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Research Article

Alkali Interaction

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Alkali Interaction with Expansive and Non Expansive Soils

Neethu John[1*], Mohamed Nihal N[2], Niveditha KS[3], Renil Das[4], Ridhick Prakash J[5]

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[1*] Neethu John, Assistant Professor, Department of Civil Engineering, APJ Abdul Kalam Technological University/Ahalia School of Engineering and Technology, Palakkad, Kerala, India.

[2] Mohamed Nihal N, B.Tech Final Year Student, Department of Civil Engineering, APJ Abdul Kalam Technological University/Ahalia School of Engineering and Technology, Palakkad, Kerala, India.

[3] Niveditha KS, B.Tech Final Year Student, Department of Civil Engineering, APJ Abdul Kalam Technological University/Ahalia School of Engineering and Technology, Palakkad, Kerala, India.

[4] Renil Das, B.Tech Final Year Student, Department of Civil Engineering, APJ Abdul Kalam Technological University/Ahalia School of Engineering and Technology, Palakkad, Kerala, India.

[5] Ridhick Prakash J, B.Tech Final Year Student, Department of Civil Engineering, APJ Abdul Kalam Technological University/Ahalia School of Engineering and Technology, Palakkad, Kerala, India.

This research examines the interaction of alkali contaminants with both expansive and non-expansive soils, specifically black cotton soil and red soil, while assessing the effectiveness of sulphur and gypsum in restoring soil pH for geotechnical stability. Alkaline contamination, commonly caused by industrial effluents, construction activities, and agricultural practices, alters soil behavior by influencing its strength, swelling-shrinkage properties, and overall suitability for construction and infrastructure development. Laboratory experiments are conducted to evaluate the impact of alkalinity on key soil properties, including Atterberg limits, swelling potential, shear strength, permeability, and consolidation characteristics.

Expansive soils, such as black cotton soil, exhibit significant volume changes with moisture fluctuations, whereas non-expansive soils like red soil respond differently to alkali exposure. The presence of alkali contaminants can lead to reduced cohesion, increased dispersibility, and diminished bearing capacity, which pose risks to foundations, pavements, and embankments. This study investigates the potential of sulphur and gypsum as chemical stabilizers to counteract the negative effects of alkalinity. Controlled soil treatment trials are conducted to systematically assess variations in soil pH, structural integrity, and overall engineering performance.

The results offer valuable insights into the geotechnical consequences of alkaline contamination and the effectiveness of remediation techniques in stabilizing affected soils. By addressing the challenges posed by contaminated soils in civil engineering applications, this research contributes to sustainable ground improvement strategies, enhancing the durability and safety of infrastructure projects in impacted areas.

Keywords: alkali, soil, properties

Corresponding Author

Neethu John, Assistant Professor, Department of Civil Engineering, APJ Abdul Kalam Technological University/Ahalia School of Engineering and Technology, Palakkad, Kerala, India.
Email: neethu.john@ahalia.ac.in

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1. Introduction

Alkali Contaminants

Alkali contaminants significantly impact soil chemistry and physical properties, often posing challenges in construction, agriculture, and environmental management. Among these, calcium carbonate is particularly influential, especially in areas affected by industrial activities, agricultural amendments, or natural limestone deposits. Its presence affects soil stability, water retention, and nutrient availability, making it a key factor in geotechnical and environmental studies.

When exposed to moisture and varying pH levels, calcium carbonate interacts with soil minerals through dissolution and precipitation. In acidic conditions, it dissolves, releasing calcium and carbonate ions that influence soil aggregation and permeability. Conversely, in alkaline or arid environments, it tends to accumulate, forming hard layers that affect drainage and compaction. These processes are further influenced by external factors such as carbon dioxide levels, groundwater movement, and the presence of other dissolved salts.

In expansive soils, calcium ions from calcium carbonate can replace sodium ions, reducing swelling potential and increasing soil stiffness. While this can help stabilize problematic soils, it may also lead to increased brittleness under certain conditions. In non-expansive soils like sandy or silty deposits, excessive accumulation can cause cementation, reducing porosity and altering load-bearing capacity.

A thorough understanding of these interactions is crucial for effectively managing soil contamination and developing suitable construction or remediation strategies.

Effects of Alkali Contaminants in Soil

Alkaline contaminants significantly influence soil geotechnical properties, directly affecting civil engineering applications such as foundation stability, pavement performance, and soil improvement techniques. The accumulation of alkaline substances raises soil pH, altering both its chemical composition and mechanical behavior.

In expansive soils, the presence of alkaline compounds, particularly calcium carbonate, triggers ion exchange reactions where calcium ions replace sodium ions in the clay structure. This increases swelling potential while reducing stiffness and load-bearing capacity, making the soil less suitable for construction. Excessive alkalinity can also lead to brittle soil behavior, increasing susceptibility to cracking under mechanical stress, which poses risks to structures. Additionally, alkaline contamination can cause clay particles to flocculate and aggregate, affecting compaction and permeability. While lime stabilization is commonly used to improve soil properties, uncontrolled exposure to lime or other alkaline materials can lead to unpredictable soil behavior, necessitating careful evaluation before implementing stabilization techniques.

In non-expansive soils, such as sandy or silty deposits, alkali contamination primarily induces cementation, where dissolved calcium carbonate precipitates and binds soil particles together. This process can form hardpan or calcrete layers, significantly reducing permeability and flexibility. Cemented soil tends to become brittle, leading to cracks that compromise the integrity of foundations, road subgrades, and retaining structures. On construction sites, concrete residues, lime-based materials, and industrial waste can contribute to soil alkalinity, requiring chemical treatment to restore proper soil conditions.

Furthermore, groundwater with high bicarbonate and carbonate concentrations can cause natural alkalization, particularly in arid and semi-arid regions where high evaporation rates lead to the accumulation of dissolved salts in the upper soil layers. This phenomenon presents long-term geotechnical challenges, necessitating mitigation measures such as controlled drainage, acid treatment, or alternative foundation designs.

Understanding how alkaline contaminants affect both expansive and non-expansive soils is essential for maintaining structural stability, optimizing construction practices, and preventing long-term soil degradation in civil engineering projects.

Sources of Alkali Contamination

Alkaline contaminants in soil originate from various sources, primarily industrial, agricultural, and construction activities, all of which contribute to increased pH levels and altered geotechnical properties.

One major source is industrial waste, where processes like cement manufacturing, lime production, mining, and chemical processing release alkaline byproducts into the environment. These byproducts, rich in calcium, sodium, and potassium compounds, can leach into the soil, causing long-term alkalization. Additionally, materials like fly ash and slag from power plants, which contain high concentrations of calcium oxide and other alkaline minerals, contribute to contamination—especially in areas where industrial waste is used as landfill material or for soil stabilization.

Agricultural practices also play a significant role in increasing soil alkalinity. The excessive application of lime, potash, and certain fertilizers leads to the accumulation of alkaline compounds in the soil. While farmers use calcium carbonate or lime to neutralize soil acidity and enhance crop yields, overuse can cause unintended alkalization, altering soil structure and nutrient availability. Furthermore, irrigation with groundwater containing high levels of dissolved bicarbonates and carbonates can gradually increase soil pH, particularly in arid and semi-arid regions where high evaporation rates promote salt accumulation on the soil surface.

Construction activities introduce substantial alkaline contaminants into the soil, particularly in urban and infrastructure projects. Cement-based materials, concrete residues, and lime-treated soils contribute high amounts of calcium hydroxide and other alkaline compounds to the surrounding environment. During excavation, construction debris often mixes with native soil, altering its pH, stability, and permeability. Additionally, lime stabilization, commonly used in road construction and foundation improvement, can lead to excessive alkalization if not properly controlled, affecting soil strength and flexibility. Land reclamation projects that involve dredged materials or construction waste can also introduce alkaline substances, further disrupting the soil's natural pH balance.

Apart from human activities, natural sources also contribute to soil alkalization. These include the weathering of carbonate-rich parent rocks, groundwater movement carrying dissolved alkaline minerals, and wind-blown dust from arid regions. In coastal and desert areas, alkaline salts from seawater spray or dry sediments can accumulate in the soil, naturally increasing pH levels.

Understanding these contamination sources is essential for developing effective strategies to control soil alkalization, mitigate its impact on civil engineering structures, and ensure long-term soil stability for both construction and agricultural applications.

2. Objectives

The primary aim of this study is to examine the interaction of alkalis with both expansive and non-expansive soils, specifically focusing on black cotton soil and red soil. The research explores how calcium carbonate ($CaCO_3$) contamination influences various soil properties, including pH, permeability, plasticity, swelling behavior, and strength characteristics. Black cotton soil, known for its high expansiveness due to montmorillonite content, undergoes substantial volume changes when exposed to moisture variations, causing instability in construction applications. In contrast, red soil, being non-expansive, responds differently to alkali contamination, particularly in terms of permeability and compaction. Understanding these effects is essential for developing effective stabilization techniques for soils affected by alkali contamination.

A significant aspect of this study involves evaluating the effectiveness of sulfur in reducing soil alkalinity and dissolving excess carbonate deposits formed due to $CaCO_3$ contamination. Elevated alkalinity often results in undesirable cementation, which diminishes soil workability and structural integrity. Sulfur, as an acidifying agent, is anticipated to counter these effects, enhancing overall soil stability. Additionally, the study examines the role of gypsum as a stabilizing agent, offering calcium without contributing to increased alkalinity. The use of gypsum is expected to Improve soil permeability, minimize swelling, and enhance compaction properties. By investigating the combined effects of sulfur and gypsum, the research aims to determine the most efficient stabilization method to mitigate alkali-induced soil degradation.

Furthermore, this study seeks to compare the mechanical properties of treated and untreated soils, analyzing variations in shear strength, compressive strength, and durability following stabilization. The long-term behavior of these stabilized soils is also assessed under different environmental conditions, such as wetting-drying cycles, to ensure the sustainability of the proposed treatment techniques.

Establishing the optimal dosage of sulfur and gypsum is crucial to achieving cost-effective soil stabilization while minimizing environmental impact.

Ultimately, this research aims to contribute to the development of sustainable and practical soil stabilization methods for geotechnical applications, including foundation stabilization, road construction, embankment reinforcement, and land reclamation projects. The findings will offer valuable insights to engineers, researchers, and policymakers, facilitating improvements in soil performance and ensuring long-term structural stability in construction and infrastructure development.

3. Methodology

1. Selection and Collection of Soil Samples

The collection of black cotton soil samples from Eruthempathy Panchayat was conducted with careful consideration of soil distribution and minimal external disturbances. This location was chosen due to its naturally occurring expansive clayey deposits, commonly found in agricultural fields and open lands. Black cotton soil is known for its high swelling and shrinkage properties, making it essential to collect undisturbed samples for accurate analysis.

The red soil samples were collected from Ahalia Campus, where naturally occurring lateritic soils are predominant. This location was selected due to its iron-rich composition and relatively stable soil structure, making it ideal for studying non-expansive soil behaviour in alkali contamination interactions.

2. Testing on normal soil

The initial testing of black cotton soil and red soil established baseline properties before contamination. A pH test measured alkalinity, while water content and specific gravity tests assessed moisture and particle density. Sieve analysis determined particle size distribution, and Atterberg limits evaluated plasticity. Load-bearing capacity was analyzed using the CBR test, while MDD and OMC were obtained from the light compaction test. Permeability, swelling potential (FSI test), and axial strength (UCS test) were also measured. These results served as a reference for assessing contamination and remediation effects.

The contamination process involves introducing Calcium carbonate at a concentration of 150 g/kg into two different soil types-black cotton soil and red soil. This step is carried out to simulate alkali contamination and study its effects on soil properties.

4. Tests on Contaminated Black Cotton Soil

After thoroughly mixing calcium carbonate with the soil, the contaminated samples are left undisturbed for 48 hours to allow proper interaction and chemical stabilization. This period ensures uniform distribution of the contaminant and enables initial reactions that may influence soil structure, pH, and strength characteristics.

5. Soil Remediation using Gypsum and Sulphur

The remediation process aims to restore the properties of black cotton soil and red soil after contamination with calcium carbonate . Two remediation methods are used: gypsum treatment (50 g/kg) and sulphur treatment (50 g/kg), applied separately to evaluate their effectiveness.

6. Testing on Remediated Soil

To assess remediation effectiveness, tests were conducted on treated soil. Index property tests included pH (alkalinity), water content, specific gravity, sieve analysis (particle size), and Atterberg limits (plasticity). Engineering tests covered CBR (load-bearing), light compaction (MDD & OMC), permeability (water flow), FSI (swelling potential), and UCS (strength). These evaluations measured changes in soil properties postremediation.

7. Collection of Black Cotton Soil

The collection of black cotton soil samples from Eruthempathy Panchayat was conducted with careful consideration of soil distribution and minimal external disturbances. This location was chosen due to its naturally occurring expansive clayey deposits, commonly found in agricultural fields and open lands. Black cotton soil is known for its high swelling and shrinkage properties, making it essential to collect undisturbed samples for accurate analysis.

A hoe was used for excavation, and the top 30 cm of soil was removed to eliminate any potential contamination from organic matter or external influences. Each sample was collected in a quantity ensuring sufficient material for laboratory testing.

The collected samples were placed in polythene bags and sealed containers to preserve their moisture content and prevent contamination. The samples were then transported to the laboratory, ensuring that their natural properties remained intact for further analysis.

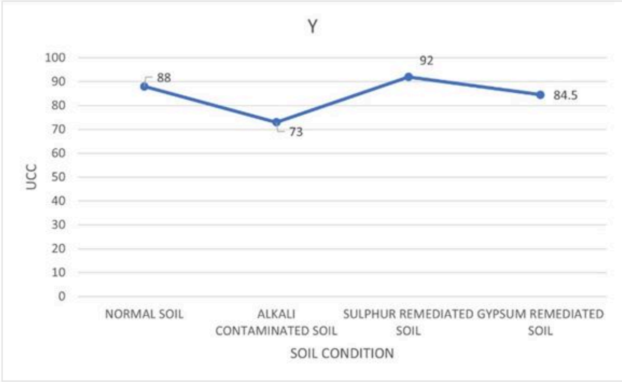
8. Collection of Red Soil

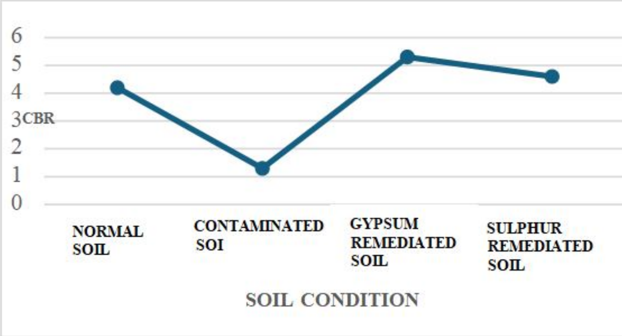
The red soil samples were collected from Ahalia Campus, where naturally occurring lateritic soils are predominant. This location was selected due to its iron-rich composition and relatively stable soil structure, making it ideal for studying non-expansive soil behaviour in alkali contamination interactions.

Similar to the black cotton soil sampling process, samples were collected using a hoe. The top 30 cm was removed to prevent contamination, and sample was gathered in quantities for adequate laboratory analysis. The collected red soil samples were stored in polythene bags to maintain their natural moisture levels and prevent external contamination. Then sample is transported to the laboratory for further geotechnical and chemical analysis.

4. Results and Comparisons of Black Cotton Soil

Test conducted	Normal soil	Contaminated soil	Remedies	
			Gypsum	Sulphur
water content (%)	18.2	12.6	19.9	17.4
specific gravity	2.83	2.24	2.7	2.55
unconfined compressive strength	335 KN/m²	280 KN/m²	342 KN/m²	312 KN/m²
sieve analysis	Cu : 4.1 Cc : 2.2	Cu : 5.9 Cc : 2.5	Cu : 3.6 Cc : 1.9	Cu : 4.4 Cc : 1.7
Atterberg limits: liquid limit	26%	31%	27%	28%
plastic limit	18.50%	16.00%	19.50%	16.00%
shrinkage limit	13%	11.50%	12%	13%
California bearing ratio	4.8	2.6	4.5	3.6
light compaction maximum dry density	1.18	0.96	1.2	1.05
permeability	10.6^-4cm/s	8^-4cm/s	10^-4cm/s	9.5^-4cm/s
pH meter test	7.2	9	7	7.5
free swell index	18%	23%	19%	28%



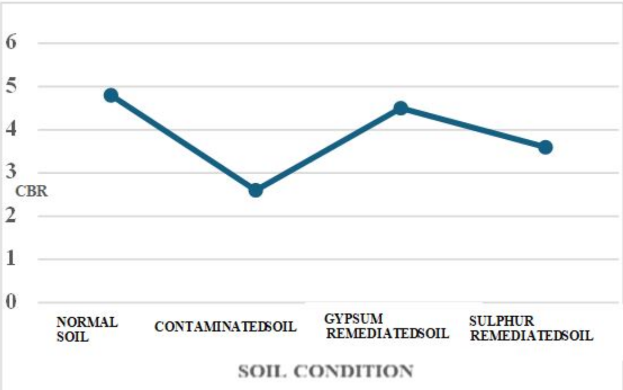


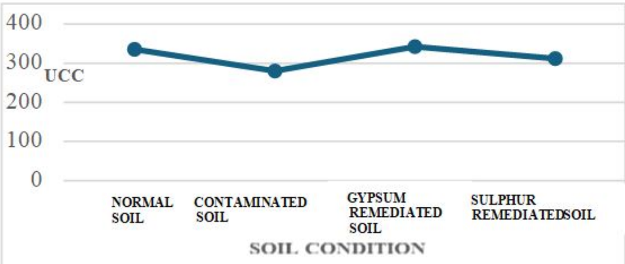
The graphs show that alkali contamination weakens Black Cotton Soil, significantly reducing CBR and UCC due to increased swelling and reduced cohesion. Gypsum remediation effectively stabilizes the soil, improving both parameters by enhancing particle bonding and reducing plasticity. Sulphur also improves soil strength but is slightly less effective than gypsum. This indicates that gypsum is the better stabilizer for mitigating alkali contamination in Black Cotton Soil.

5. Results and Comparison of Red Soil

The CBR and UCC values of red soil show a clear impact of alkali contamination and subsequent remediation. The CBR value significantly drops after contamination, indicating a reduction in soil strength. Gypsum treatment improves the CBR value, suggesting better stabilization, while sulphur treatment shows a slight reduction in improvement. Similarly, UCC strength decreases with contamination, reflecting weaker soil behaviour. Gypsum treatment effectively enhances UCC, whereas sulphur treatment also provides some improvement but remains slightly lower than gypsum. These trends highlight the influence of alkali contamination on soil properties and the effectiveness of remediation techniques in restoring strength.

Test conducted	Normal soil	Contaminated soil	Remedies	
			Gypsum	Sulphur
water content (%)	25.6	21.2	24.1	22.5
specific gravity	2.74	2.14	2.65	2.21
unconfined compressive strength	88 KN/m²	73 KN/m²	92 KN/m²	84 .6 KN/m²
sieve analysis	Cu : 4.5 Cc : 1.2	Cu : 5.2 Cc : 1.8	Cu : 4.0 Cc : 1.4	Cu :3.65 Cc :1.22
Atterberg limits: liquid limit	51	58	48	51
plastic limit	27	23	25	22
shrinkage limit	13.5	11.6	12.7	11.5
California bearing ratio	4.2	3.1	5.3	4.6
light compaction maximum dry density	1.6	1.58	1.63	1.61
permeability	5.4 cm/s X10^-7	3.2cm/sX10^-7	5.1cm/sX 10^-7	4.6 cm/s X10^-7
ph meter test	7	9	7.4	7.7
free swell index	52%	68%	43%	47%





6. Comparison and Conclusion

The comparison involved testing soil properties before and after contamination with $CaCO_3$, followed by evaluating gypsum and sulfur remediation.

Baseline tests established initial characteristics, and postcontamination tests measured changes in pH, plasticity, strength, permeability, and compaction. After 24-hour treatment with gypsum and sulfur (50 g/kg), postremediation tests assessed recovery.The study found that contamination weakened soil properties, making it less suitable for construction. Gypsum effectively reduced alkalinity, improved load-bearing capacity (CBR), and enhanced compaction (MDD & OMC), while sulfur better controlled swelling (FSI) and restored plasticity but showed slightly lower strength improvement. Gypsum-treated soil was more stable for construction, whereas sulphur was preferable for expansive soils. Further research is needed to optimize remediation methods.

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