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Experimental Investigation of Lime and Cement Stabilization for Sustainable Pavement Subgrade Applications

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Abstract

The subgrade soil strength and stability under pavement structures are important factors affecting pavement structure performance. In this study the efficiency of lime and cement stabilization on compaction and strength properties of locally available loamy sand soil collected from Faridabad, Haryana, India is evaluated. The soil samples were stabilized with lime and cement at 5%, 10%, 15% and 20% by dry weight and tested by Standard Proctor Compaction, Direct Shear and Unconfined Compressive Strength (UCS) tests.

The results indicated that both of the stabilizers greatly enhanced the engineering properties of the soil. With the increase in the stabilizer content, the maximum dry density, cohesion and compressive strength increased. Lime improved the soil structure and bonding by means of pozzolanic reactions and cement provided quick strength development and load bearing capacity. The maximum dry density increased from 1.62 g/cc for the untreated soil to 1.76 g/cc for the stabilized soil with UCS value of about 285 kPa. The best performance was observed for stabilizer contents of 10 to 15 %.

The results indicate that lime and cement stabilization can be an effective method to improve the performance of loamy sand soils and to provide a practical and sustainable solution in pavement subgrade applications.

Keywords: Soil Stabilization; Loamy Sand; Lime; Cement; Subgrade Soil; Pavement Engineering.

Introduction

The development of transportation infrastructure requires stable and durable materials for the 366 subgrade to withstand the traffic loads and environmental stresses over long periods of service. The performance of pavements, embankments and foundation systems is controlled by the engineering subgrade of the underlying soil. However, many natural soils are weak, highly deformable, moisture sensitive and poor load carriers and therefore cannot be used directly in civil engineering works. Hence, soil stabilization is widely used as an efficient ground improvement method to modify the physical and chemical properties of soil in order to enhance strength, reduce compressibility, improve durability, and mitigate structural distress (Gruchot et al., 2025). Properly stabilized soils provide better structural reliability, lower maintenance costs, increased pavement life, and safer infrastructure systems, while untreated weak soils often result in settlement, rutting, erosion, cracking, and premature structural failure (Nan et al., 2025).

One of the most important geotechnical and economic problems in the world is soils that are problematic. Weak, expansive, collapsed and moisture sensitive soils are the main causes of land degradation and damage to infrastructure. These soils cause considerable financial losses and increase the costs of maintenance . Particularly, expansive soils exhibit a spectacular shrink-swell subgrade with change in moisture content causing pavement heave, cracking of foundations and deformation of engineered structures. Lime and cement stabilization has proven to be effective in improving the strength and durability of expansive soils by reducing plasticity, swelling potential and moisture sensitivity (Wan et al., 2022; Consoli et al., 2020). Problem soils create large-scale socio-economic and environmental problems. The costs of maintenance of infrastructures increase, the use of land decreases and the sustainable growth of the region is hindered. The damage to the transportation and agricultural infrastructure can lead to indirect economic constraints and reduced resilience in vulnerable areas (Suparma & Rifa'i, 2024). Some clays have been studied in great details. Loamy sand and other non expansive granular soils have been given less attention due to their particular engineering subgrade.

Loamy sand is not governed by the mineralogical swelling behavior, as is the case with expansive clay soils, but primarily by the engineering response to density variation, resistance to friction, permeability, inter-particle interaction and moisture to density relation (Das & Sobhan, 2022). The subgrade of loamy sand is governed by the particle size distribution, the relative density, the effective stress conditions and the frictional interaction between the soil particles, from the point of view of soil mechanics (Budhu, 2021). The shear strength of loamy sand under loading is mainly mobilized by inter-particle friction and mechanical interlocking, but not by cohesive bonding. The fluctuation of moisture content has a significant impact on the compaction efficiency, pore structure, mechanisms of stress transfer, and load-bearing capacity. Insufficient densification can lead to higher compressibility, lower stiffness, and progressive deformation under repeated traffic loading (Coduto et al., 2022). Hence, stabilization techniques that can enhance particle bonding, density characteristics and stress distribution are vital to improve the engineering behavior of loamy sand. Subgrade loamy sand soils usually have low cohesion, poor inter-particle bonding, high permeability and negligible plasticity, which makes them highly susceptible to deformation and reduced shear resistance under saturated and repeated traffic loading conditions (Sukmak et al., 2023). Such soils often have low bearing capacity, rutting, settlement and instability in pavement applications when subjected to cyclic loading and environmental variations. Therefore, from soil mechanics point of view, improvement in compaction characteristics, shear strength, stress transfer mechanisms and California Bearing Ratio (CBR) performance is essential for adequate subgrade stability and long term pavement durability (Wang et al., 2023). Engineering performance enhancement of loamy sand soils is critical to obtain durable and cost-effective pavement systems as loamy sand soils are widely encountered in road subgrades and embankment construction in semi-arid regions of northern India (Roshan et al., 2023). In several regions like Faridabad, the infrastructure projects encounter locally available loamy sand soils and there is a need for economical and sustainable stabilization approaches for regional geotechnical conditions (Azimi et al., 2024).

Majority of the soil compaction methods are based on the mechanical instruments like vibratory compactors, tampers and rollers for the densification of soil and reduction of the vacancy ratios. These techniques are useful to increase the soil compaction, but they have some practical and environmental disadvantages (Al-Subari et al., 2023). Mechanical compaction, to reach the same density, requires large equipment, high power consumption, professional operation and multiple visits to the field. Also on construction sites, the heterogeneity of soils usually leads to uneven compaction and variation of bearing capacity (Onyelowe et al., 2024). Besides, use of heavy equipment results in fuel consumption, noise pollution, greenhouse gases emissions and environmental degradation (Rehman et al., 2025). Consequently geotechnical engineering practice increasingly looks toward alternative stabilization techniques that can improve soil performance with less impact on the environment.

Among the various stabilization methods, the chemical stabilization of soils using cement and lime is one of the most popular and successful approaches to improve problematic soils. The improvement of soil subgrade by lime stabilization is due to cation exchange and pozzolanic reactions, leading to lower flexibility, higher workability, more cohesiveness and better long term strength. Reactions of pozzolans form cementing compounds that improve resistance to deformation by moisture and decrease volume instability (Amadi, 2025). In contrast, cement stabilization enhances soil performance through the formation of cementitious matrix around soil particles as a result of hydration processes. This method speeds up construction and enhances the structural stability by increasing the bond strength between particles, improving the stiffness, increasing the load bearing capacity, reducing the compressibility and accelerating the strength development.

Cement and lime synergic stabilization is the combination of cement's rapid strength gaining features and lime's reduced plasticity and enhanced workability (Padmaraj & Arnepalli, 2023). The combination has been found to enhance the engineering performance of pavement subgrades, embankments and foundation soils under a range of loading and environmental conditions. The stabilization of lime and cement also promotes sustainable construction practices through the reduction of high mechanical compaction and the improvement of the use of locally available soils. Moreover, the use of local soils and traditional stabilizers promotes sustainable infrastructure development by avoiding the excessive replacement of materials, reduction of waste generation in construction and improvement of resource efficiency in pavement construction. Several studies have reported that the addition of lime and cement can significantly improve the compaction subgrade, shear strength, unconfined compressive strength (UCS) and California Bearing Ratio (CBR) values (Yoshida et al., 2005; Xiao et al., 2013). Previous studies have shown that the optimal engineering performance is obtained with a stabilizer content of 10% to 15% while keeping economic viability and environmental sustainability (Bae & Siddiki, 2018; Gour et al., 2019).

Even though a lot of research has been done on chemical stabilization of expansive and clayey soils, there is still a lack of comparative research on the stabilization behavior of loamy sand soil under the same laboratory conditions. Most of the previous investigations have studied lime and cement stabilization mostly for expansive or fine-grained soils, and only a few studies have compared their relative performance for loamy sand soils under the same laboratory conditions applicable to pavement applications. Moreover, very few studies have systematically investigated the effect of different percentages of stabilizers on the compaction characteristics, shear strength behavior, moisture–density relationships, compressive strength, and bearing capacity of locally available loamy sand soils under controlled experimental conditions. Thus, a comprehensive understanding of the interaction between lime, cement, and loamy sand soil behavior is needed to develop cost-effective, region-specific, and durable pavement stabilization strategies.

The novelty of the present study consists in the comprehensive comparative evaluation of lime and cement stabilization on locally available loamy sand soil through integrated geotechnical characterization and strength assessment. Many previous studies have been mostly focused on expansive soils. The present study emphasizes the engineering behavior of non-expansive granular soil typically encountered in construction of pavement. Effect of different stabilizer contents (5%, 10%, 15% and 20%) on the compaction and strength properties of loamy sand soil is systematically investigated by using Standard Proctor Test, Direct Shear Test, Unconfined Compressive Strength

(UCS) Test and California Bearing Ratio (CBR) Test. Preliminary characterization indicated typical compaction subgrade of loamy sand soils, requiring stabilization for better pavement suitability and engineering performance. Cement and lime were selected because their mechanisms of stabilization are complementary, applicable in field, available and practically relevant in transportation infrastructure projects. Stabilization of subgrade strength can provide opportunities to reduce pavement thickness, construction costs and long-term maintenance costs.

The main objective of the present study is to evaluate the efficiency of lime and cement as stabilizing agents for improving the engineering performance of loamy sand subgrade soil for use in infrastructure applications. In this work, large scale laboratory experiments were carried out to find out the effect of various percentages of lime and cement on physical and mechanical properties of soil. The specific objectives are to evaluate the effect of stabilizer content on compaction characteristics, shear strength behavior, stress-strain response, unconfined compressive strength and bearing capacity, to determine the optimum stabilizer content for maximum performance improvement. The results of this study are expected to provide useful guidelines for the sustainable and economical stabilization of pavement subgrades, which will help in building safer, more durable and environmentally friendly infrastructure.

Materials and Methods

Study Area

Soil used in this study was collected from Faridabad region of Haryana, India where loamy sand deposits are commonly encountered in transportation and infrastructure projects. Low natural cohesion and high sand content limits the strength and bearing capacity of the soil and makes it less suitable for direct use as a pavement subgrade material. The increasing demand for durable and cost-effective road infrastructure in the region calls for the improvement of locally available soils. Therefore, lime and cement stabilization was studied to improve the compaction characteristics, shear strength and compressive strength of the selected soil of loamy sand.

Soil Sample

A soil sample used in the present study was collected from an open ground near Lingaya’s Vidyapeeth, Faridabad, India (approximate coordinates 28.416° N latitude and 77.317° E longitude). Sampling was done using a disturbed sampling method from a depth of about 0.5m below ground surface to avoid organic matter and surface contamination. Altogether some 50 kg of soil were collected, which was sufficient material for all the laboratory tests. Based on visual identification, the collected soil was loamy sand with low plasticity and high permeability, resulting in limited natural retention of water. The soil was air dried, pulverized and sieved through a 4.75 mm sieve to remove oversized particles and to obtain uniformity for testing. The engineering properties of untreated soil, viz. natural moisture content, maximum dry density, optimum moisture content, cohesion and angle of internal friction were determined as per relevant Indian Standard Codes (IS 2720 series).

Basic Characterization of Soil

The untreated soil (loamy sand) was tested for basic index properties prior to stabilization for classification and characterization purposes. The natural moisture content, specific gravity, grain size distribution and Atterberg limits were determined in accordance with the relevant Indian Standard codes of IS 2720 series. Natural moisture content was determined as per IS 2720 Part 2 Specific gravity was determined as per IS 2720 Part – 3 . The grain size analysis was done as per IS 2720 Part 4. The Atterberg limits test was conducted according to IS 2720 Part 5. The percentage distribution of sand, silt and fines were determined by grain size analysis. The Atterberg limit tests were performed to determine the plasticity characteristics of the soil. The soil classification was done based on index properties defined as per Indian Standard Soil Classification System (ISSCS). The tests provided useful information regarding physical behavior, gradation characteristics and suitability of soil for pavement subgrade applications.

Stabilizing Materials

Lime

In this investigation hydrated lime was used as chemical stabilizer. For the experiment, about 25 kg of lime was purchased from a nearby supplier of building materials in Faridabad, India. Soil properties are improved by lime. This is due to the pozzolanic properties of lime improved workability, reduced plasticity and increased cohesiveness. Soil was treated with lime at four levels, 5, 10, 15 and 20 % of the dry weight of soil. Lime stabilization is an effective method to control volumetric change in clayey soils containing expansive minerals. The primary purpose of the lime stabilizer is to improve the inter-particle bonding and the overall strength properties of the loamy sand soil used in this study.

Cement

Ordinary Portland cement (OPC) was used as a stabilizing component for the soil to improve the bonding and strength gain at a faster rate by hydration and cementation reactions. The cement was bought from a local supplier in Faridabad, India. This was mixed with soil at 5%, 10%, 15% and 20% dry weight of soil.

In the case of combined stabilization, the soil samples were stabilized with equal amounts of lime and cement (1:1 ratio) to study the synergistic effect of both stabilizers. The total additive content was varied to 10%, 15% and 20 % corresponding to 5% lime + 5% cement, 7.5% lime + 7.5% cement and 10% lime + 10% cement respectively. These dosage levels were chosen to match commonly used stabilization ranges reported in the literature and to find the best proportion leading to maximum increase in strength and performance while still being practical.

Characterization of Stabilizing Materials

Laboratory characterization tests were performed on lime and cement before their use in stabilization. The properties of hydrated lime were evaluated by fineness test, slaking test and setting time test and Ordinary Portland Cement (OPC) were characterized by fineness test, standard consistency test and setting time test as per the relevant Indian Standard specifications. The tests were performed to check the suitability, quality and reactivity of the stabilizing materials for use in soil treatment applications.

Sample Preparation

The soil and stabilizing materials were completely mixed, in order to obtain homogeneity. The soil and stabilizers were mixed dry initially to ensure even distribution of the additives before the water was added. The mix was moistened to the desired water content determined from preliminary Standard Proctor Test results. Three replicate samples were prepared for each stabilization percentage.

Curing Procedure

The stabilized soil specimens were then wrapped in air-tight polythene bags to prevent the loss of moisture and stored under controlled laboratory conditions for the required curing periods of 7, 14 and 28 days. The curing process was carried out to accelerate the hydration and pozzolanic reaction between soil and the stabilizing agents, which in turn, improved the strength development and inter-particle bonding in the stabilized matrix.

Laboratory Testing

Standard Proctor Test

The Standard Proctor Test (IS 2720 Part 7) was conducted to determine the maximum dry density (MDD) and optimum moisture content (OMC) of plain and stabilized soils. Cylindrical molds of 1000 cm3 were used and the soil was compacted in three layers with 25 blows per layer with a standard 2.5 kg rammer . The test was carried out to evaluate the moisture-density relationship and compaction properties of untreated and stabilized loamy sand soils.

Direct Shear Test

The shear strength parameters (cohesion, (c), and internal friction angle, (φ)) of stabilized and unstabilized soils were determined by conducting direct shear tests as per IS 2720 Part 13. Specimens with a square shape (60 × 60 × 25 mm) were prepared and three normal stresses, 136.2, 272.5 and 408.8 kPa, were applied to obtain the stress-strain behavior. The specimens were tested under drained conditions to determine peak shear stress and evaluate the shear strength behaviour of untreated and stabilized soils.

Unconfined Compressive Strength (UCS) Test

To determine the load bearing capacity of stabilized soil samples UCS tests (IS 2720 Part 10) were conducted. Cylindrical specimens of 38 mm diameter and 76 mm height were compacted to OMC and cured for 7, 14 and 28 days. The specimens were loaded to failure at a constant strain rate of 1 mm/min and the peak compressive strength was recorded.

California Bearing Ratio (CBR) Test

The California Bearing Ratio (CBR) tests were conducted as per IS 2720 part 16 to determine the subgrade strength and bearing capacity of loamy sand soils both untreated and stabilized for pavement application. The specimens are prepared at their respective optimum moisture content (OMC) and maximum dry density (MDD) as determined from Standard Proctor Test. Soaked and unsoaked CBR tests were done to know the effect of moisture condition on the performance of subgrade. The compacted specimens were loaded by using a standard plunger at the rate of 1.25 mm/min and the load was recorded at penetration depth of 2.5 mm and 5 mm. The CBR values obtained were used to assess the suitability of stabilized soil for the construction of pavement subgrade and to evaluate the improvement in load bearing capacity achieved by stabilization of lime and cement.

Data Analysis and Evaluation

The effects of lime and cement stabilization on the compaction behavior, strength properties and load bearing capacity of loamy sand soil were evaluated through analysis of the results of Maximum Dry Density (MDD), Optimum Moisture Content (OMC), California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS) and Direct Shear tests. A comparison between untreated soil, individually stabilized samples and combined lime–cement treated samples was done to find the optimum percentage of stabilization for pavement subgrade applications. All tests were carried out in triplicate and the results were expressed as mean values ± standard deviation and standard error to account for experimental variability and to guarantee data reliability. The results of the Direct Shear Test were used to determine the cohesion (c) and the angle of internal friction (φ) using the Mohr–Coulomb failure criterion. The effect of chemical stabilization on the improvement of soil behavior and subgrade performance was also investigated by evaluating the change in compaction, shear strength, compressive strength and bearing capacity with an increase in stabilizer content and curing period. Trend of engineering properties was identified graphically and comparatively for different percentages of stabilization.

The combined lime-cement stabilization was designed with a minimum total additive content of 10%, which corresponds to 5% lime and 5% cement. A lower combined dosage of 5 % total additive content was not considered, due to not enough quantities of individual stabilizers to induce significant pozzolanic and cementitious reactions at such low proportions in the loamy sand matrix Past studies on stabilization have indicated that very low dosages of additives are likely to produce little or no improvement in strength and compaction characteristics, especially for the low-cohesion granular soils. Therefore, the stabilization percentages of 10%, 15%, and 20% were combined to ensure proper interaction between the soil particles and stabilizing agents and to allow for an effective evaluation of the synergistic stabilization behavior.

Table No. 1: Experimental Design Summary

Stabilizer Type	**Percentages Used**	**Number of Samples**	**Tests Conducted**
Lime	5%, 10%, 15%, 20%	3 per percentage	Proctor, Direct Shear, UCS, CBR
Cement	5%, 10%, 15%, 20%	3 per percentage	Proctor, Direct Shear, UCS, CBR
Lime + Cement	10%, 15%, 20%	3 per percentage	Proctor, Direct Shear, UCS, CBR

The experimental methodology adopted provides a systematic framework for the evaluation of the influence of lime and cement stabilization on the engineering behavior of loamy sand soil. The integrated assessment of compaction characteristics, shear strength, compressive strength and bearing capacity makes it possible to find out the optimum stabilizer content for the improvement of pavement subgrade performance under different loading conditions. The present study was carried out under controlled laboratory conditions. Therefore, long-term environmental effects and field scale variations were not the objective of the present investigation.

Results and Discussion

Geotechnical Characterization of Untreated Soil

The untreated soil collected from the Faridabad region was tested for basic index and engineering property tests before stabilization to determine the baseline geotechnical characteristics. The soil was composed mainly of sand particles with moderate percentage of fines which is representative of the typical behavior of loamy sand. The obtained properties indicated low plasticity, relatively high permeability and limited natural cohesion which are typical characteristics of coarse grained alluvial soils commonly found in pavement subgrade applications.

The natural moisture content of the soil was found to be 33.12% which shows that there is considerable moisture retention under field condition at the time of sampling. The specific gravity of soil was observed to be 2.64 which is in normal range of sandy soils rich in quartz. Grain size analysis showed that the soil was composed of about 78% sand and 22% fines. This shows that the soil was granular in nature. The Atterberg limit tests revealed the liquid limit, plastic limit and plasticity index to be 24%, 19% and 5% respectively which indicates low plasticity and negligible swelling characteristics. The index properties and gradation characteristics obtained classified the soil as loamy sand in Indian Standard Soil Classification System (ISSCS).

The results of Standard Proctor Test, 1.62 g/cc for Maximum Dry Density (MDD) and 11.88% for Optimum Moisture Content (OMC) are consistent with the compaction behavior of loose coarse-grained soils with relatively low fines content. The lower MDD in the untreated state indicated that the bonding between particles was limited and the packing of particles was inefficient. The moderate OMC indicated the moisture at which compaction was efficient. The result of the Direct Shear Test showed that the internal friction angle and cohesiveness of the untreated soil were 41.8° and 28.78 KPa. The results indicate that the cohesive bonding was not as important as the frictional resistance in controlling the shear strength of untreated soil.

In general, the untreated loamy sand soil had a moderate load bearing capacity but a poor structural stability when saturated and repeatedly loaded. The low plasticity, poor inter-particle bonding and moderate shear strength indicate stabilization is needed to enhance the compaction characteristics, bearing capacity and long-term pavement performance. These baseline properties thus served as a reference for evaluating the effectiveness of lime and cement stabilization in the subsequent experimental studies.

Table No. 2: Engineering Properties of Untreated Soil

S. No.	**Property**	**Value**	**Unit**

1	Natural Moisture Content	33.12	%
2	Specific Gravity	2.64	—
3	Sand Content	78	%
4	Silt/Fines Content	22	%
5	Liquid Limit	24	%
6	Plastic Limit	19	%
7	Plasticity Index	5	%
8	Soil Classification	Loamy Sand	—
9	Maximum Dry Density	1.62	g/cc
10	Optimum Moisture Content	11.88	%
11	Cohesion (c)	28.78	kPa
12	Angle of Internal Friction (φ)	41.8	Degree

Characterization of Stabilizing Materials

The physical properties of hydrated lime and Ordinary Portland Cement (OPC) were assessed before their use in soil stabilization, to ascertain their suitability and reactivity for stabilization purposes. The characterization of stabilizing materials is of great importance, because the fineness, consistency and setting behaviour of stabilizers significantly affect hydration reactions, pozzolanic activity, strength development and stabilization efficiency as a whole.

The hydrated lime used in the present study showed good fineness and reactivity characteristics for soil stabilization. The fineness of lime provides the means for better interaction with soil particles, and therefore, to encourage cation exchange and pozzolanic reactions which can enhance inter-particle bonding and soil workability . The slaking behavior showed the adequate reactivity of the lime, which is necessary for the formation of cementitious compounds during the stabilization. The setting time characteristics further confirmed the suitability of the lime for the gradual strength development and long term stabilization performance.

The Ordinary Portland cement (OPC) exhibited standard consistency and setting time values which conform to the acceptable range as per the relevant Indian Standard regulations. Fineness of cement is very important for hydration and development of strength as finer cement particles provide a larger surface area for the hydration of water and soil particles. The observed setting time characteristics suggest adequate hydration behaviour and sufficient workability during sample preparation and compaction. Hydration reactions in cement treated soil result in a dense cementitious matrix, which improves stiffness, strength and load bearing capacity.

The results of the lime and cement parameters show that both the stabilizing agents have adequate physical and chemical properties to enhance the engineering properties of loamy sand soil. The combined application of these stabilizers is expected to improve compaction behavior, shear strength, compressive strength and bearing capacity through flocculation, cementation and modification mechanisms.

Table 3: Physical Properties of Stabilizing Materials

S. No.	**Property**	**Lime**	**Cement**
1	Fineness	92% passing 90 μ sieve	94% passing 90 μ sieve
2	Specific Gravity	2.32	3.15
3	Standard Consistency	—	31%
4	Initial Setting Time	95 min	38 min
5	Final Setting Time	310 min	585 min
6	Slaking Behavior	Moderate to High Reactivity	—

Effect of Lime and Cement on Compaction Characteristics

The compaction characteristics of the soil of loamy sand in untreated and stabilized condition were determined by conducting the Standard Proctor Test (IS 2720 Part 7). Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) were determined for the soil stabilized with different proportions of lime, cement and combined lime-cement stabilization. The condition of the pavement subgrade has a great influence on the compaction behaviour. This gives improved density characteristics and consequently higher load bearing capacity, lower compressibility and better structural stability under traffic loading.

The untreated loamy sand showed a relatively loose particle arrangement and moderate moisture requirement for effective compaction with MDD of 1.62 g/cc and OMC of 11.88%. The untreated soil had moderate compaction efficiency and relatively poor inter-particle bonding due to the fact that the soil was mostly granular and had few particles.

Effect of Lime Stabilization on MDD and OMC

Addition of lime markedly affected the moisture-density relationship of the soil. With increase in lime content, the OMC decreased gradually and the MDD increased from 1.62 g/cc for untreated soil to 1.72 g/cc at 20% lime content. The increase in dry density is attributed to flocculation and aggregation of soil particles due to cation exchange reactions between lime and soil minerals . These interactions help in packing of particles and reducing the voids of the soil matrix, thereby increasing the efficiency of compaction.

The addition of lime can reduce the OMC by changing the soil structure and reducing the thickness of the diffuse double layer thus reducing the moisture for proper compaction. Furthermore, lime pozzolanic reactions promote the formation of cementitious compounds and particle bonds which improve density characteristics and workability. Similar trends were also observed in previous stabilization studies where lime treatment improved engineering performance and compaction behavior of granular soils .

Effect of Cement Stabilization on MDD and OMC

The compaction characteristics of cement treated soils also improved progressively with increase in stabilizer content. At 20% cement content, the maximum dry density (MDD) increased up to 1.74 g/cc with optimum moisture content (OMC) showing a marginal decrease. The increase in dry density is due to the hydration and cementation reactions which increase the inter-particle bonding and encourages the denser packing of soil particles.

The slight decrease of OMC with the increase of cement content may be attributed to the hydration reactions which consume some of the water added during the development of cementitious products. Cement stabilization increases the stiffness and decreases the compressibility by forming a rigid matrix around the soil particles. The better density properties exhibited by the cement treated samples show better ability to carry loads and better suitability as a subgrade for pavements.

Effect of Combined Lime–Cement Stabilization

Of all stabilization methods, the combined lime–cement stabilization showed the most improvements in compaction characteristics. The MDD increased up to 1.76 g/cc and the OMC further decreased in comparison with individually stabilized samples. The synergistic behavior is due to the combined effect of lime-induced modification and cementitious bonding formed by cement hydration.

Lime is responsible for initially improving the workability of the soil and the rearrangement of its particles by means of the mechanisms of flocculation. Cement is responsible for the rapid gain in strength and formation of a dense cementitious matrix. The combination of these stabilization mechanisms increases particle packing which reduces void ratio and improves the overall compactability of the soil The combined stabilization was therefore able to achieve better densification and engineering performance than individual stabilizers.

The results indicate that lime and cement stabilization greatly improve the compaction characteristics of loamy sand soil, while combined stabilization gives maximum improvement of density and workability. Enhanced compaction features directly lead to increased subgrade strength, improved pavement stability and less susceptibility to deformation under traffic loading conditions. The experimental data showed good consistency and reliability with low standard deviation among the replicate samples.

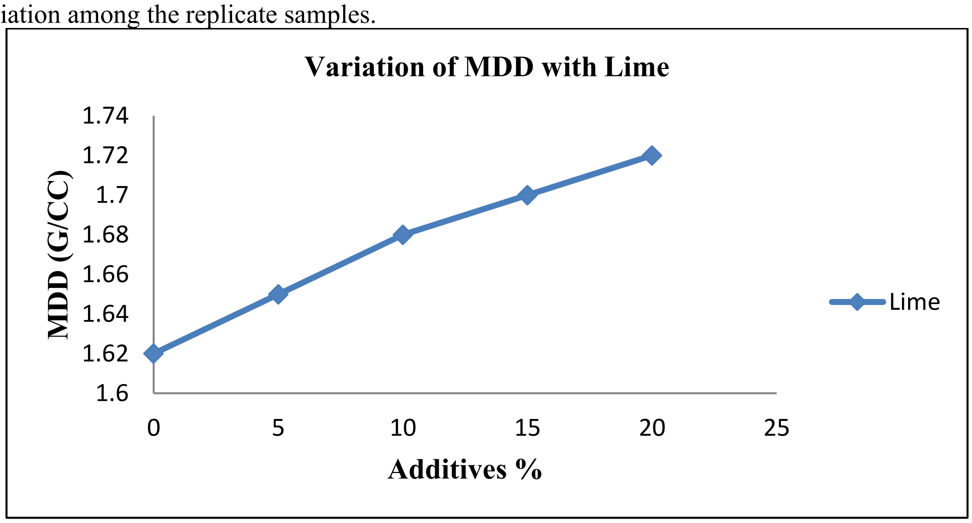

Figure 1: Variation of Maximum Dry Density with Lime Content

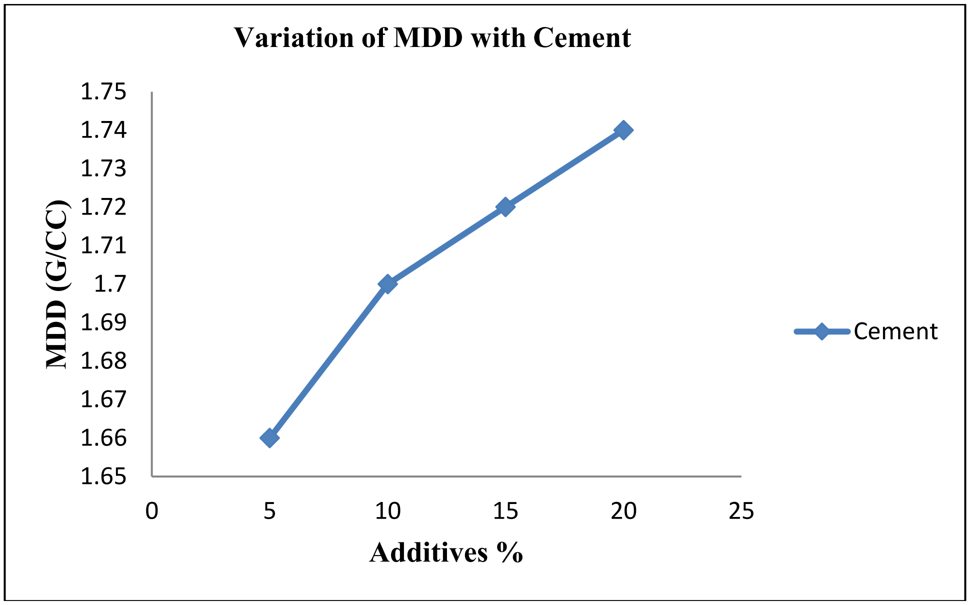

Figure 2: Variation of Maximum Dry Density with Cement Content

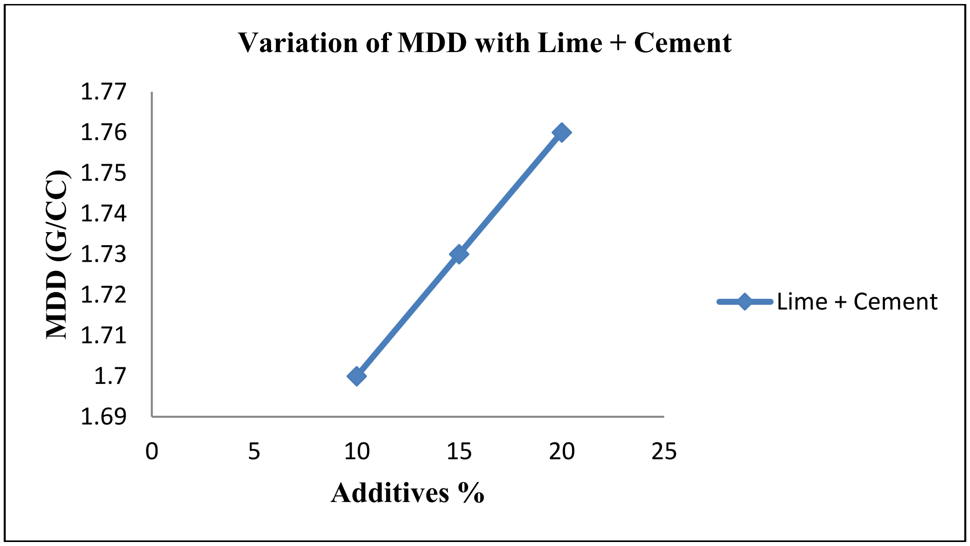

Figure 3: Variation of Maximum Dry Density with Combined Lime–Cement Content

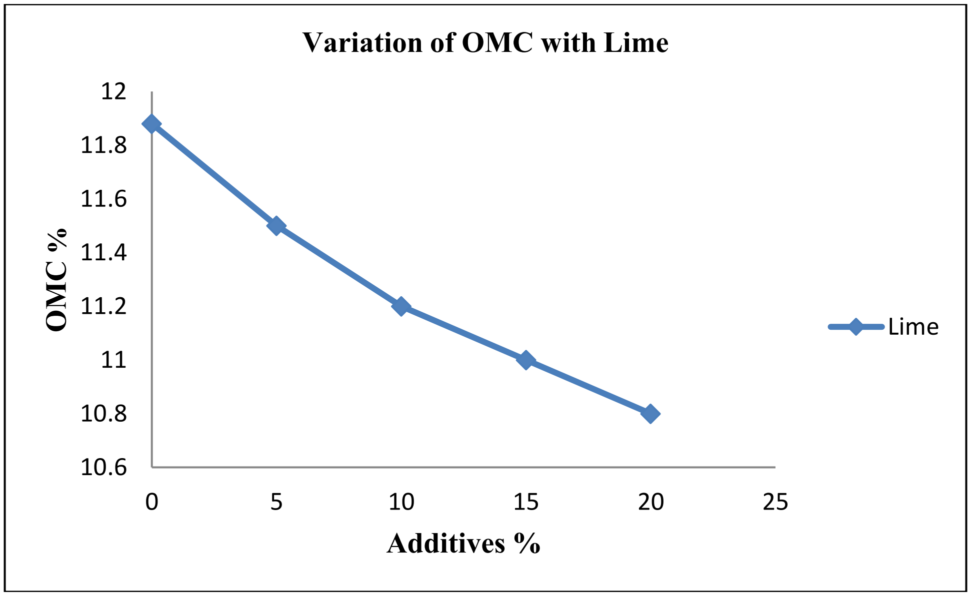

Figure 4: Variation of Optimum Moisture Content with Lime Content

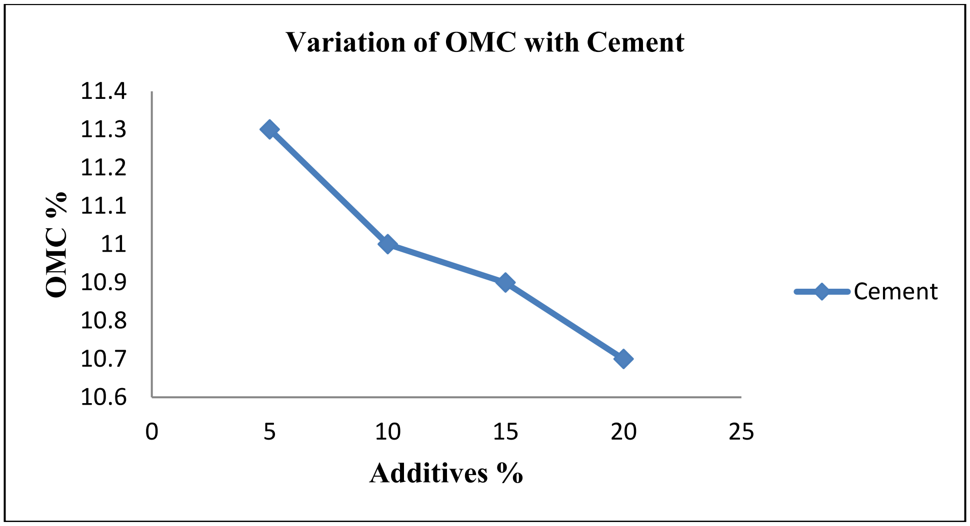

Figure 5: Variation of Optimum Moisture Content with Cement Content

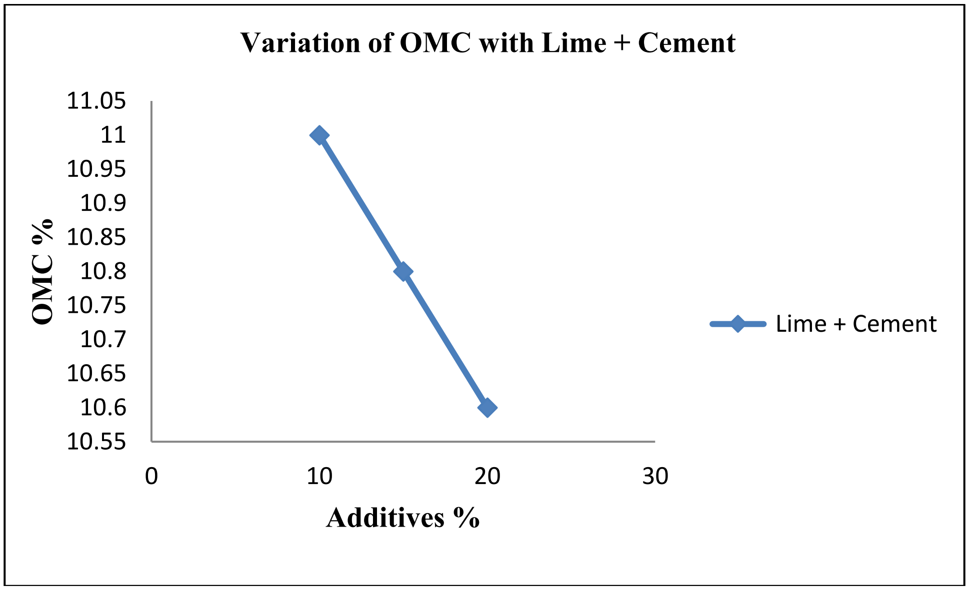

Figure 6: Variation of Optimum Moisture Content with Combined Lime–Cement Content

Direct Shear Test Results

The effect of stabilization by cement and lime on shear strength characteristics of loamy sand soil was studied by conducting direct shear test as per IS 2720 Part 13. The cohesiveness (c) and angle of internal friction (ϕ) of the untreated and stabilized soil samples were determined using the Mohr-Coulomb failure criterion under three normal loads of 136.2 kPa, 272.5 kPa and 408.8 kPa. Shear strength behavior is an important parameter in pavement subgrade evaluation as it determines the resistance to deformation, shear failure and load induced instability.

The untreated loamy sand soil had a cohesion of 28.78 kPa and an internal friction angle of 41.8°, and the shear resistance of the soil was mainly due to the frictional interaction between the soil particles, rather than the cohesive bond. Cohesion is low in granular soils that are untreated, have poor interparticle connection, and have little cementation.

Effect of Lime Stabilization on Shear Strength

After adding lime, stabilization increased the cohesion significantly by increasing the amount of stabilizer. The cohesion value for untreated soil was 28.78 kPa and for 10% and 20% lime stabilized soils it was increased to 42.26 kPa and 51.10 kPa respectively. The improvement in cohesion is mainly due to the cation exchange and pozzolanic reactions taking place between lime and soil particles. These reactions promote the flocculation and aggregation of particles, resulting in improved inter-particle bonding and improved resistance to shear deformation.

The angle of internal friction was little changed with increase in lime content and was approximately around 42°. This indicates that the gain in strength obtained from lime stabilization is mainly due to modification and cementation mechanisms, and not due to a major change in frictional resistance. Similar trends have been reported in previous studies where lime treatment significantly increased apparent cohesion with only limited changes in friction angle .

Effect of Cement Stabilization on Shear Strength

The shear strength characteristics of cement treated soil samples improved significantly. The cohesion increased with the increase in cement contents and attained the maximum value of about 43.05 kPa at 20% cement stabilization. The rise in cohesion is due to hydration reactions and the formation of cementitious compounds that cement soil particles together and form a rigid soil matrix.

The angle of internal friction changed slightly with the increase of cement content, being close to 41°. The slight improvement in frictional resistance at lower cement contents was attributed to interlocking effect of particles, while gain in strength at higher cement contents was dominated by cementation and bonding effects. The generation of cementitious products reduced the dependence of shear resistance on friction between particles and helped to improve the structural stability of the stabilized soil.

Effect of Combined Lime–Cement Stabilization

The highest shear strength improvement was achieved for stabilization with a mixture of lime and cement in comparison with the other stabilization techniques. The internal angle of friction was increased slightly to about 42.5° and the value of cohesiveness was found to be greater than 53 kPa. The improved performance is due to a synergistic interaction between cementation by the cement and alteration by the lime.

The cement gives fast hydration and strength development while the lime gives improved workability and particle rearrangement by flocculation mechanisms. Thus, the combined stabilization enhances the short- and long-term shear resistance by increasing the interaction between the particles, reducing the void spaces and developing a denser and more stable soil structure. The synergistic interaction between cementation and modification procedures increased the resistance to shear failure and deformation under the imposed loading conditions.

Results generally show cement stabilization, although cementation and hydration reactions are involved to some degree, increases strength while lime stabilization primarily influences apparent cohesion through pozzolanic reactions. The lime-cement treatment has most enhanced the shear strength characteristics of loamy sand soil and consequently its load bearing capacity and structural stability. The small standard deviation for the repeated samples indicates the experimental results are consistent and reliable.

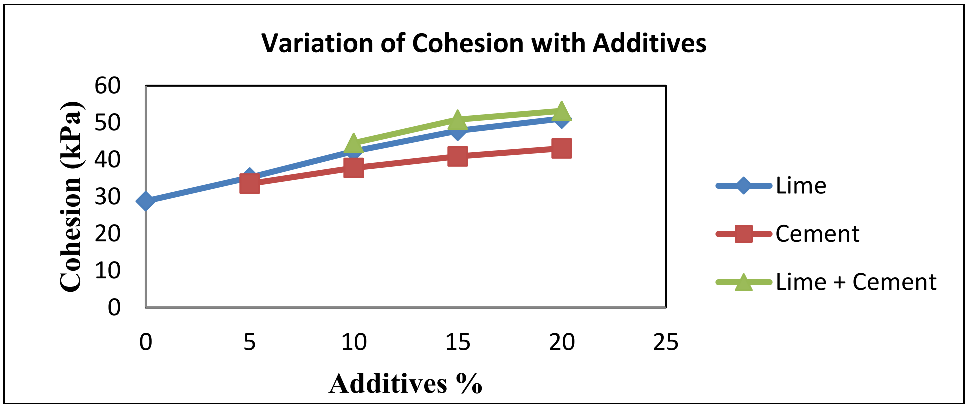

Figure 7: Variation of Cohesion with Stabilizer Type and Content

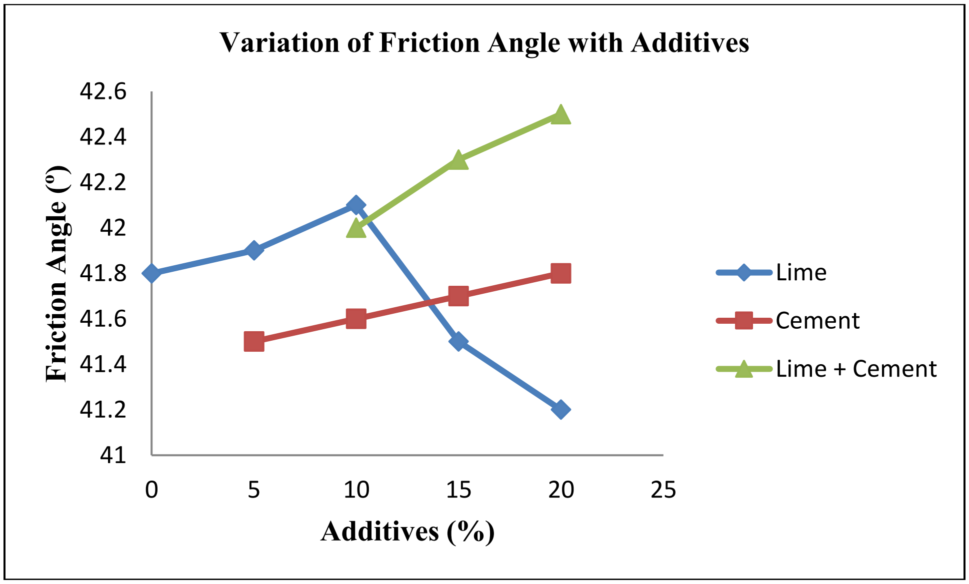

Figure 8: Variation of Internal Friction Angle with Stabilizer Type and Content

Unconfined Compressive Strength (UCS) Results

The effect of lime and cement stabilization on the behaviour of compressive strength of loamy sand soil was studied by carrying out Unconfined Compressive Strength (UCS) tests as per IS 2720 Part 10. The specimens were tested after curing for 7, 14 and 28 days after compaction at their respective Optimum Moisture Content (OMC). The UCS is the capacity of the soil to resist axial compressive stress and deformation. It is an essential parameter for evaluation of load bearing capacity, structural integrity and durability of stabilized subgrade soils.

The UCS of the untreated loamy sand soil was 112 kPa. This value is rather low as regards compressive strength. This suggests that the soil has a naturally weak bond and is not structurally stable under loading. Generally, coarse-grained soils with low UCS values are weakly cohesive with low cementation between particles.

Effect of Lime Stabilization on UCS

The compressive strength with lime stabilization increased steadily as the stabilizer concentration and cure time increased. The UCS value of 28 days cured soil increased from 112 kPa (untreated soil) to approximate 245 kPa for 20% lime content gradually. The increase of strength is mainly due to cation exchange and pozzolanic reactions between lime and soil particles

During stabilization, lime reacts with the silica and alumina present in the soil to form cementitious compounds which improve structural integrity and interparticle bonding. The steady increase in UCS with curing time is an indication of the gradual formation of cementitious products in the stabilized soil matrix and the continuing pozzolanic activity. Thus, lime stabilization greatly enhances resistance to deformation and long-term strength gain.

Effect of Cement Stabilization on UCS

Cement treated soils showed relatively higher early strength gain because of fast hydration reactions. The UCS increased gradually with increase in cement content. At 20% cement stabilization, the UCS was around 260 kPa after 28 days of curing. Thus, hydration products such as calcium silicate hydrates (C–S–H) and calcium aluminate hydrates (C–A–H) are formed, which create a stiff cementitious matrix around the soil particles.

The quick strength gain of the cement treated samples indicates enhancement in the stiffness, decrease in compressibility and improved load bearing capacity. Cement stabilization therefore provides immediate improvement in structural performance and goes a long way towards the development of stable pavement subgrade conditions.

Effect of Combined Lime–Cement Stabilization

The highest compressive strength was achieved by the combination of cement and lime stabilization among all the stabilizations. The UCS value was 285kPa for 20% combined stabilization after 28 days curing. The total stabilization shows the improved efficiency due to the synergy of process of cement hydration and lime modification.

Cement allows for rapid hydration and the formation of cementitious compounds. Lime improves soil workability, flocculation and particle aggregation initially. The combined action of the mechanisms of modification, pozzolanic reaction and cementation results in a more compact and robust soil matrix, with enhanced structural stability and resistance to compressive deformation.

The trend of UCS with curing time which increases continuously also supports the continuous production of cementitious products and the improved inter particle bonding in the stabilized soil structure. The combined stabilization greatly improves the engineering performance of loamy sand soil as subgrade of pavement, providing both short-term and long-term mechanical benefits.

The UCS test results demonstrate that the compressive strength characteristics of the loamy sand soil can be significantly improved by stabilizing with lime and cement. Out of the different combinations of the treatment, the lime-cement combination treatment gives the maximum gain in the load bearing capacity and in the structural integrity. The small standard deviation of the replicate samples indicates that the experimental results are highly consistent and reliable.

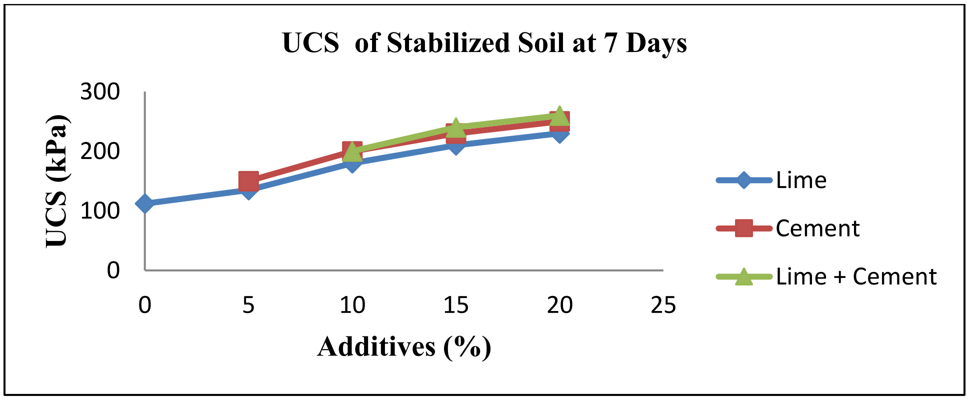

Figure 9: UCS Development of Stabilized Soil at 7 Days

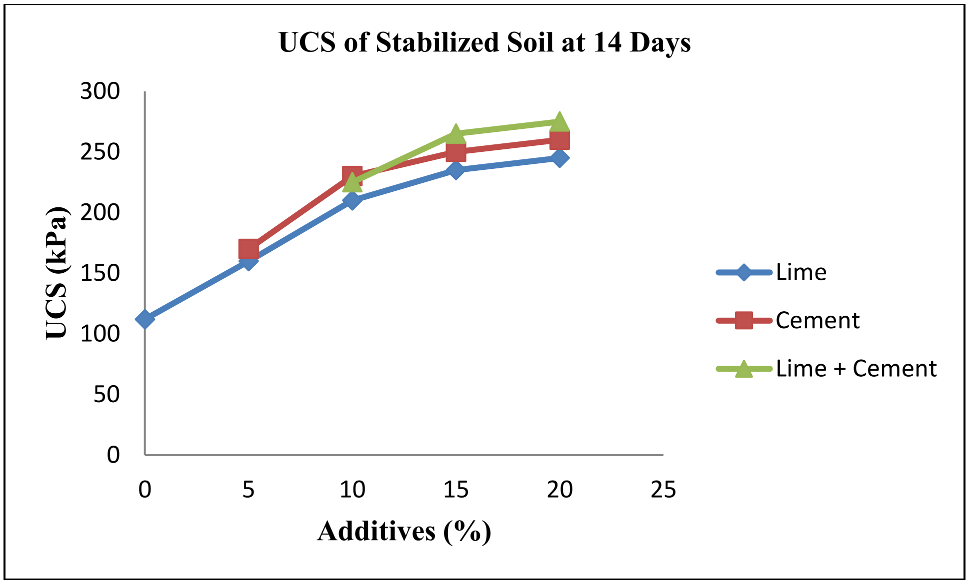

Figure 10: UCS Development of Stabilized Soil at 14 Days

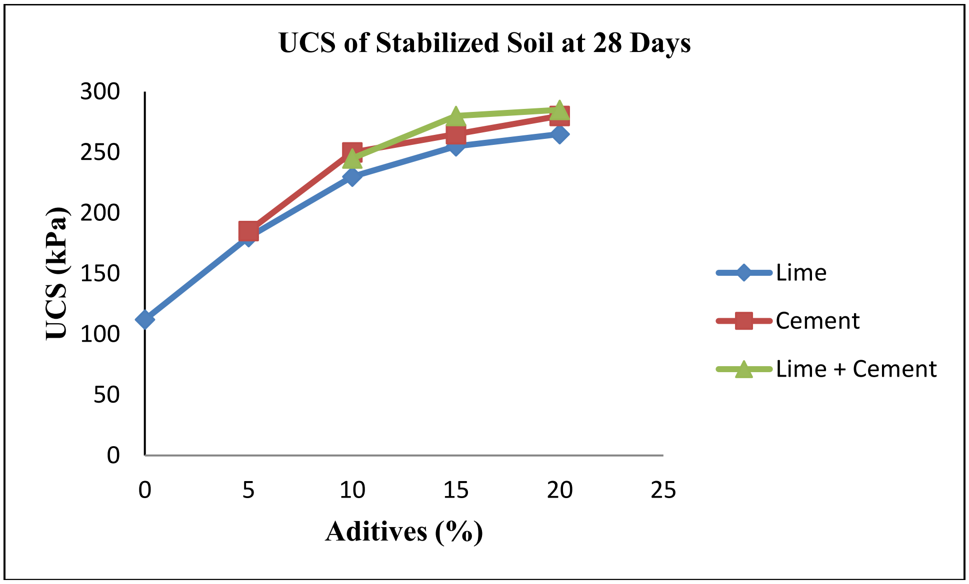

Figure 11: UCS Development of Stabilized Soil at 28 Days

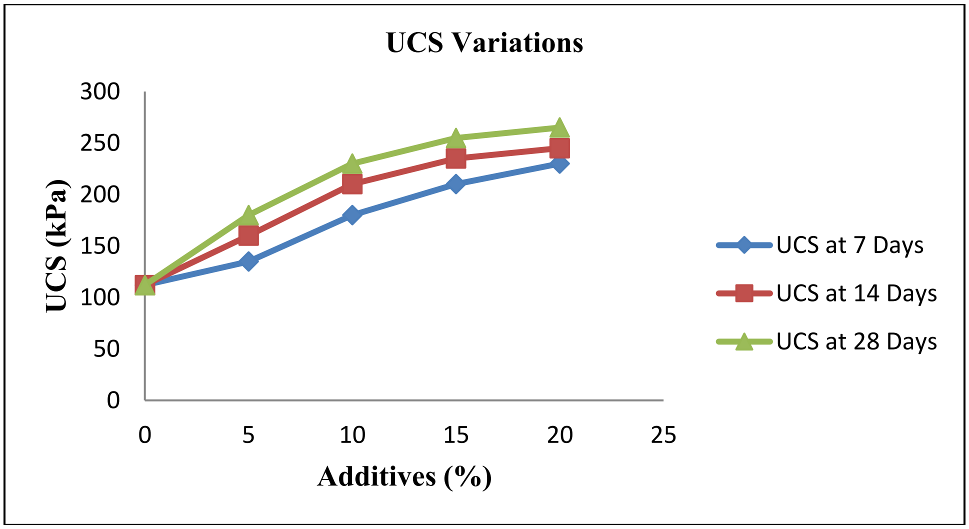

Figure 12: Combined UCS Development of Stabilized Soil

California Bearing Ratio (CBR) Test Results

The effect of lime and cement stabilization on the bearing capacity and the suitability of loamy sand soil for pavement was studied through the California Bearing Ratio (CBR) tests carried out as per IS 2720 Part 16. Among the most important parameters for the design of flexible pavements is the CBR test to measure the load bearing capacity and resistance of subgrade soils to penetration under loading conditions. The efficiency of chemical stabilization was evaluated on untreated and stabilized soil samples.

The untreated loamy sand soil showed comparatively low values of the soaked and unsoaked CBR values which indicated low subgrade strength and moderate resistance to penetration under loading conditions. The reduction in the soaked CBR value for the untreated soil reflects the negative influence of moisture on the stiffness and the structural stability of the soil. If not stabilized, these low bearing capacity characteristics could lead to excessive pavement deformation, rutting and increased pavement thickness needs.

Effect of Lime Stabilization on CBR

Lime stabilization showed a gradual increase in both soaked and unsoaked CBR values with an increase in stabilizer amount. The increase in CBR is mainly due to cation exchange and pozzolanic reactions between lime and soil particles resulting in improved inter-particle bonding and reduced susceptibility of the soil to moisture induced weakening.

The increase in soaked CBR values indicates better resistance against softening under saturated conditions whereas the increase in unsoaked CBR values indicates better penetration resistance and load bearing capacity. The improvement of the CBR behavior is also in agreement with increase in cohesion and dry density found in Direct Shear and Standard Proctor Tests respectively. Hence, lime stabilization has a major contribution to the improved subgrade performance and pavement stability.

Effect of Cement Stabilization on CBR

The CBR values of the cement-treated soils were higher than those of the lime-treated samples, particularly at higher stabilizer contents. The rise of CBR values is attributed to the hydration and cementation reactions which result in the formation of rigid cementitious compounds in the soil matrix. These reactions lead to higher stiffness, lower compressibility, and higher resistance against penetration under load conditions.

The improved CBR behavior of cement stabilized soil indicates the improvement of particle bonding and stress transfer mechanism of compacted soil structure . Hence, cement stabilization improves the subgrade strength quickly and helps in better pavement performance under traffic loading conditions.

Effect of Combined Lime–Cement Stabilization

Among all the stabilization methods, the combined lime and cement stabilization gave the maximum improvement in soaked and unsoaked CBR value. The combined effect of cement hydration and lime alteration led to denser and stronger soil matrix with better penetration resistance and better load carrying capacity.

Cement forms cementitious compounds that provide stiffness and structural strength. Initially lime helps to improve the workability and particle structure of the soil by flocculation mechanisms. The combined stabilization was superior to the single stabilizers in adaptability to the pavement and subgrade properties.

The increased CBR values after stabilisation shows the better performance characteristics of the pavement and increased bearing capacity of the stabilized loamy sand soil. Increase in the strength of subgrade results in reduction of pavement thickness, long term maintenance cost and increases the service life of flexible pavement systems. The small standard deviation of the replicate samples shows that the experimental results are consistent and reliable.

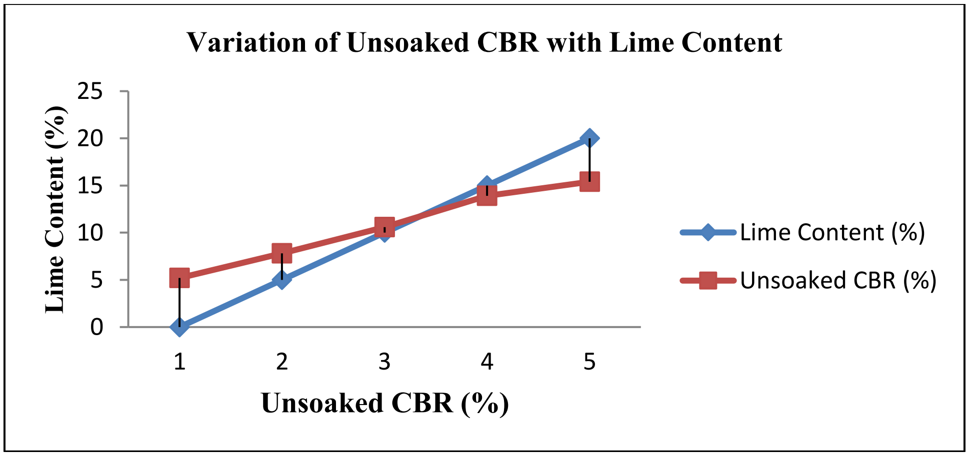

Figure 13: Variation of Unsoaked CBR with Lime Content

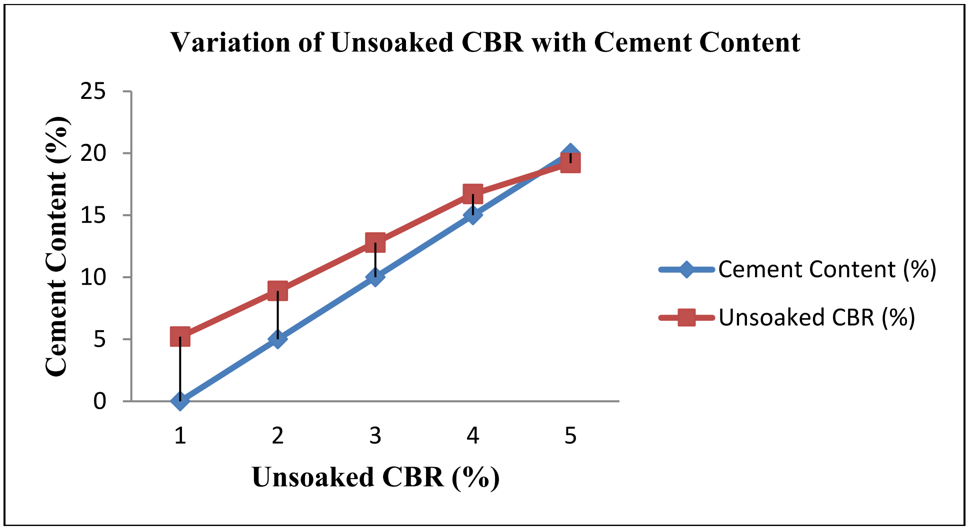

Figure 14: Variation of Unsoaked CBR with Cement Content

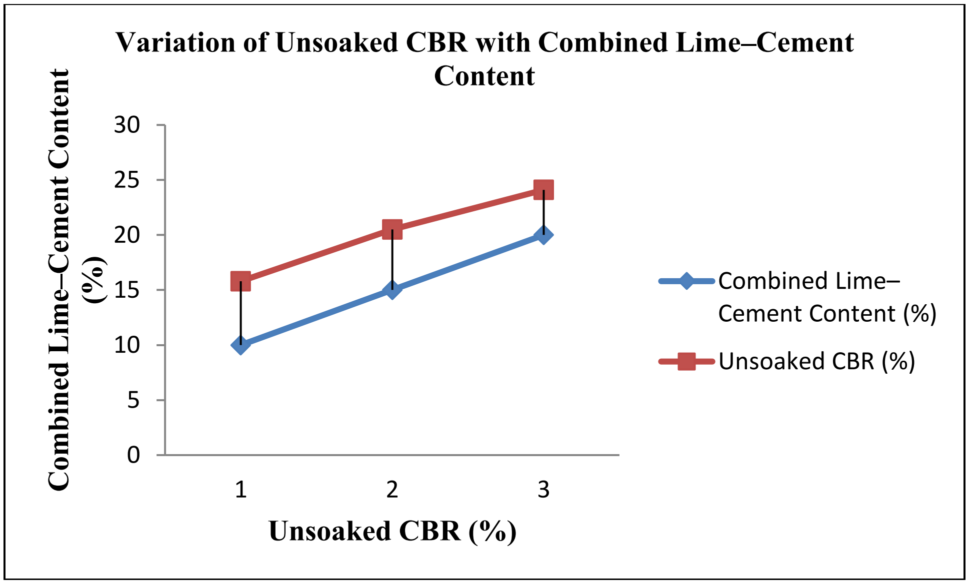

Figure 15: Variation of Unsoaked CBR with Combined Lime–Cement Content

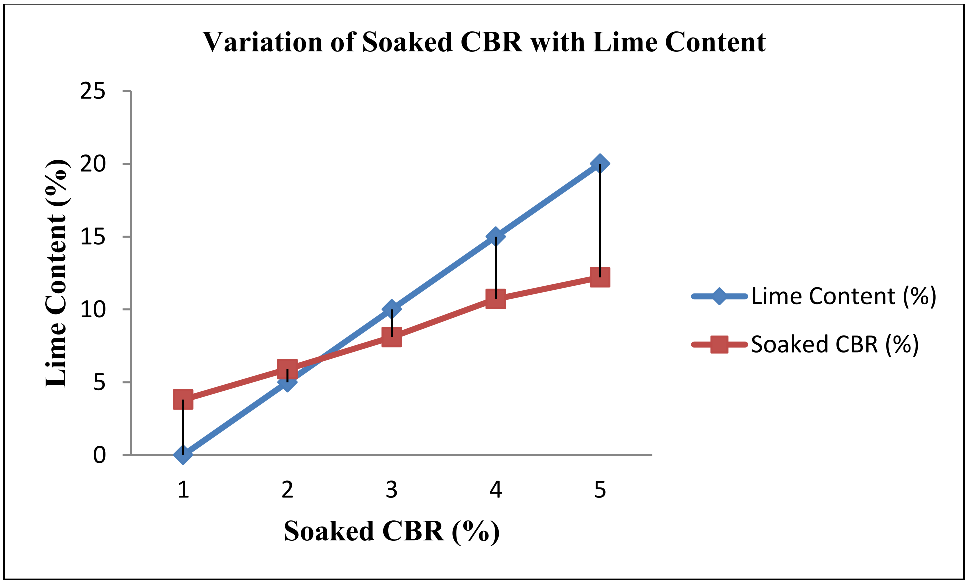

Figure 16: Variation of Soaked CBR with Lime Content

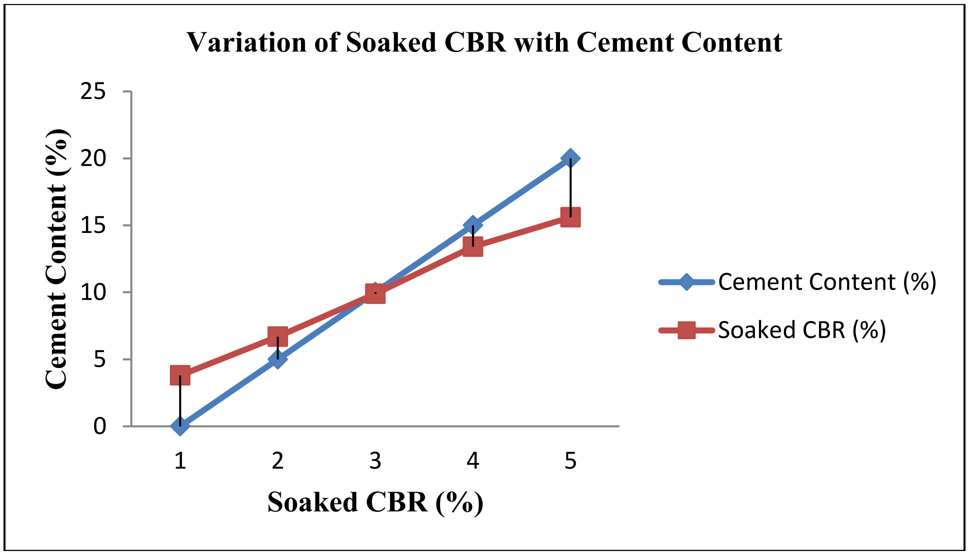

Figure 17: Variation of Soaked CBR with Cement Content

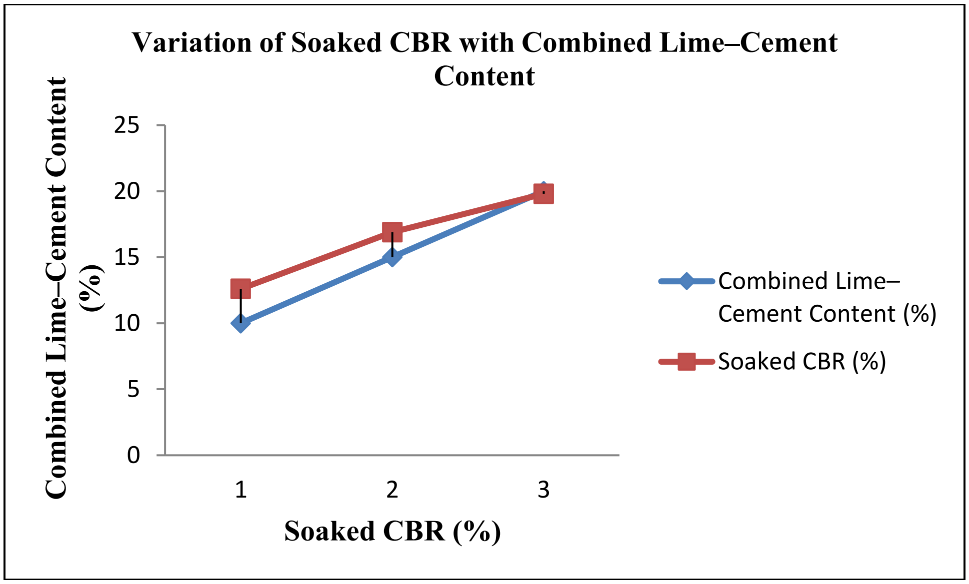

Figure 18: Variation of Soaked CBR with Combined Lime–Cement Content

Comparative Evaluation of Stabilization Performance

Comparison of lime, cement and lime-cement stabilization shows that all the stabilizers have improved the engineering behavior of loamy sand soil to a large extent. The bearing capacity, shear strength, compressive strength, and compaction characteristics were all enhanced with the increase of the stabilizer content. Lime stabilization was mainly due to pozzolanic processes which improved the cohesiveness and long-term strength, while cement stabilization showed a higher early strength gain due to cementation and hydration mechanisms.

The lime-cement combination was the best stabilization method overall for cohesiveness, Maximum Dry Density (MDD), Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR). The lime alteration and cement hydration helped to produce a denser and stable soil structure with better interparticle bonding, reduced vacancy ratio and increased load bearing capacity.

Overall, the results indicate that stabilization greatly improves the potential of loamy sand soil for pavement subgrade. The improvement of the engineering properties by lime and cement treatment will lead to a reduced thickness of flexible pavement solutions, which will be more stable structurally and will require less maintenance in the long run. Hence, the results of the current investigation indicate that combined lime-cement stabilization is a feasible and effective approach to enhance the geotechnical behavior of problematic loamy sand soils used in transportation infrastructure projects.

Conclusion

The study examined the possibility of stabilizing locally available loamy sand soil using lime and cement to improve its engineering properties for use as pavement subgrade. Laboratory tests like compaction, direct shear, UCS and CBR shows that stabilization significantly improves the strength, density and bearing capacity of the soil in comparison to untreated state.

The results revealed that increase in stabilizer content resulted in decrease of Optimum Moisture Content (OMC) and increase of Maximum Dry Density (MDD), shear strength, compressive strength and CBR values . The combined lime-cement treatment gave the highest strength and bearing capacity of all the mixtures studied because of the synergistic effects of pozzolanic and cementitious reactions.

Therefore, lime-cement stabilization can be considered as an efficient and sustainable method to enhance the durability and service life of pavement subgrades and the performance of loamy sand soils.

Recommendations for Future Work:

The present study has shown that stabilization of loamy sand soil with lime and cement markedly improved its engineering behaviour but further studies are suggested to increase its practical utility. Future research should consider longer curing times, field-scale trials to verify laboratory results, and evaluation of the long-term durability of stabilized soils subjected to traffic loading and environmental effects. The use of sustainable additions such as fly ash, rice husk ash, and ggb can also be studied. Numerical modeling and economic analysis are useful tools in assessing the long term performance and cost effectiveness of stabilization procedures in pavement applications, but advanced microstructural analyses (SEM, XRD and EDS) can be performed to better understand the strength development mechanisms.

References

1. Abdalla, T. A., & Salih, N. B. (2020). Hydrated lime effects on geotechnical properties of clayey soil. *Journal of Engineering*, *26*(11), 150-169.
2. Ali, A. B., Rashid, M., Rahman, Z., Talukder, T., & Joy, I. A. (2023). A comparative study on soil stabilization techniques. *Journal of Advances in Geotechnical Engineering*, *6*(2), 19-25.
3. Al-Subari, L., Aldakheel, F., Al-Mahbashi, A., & Huseien, G. F. (2023). Life cycle assessment of soil stabilization using cement and waste-based additives. *Construction and Building Materials, 405*, 133286.
4. Amadi, A. A. (2025). Stabilization characteristics of cemented lateritic soil using different cement types. *Results in Engineering, 25*, 103456.
5. Azimi, M., et al. (2024). Biopolymer stabilization of clayey soil: Strength and durability performance. *Transportation Geotechnics, 48*, 101234.
6. Bae, H. J., & Siddiki, N. Z. (2018). Long-term behavior of soil-cement-lime treated expansive clay. Journal of Materials in Civil Engineering, 30(7), 04018044.https://doi.org/10.1061/(ASCE)MT.1943-5533.0002254
7. Bouras, F., Al-Mukhtar, M., Tapsoba, N., Belayachi, N., Sabio, S., Beck, K., & Martin, M. (2022). Geotechnical behavior and physico-chemical changes of lime-treated and cement-treated silty soil. *Geotechnical and Geological Engineering*, *40*(4), 2033-2049.
8. Budhu, M. (2021). *Soil Mechanics and Foundations* (4th ed.). Soil Mechanics and Foundations Wiley.
9. Coduto, D. P., Yeung, M. R., & Kitch, W. A. (2022). *Geotechnical Engineering: Principles and Practices* (3rd ed.). Geotechnical Engineering: Principles and Practices Pearson.
10. Consoli, N. C., da Silva, A., Barcelos, A. M., Festugato, L., & Favretto, F. (2020). Porosity/cement index controlling flexural tensile strength of artificially cemented soils in Brazil. *Geotechnical and Geological Engineering*, *38*(1), 713-722.
11. Daimary, N., Sarmah, D., Bhattacharjee, A., Barman, U., & Saikia, M. J. (2025). Geotechnical Performance of Lateritic Soil Subgrades Stabilized with Agro-Industrial Waste: An Experimental Assessment and ANN-Based Predictive Modelling. *Geotechnics*, *5*(3), 65.
12. Das, B. M., & Sobhan, K. (2022). *Principles of Geotechnical Engineering* (10th ed.). Principles of Geotechnical Engineering Cengage Learning.
13. Engineering, A. (2024, February 27). Unconfined compressive strengths in Geotech engineering — AWM Engineering. AWM Engineering. https://www.awm-engineering.com/blog/unconfined-compressive-strengths-in-geotech-engineering
14. Gruchot, A., Kamińska, K., & Woś, A. (2025). The Effects of Lime and Cement Addition on the Compaction and Shear Strength Parameters of Silty Soils. *Materials*, *18*(5), 974
15. Gruchot, A., Kamińska, K., & Woś, A. (2025). The Effects of Lime and Cement Addition on the Compaction and Shear Strength Parameters of Silty Soils. *Materials*, *18*(5), 974.
16. INDIANA DEPARTMENT OF TRANSPORTATION, & Geotechnical Engineering Division, I. (2021). FIELD TESTING OF SOIL, GRANULAR SOIL, COARSE AGGREGATE AND CHEMICALLY MODIFIED SOILS. https://www.in.gov/indot/doing-business-with-indot/files/Fieldtesting.pdf

17. Li, S., Liu, S., Zhang, T., Wang, Z., & Zhao, W. (2025). Experimental study on the durability and microstructural characteristics of lime-stabilized silty clay in seasonally frozen region. *Construction and Building Materials*, *463*, 140158.
18. Magara, D., & She, H. (2024). A systematic review of the effects of soil stabilization on soil mechanical properties: a comparative study of fly ash, cement and lime. *Open Access Libr. J*, *11*, 1-19.
19. Nan, J., Liu, J., Chang, D., Lee, J. S., & Li, X. (2025). Non-destructive evaluation of freeze-thaw performance in ISS-lime-fly ash stabilized saline soils. *Journal of Cleaner Production*, *528*, 146728.
20. Onyelowe, K. C., et al. (2024). Estimating the strength of soil stabilized with cement and lime using predictive modeling approaches. *Scientific Reports, 14*, Article 15037.
21. Raju, E. R., Phanikumar, B. R., & Heeralal, M. (2021). Effect of chemical stabilization on index and engineering properties of a remoulded expansive soil. *Quarterly Journal of Engineering Geology and Hydrogeology*, *54*(4), qjegh2020-142.
22. Rehman, Z. U., Rauf, M., Chaozhe, J., Xu, F., Jamal, A., Rahman, A., & Iqbal, J. (2025). Clayey soil stabilization with ordinary Portland cement using the stabilized soil as a mortar. *Discover Geoscience*, *3*(1), 30.
23. Roshan, M. J., & Rashid, A. S. B. A. (2024). Geotechnical characteristics of cement stabilized soils from various aspects: A comprehensive review. *Arabian Journal of Geosciences*, *17*(1), 1.
24. Roshan, M. J., Horpibulsuk, S., Arulrajah, A., & Mohajerani, A. (2023). Geotechnical characteristics of cement stabilized soils from various aspects: A comprehensive review. *Geotechnical and Geological Engineering*.
25. Sengupta, J., Dhang, N., & Deb, A. (2025). Life cycle sustainability assessment of one-part alkali-activated concrete activated with industrial grade soda ash and hydrated lime-A comparative study. *Sustainable Chemistry and Pharmacy*, *48*, 102254.
26. Shen, Y. S., Tang, Y., Yin, J., Li, M. P., & Wen, T. (2021). An experimental investigation on strength characteristics of fiber-reinforced clayey soil treated with lime or cement. *Construction and Building Materials*, *294*, 123537.
27. Sukmak, G., Horpibulsuk, S., Shen, S. L., Arulrajah, A., & Disfani, M. M. (2023). Generalized strength prediction equation for cement stabilized clays. *Engineering Geology, 315*, 107010.
28. Sukmak, G., Sukmak, P., Horpibulsuk, S., Arulrajah, A., & Horpibulsuk, J. (2023). Generalized strength prediction equation for cement stabilized clayey soils. *Applied Clay Science*, *231*, 106761.
29. Sukmak, G., Sukmak, P., Horpibulsuk, S., Phunpeng, V., & Arulrajah, A. (2024). An approach for strength development assessment of cement-stabilized soils with various sand and fine contents. *Transportation Geotechnics*, *48*, 101323.
30. Suparma, L. B., & Rifa'i, A. (2024). Determination of optimum cement content for silty sand soil stabilization as the base course. *Geomate Journal*, *26*(115), 124-133.
31. Wan, X., Ding, J., Jiao, N., Mou, C., & Gao, M. (2022). Mechanical and microstructural properties of cement-treated marine dredged clay with red mud and phosphogypsum. *Bulletin of engineering geology and the environment*, *81*(7), 266.
32. Wang, S., Zhang, N., Wang, J., & Li, Y. (2023). Strength performance and stabilization mechanism of fine sandy soil treated with cement and metakaolin. *Sustainability, 15*(4), 3431.
33. Zafar, T., Ansari, M. A., & Husain, A. (2023). Soil stabilization by reinforcing natural and synthetic fibers–A state of the art review. *Materials Today: Proceedings*.