Experimental study of the effect of alkali contamination on geo-mechanical properties of the soil

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Abstract. As a civil engineer, we all are quite aware that the soils expansive in nature are not at all suitable as a material for foundation engineering purposes. Due to this very nature, geotechnical failures in expansive soil have been observed at various sites. Seasonal variations are responsible for swelling and shrinking that causes large volume changes in the expansive soil. Similar effects are also shown by the interaction of non-expansive soil with industrial sewage or effluent. It is a fact that engineering behavior of soil can be changed with the interaction of alkali. Alkali base solutions are discharged into the soil mass from differs industries, for example, paint and dyeing, paper manufacturing ventures, cotton factories and aluminum factories, etc. In this paper, an attempt has been made to investigate the effect of alkali interaction on engineering behavior of soil. For this, the samples of normal soil and contaminated soil were collected from Hindalco Industries Ltd., Renukoot (U.P.). The contamination was due to caustic liquor. The mechanical properties of normal soil and contaminated soil samples were investigated in laboratory by performing various geo-mechanical tests like specific gravity, grain size distribution, Atterberg’s limit, compaction characteristic, permeability, free swelling index, swelling pressure, shear strength parameter and consolidation characteristic.

Keywords: Alkali interaction, Geo-mechanical properties, geotechnical properties, caustic liquor.

1. Introduction
Behavior of granular soil is generally controlled by texture and relative density and behavior of clay soils is controlled by mineral type (mineralogy), fabric (micromorphology), chemistry, plasticity and stress history. Properties of soils get significantly altered by Soil–pollutant interactions. The extent of change in geotechnical properties of foundation soil depends not only on the nature and concentration of the pollutants, but also on mineral structure, such as particle size, bonding characteristics between particles, ion exchange capacity, and specific surface. The smaller the soil particle, the higher is the probability for a soil particle to interact with the environment [1]. Soil degradation is a problem of concern worldwide. Historically, it has been thought that the ground was a kind of sink with no limit to the release of waste product from human activity. These wastes are often acidic or alkaline in nature and are usually aggressive to soil which erode the appearance of soil and caused adverse environmental impact, sometimes involving serious risks like groundwater contamination, irreversible
ecosystem modifications or even total destruction. Mineral dissolution and precipitation may occur in clay minerals on the contact of highly alkaline solutions. The impact of alkaline solution on the change of clay earth minerals has been the subject of numerous investigations. As of late, as indicated by the particular service conditions, the mechanical property and degradation rule of various soils bit by bit become research hotspot in the ecological geotechnology. For example red mud which is a by product from the aluminum refinery industry has a high pH in the range of 11 – 13 could results in alkali soil when industrial waste mixed with soil. Soil has its importance not just because it acts as a bearing surface for the footings; it also serves as one of the most important ingredient in cement mortar, cement concrete and geopolymer mortar and concrete.

Hindalco Industries limited at Renukoot operates Bauxite mining, alumina refining etc. Bauxite ore is processed through Bayer’s process and is digested by washing it with highly concentrated caustic liquor (NaOH) at 175°C under pressure. Due to the accidental event or unknown contamination spills at the site, hydroxides seep into the ground and are causing contamination of soil and considerably affecting the soil behavior like heaving of ground below the structure, formation of crack in pavement, change in level of railway tracks.

2. Materials And Methods
Normal soil (US) and alkali contaminated soil (CS) were taken from the Hindalco Industries Ltd. at Renukoot (U.P.). These soils are collected from a depth of 0.5 m to 1.0 m below the ground level near the railway track area. The investigation report includes the geo-mechanical properties of normal soil and alkali contaminated soil namely specific gravity, grain size distribution, Atterberg’s limit, compaction characteristic, permeability, free swelling index, swelling pressure, shear strength parameter and consolidation characteristic. [11]

3. Results And Discussion
Specific gravity, atterberg’s limit, compaction characteristics, coefficient of permeability, differential free swell index and swelling pressure, shear strength parameters and consolidation test were performed on normal soil and alkali contaminated soil. Result for each test have been discussed below in detail and the geo-mechanical properties investigated are tabulated in Table 1.

3.1. Specific Gravity
The specific gravity of soil has been obtained by conducting laboratory tests based on the method prescribed in (IS-2720-PART-3-1980). The specific gravity of soil solids is essential in calculating the phase relationships of soils, such as void ratio and degree of saturation. It is also used while calculating the density of the soil solids. The term soil solids are typically assumed to mean naturally occurring mineral particles or soil like particles that are not readily soluble in water. Therefore, the specific gravity of soil solids containing extraneous matter, such as cement, lime, and the like, water-soluble matter, such as sodium chloride, and soils containing matter with a specific gravity less than one, typically require special treatment or a qualified definition of their specific gravity. In our case, specific gravity of alkali-contaminated soil is higher than normal soil which is due to some mineralogical alteration on alkali interaction.

3.2. Atterberg’s limit
Atterberg’s limits are very important in terms of soil classification. Atterberg’s limits or consistency limits plays and important role in classifying soil on the basis of its behavior under varying moisture content. Practices mentioned in IS-2720-part-5 and IS-2720-part-6 has been followed to determine liquid limit, plastic limit and shrinkage limit of both alkaline and normal soils. The liquid limit, plastic limit, shrinkage limit of normal soil is shown in Table 1, and flow curve is shown in Figure 1. In case of alkali-contaminated soil it was not possible to cut the sample during liquid limit test and it followed non-plastic behavior.
3.3. Compaction Characteristics

The graph for standard compaction test is shown in Figure 2 and Figure 3 and maximum dry density (MDD) and corresponding optimum moisture content (OMC) is shown in Table 1. The MDD and OMC values in case of alkali-contaminated soil are indicating the high moisture absorbing capacity though the soil becomes non-plastic in nature. This might be possible because of water absorbing compounds formed in soil due to alkali interaction.

Table 1. Geo-mechanical Properties of Normal Soil and Contaminated Soil.

| S. No. | Geo-mechanical properties   | Value | Value |
|--------|-----------------------------|-------|-------|
|        |                             | US    | CS    |
| 1.     | Specific Gravity            | 2.41  | 3.04  |
| 2.     | Clay (%)                    | 2     | 0.9   |
| 3.     | Silt (%)                    | 9.24  | 6.4   |
| 4.     | Sand (%)                    | 88.76 | 92.7  |
| 5.     | Cu                          | 33.33 | 4.074 |
| 6.     | Cc                          | 2.28  | 0.957 |
| 7.     | Classification(as per IS)   | SW-ML | SP-ML |
| 8.     | Liquid Limit (%)            | 32.0  | --    |
| 9.     | Plastic Limit (%)           | 30.50 | --    |
| 10.    | Plasticity Index (%)        | 1.50  | --    |
| 11.    | MDD (g/cc)                  | 1.83  | 1.84  |
| 12.    | OMC (%)                     | 11.50 | 13.50 |
| 13.    | Permeability (cm/sec)       | 1.8 X 10^{-7} | 4.6 X 10^{-5} |
| 14.    | Free Swell Index (%)        | 5.00  | 0     |
| 15.    | Swelling Pressure (kg/cm²)  | 0.1   | 0.12  |
| 16.    | Cohesion (kg/cm³)           | 0.27  | 0.48  |
| 17.    | ϕ (degree)                  | 22.490 | 21.20 |
| 18.    | Compression Index (CC)      | 0.0498 | 0.0432 |

Figure 1. Flow Curve for Normal Soil by Casagrande Method.
3.4. Coefficient of Permeability
Permeability is one of the most significant engineering properties of the soil that is an answer for a various engineering issues encountered in construction. Some of them are: seepage below the earth structures, settlement of foundation and buildings, seepage through the earth structures, the yield of the wells, control of Hydraulic Stability of masses, for designing filter in hydraulic structures in order to prevent piping.

For obtaining coefficient of permeability IS-2720-part-17-1986 has been followed. The coefficient of permeability of normal soil and alkali-contaminated soil are $1.8 \times 10^{-7}$ cm/sec and $4.6 \times 10^{-5}$ cm/sec respectively. It is evident from here that contamination of alkali’s with soil render its permeability from impervious state to pervious state.

3.5. Differential Free Swell Index and Swelling Pressure
The differential free swelling index and swelling pressure of soil samples are shown in Table 1. The differential free swelling index was found to be 5% and 0% for normal soil and alkali contaminated soil respectively. From the results of swelling pressure test it can be informed that the soil does not possess any rich clay mineral clay mineral. The caustic liquor interaction for short duration could not be able to make the soil expansive, but for longer period of interaction the same has exhibited increased expansive behavior. [3] The expansive behavior of the normal soil can be explained as alkali-silica reaction due to interaction of reactive silica with caustic liquor as swelling pressure of normal soil inundated in caustic liquor for 28 days is 0.20 kg/cm$^2$. 

![Figure 2. Compaction Curve for Normal Soil (US).](image-url)
Figure 3. Compaction Curve for Alkali-Contaminated Soil (CS).

3.6. Shear Strength Parameters
The Mohr’s circle of the soil samples are shown in Figure 4 and Figure 5 and summary of shear strength parameters ($c$ and $\phi$) are described in Table 2 and Table 3. It was observed that cohesion value of contaminated soil was high compared to normal soil. The angle of internal friction values have shown decreasing trend. All the soil samples have exhibited Strain-hardening behavior for the applied cell pressures during the test.

Table 2. Tri-Axial Test for Normal Soil (US).

| Test No. | $\sigma_3$ (kg/cm$^2$) | $\sigma_d$ (kg/cm$^2$) | $\sigma_1$ (kg/cm$^2$) | $\sigma_1/\sigma_3$ |
|----------|---------------------|---------------------|---------------------|-----------------|
| 1.       | 0.5                 | 1.42                | 1.94                | 3.88            |
| 2.       | 1                   | 2.06                | 3.06                | 3.06            |
| 3.       | 1.5                 | 2.67                | 4.17                | 2.78            |

Figure 4. Failure Envelope for Normal Soil (US) $C = 0.27$ kg/cm$^2$ & $\phi = 22.490$.

Table 3. Tri-Axial Test for Alkali-Contaminated Soil (CS).

| Test No. | $\sigma_3$ (kg/cm$^2$) | $\sigma_d$ (kg/cm$^2$) | $\sigma_1$ (kg/cm$^2$) | $\sigma_1/\sigma_3$ |
|----------|---------------------|---------------------|---------------------|-----------------|
| 1.       | 0.5                 | 1.96                | 2.46                | 4.92            |
| 2.       | 1                   | 2.53                | 3.53                | 3.53            |
| 3.       | 1.5                 | 2.82                | 4.32                | 2.88            |
Figure 5. Failure Envelope for Alkali-Contaminated Soil (CS) $C = 0.48 \text{ kg/cm}^2$ & $\phi = 21.20$.

3.7. Consolidation Test

One-dimensional consolidation test was performed for both normal and alkali-contaminated soil samples inundating in water and caustic liquor. Soil was compacted at maximum dry density and optimum moisture content. [12] All the samples were loaded to 8 kg/cm$^2$, with a standard load increment of two, and unloaded to 0.05 kg/cm$^2$. The variation of void ratio ($e$) vs Pressure ($\log \sigma'$) graphs are drawn and shown in Figure 6 to Figure 9. The compression index ($Cc$) of US and CS samples inundated in water are calculated as 0.0498 and 0.0432 respectively, while the compression index of US and CS samples inundated in caustic liquor are observed as 0.0631 and 0.1163 respectively. It was observed that the compression index of US is greater than CS when inundated in water. For the samples inundated in caustic liquor, compression index of US is smaller than CS. From Table 4 compression index and pre-consolidation stress of all soil samples it could be referred that the highest $Cc$ value has been identified as contaminated soil inundated in caustic liquor and lowest value in water.

| S. No. | Soil Samples                  | Compression Index Cc | Induced Pre-consolidation Stress (kg/cm$^2$) |
|-------|-------------------------------|----------------------|-----------------------------------------------|
| 1.    | US inundated in water         | 0.0498               | 1.3                                           |
| 2.    | CS inundated in water         | 0.0432               | 1.8                                           |
| 3.    | US inundated in caustic soda  | 0.0631               | 3.3                                           |
| 4.    | CS inundated in caustic soda  | 0.1163               | 4.0                                           |
Figure 6. Comparison between Compression Curves of Normal Soil Inundated in Water and Caustic Liquor.

Figure 7. Comparison between Compression Curves of Contaminated Soil Inundated in Water and Caustic Liquor.

The comparative graph of normal and contaminated soil inundated in water and caustic liquor have been presented in Figure 8 & Figure 9 respectively. The method to determine pre-consolidation stress has been proposed by Casagrande. In general, pre-consolidation stress indicates the stress history of soil. Cementation or binding of particles does also induce similar changes to \( e \)-log \( \sigma' \) plot in which case it is termed as apparent pre-consolidation pressure.[12] Hence pre-consolidation shall not arise from stress history but due to binding or cementing action of alkali or the reaction compounds formed due to physio-chemical interactions of alkali and soil pre-consolidation stresses have occurred. The pre-consolidation stress for US and CS inundated in water are 1.3 kg/cm\(^2\) and 1.8 kg/cm\(^2\) respectively while the pre-consolidation stress for US and CS inundated in caustic soda are 3.3 kg/cm\(^2\) and 4.0 kg/cm\(^2\) respectively. In samples inundated in caustic soda, the pre-consolidation pressures were found very high as compared to the samples inundated in water. This might be the reason for exhibiting the expansive behavior of alkali-contaminated soils.[13]
Figure 8. Comparison among Compression Curves of Soil Samples Inundated in Water.

Figure 9. Comparison among Compression Curves of Soil Samples Inundated in Caustic Liquor.

4. Conclusion
- The soil as a material has significant effect of alkali contamination on it and the major changes in geo-mechanical properties of contaminated soil are due to alkali-soil interaction. Due to alkali contamination the soil classification has changed from plastic to non-plastic type. [14]
- The specific gravity (G) value of contaminated soils had also changed. The specific gravity (G) value found high in case of contaminated soil it might be due to the formation of some compounds due to alkali-soil interaction.
- The permeability characteristic of contaminated soils is greatly affected. The normal soil which is impervious now is changed to pervious one due to alkali-soil interaction.
- The compaction characteristics have also been affected due to alkali contamination. The OMC value of contaminated soil found to be high in comparison to normal soil.
- The shear strength parameters (c, $\phi$) got increased in case of contaminated soil unlike normal soil.
- From the results of one dimensional-consolidation tests conducted on soil samples it can be concluded that the caustic liquor interaction caused more expansive behavior in comparison to water.
- The swelling pressure tests on both normal and contaminated soils inundated with water and caustic liquor gave an idea on expansive behavior of the soils. The normal soil inundated in caustic liquor had shown more expansive behavior after 28 days interaction.
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