METHODS FOR STRENGTHENING AND STABILIZATION OF SALINE SOILS IN ROAD CONSTRUCTION

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Abstract
Saline soils are among the most problematic geomaterials for road construction in arid and semi-arid regions. This article evaluates chemical, geosynthetic, electrokinetic, and hydraulic methods of improving saline subgrades under the engineering-geological conditions typical of Uzbekistan. Laboratory tests on sulfate-bearing loam with 3.5% salinity showed that the combined use of cement, lime, and bituminous emulsion provided the best overall performance, increasing compressive strength from 0.42 MPa to 2.35 MPa, reducing swelling from 8.4% to 1.4%, and increasing the elastic modulus from 18.5 MPa to 65.2 MPa. An empirical exponential model is proposed to relate stabilized soil strength to salt concentration. Practical recommendations are given for selecting stabilization methods by salinity degree and salt type.

Keywords: Saline soils; road subgrade; soil stabilization; sulfate salinity; cement stabilization; lime treatment; geosynthetics; capillary break layer; electrokinetic treatment.

Introduction

Saline soils create serious geotechnical difficulties for highway embankments and pavement foundations because their behavior changes sharply under wetting-drying cycles, salt migration, and groundwater fluctuations. In Uzbekistan and other irrigated arid regions, the problem is aggravated by shallow mineralized groundwater and insufficient drainage, which promote secondary salinization and reduce the long-term durability of transport infrastructure. From an engineering perspective, chloride salinity mainly increases hygroscopicity and moisture sensitivity, while sulfate salinity is more dangerous because it may cause swelling, strength loss, and chemically aggressive interaction with calcium-based binders. Therefore, road design on saline soils must combine material stabilization with capillary control, drainage, and measures preventing upward salt migration.

The aim of this study is to compare major methods of stabilizing saline road subgrades and to develop practical recommendations for selecting the most appropriate treatment depending on salinity degree and salt composition. The paper also presents an empirical relationship between stabilized soil strength and salt content.

2. Classification and Engineering Properties of Saline Soils

For highway engineering, saline soils may be classified by the content of water-soluble salts. As salt concentration increases, the soil usually exhibits greater moisture sensitivity, volume instability, and loss of bearing capacity.

Table 1. Classification of saline soils by salinity degree.

Salinity degree	Salt content, % by mass	Typical engineering behavior
Non-saline	< 0.3	No significant salt-related deformation
Slightly saline	0.3-1.0	Minor swelling, moderate softening
Moderately saline	1.0-3.0	Noticeable swelling, strength reduction
Highly saline	3.0-5.0	Major volume change, low durability
Very highly saline	> 5.0	Severe loss of bearing capacity

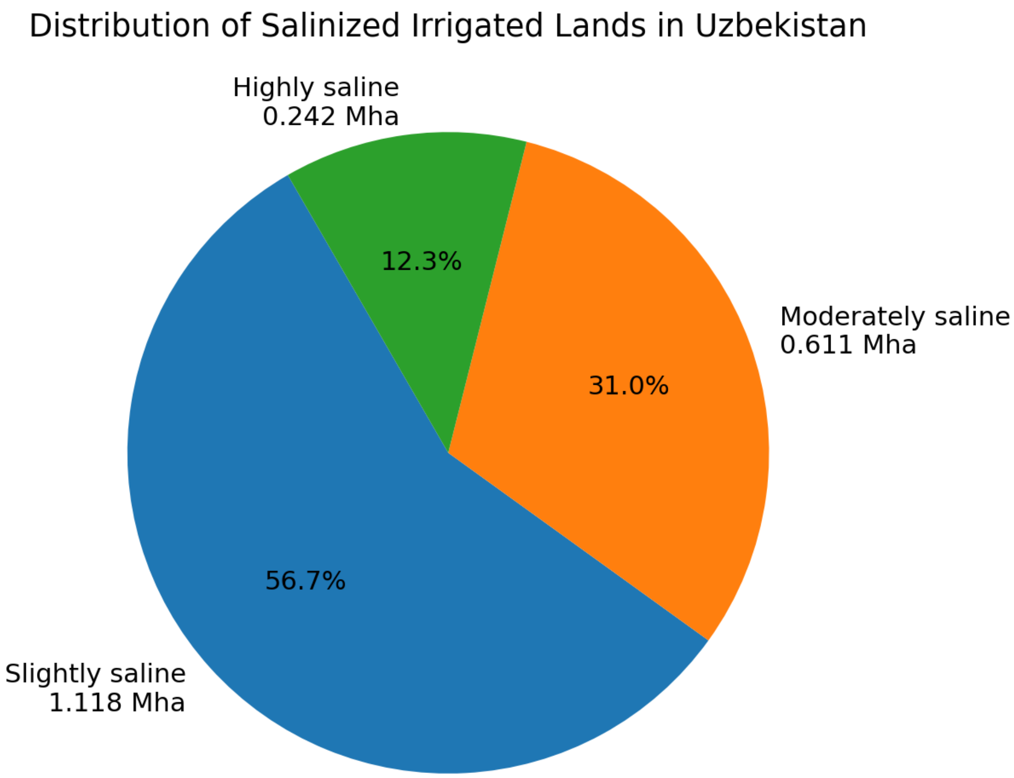

Figure 1. Distribution of salinized irrigated lands in Uzbekistan by salinity degree.

The degradation of saline subgrades is controlled by groundwater depth, capillary rise, evaporation, irrigation seepage, and drainage deficiency. For this reason, the subgrade problem is not only a strength problem, but also a hydraulic one.

3. Materials and Methods

3.1 Experimental soil and stabilization methods

Laboratory tests were conducted on sulfate-bearing loam with a salt content of 3.5%, representative of problematic subgrade conditions in the Syrdarya region. The following stabilization methods were compared: untreated soil; cement stabilization (10%); lime stabilization (8%); cement 8% plus bituminous emulsion 3%; geotextile with crushed-stone layer; and a combined system consisting of cement 8%, lime 4%, and bitumen 2%.

3.2 Specimen preparation and testing

The soil was air-dried, pulverized to pass a 2 mm sieve, mixed with stabilizers in the required proportions, and compacted at optimum moisture content. Cylindrical specimens with diameter 50 mm and height 50 mm were cured for 28 days at 20 ± 2 °C and 95% relative humidity before testing.

$$Rc = P / A \quad (1)$$

where Rc is the compressive strength of the sample, P is the failure load, and A is the cross-sectional area.

$$\rho = m / V \quad (2)$$

where ρ is the average density, m is the sample mass, and V is the specimen volume.

3.3 Performance indicators

The effectiveness of the stabilization methods was evaluated using four main indicators: compressive strength, water saturation coefficient, elastic modulus, and swelling.

4. Results

Table 2. Mechanical and deformation characteristics of saline soil after stabilization.

Stabilization method	Compressive strength, MPa	Water saturation coefficient	Elastic modulus, MPa	Swelling, %
Untreated soil	0.42	0.95	18.5	8.4
Cement 10%	1.85	0.68	42.3	3.2
Lime 8%	1.60	0.72	38.7	3.8
Cement 8% + bitumen 3%	2.10	0.45	58.6	1.9
Geotextile + crushed stone layer	1.20	0.80	35.4	4.5
Combined system: cement 8% + lime 4% + bitumen 2%	2.35	0.38	65.2	1.4

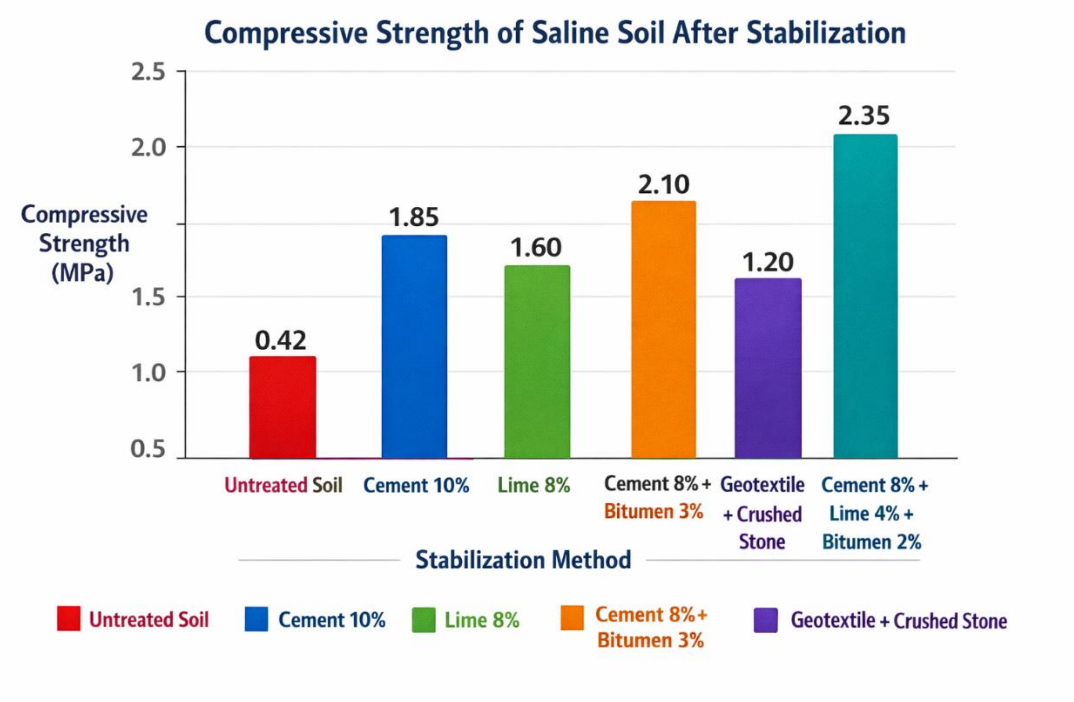

Figure 2. Compressive strength of saline soil after treatment by different stabilization methods.

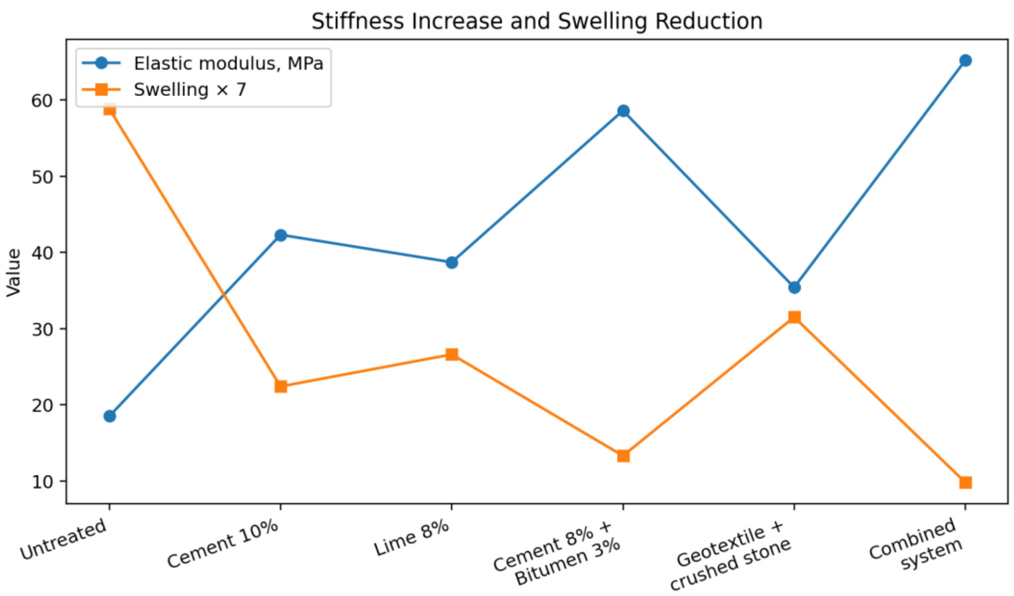

Figure 3. Comparison of stiffness gain and swelling reduction after stabilization.

4.1 Interpretation of test results

The combined stabilization system achieved the highest compressive strength (2.35 MPa), the lowest water saturation coefficient (0.38), and the lowest swelling (1.4%). This indicates a strong synergistic effect: cement forms a rigid bonded skeleton, lime modifies the clay fraction and improves workability, while bituminous emulsion reduces permeability and suppresses capillary moisture transport.

Cement-only and lime-only treatments also improved the engineering properties of the soil, but their performance remained lower than that of the combined system. The geotextile-based solution did not provide the highest intrinsic compressive strength; however, it remains essential in field practice because it improves separation, filtration, and long-term preservation of the pavement structure.

5. Discussion

In sulfate-bearing soils, the choice of binder must be made carefully because excessive sulfate content may promote expansive reactions and reduce the long-term durability of lime- and cement-treated soils. Therefore, sulfate-resistant cement, mineral additives, and hydrophobic components are recommended where aggressive salinity is present.

The obtained results confirm that stabilization of saline road foundations should be treated as a combined material-hydraulic task. Even a high-strength stabilized layer can degrade prematurely if upward moisture movement is not blocked. Consequently, binder treatment should be integrated with drainage, capillary-break layers, and geosynthetic separation.

$$R_c = R_0 e^{-kC} \quad (3)$$

Equation (3) expresses the empirical reduction in stabilized soil strength with increasing salt content, where R_c is the strength of stabilized saline soil, R_0 is the strength of equivalent stabilized non-saline soil, C is salt content in percent, and k is a coefficient depending on salt type. For engineering estimates, k may be taken as 0.35 for sulfate salinity and 0.28 for chloride salinity.

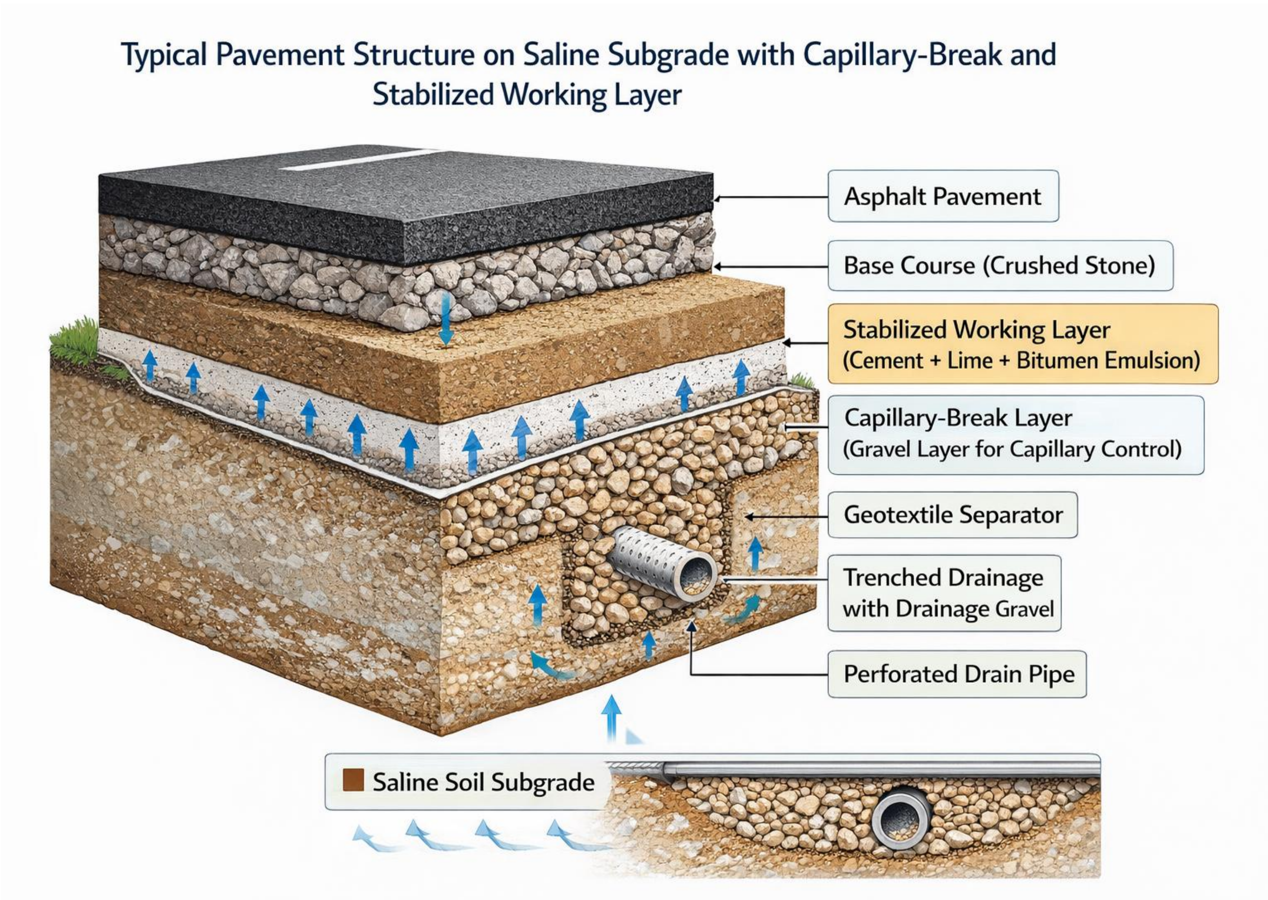

Figure 4. Typical pavement structure on saline subgrade with a capillary-break and stabilized working layer.

6. Practical Engineering Recommendations

Table 3. Recommended stabilization methods according to the degree of salinity.

Salinity degree	Recommended treatment	Engineering note
0.3-1.0%	Compaction + geotextile; cement 6-8%	Conventional methods usually acceptable
1.0-3.0%	Sulfate-resistant cement 8-12%; lime 6-10%; bituminous emulsion	Capillary-break layer required
3.0-5.0%	Combined binders; partial soil replacement; electrokinetic treatment where justified	Waterproofing and drainage are essential
> 5.0%	Full replacement or imported embankment fill	Native saline soil should not be used as structural subgrade

At the design stage it is necessary to determine the type and degree of salinity, groundwater depth, and sulfate aggressiveness. During construction, compaction should be maintained at not less than 0.98-1.00, moisture should be kept near optimum, and geosynthetic separators with granular capillary-break layers should be installed where required. During operation, drainage systems, shoulders, and pavement cracks must be maintained to prevent water ingress and secondary salinization.

7. Limitations of the Study

The experiments were carried out in laboratory conditions and therefore cannot fully reproduce field moisture fluctuations, seasonal thermal effects, and long-term recrystallization of salts. The data represent one dominant soil type and one principal salinity level (3.5% sulfate salinity). The proposed empirical model should be calibrated further using broader field datasets and long-term monitoring.

8. Conclusions

1. Saline soils are a critical constraint for road construction in Uzbekistan because salinity, shallow groundwater, and poor drainage act together to reduce subgrade durability.
2. Sulfate salinity is the most dangerous type because it combines swelling potential with chemical aggressiveness toward calcium-based binders.
3. The combined stabilization system of cement, lime, and bituminous emulsion provided the best overall engineering performance in the present study.
4. Geosynthetics and capillary-break layers should be considered mandatory protective elements where upward moisture and salt migration are expected.
5. The most reliable engineering strategy is a combined approach integrating binder stabilization, hydraulic protection, and drainage control.

ISSN (E): 2938-3625
Volume 4, Issue 4, April - 2026

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