Cuadros and Linares 1996; Bauer and Berger 1998; Bauer and Velde 1999; Taubald et al. 2000). The mineral transformations depend on the nature and chemical composition of the reacting alkaline solutions and the nature of the reacting mineral. Rao and Subba Rao (1994) and Sivapullaiah and Manju (2006) studied the effect of alkali contamination on the swelling properties of kaolinite. Rao and Subba Rao (1994) studied a ground heave of an inherently non-swelling, kaolinitic-rich red soil due to prolonged spillage of concentrated caustic soda solution into the subsoil in an industrial establishment. They observed about 5% swelling of the undisturbed soil by passage of 40% caustic soda solution in the oedometer test. Loss of cementitious iron oxide coatings coupled with the negative charge imparted to the soil particles by the seepage of the caustic soda solution has been attributed as the cause for the observed heaving. Treatment of the contaminated soil with 5% ferric chloride solution besides minimization of caustic soda spillage has been suggested as remedial measures. Recently detailed experimental investigation has been carried out to study the use of ferric chloride salt to control the undesirable volume changes induced by high concentrated alkali contamination on kaolinitic red earth (Sivapullaiah and Manju 2006). It was shown that ferric chloride treatment can overcome the effects of small concentrations of alkali; it is ineffective to overcome the large and continuous exposure of soil with alkali contamination. Sinha et al. (2003) reported the results of investigations on the effect of spilled liquid caustic soda during operation of an alumina plant in India on the bearing capacity of foundation rock. Plate load tests were carried out on contaminated as well as uncontaminated locations and noticed that safe bearing capacity of contaminated site is lower by about 33% compared to uncontaminated location. Neutralization of sub-surface layer with 5% $FeCl_3$ solution and provision of impermeable layer under the high grade concrete has been considered as remedial measures.

The main objective of the study is to explore the possibility of using potassium salt to control the alkali induced heave in soils. Clays of the 2:1 type such as vermiculite, fine-grained mica (illite), and smectite, fix potassium very readily (Fig. 1) and in large quantities. This fixation of potassium ions can restrict the swelling in soils. To understand the concept of potassium fixation at high pH an attempt is made to study the effect of potassium hydroxide on the volume change behaviour of soils is studied. Further studies were carried out with 2 and 5% of potassium chloride salt solutions to control alkali (sodium hydroxide) induced heave in black cotton soil.

2 Materials and Methods

2.1 Soil Used

The natural black cotton soil (BC) used in this study was collected from Belgaum India. Belgaum is situated in northern Karnataka Plateau, a part of Deccan Plateau of India. The soil was collected by open excavation, from a depth of 1 m from natural ground level. The soil was air dried and used after sieving through Indian Standard 425-micron sieve. The properties of soil are summarised in Table 1. Based on the index properties and the grain-size distribution (Fig. 2), soil is classified as CH. X-ray diffraction studies show that the soil understudy contains a mixed layered illite–smectite mineral as the dominant component.

2.2 Fluid Used

The fluids used were distilled water, 1 and 4 N NaOH solution, 1 and 4 N KOH solution and potassium chloride solution. One and 4 N solutions were prepared by dissolving the required amount of Analar Grade sodium and potassium hydroxide pellets in distilled water. Potassium chloride solution is

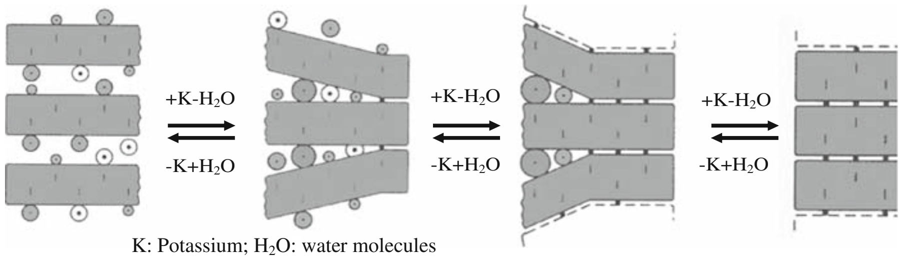


Fig. 1 Diagrammatic illustration of the fixation and release of potassium (Brady 1995)

Table 1 Properties of natural soil

Index properties	Black cotton soil
Liquid limit (LL) (%)	82
Plastic limit (PL) (%)	35
Plasticity index (PI) (%)	47
Shrinkage limit (SL) (%)	10
Free swell index (ml/g)	2.2
Grain size distribution	
Clay content (%)	40
Silt content (%)	54
Fine sand content (%)	6
Soil classification	CH
Standard proctor's	
Maximum dry unit weight (KN/m^3)	12.9
Optimum water content (%)	35

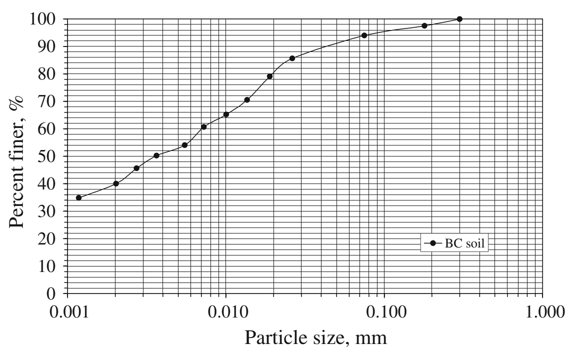


Fig. 2 Grain size distribution curves of BC soil

prepared by dissolving the chemically pure salt in distilled water.

2.3 Free Swell Index

The testing procedure adopted for determining Free swell was as follows: 10 g oven dried powder samples were submerged in 40 ml of distilled water or other alkali solvents in 100 ml standardized graduated cylinders. The suspensions were repeatedly stirred for thorough mixing and allowed to equilibrate for 24 h to ensure thorough wetting of the samples. The suspensions were then made up to the 100 ml mark with the respective solvents, with stirring. The cylinders were covered with caps and left undisturbed for a further period of 24 h at which time the volumes occupied by sample particles on settling were noted. As the bentonite clay is highly expansive, sediment volume of bentonite clay in water was measured using only 5 g of soil. Free swell index is expressed as sediment volume per one gram of soil (Rao and Sridharan 1985).

2.4 Oedometer Tests

The one-dimensional consolidation tests were performed as per ASTM (1996) D2435 to study the effects of different alkali solutions on swelling and compressibility of soils. To understand the effect of chemicals on volume change behaviour of the soil, it is necessary to examine the behaviour of soil with water as pore fluid in standard oedometer test. Oedometer tests were also performed on the same soil mixed with salt solution to study effect of salt to use as a stabilizer.

A cylindrical specimen of soil compacted to proctors maximum density at optimum water content, enclosed in a metal ring of 60 mm diameter and 20 mm height is allowed to swell fully and reach equilibrium at seating load before subsequent loading and unloading. After reaching the equilibrium the samples were loaded to 800 kPa, in the conventional manner and unloaded to 6.25 kPa. A load increment ratio of unity was adopted and the load increment duration was kept as 24 h or until primary consolidation was complete. The changes in thickness of the specimen are recorded against time to obtain the swelling at seating load and the compression at the end of each load stage.

Volume change behaviour of soils has been studied in terms of the following:

1. Heave/Swell at seating load upon exposure of compacted sample to inundating fluid in the oedometer cell
2. Compressibility after full swell

2.5 X-Ray Diffraction Studies

Samples after consolidation test were used for X-ray analysis. The analysis was made on a Philips X-ray diffractometer model PW3710 using K alpha radiation monochromated on powder samples. Randomly oriented samples were prepared by manually grinding the specimen in a porcelain mortar and pestle to powder form and subsequently pressing the material lightly into rectangular glass holders. Samples were scanned from 3° 2θ to 70° 2θ using 0.02° steps and counting for at least 1 s/step. The mineral composition of each sample was determined using the XRD peak positions and intensities (JCPDF 1990).

2.6 SEM Studies

The microstructures of selected samples after consolidation tests were examined by the Sirion high resolution scanning electron microscope (SEM). A very small amount of oven-dried and finely powdered sample is mounted on to the tape glued to the flat surface of SEM stub and sputter coated with gold prior to scanning.

3 Results and Discussions

To assess the efficiency of potassium chloride solution in controlling the alkali (NaOH) induced heave in soil, it is necessary to study the volume change behaviour of soil with and with out alkali (sodium hydroxide) and to understand the effect of high pH on potassium fixation studies were also carried out with potassium hydroxide on the volume change behaviour of soils.

Hence studies were carried out with NaOH and KOH solutions before assessing the effect of KCl in soil.

3.1 Effect of 1 N Alkali Solutions on the Volume Change Behaviour of BC Soil

Figure 3 shows the percent swell of black cotton soil compacted with water and inundated with water and 1 N alkali solutions at seating load. It is observed from figure that 2% swell occurs in soil with water. This swell is due to adsorption of water molecules on the negatively charged clay surface and form diffuse double layer. The swell increases considerably to about 17% in presence of 1 N NaOH solution. It is known that with increase in the pH of the soil the charges on clay particles increase (Brady 1995) and increases the thickness of diffused double layer due to increased repulsion between clay particles. However, in the case of 1 N KOH solution this abnormal swelling is not observed. This difference in the swelling of soil with NaOH and KOH is due to the fixation of potassium ions between unit layers of interstratified illite–smectite mineral, as explained earlier. The potassium fixation is enhanced due to alkalinity of the pore fluid. Thus smectite present in the soil is converted to illite. Though the peak due to illite mineral is sufficiently crystalline to be detected in diffraction patterns the peaks due to illite–smectite mixed layer mineral are not observed in samples after consolidation tests (Fig. 4;

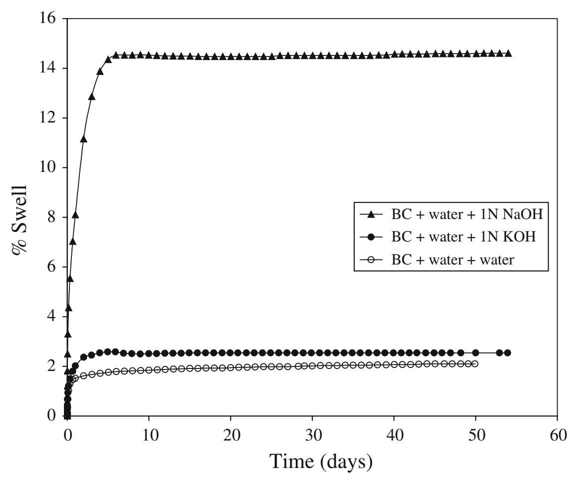


Fig. 3 Variation of swell with time for BC soil compacted with water and inundated with water, 1 N NaOH and 1 N KOH solutions

Table 2). The absence of the peaks due to illite–smectite mixed layer mineral in the samples tested with sodium hydroxide may due to disintegration of the mixed layer minerals. These trends become clearer in samples tested with higher concentration sodium and potassium hydroxide solutions.

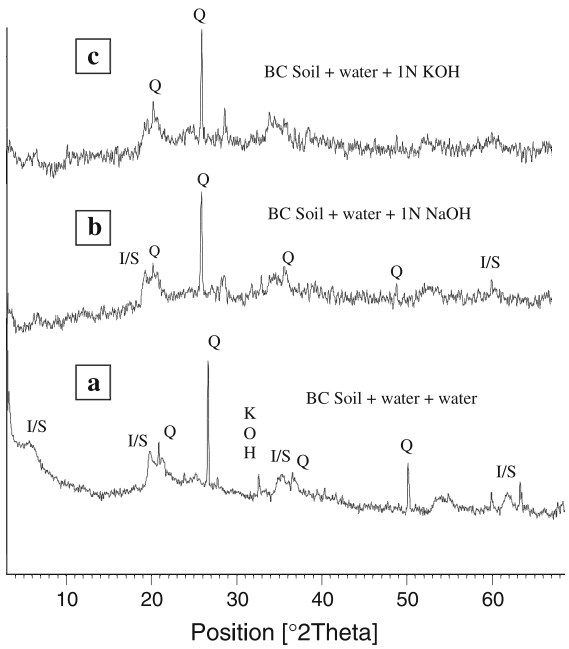


Fig. 4 X-ray diffraction pattern of consolidated BC soil samples

The micrographs of samples tested with sodium and potassium hydroxide shows that while the particles have decomposed in sodium hydroxide the same is not observed in case of 1 N KOH solution (Fig. 5a–c).

Figure 6 shows the differences in compressibility of soil with water, 1 N NaOH and 1 N KOH in the form of conventional void ratio–pressure relationships. The results indicate that the compressibility of the sample inundated with 1 N KOH solution is significantly reduced compared to samples inundated with water or 1 N NaOH solution. This reduction in compressibility results due to favourable fixation of potassium between unit layers of interstratified illite–smectite mineral in presence of KOH solution. The variation in the compressibility is reflected in the value of compression index (C_c), which is given in Table 3.

3.2 Effect of 4 N Alkali Solution on the Volume Change Behaviour of BC Soil

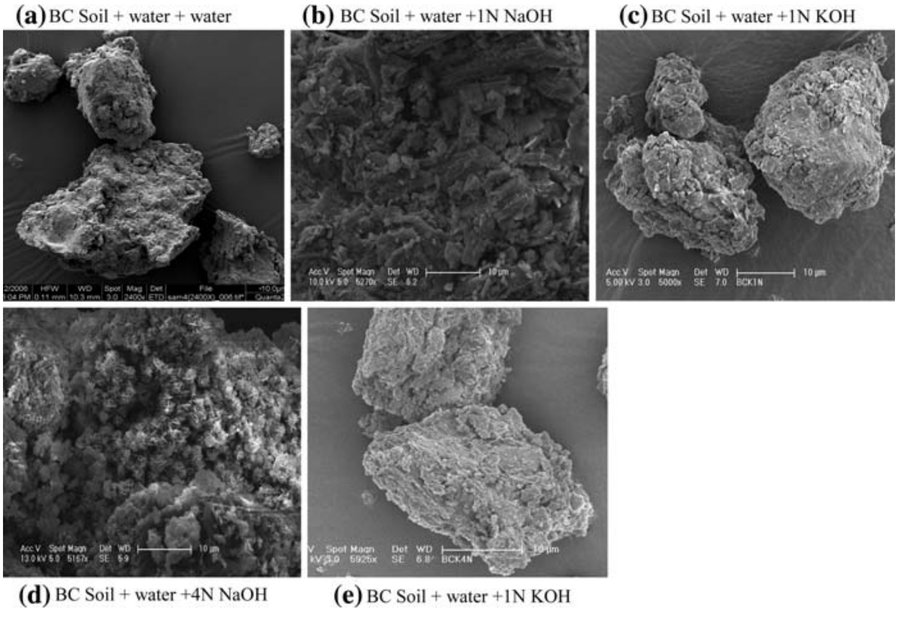
Figure 7 shows the time-swell relationships of black cotton soil compacted with water and inundated with 4 N alkali solutions at seating load. It can be noticed

Table 2 X-ray diffraction of data of black cotton soil-alkali reaction products

d-Spacing (A°)	Minerals identified	Relative intensity (%)						
		BC soil water	BC soil 1 N NaOH	BC soil 1 N KOH	BC soil 4 N NaOH	BC soil 4 N KOH	BC soil + 2% KCl 4 N NaOH	BC soil + 5% KCl 4 N NaOH
15.9	I/S	12.9						
6.30	NASH				22.89		45.43	40.71
4.51	I or I/S	15.46	24.86			12.91	13.30	
4.24	Q	25.55	22.98	30.50	25.65	9.53	20.33	13.70
3.65	NASH				25.02		66.67	63.78
3.34	Q	100	100	100	100	100	100	100
2.85	NASH1						18.30	26.48
2.75	KOH	10.23			14.65		25.25	26.34
2.58	NASH				16.78		34.37	31.38
2.54	I/S	9.74			15.8			
2.47	Q	11.88	12.03		11.03		12.95	13.15
2.12	NASH				9.44		18.53	16.27
1.82	Q	23.60	12.98			8.84	9.39	16.68
1.50	I or I/S	6.05	8.02			4.52		

I/S, illite–smectite; *NASH or NASH1*, sodium aluminum silicate hydrate; *I*, illite; *Q*, quartz; *KOH*, potassium hydroxide

Fig. 5 Photomicrograph of consolidated black cotton soil samples



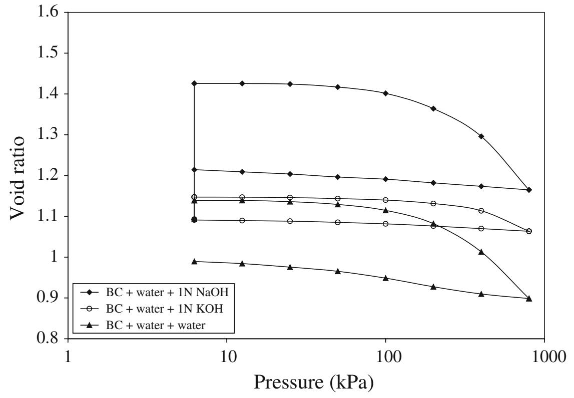


Fig. 6 Void ratio–pressure relationship for BC soil compacted with water and inundated with water, 1 N NaOH and 1 N KOH solutions

Table 3 Effect of fluids on volume change behaviour

Soil	Inundating fluid	Maximum swelling at 6.25 kPa (%)	Compression index C_c
BC + water	Water	2.1	0.24
	1 N NaOH	16	0.26
	1 N KOH	2.5	0.09
	4 N NaOH	36	0.33
	4 N KOH	2.3	0.02
BC + 2% KCl	Water	2.3	0.25
	4 N NaOH	21	0.17
BC + 5% KCl	4 N NaOH	17	0.16

that a very high swell of about 36% has occurred when the soil is contaminated with 4 N NaOH. Further it is observed that the swelling with 4 N alkali solution occurs in two stages, viz., steep initial swell (of about 25%) for about 10 days and gradual swell (of about 11%) beyond this period. Increase in negative charges on soil particles and mineralogical changes after interaction with soil, respectively, are responsible for the swelling in these two stages. The first stage of swell is rapid, like in swelling soils. The second stage of swell is slow and may be due to mineralogical changes occurring during consolidation testing. X-ray diffraction patterns obtained on samples after interaction with 4 N NaOH during consolidation test have not shown peaks of illite–smectite but showed new peaks due to formation of sodium aluminium silicate hydrate (NASH) which is a form zeolite (Fig. 8b; Table 2). This supports the view that mixed minerals particles are dissociated and new mineral formation takes place. The morphology has changed to rosette type as shown by SEM photographs (Fig. 5d). However, from figure it can be noticed that the swelling of soil with 4 N KOH solution is significantly less and occurs in one stage unlike with sodium hydroxide which can be due to the fixation of potassium ions between unit layers of interstratified illite–smectite mineral. Thus new peaks due to illite are observed and peaks due to illite–smectite mixed mineral are absent from X-ray

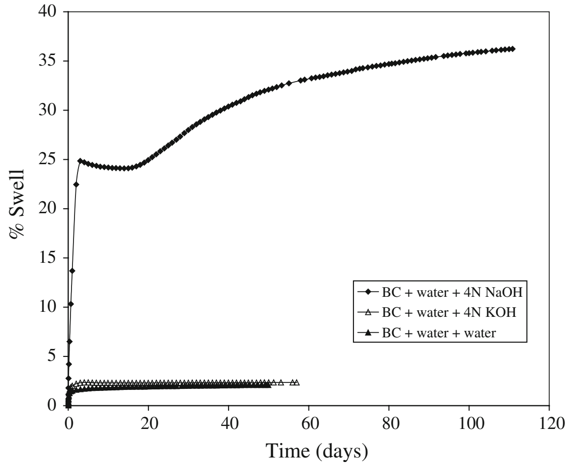


Fig. 7 Variation of swell with time for BC soil compacted with water and inundated with water, 4 N NaOH and 4 N KOH solutions

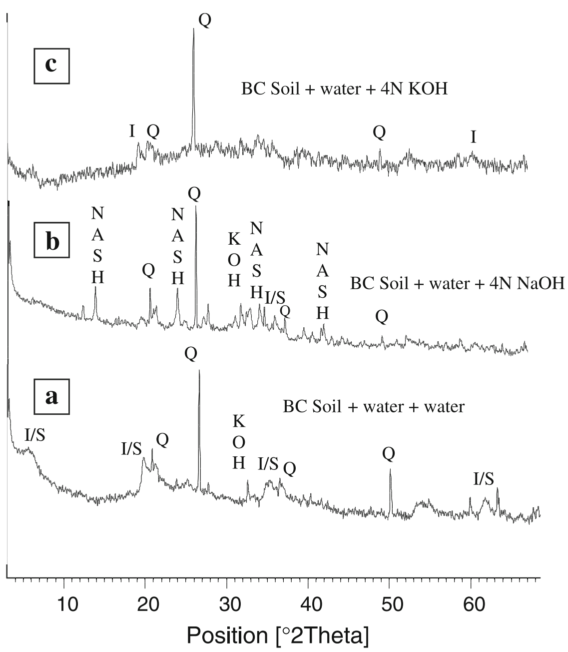


Fig. 8 X-ray diffraction pattern of consolidated black cotton soil samples

diffraction patterns shown in Fig. 8. SEM studies from Fig. 5e shows that soil particles treated with potassium hydroxide relatively aggregated. The variations in the swell values are given in Table 3.

The void ratio–pressure relationship for the soil remoulded with water and inundated with (1) water, (2) 4 N NaOH, and (3) 4 N KOH are compared in

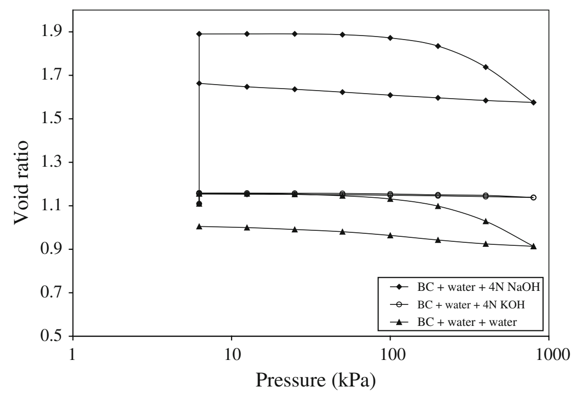


Fig. 9 Void ratio–pressure relationship for BC soil compacted with water and inundated with water, 4 N NaOH and 4 N KOH solutions

Fig. 9. It can be seen that the soil compacted and inundated with 4 N NaOH solution undergoes relatively high compression compared with water, whereas in case of 4 N KOH the compression is almost negligible. Thus the potassium ions that are fixed between layers in the crystals of these normally expanding clays become an integral part of the crystal and reduce the compression. Table 3 shows the variation in the compressibility which are reflected in the form of compression index (C_c).

It is clear from this section that the potassium fixation is favorable at high pH solution. Thus it is proposed to control the alkali induced heave in interstratified soil in presence of alkali by linking liberated smectite lattice units by potassium ions.

3.3 Volume Change Behaviour of BC Soil Treated With Potassium Chloride Solution During Contamination With 4 N NaOH Solution

Studies on volume change behaviour of soil with KCl using water as inundating solution helps to assess the effect of salt in altering the behaviour of soil due to alkali contamination.

Figure 10 shows the effect of potassium chloride solution mixed with black cotton soil and inundated with water on the swell at seating load. From figure, a swell of about 2% has been noticed at seating load in case of soil mixed with KCl, which is about the same as that of BC soil with water. Thus KCl solution cannot reduce the swelling in soil containing illite–smectite mineral as potassium fixation is not

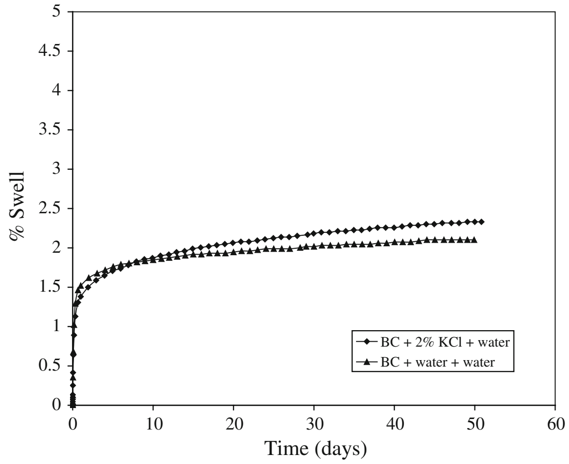


Fig. 10 Variation of swell with time for BC soil compacted with and without KCl solution

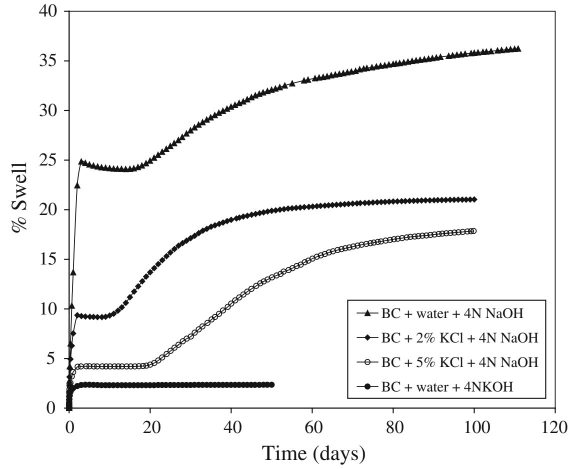


Fig. 12 Variation of swell with time for BC soil compacted with and without KCl solution and inundated with 4 N NaOH

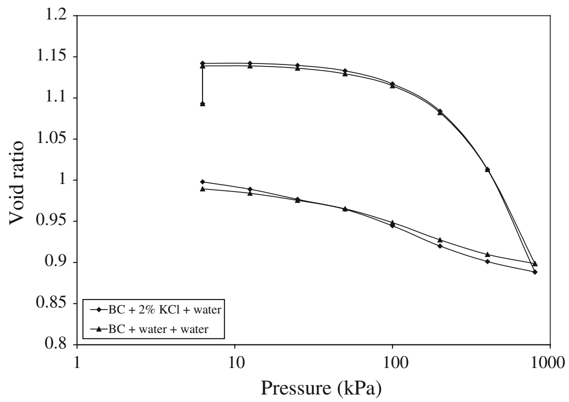


Fig. 11 Void ratio–pressure relationship for BC soil compacted with and without KCl solution

substantial at neutral pH. The variation in the swell is given in Table 3.

Figure 11 gives the void ratio–pressure relationship obtained from the one-dimensional consolidation test for black cotton soil mixed with KCl. The results indicate that KCl treatment has no effect even on the compressibility of the soil. The value of compression index (C_c) presented in Table 3 confirm the same.

Figure 12 shows the effect of 2 and 5% KCl solution mixed with black cotton soil and compacted with water and inundated with 4 N sodium hydroxide solution on the swelling at seating load. From figure it can be observed that the swelling in soil treated with KCl solutions also exhibited two stages, viz., steep initial swelling for about 2 days and gradual swelling for the rest of the period. From figure it can be noticed that the first stage of swelling is considerably reduced to about 9% (25% in case of soil alone with 4 N NaOH) in the soil compacted with 2% KCl; where as the effect of KCl is not observed in the case of secondary swelling. The increase in the percentage of KCl (5%) solution has further reduced the first stage of swelling to about 4% with no effect on second stage of swelling.

This variation in swell behaviour of soil can be explained as follows:

The first stage of swelling in case of alkali solution which is due to increase in the negative charges is controlled when soil is mixed with KCl solution due to enhanced fixation of potassium ions between unit layers in presence of alkali solution. It has been observed earlier that KCl could not reduce the swelling in soil with water by increased electrolyte concentration. But the swelling due to mineralogical changes by long-term soil-alkali interaction, represented by second stage of swelling, is not reduced. It can be seen from XRD (Fig. 13; Table 2) that soil treated with 2 or 5% potassium chloride salt solutions and inundated with 4 N NaOH solution also shows the presence of zeolite minerals, indicating that potassium chloride solution can not prevent the formation of swelling compounds which cause abnormal volume change behaviour. This confirms the mineralogical alteration can neither be prevented nor altered and smectite can not be converted to illite under the experimental conditions. Rosette-type of

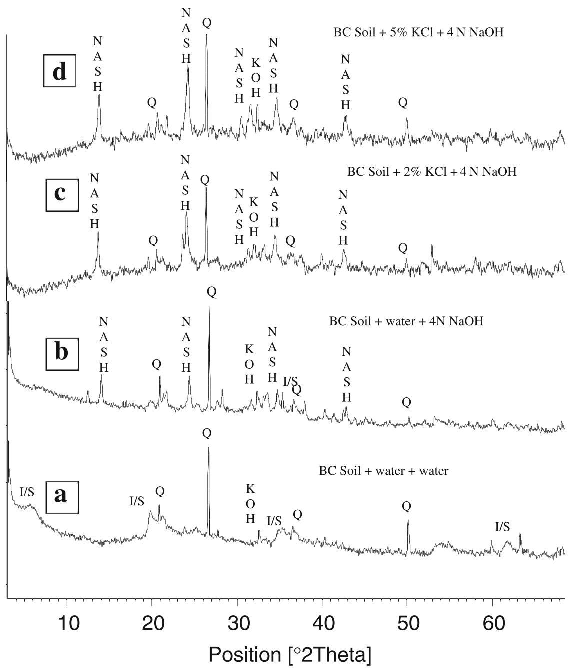


Fig. 13 X-ray diffraction pattern of consolidated BC soil samples

morphology with 2 and 5% KCl has been observed from SEM photographs (Fig. 14a, b). The variations in two stages of swell are given in Table 4.

After completion of swelling, conventional consolidation test was conducted and e −log p curve obtained is shown in Fig. 15. It can be seen that the soil compacted with KCl and inundated with 4 N NaOH shows considerable reduction in compressibility than the soil compacted without KCl. Reduction in first stage of swelling in presence of KCl solution, is a major reason for reduction in the compressibility. The values of compression index (C_c) are given in Table 3.

Table 4 Effect of fluid on swelling

Soil	Inundating fluid	Swelling at 6.25 kPa (%)		
		First stage	Second stage	Total
BC + water	4 N NaOH	25	11	36
BC + 2% KCl	4 N NaOH	9	12	21
BC + 5% KCl	4 N NaOH	4	13	17

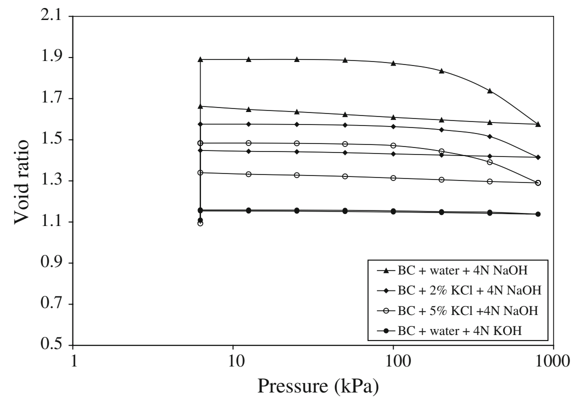
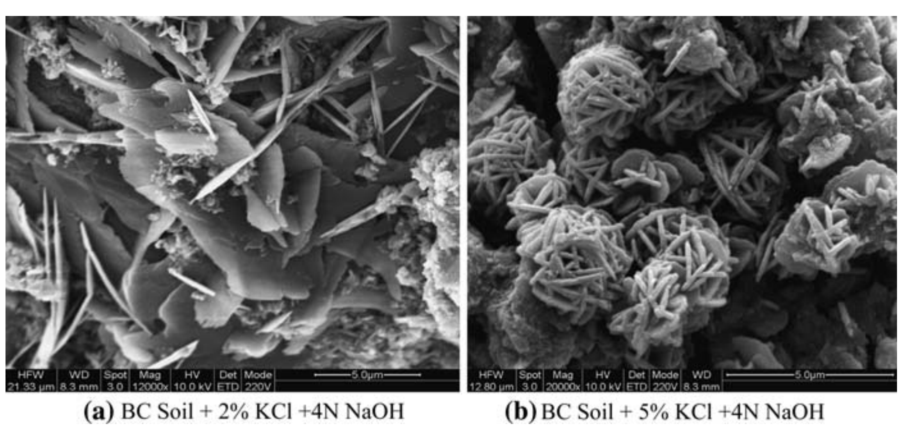


Fig. 15 Void ratio–pressure relationship for BC soil compacted with and without KCl solution and inundated with 4 N NaOH

4 Conclusions

1. The alkali induced heave in soils can be partially controlled with the use of potassium salts.
2. Of the two stages of swelling in soil in presence of sodium hydroxide solution only the first phase of swelling is reduced in presence of potassium

Fig. 14 Photomicrograph of consolidated black cotton soil samples



salt due to potassium fixation between unit layers of smectite mineral.

3. The second phase of swelling that occurs in soil with alkali solution due to mineralogical alterations and due to formation of zeolite minerals can not be controlled with the use of potassium salt as these mineralogical changes is not prevented.
4. The reduction in swelling of soil in presence of potassium salt also leads to reduction in the compressibility of soil in sodium hydroxide solution.

References

American Society for Testing and Materials (1996) Standard test method for one-dimensional consolidation properties of soil: ASTM designation D 2435-90. Annual book of ASTM Standards, ASTM, Philadelphia

Bauer A, Berger G (1998) Kaolinite and smectite dissolution rate in high molar KOH solutions at 35° and 80°C. Appl Geochem 13:905–916

Bauer A, Velde B (1999) Smectite transformation in high molar KOH solutions. Clay Miner 34:259–273

Brady NC (1995) The nature and properties of soils, X edn. Prentice Hall of India Private Limited, New Delhi

Cuadros J, Linares J (1996) Experimental kinetic study of the smectite-to-illite transformation. Geochim Cosmochim Acta 60:439–453

JCPDF (1990) Powder diffraction file alphabetical indexes, inorganic phases. International Center for Diffraction Data, USA

Rao SM, Sridharan A (1985) Mechanism controlling the volume change behaviour of kaolinite. Clays Clay Miner 33(4):323–328

Rao SM, Subba Rao K (1994) Ground heave from caustic soda solution leakages—a case study. Soils Found 34:13–18

Sinha UN, Sharma AK, Bhargava SN, Minocha AK, Pradeep Kumar (2003) Effect of seepage of caustic soda on foundation and remedial measure in alumina plant. Proceeding of the Indian Geotechnical Conference. Roorkee, India, pp 229–234

Sivapullaiah PV, Manju (2006) Ferric chloride treatment to control alkali induced heave in weathered red earth. Geotech Geol Eng 23(5):601–614

Taubald H, Bauer A, SchÄafer T, Satir M, Kim JI (2000) Experimental investigation of the effect of high-pH solutions on the Opalinus shale and the Hammerschmiede smectite. Clay Miner 35:515–524