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Effect of alkali contamination on swelling and strength characteristics of soils

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Abstract. Alkali as pore fluid due to contamination from various sources affects the soils in different ways depending upon the mineralogical content present in the soil, and the concentration and duration of pore fluid. Properties of the soil get altered by the contamination of alkali. So, the present study aims to understand the mechanism of soil-alkali interaction and also to have a better knowledge about the changes in swelling, strength characteristics, and index properties in the soil due to the alkali interaction with the soil. Thonnakkal Clay and Kuttanad soil are selected to study the changes that occur when they are exposed to sodium hydroxide alkali contamination from various sources and to better understand the behavior of soil when contaminated with sodium hydroxide at 1 N and 4 N concentrations with varying percentages of 2.5%, 5% and 10% by weight of the sample. The variations in index properties, strength characteristics, and swelling behavior are reported in this paper.

Keywords: Alkali contamination, Swelling behavior, Index properties, Strength characteristics.

1 Introduction

Soil contamination is mainly caused by the release of human-made chemicals into the soil or other alterations in the natural soil environment. It is usually caused by industrial activity, agricultural chemicals, pesticides, industrial wastes, accidental spills and leakages, or improper disposal of waste. A growing cause for concern is how we dispose of waste. The major types of contaminants include various substances such as inorganic acids, sulfates, alkalis, organic contaminants, toxic or phytotoxic metals, and combustible substances. The natural soil water system may get polluted and affect the properties of soil depending on the type of pollutant.

The behavior of soil-water systems is primarily controlled by the type and amount of clay mineral, the nature of pore fluid, associated cations and anions, and organic matter. It is evident from the studies that alkali contamination causes significant effects on the geotechnical properties of different clayey soil. The changes in the properties have so far shown a good relationship with the change in internal microstructure, chemistry, and mineralogy. Changes occurred mainly depending on the type and composition of the soil along with the concentration and duration of pore fluid. Not all soil with common predominant clay minerals shows similar properties when contaminated with alkali. The present study is conducted to understand the variation in index properties, swelling behavior, strength characteristics, and microstructural variation of clayey soils due to the interaction with sodium hydroxide

2 Materials and properties

Soils

The soil selected for the present study was Thonnakkal soil and Kuttanad soil and the alkaline pore fluid selected is sodium hydroxide. The Thonnakkal soil was collected from English India Clay Limited and Kuttanad soil was collected from Chakku-lathukavu, Alappuzha. The properties of the soils are listed in Table 1 and the chemical composition of the soil is shown in Table 2.

Table 1. Properties of soils.

Properties	Thonnakkal clay	Kuttanad soil
Specific Gravity	2.8	2.25
Percentage of Clay (%)	59	43
Percentage of Silt (%)	28	55
Percentage of Sand (%)	13	2
Liquid limit (%)	36.01	72.18
Plastic Limit (%)	19.20	45.28
Shrinkage Limit (%)	15.33	35.15
Plasticity Index (%)	16.91	26.9
Soil Classification	CI	MH
Free Swell Index (%)	8.33	-
Optimum Moisture Content (%)	15.20	35.80
Maximum Dry Density (kN/m^3)	17.26	11.67
UCS (kN/m^2)	41.24	64.13

Table 2. Chemical composition of soils.

	Thonnakkal clay	Kuttanad soil
SiO_2	59.80%	50.42%
TiO_2	1.65%	1.07%
Al_2O_3	29.60%	23.95%
MnO	38.1 ppm	0.07%
Fe_2O_3	1.27%	11.79%
CaO	911 ppm	1.32%
MgO	444 ppm	2.45%
Na_2O	383 ppm	0.84%
K_2O	0.22%	2.49%
P_2O_5	525 ppm	0.52%
Total	92.54%	99.57%

Presence of organic content in Kuttanad soil
Visible organic content was present in the soil. The percentage of organic content was found to be 3.15%, which indicates the presence of a high amount of organic content in the soil. SEM images of Kuttanad soil further showcase the abnormal behavior of the soil. Fig. 1 shows the presence of siliceous diatom frustules. Diatoms are microscopic, single-celled algae that possess rigid cell walls or frustules. They are composed of amorphous silica. these frustules settle down forming a part of the marine sediments after the death of the organisms, as fossilized remains [5]. The abnormal behavior of Kuttanad soil is because of the presence of diatom frustules which have a significant effect on the various properties of the clay

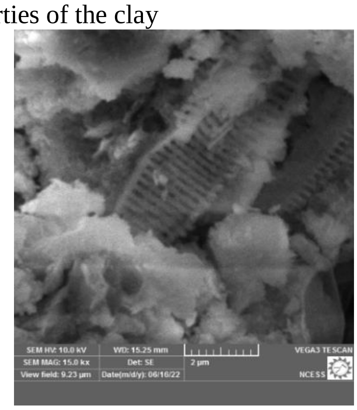


Fig. 1. SEM images of Kuttanad soil showing diatom frustules

Pore Fluid
Sodium hydroxide is used as pore fluid in the present study. It is an inorganic compound with the chemical formula NaOH. In this study, tap water along with the solution of sodium hydroxide (NaOH) of 1N and 4N concentrations with varying percentages (2.5%, 5%,10% by weight of the soil) were used as pore fluid. Sodium hydroxide solutions of concentrations 1 N and 4 N were prepared by dissolving required molecular weights, 40 g and 160 g of analytical grade sodium hydroxide flakes in water respectively, to make 1 litre of solution.

3 Experiments

Laboratory contamination
Soils were oven dried and mixed with sodium hydroxide solution in different percentages, 2.5%, 5%, and 10% by weight of soil sample at different concentrations of 1N and 4N. This mixture of soil and alkali solution is then transferred to the polythene bags to allow alkali to react with the soil for a short period of 3 days. After 3 days the tests were performed on alkali-treated soils.

Test conducted
Experiments were conducted to determine the variation in index properties, swelling behavior, and strength characteristics.

Atterberg's limits
To understand the plasticity characteristics Atterberg's limits were determined according to IS 2720 (part V) 1985 and the shrinkage limit was determined as per IS 2720 (PART VI) 1972.

Specific gravity
The specific gravity of uncontaminated and contaminated soil samples is determined as per IS 2720 (Part III) 1976.

Free swell
The free swell is the sediment volume per gram of soil in pore fluids and is determined by using the method of [2]. In a 100 ml standardized graduated cylinder, 10 g of oven-dried sample was submerged in 40 ml of distilled water. After stirring and being allowed to equilibrate for 24 hrs, the sample is made up to 100 ml. It is left covered for another 24 hrs. The sample particles are left to settle down and the volume on settling is noted. The free swell index is expressed in cc/g.

One dimensional free swell Test
To study the swelling behavior of clayey soil in the vertical direction of a confined specimen during alkali interaction, a consolidation test needs to be conducted according to [1,3]. The soil is inundated with 1 N and 4 N of NaOH aqueous solutions as pore fluid and allowed to swell fully under a seating load of 0.05 kg/cm^2. For reference, soil specimens are also to be tested using distilled water as a pore fluid. The swell displacement readings need to be measured using dial gauges until no significant changes in displacements are observed. The swell displacements along with the original height of the specimen were used to calculate the percentage swell in the vertical direction.

Compaction tests
The compaction characteristics of uncontaminated and contaminated soils are determined as per IS: 2720 (Part VII) – 1980.

Unconfined Compressive Strength Tests
Unconfined Compressive Strength tests need to be conducted as per IS: 2720 (part 10)-1973 and load-deformation behavior of Kuttanad soil and Thonnakkal kaolinite clay at different concentrations of sodium hydroxide are studied.

SEM analysis
To study the morphological variation due to alkali interaction, a Scanning Electron Microscopy was conducted.

4 Results and Discussions

4.1 Variation in Atterberg's Limit

Thonnakkal clay when contaminated with different concentrations of alkali shows an increase in the liquid limit and plastic limit when compared to water. When the pH

increases, the negative charges on clay particles increase and the increased electrolyte concentration increases the diffuse double layer. Thonnakkal kaolinite clay is predominant in kaolinite clay which has a low cation exchange capacity, therefore the effects of the double layer are considered to have a very low effect and the changes are particularly due to the formation of new compounds. NaOH solutions contain Na+ ions which are smaller in size and enhance the dissolution process of alumina-silicate minerals present in the soil. The increased liquid limit and plastic limit results in an increased plasticity index. Fig.2 shows the variation in Atterberg's limit in both soils.
The unique morphology of Kuttanad soil is destroyed when contaminated with sodium hydroxide which results in decreasing liquid limit and plastic limits values. The diatom frustules are no longer available to provide high porous and water-holding nature.

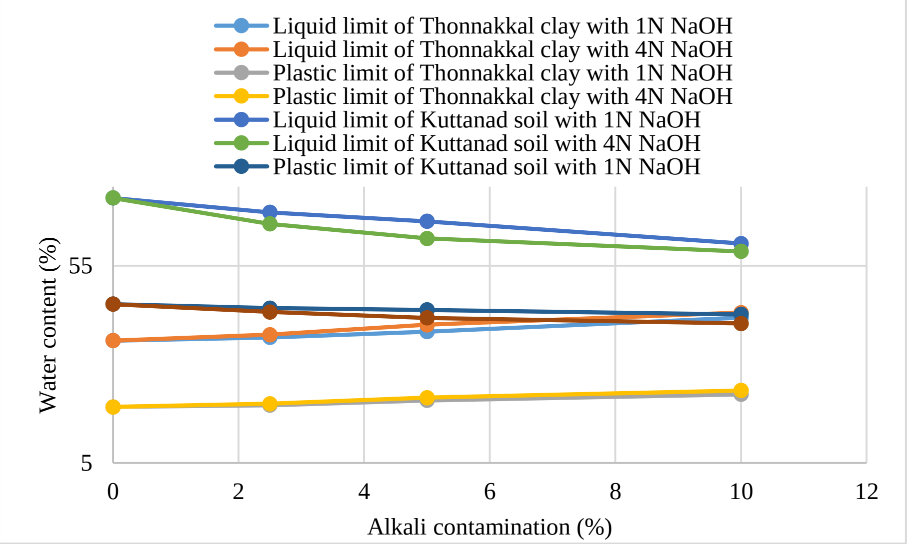


Fig. 2. Atterberg's limits of Thonnakkal clay and Kuttanad soil

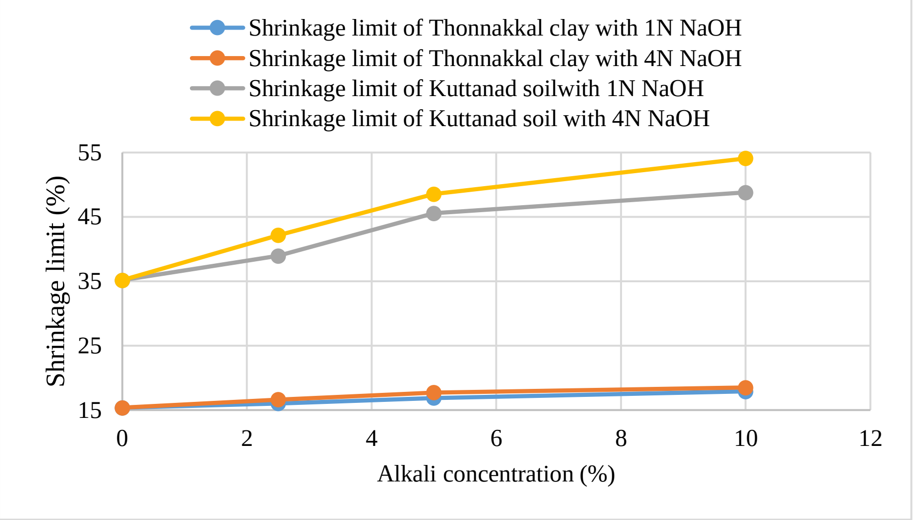


Fig. 3. Shrinkage limits of Thonnakkal clay and Kuttanad soil

A higher Liquid limit and higher shrinkage limit usually point to the formation of a well-graded system after the reaction with sodium hydroxide solution in the case of Thonnakkal clay. The increase in Shrinkage limit may also be attributed to the decrease in double layer due to alkali interaction and the destruction of features present in the Kuttanad soil. Fig. 3. shows the variation of Thonnakkal clay and Kuttanad soil

4.2 Variation in Specific gravity

Specific gravity is actually a characteristic of soil material that depends on its chemical composition. Any change in the values of specific gravity mostly indicates the change in the chemical composition in soils, which is likely to have occurred during the pore fluid interaction [4]. Specific gravity decreases with an increase in alkali concentration in both soils as in fig. 4.

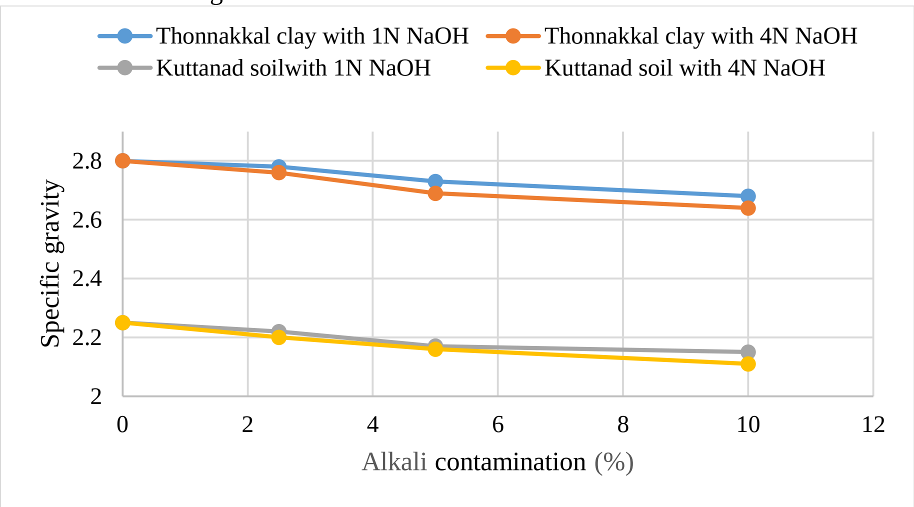


Fig. 4. Shrinkage limits of Thonnakkal clay and Kuttanad soil

4.3 Variation in Free swell

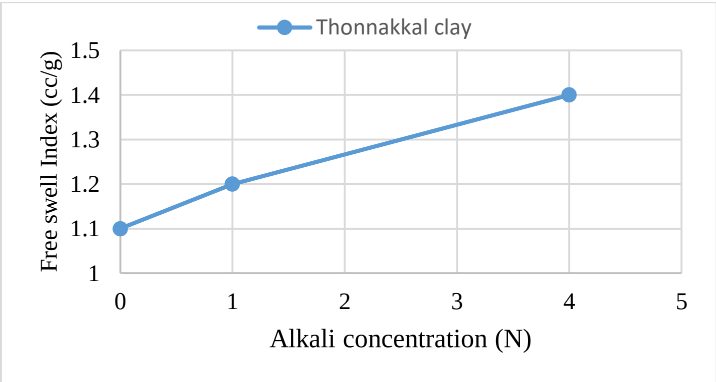


Fig. 5. Variation in Free Swell Index in Thonnakkal clay

A free swell test according to [2] was conducted for Kuttanad soil and reported non-swelling nature. The free swell volume of Thonnakkal clay increases due to the interaction of alkali and it increased with an increase in concentration as shown in fig.5. Even though these test are widely used, it is not a reliable test to indicate swelling characteristics. Therefore, tests were done according to [3].

4.4 Variation in Free swell

Thonnakkal clay reported maximum swelling of 12.5% when inundated with 4 N alkali solution and no swell when inundated with water. The mechanism of swelling in kaolinitic clay under alkaline solutions is explained as follows. Fig. 6. shows the variation in swelling behavior. The first one is due to dispersion of structure due to changes in the charge on the edges of the clay particles and the second one is explained on the basis of new compounds formed due to alkali interaction. The charges on the surface of clay become increasingly negative due to the adsorption of hydroxyl (OH^-) ions in NaOH which leads to dispersion of clay minerals which is evident from the SEM analysis, thus increasing swelling. Severe weathering was observed in the micrographs in the presence of sodium hydroxide solution when compared to the original particles. In Thonnakkal clay swelling occurs in the second stage due to the interaction of alkali with clay. No swelling is observed for about 15 days for 4 N NaOH and 21 days for 1N NaOH. This may be the period required for the changes to occur in Thonnakkal clay due to the alkali solution. The swelling for 1N alkali solution is very low compared to that for 4N NaOH solution. It was also observed that the delay period decreased with an increase in alkali concentration.

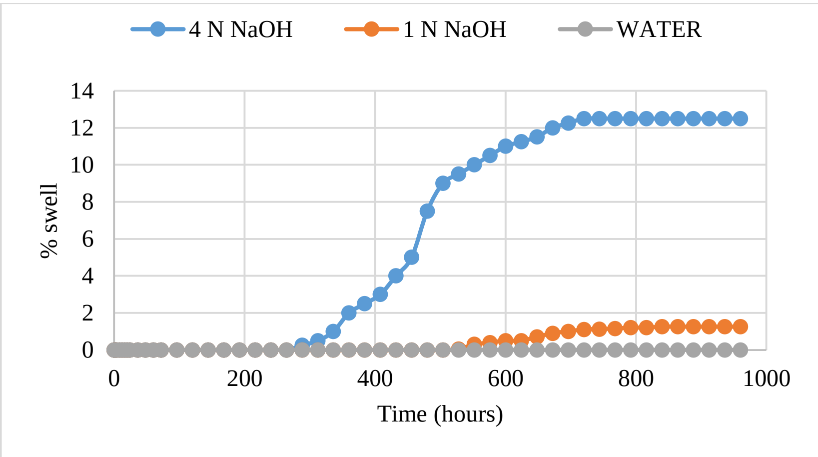


Fig. 6. Swelling variation in Thonnakkal clay

4.5 Variation in compaction characteristics

The maximum dry density of Thonnakkal clay decreases as in fig. It is the shear resistance at the particle behavior that affects the compactive effort which results in behavioral changes in the soil. The well-adsorbed layer of water developed around soil particles effectively resists the compactive effort, thus the particles do not come any closer which results in the reduction of density which was achieved by the adsorption of the OH^- ions on the clay minerals. In the case of Kuttanad soil, the decreased presence of organic content as evident from the SEM images has caused the particles to come closer which assists the compactive effort leading to increased density.

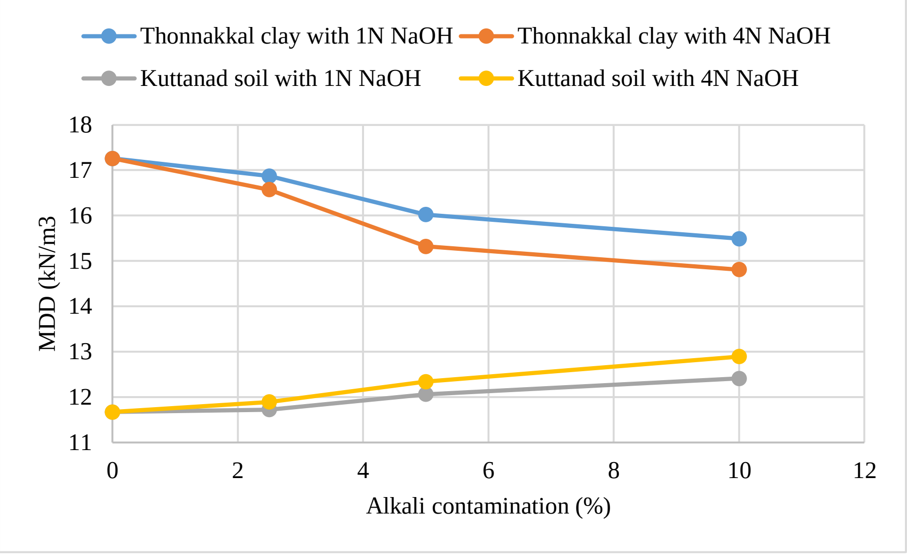


Fig. 7. Variation in Maximum dry density

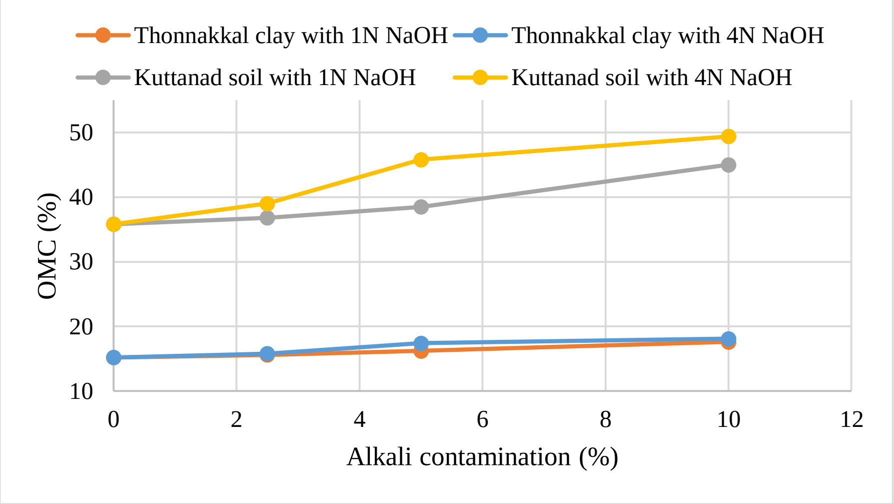


Fig. 8. Variation in Optimum moisture content

Optimum moisture content increases for Thonnakkal clay as shown in fig. 8. This is due to the increased dispersion of clay particles leading to increased water holding capacity of the soil. From the SEM results, it was evident that the particles get dispersed by the alkali interaction. For Kuttanad soil even though the presence of organic content is reduced, OMC still showed an increasing trend. This may be attributed to the increased affinity for water due to the increase in electrolyte concentration in the pore fluid

4.6 Variation in unconfined compressive strength

It plays a vital role in making many engineering decisions for any soil. Usually, liquid limit values can be well correlated with strength properties. But in the presence of alkali solutions, the variations in liquid limit are not to the extent of morphological changes. Therefore, direct prediction of strength properties on the basis of liquid limits may be inaccurate. The unconfined compressive strength increases due to alkali contamination as in fig. 9. The alkali contamination provides more shear and cohesion to bind the particles which results in the rise of strength due to the occupancy of disintegrated particles into pore spaces which makes it a well-graded system.

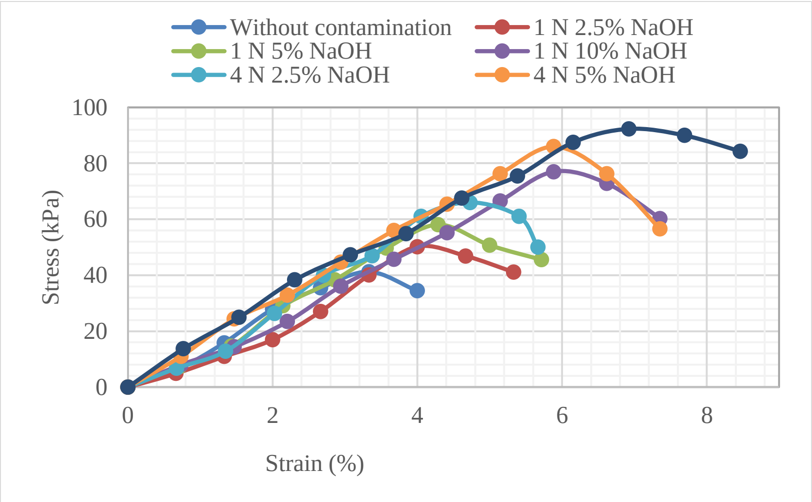


Fig. 9. Stress-strain graph for different concentrations of alkali contamination Thonnakkal clay

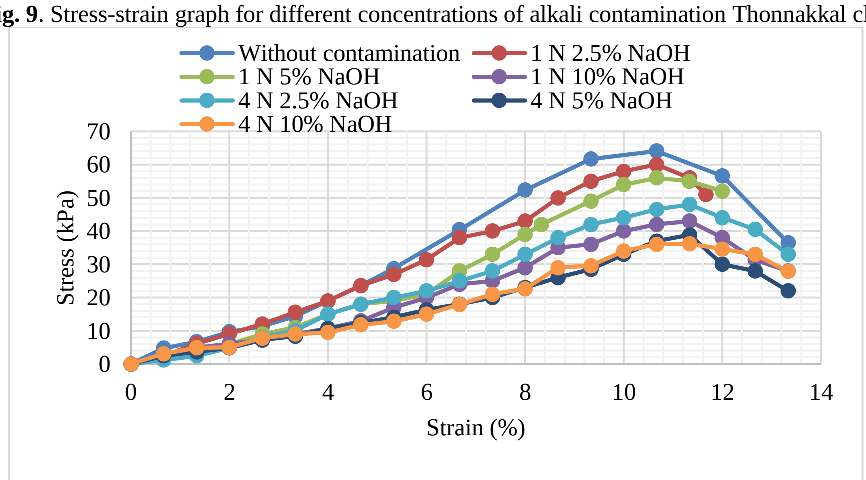
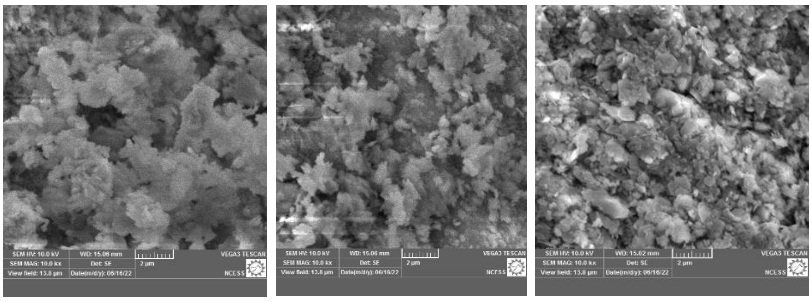


Fig. 10. Stress-strain graph for different concentrations of alkali contamination Kuttanad soil

There observed a disappearance of unique features from the soil making the surface of the particle smooth and fine compared to that of uncontaminated soil. The diatom frustules have eroded away in an alkaline environment. The disappearance of its unique features and smoothing of the surface of particles leads to a reduction in the shear strength of the clay. Fig.10 shows the stress-strain graph for uncontaminated and contaminated Kuttanad soil.

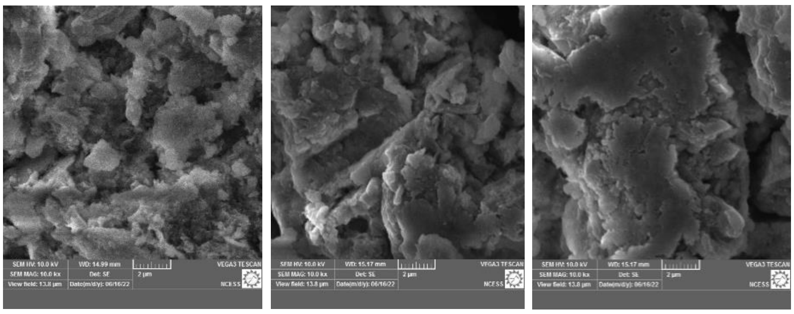
4.6 Effect of alkali on microstructural variation

SEM images shown in this section are selected from numerous images. To study the microstructural difference in an alkaline environment 3 soil samples (sample A: uncontaminated, sample B: samples contaminated with 10 % 4 N NaOH and sample C: sample contaminated with 4 N NaOH after the one-dimensional free swell test were used.
The microstructural behavior of alkali-contaminated Thonnakkal clay is presented in Fig. 10. From the SEM images, it was clearly evident that there occurred weathering of clay due to alkali contamination, the usual microstructure of clay is altered and it is observed that the soil particles get dispersed in the presence of 4 N sodium hydroxide alkali solution. The dispersed nature is due to the weathering action of clay particles to finer particles. The extent of weathering is very severe in this sample due to the prolonged contamination period of higher concentrated alkali solution. The cause for the morphological changes may be due to the formation of new compounds which significantly affect the properties of Thonnakkal clay.



(a) **(b)** **(c)**

Fig. 10. SEM images of Thonnakkal clay (a) Sample A (b) Sample B (c) Sample C



(a) **(b)** **(c)**

Fig. 11. SEM images of Kuttanad soil (a) Sample A (b) Sample B (c) Sample C

when the samples were contaminated with sodium hydroxide all the morphological features were lost (Fig.11). Thus affecting various properties of Kuttanad soil when contaminated with alkali solutions. Very little or no presence of diatom frustules was noticed upon contamination with sodium hydroxide. The surface appeared to be smoother than the uncontaminated soil sample. The features that provide the unique nature of soil are lost in an alkaline environment. The SEM images are in good relation with the property changes that occurred due to the alkali contamination.

5 Conclusions

An experimental study is conducted to know the effect of alkali contamination on Thonnakkal clay and Kuttanad soil. The following are the conclusions derived from the present study.

- With an increase in the concentration of NaOH liquid limit and plastic limit increases but, shrinkage limit and specific gravity decreased for Thonnakkal clay
- For Kuttanad soil liquid limit and plastic limit decrease with an increase in alkali concentration whereas shrinkage limit and specific gravity increased
- Thonnakkal clay showed maximum swelling when inundated with 4N NaOH with a percentage swell of 12.5%. the swelling was reported after a period of 15 days.
- When NaOH concentration increased, UCS increases for Thonnakkal clay and decreased for Kuttanad soil
- The weathering of soil particles which leads to the dispersed nature due to alkali contamination is observed in Thonnakkal clay. In Kuttanad soil, all the morphological features present were disappeared

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