Stabilization of Soft Subgrade Soil Using Alkaline Solution and Natural Fibers

Bathina Vinodh Babu, Dr. G.Vijayakumar
Department of Civil Engineering St. Ann's College of Engineering & Technology, Nayanipalli (V), Vetapalem (M), Bapatla (Dist) Chirala – 523 187, AP, India.

Abstract: Soft soils, such as clay and cohesive soils, exhibit undesirable engineering properties, including low strength, swelling, and shrinkage. This study aims to enhance these properties through stabilization techniques combining alkaline solutions and natural fibers. Alkaline solutions, like NaOH, improve soil properties, while sisal fibers reinforce and increase shear strength, load-bearing capacity, and other engineering characteristics. Experimental investigations focused on optimal dosages of alkaline solutions, fly ash (20% by soil weight), and sisal fibers (up to 3.0 cm length, various percentages). Results showed significant improvements in California Bearing Ratio (CBR), unconfined compressive strength (UCC), and shear values of stabilized soils. The study also highlighted the impact of fiber and chemical combinations on stress-strain behavior, moisture content, and dry density. Optimal outcomes were achieved with 30mm sisal fibers treated with turpentine oil for durability. A comparative analysis indicated superior performance of chemically stabilized and reinforced soils over untreated soils. This eco-friendly and cost-effective methodology offers substantial benefits for subgrade and embankment applications.

Keywords: Soil Stabilization, Alkaline Solution, Sisal Fiber, Soft Subgrade, CBR, UCC, Eco-friendly Reinforcement, Fly Ash

INTRODUCTION

Soft soils, such as clay and cohesive soils, often pose significant challenges in geotechnical engineering due to their inherent low strength, high compressibility, and swelling-shrinkage behavior. These properties make them unsuitable for direct use in subgrade and embankment construction. To address these limitations, various soil stabilization techniques are employed, including the use of chemical additives and natural fibers. Stabilization with alkaline solutions like sodium hydroxide (NaOH) has been widely studied, as it enhances the soil's load-bearing capacity and reduces its plasticity and moisture sensitivity. Fly ash, a by-product of coal combustion, is often used as a cementing material to further improve the strength and durability of treated soils. Sisal fiber, a natural, eco-friendly reinforcement material, has gained attention for its ability to significantly enhance the shear strength and load-bearing capacity of soils (Jamellodin, 2011; Prabakar and Siridihar, 2005).

The integration of chemical and fiber stabilization methods offers a synergistic approach to improving soil properties, making them suitable for pavement construction and other civil engineering applications. This study focuses on the combined effects of NaOH, fly ash, and sisal fibers on soil stabilization. Laboratory experiments were conducted to determine the optimal proportions of these materials, resulting in significant improvements in the California Bearing Ratio (CBR), unconfined compressive strength (UCC), and shear parameters. The use of natural fibers, such as sisal, not only provides cost-effective and sustainable solutions but also aligns with global trends toward eco-friendly construction practices (Abtahi et al., 2013). This research contributes to the growing body of knowledge on advanced soil stabilization techniques and offers practical solutions for enhancing subgrade performance in road and embankment projects.

METHODOLOGY

The study involves the systematic investigation of soft subgrade soil stabilization using alkaline solutions, fly ash, and sisal fibers. The process includes material selection, preparation, and experimental analysis to optimize soil stabilization parameters. The steps are as follows:

1. Material Selection

Soil: Expansive clay soil from Musunuru village, Andhra Pradesh, was used as the base material, meeting physical requirements as per IS 1498-1972 and IS 2720. Alkaline Solution: Sodium hydroxide (NaOH) solution was prepared in varying normalities (3N to 15N) by dissolving NaOH pellets in distilled water at concentrations of 40g per liter for a 1N solution. Fly Ash: Class F fly ash was selected for its cementitious properties, fixed at 20% by soil weight based on prior research (Prabakar and Siridihar, 2005). Sisal Fibers: Natural sisal fibers of 30mm length, treated with turpentine oil to improve durability, were used as a reinforcement material.

2. Sample Preparation

The soil was sieved through a 425µ IS sieve. Fly ash and NaOH were added to the soil in varying proportions. Prepared soil samples were packed in airtight polythene covers and kept in a desiccator for two weeks to achieve chemical maturity (Jamellodin, 2012).

3. Testing Procedures

Free Swell Index (FSI): FSI was calculated using distilled water and kerosene to assess the soil's swelling potential. The FSI decreased significantly with the addition of NaOH and fly ash, as shown in Table 1. CBR Test: California Bearing Ratio tests were conducted to evaluate the strength of the soil samples. Sisal fibers were added incrementally (0.2% to 3.0%) by soil weight to determine the optimal content for reinforcement. UCC Test: Unconfined Compressive Strength tests were performed to measure the axial stress and shear strength of the stabilized soil.

1. Data Analysis

   Results from the FSI, CBR, and UCC tests were analyzed to identify the optimal mix of NaOH, fly ash, and sisal fibers. Table 2 presents the CBR values at different lengths of sisal fibers for 0.2% fiber content.

Table 1: FSI Values for NaOH Mixed Soil at Different Normalities and Percentages

Normality	3%	6%	9%	12%	15%
3N	80	72.4	66.67	42.4	66.1
6N	52.23	42.44	42.44	40.23	52
9N	41.43	40.26	42.1	52	50

Table 2: CBR Values at Different Lengths of Sisal Fiber (0.2% by Soil Weight)

Fiber Length (cm)	CBR Value
0.5	2.365
1.0	2.593
1.5	2.670
2.0	2.746
2.5	2.822
3.0	3.124

These tests demonstrated that the combination of NaOH, fly ash, and sisal fibers significantly enhanced the engineering properties of the soil. The methodology aligns with prior research emphasizing the benefits of chemical stabilization and natural fiber reinforcement (Abtahi et al., 2013).

RESULTS & CONCLUSION

The details the findings from the experimental investigations, highlighting the improvements in soil properties achieved through stabilization using alkaline solutions, fly ash, and sisal fibers. The results are supported by numerical data and relevant citations to validate the observations.

1. Free Swell Index (FSI)

The Free Swell Index (FSI) test measures the swelling potential of soil. Untreated soils exhibited high FSI values, indicating severe swelling behavior. With the addition of NaOH, the FSI values decreased significantly due to the reduction of clay minerals' water-absorption capacity.

$$\text{FSI} = \frac{V_d - V_k}{V_k} \times 100$$

Where Vd and Vk are the soil volumes in distilled water and kerosene, respectively.

Table 3: FSI Values for NaOH-Stabilized Soil

Normality	FSI (%) at 3%	FSI (%) at 6%	FSI (%) at 9%	FSI (%) at 12%	FSI (%) at 15%
3N	80	72.4	66.67	42.4	66.1
6N	52.23	42.44	42.44	40.23	52
9N	41.43	40.26	42.1	52	50

As seen in Table 3, FSI values decreased with increasing NaOH normality up to 12%. This reduction indicates better stabilization, consistent with findings by Jamellodin (2012), who observed similar improvements using alkaline stabilizers in swelling soils. However, at higher normality (15%), the stabilization effect diminished, suggesting an optimal NaOH concentration for maximum effectiveness.

2. California Bearing Ratio (CBR): CBR tests were conducted to assess soil strength improvements.

Reinforcement with sisal fibers significantly increased CBR values.

$$\text{CBR} = \frac{\text{Measured Load (kN)}}{\text{Standard Load (kN)}} \times 100$$

Table 4: CBR Values for Different Fiber Lengths (0.2% Fiber Content)

Fiber Length (cm)	CBR Value (%)
0.5	2.365
1.0	2.593
1.5	2.670
2.0	2.746
2.5	2.822
3.0	3.124

The highest CBR value was observed at a fiber length of 3.0 cm, (Table 4) reflecting the optimal reinforcement effect. Shorter fibers were less effective in distributing tensile forces. These results align with studies by Prabakar and Siridihar (2005), who demonstrated significant strength gains using natural fibers for soil reinforcement.

3. Standard Proctor Test

The Standard Proctor Test was performed to determine Maximum Dry Density (MDD) and Optimum Moisture Content (OMC).

$$\rho_d = \frac{\rho}{1 + w}$$

Where ρd = dry density, ρ = bulk density, and www = water content.

Table 5: Dry Density vs. Water Content

Water Content (%)	Bulk Density (g/cc)	Dry Density (g/cc)
6	1.775	1.6745
8	1.96	1.8148
10	2.06	1.8727
12	2.21	1.9732
14	1.928	1.6912

The MDD was (Table 4) found to be 1.9732 g/cc at an OMC of 11.9%. The results indicate improved compaction characteristics due to the addition of stabilizers, which reduced void spaces and enhanced particle binding.

4. Unconfined Compressive Strength (UCC)

The UCC test evaluated the soil's compressive stress and shear strength.

$$q_u = \frac{P}{A_c}$$

Where qu = compressive stress, P= applied load, and Ac = cross-sectional area.

Table 6: UCC Test Results

Strain (%)	Compressive Stress (quq_uqu, kg/mm2^22)	Shear Strength (τ=qu/2\tau = q_u / 2τ=qu/2, kg/mm2^22)
0.027	1.778	0.889
0.053	1.913	0.957
0.080	2.128	1.064

The maximum compressive stress observed (Table 6) was 2.128 kg/mm2^22, with a corresponding shear strength of 1.064 kg/mm2^22. These values confirm significant soil strength enhancement due to stabilization, consistent with findings by Abtahi et al. (2013), who reported similar gains using fiber and chemical reinforcement.

5. Comparative Analysis

A comparison of untreated, chemically stabilized, and fiber-reinforced soils revealed substantial improvements in engineering properties.

Table 7: Summary of Results

Test Parameter	Untreated Soil	Stabilized Soil	Reinforced Soil
FSI (%)	101.83	42.4	66.67
CBR (%)	2.136	2.822	3.124
Shear Strength (kg/mm2^22)	0.889	1.064	1.200

The combined use of NaOH, fly ash, and sisal fibers yielded the best results, enhancing soil stability, reducing swelling potential, and increasing load-bearing capacity. These findings validate the efficacy of the stabilization approach and its suitability for subgrade applications.

CONCLUSION

The stabilization of soft subgrade soils using a combination of NaOH, fly ash, and sisal fibers has proven to be an effective method for enhancing soil engineering properties. The study demonstrated significant improvements in critical parameters such as Free Swell Index (FSI), California Bearing Ratio (CBR), unconfined compressive strength (UCC), and compaction characteristics. The optimal dosages and combinations of these materials resulted in reduced swelling potential, increased shear strength, and improved load-bearing capacity. These findings align with previous studies, emphasizing the potential of eco-friendly, cost-effective stabilization techniques for infrastructure applications. This approach is particularly beneficial for sustainable development in areas with problematic soils, offering improved subgrade performance and reduced environmental impact.

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