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COMPARATIVE EFFICACY OF CONVENTIONAL STABILIZERS IN IMPROVING ENGINEERING BEHAVIOR OF EXPANSIVE SUBGRADES

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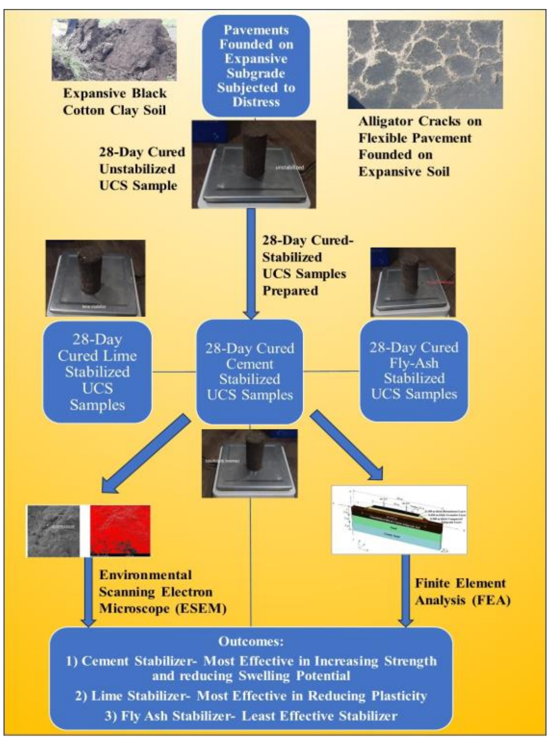
Graphical abstract



Abstract

This paper addresses the critical issue of distress in flexible pavements built on expansive Black Cotton soil, where seasonal moisture variations lead to swelling and shrinking, posing a serious threat to durability. Despite extensive research utilizing conventional stabilizers such as cement, lime, and fly ash, the comparative effectiveness of these stabilizers remains uncertain. This study employs a comprehensive approach, integrating conventional tests and microanalysis techniques to assess the engineering behavior of stabilized expansive soil samples. The investigation includes tests like Unconfined Compressive Strength (UCS) for strength evaluation, Free Swelling Index (FSI) for swelling potential estimation, and Atterberg's limits for evaluating plasticity properties. Additionally, Environmental Scanning Electron Microscope (ESEM) microanalysis is employed to examine the morphology of uncured-unstabilized expansive soil samples and those stabilized with cement, lime, and fly ash after a 28-day curing period. Results indicate that cement emerges as the most effective stabilizer, significantly reducing swelling by up to 42% and increasing strength post-curing by a remarkable fivefold compared to unstabilized-uncured expansive soil. Lime demonstrates exceptional efficacy in reducing plasticity, diminishing Liquid Limit (LL) and Plasticity Index (PI) by 30% and 79%, respectively. In contrast, fly ash is identified as least effective stabilizer, displaying the lowest efficacy in reducing swelling, plasticity, and enhancing strength. Furthermore, the study extends its analysis to evaluate the impact of these stabilizers on rutting and fatigue life of pavements through Finite Element Analysis (FEA) using PLAXIS. The findings contribute valuable insights for practitioners and researchers seeking optimal stabilizer selection for expansive soil-based pavement projects.

Keywords: Expansive clay subgrades, sustainable stabilizing materials, soil stabilization, lime, cement, fly ash stabilization

1.0 INTRODUCTION

Infrastructure has remained the key element in the growth of economy of any country. Among different types of infrastructure pavement network plays a vital role. This growth in economy is the outcome of overall development of a region taking place due to development in different sectors such as industry, commerce, health, culture, education, etc. which is improved due to better connectivity by pavement network. One of the important indicators of Logistics Performance Index (LPI) published by World Bank is affected by the parameters like quality of pavement infrastructure [1]. It has been observed that the quality of pavement network is affected due to surface distress, cracks, deformations, and disintegration. One of the major reasons of these distress conditions is weak and soft subgrades like expansive clay subgrades which are subjected to frequent volume changes due to swell-shrink cycles caused because of seasonal moisture variations. In India, about 20 % of land has been covered with this soil in seven states of India, namely Maharashtra, Karnataka, Andhra Pradesh, Telangana, Chhattisgarh, Madhya Pradesh, and Gujarat. Apart from India the expansive subgrade soils are also posing problems in Australia, Canada, China, Israel, South Africa, and United States of America, etc. With the increasing moisture there has been reduction in shear strength of this soil to considerable extent coupled with swelling and with the reduction in moisture content there is shrinking of soil causing distress conditions in pavements.

Many investigators have tried to improve the engineering behavior of such soils by reducing swelling and plasticity while increasing their strength. For this purpose, they have used different types of stabilizers which cover both non-conventional and conventional materials. In the non-conventional materials, researchers have used Expanded Poly-Styrene (EPS) Geofoam [2], Geofibers [3], Geofoam Granules Columns (GGC) [4], Geogrids [5], Geocells [6], Ground Granulated Blast Furnace Slag (GGBFS) [7], Rice Husk Ash [8], Pond Ash [9] to control the swelling properties of expansive soils.

Many researchers have used conventional stabilizers such as lime, cement, and fly ash. Researchers [10], [11], [12], [13], [14] have shown that lime can be used to reduce the plasticity and swelling properties of soils and increasing the strength of such soils. The effect of fly ash as stabilizer on soil properties like plasticity, hydraulic conductivity and swelling properties has been studied by the researchers [15]. Some researchers have used bottom ash for stabilization of expansive soils[16]. Researchers [17] have used the another conventional stabilizer that is cement.

After going through the literature, it is observed that, the non-conventional stabilizers are used primarily in the academic research. However, its use for commercial and actual pavement construction projects is limited due to the requirement of its availability in considerable quantity for such projects. The conventional stabilizers like Fly Ash, Lime and Cement are therefore popularly used in pavement construction project for stabilization of expansive soils. However, each of these stabilizers have their individual merits and demerits. Fly ash is an inert material. However, 'C' class fly ash contains up to 65 % of lime (CaO) which reacts with clay minerals causing base exchange reactions responsible for stabilization. 'F' class fly ash contains only up to 10 % lime (CaO) and therefore, to satisfy such reactions more percentage of 'F' class fly ash is required as compared to 'C' Class fly ash. Lime (CaO) reacts directly with the clay minerals to cause its stabilization through base exchange reactions controlling plasticity. This is short-term benefit of the stabilization, whereas, the pozzolanic reactions in long-term help for strength gain. Cement has also proved its performance as a stabilizer over a long time, but it is costly as compared to lime and fly ash.

This study therefore, compares the efficacy of these three conventional stabilizers by comparing the improvement caused by them in stabilized soil over unstabilized soil with respect to engineering behavior of expansive soil. The parameters for measurement of improvement in engineering behavior are reduction in plasticity (LL and PI), swelling (FSI) and increase in shear strength (Unconfined Compressive Strength (UCS)) and microlevel changes taking place in the stabilized subgrade responsible for improvement in this behavior (Environmental Electron Scanning Microscope (ESEM) and Energy Dispersive Spectrometry (EDS)). The materials used and the methodologies adopted for studying these parameters are mentioned in the subsequent section.

2.0 METHODOLOGY

2.1 Materials

2.2.1 Subgrade Soil

Expansive Black Cotton Clay soil from Ahmednagar district of Maharashtra in central India is used for this study.

2.2.2 Stabilizers

The stabilizing materials used for this study are class 'F' fly ash, 100% pure Calcium Oxide (CaO) (Lime) and 53 Grade Ordinary Portland cement.

2.2 Methods

2.2.1 Methods of Testing Adopted for Un-stabilized Soil Samples

Initially, for soil identification, 'Grain Size Analysis' has been carried out as per IS 2720 Part 4-1985. The Liquid

Limit (LL) and the Plastic Limit (PL) tests have been performed on the soil samples as per IS 2720 Part 5-1985, in order to assess the plasticity properties. For assessing the swelling property of the soil, Free Swell Index (FSI) Tests have been performed on the soil samples as per IS 2720 Part 40- 1977. After confirming the soil as highly plastic expansive clay soil, its compaction properties that is water content- dry density relation have been studied in unstabilized state by performing Light Weight Compaction Test as per IS 2720 Part 7 -1980.

The Calcium Oxide (CaO), Silica (SiO2), Alumina (Al2O3), Sodium Oxide (Na2O), Potassium Oxide (K2O), etc. present naturally in the expansive soil are responsible for the efficacy of the chemical stabilization of the expansive soil occurring through ion-exchange reactions and pozzolanic reactions. The percentage of these natural constituents as chemical elements also possibly have a role in deciding the effective percentage of the stabilizers. It has been thought necessary to confirm their presence in the unstabilized soil as they have an active role in stabilization, when flay ash, cement and lime stabilizers are added to expansive soil. Therefore, the chemical analysis of the unstabilized expansive subgrade soil has been performed. Table 1 shows the major chemical elements along with their percentages present in the unstabilized expansive subgrade soil used in this study which have active role in chemical stabilization of expansive subgrades by ion exchange. The fly ash predominantly consists of non-plastic silt sized material the composition of which is given in the Table 1. The typical composition of Ordinary Portland Cement is also shown in Table 1.

Table 1 Chemical Compositions of Unstabilized Expansive Subgrade Soil

Chemical Elements	**In Unstabilized Expansive Soil Percentages (%)**
Silica (SiO_2)	31.90
Alumina (Al_2O_3)	8.36
Titanium Dioxide (TiO_2)	0.14
Manganese Dioxide (MnO)	0.50
Calcium Oxide (CaO)	15.98
Magnesium Oxide (MgO)	3.61
Sodium Oxide (Na_2O)	1.26
Potassium Oxide (K_2O)	0.6
Iron Oxide (Fe_2O_3)	11.03
Loss on Ignition	24.86

The strength of the subgrade soil in unstabilized state is estimated for zero-day, 14-day and 28-day cured samples by performing Unconfined Compressive Strength (UCS) Test as per IS 2720 Part 10 -1973. For this test the samples have been molded at the MDD and OMC because it has been observed in earlier studies [18] that, the swelling pressure magnitudes in expansive soils are maximum at OMC when soils are compacted at MDD.

The curing of the samples has been carried out by preserving the moisture content in the soil samples throughout the curing periods of 14-day and 28-day by placing the samples in the sealed polyethylene bags. These bags have been further wrapped in the moist jute cloth. The jute cloth outside is unwrapped periodically on reduction of moistness, moistened again and re-wrapped to keep it consistently in moist condition during the curing period. The sealed bags prevent the entry of moisture in the samples from outside the bags. The moist jute cloth surrounding the bags, provide the humid surrounding preventing the transfer of moisture from the samples in the bag to outside due to humidity differential within and outside the bag. The success of the curing system has been studied by weighing the samples immediately after the molding before sealing in the bags and later after completion of the curing period before testing for UCS. It has been observed that the weights of the samples at the end of curing period have been 98% to 99% of those at the time of their molding indicating the preservation of the moisture, which means the curing was successful.

2.2.2 Methods of testing adopted for Stabilized Soil Samples

After assessing the plasticity, swelling and strength properties of unstabilized expansive soil samples, the same properties were assessed by performing all these tests on soil samples stabilized with Fly Ash at 20 %, 24 % ,28 %, 29% and 30%, with cement at 8 %, 10 %, 12%, 13% and 14%, and with lime at 4 %, 5 %, 6 %, 7% and 8%. These percentage-ranges were selected based on the general literature survey. The effective percentage for each of the stabilizers is estimated based on the criteria of maximum reduction in plasticity and swelling (that is minimum LL, PI and FSI) compared within the samples with selected percentages.

Thereafter, the compaction properties (MDD and OMC) at these effective percentages have been obtained for stabilized soils using light weight compaction Proctor test. The UCS samples for stabilized soils with 0-day, 14-day and 28-day curing periods have been molded using these MDD and OMC values. The results of plasticity (LL and PI), swelling (FSI) and strength properties (UCS) for stabilized soils with the three stabilizers have then been compared with those for uncured- unstabilized soil samples respectively.

2.2.3 ESEM Tests for Studying the Morphology of the Samples

The ESEM images of the 28-day cured unstabilized and stabilized samples were studied with respect to morphology, of their surface and to compare the crack widths using ImageJ software. The objective of ESEM study was to understand the effect of the reactions taking place post-stabilization in case of three stabilizers which decide their efficacy in strength development.

2.2.4 Numerical Analysis for Assessment of Rutting and Fatigue Life of Pavement

The study employed Finite Element Analysis (FEA) through PLAXIS software to examine and compare the expected performance of a pavement. The primary focus was on evaluating the subgrade rutting life and fatigue life of the pavement, when situated on expansive subgrade soil under both unstabilized and stabilized with cement, fly ash and lime stabilizers. The assessment of pavement rutting life and fatigue life included the estimation of load carrying capacity in terms of Million Standard Axles, based on the three-layer theory referred in Indian pavement design codes [19].

$$NR=1.4100x10^{-08}[(1/\varepsilon_V)^{4.5337} \quad (1)$$

(for 90 % reliability as per reliability criteria for national highway)

Where, N_R = Subgrade Rutting Life (It is calculated as a cumulative equivalent number of 80 kN standard axle loads responsible for the critical rut depth of 20 mm or more)
εv = Vertical compressive strain at the top of the subgrade calculated using PLAXIS 3D

$$Nf=0.5161xCx10^{-04}x[(1/\varepsilon_t)]^{3.89}x[(1/M_{RM})^{.0854} \quad (2)$$

(for 90 % reliability as per reliability criteria for national highway)

Where,
C= Constant = 10M, and

$$M = 4.84\ [(V_{be}/V_a+V_{be})- 0.69]$$

V_a = Per cent volume of air void in the mix used in the bottom bituminous layer, and in this study, it was considered as 6%

V_{be} = Per cent volume of effective bitumen in the mix used in the bottom bituminous layer which was considered as 5% in this study

N_f = Fatigue life of bituminous layer (It is calculated as a cumulative equivalent number of 80 kN standard axle loads responsible for the critical cracked area of 20 % or more of paved surface area)

ε_t = Maximum horizontal tensile strain at the bottom of the bottom bituminous layer (DBM) calculated using PLAXIS software

M_{Rm} = 2500 MPa = Resilient modulus of the bituminous mix.

For Ahmednagar the average highest annual temperature is 30^0 C. Therefore, using Table 9.2 from IRC 37:2018 the value of resilient modulus was estimated as 2500 MPa for the bitumen of Viscosity Grade VG30.

The pavement carriageway width was considered as 10 m, that is, two lane single carriageway pavement carrying 80 kN standard axle load acting at the centre of each lane. The geometrical model used for FEM in the study was as shown in Figure 1. The soil strata considered below the pavement embankment is also shown in Figure 1.

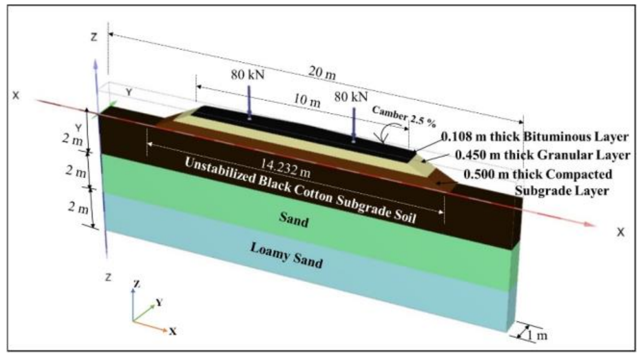


Figure 1 Geometrical Model for FEM

The model width is considered as 1 m in the 'Y' direction. The stresses ε_v and ε_t are evaluated under the position of surface loads on the top of subgrade layer and bottom of bituminous layer respectively at the coordinates as shown in Figure 2.

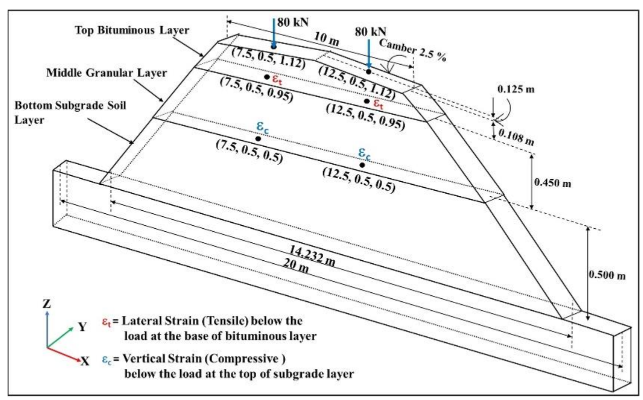


Figure 2 Stress-Strain Coordinates for FEM Model

The average of the strains under each load for the respective levels was considered for evaluation of rutting and fatigue life of pavements. (Thompson 1969, has presented Equation 3 by [20] to evaluate the modulus of elasticity for lime stabilized soil. The original equation by Thompson was in FPS system of units, have given the equation converted in IS units, is presented below,

$$E\ (kN/\ m^2) = 68810 + 124\ (UCS,\ kN/\ m^2) \quad (3)$$

Where,
E = Elastic Modulus of Lime Stabilized Soil (kN/ m^2)

UCS = Unconfined Compressive Strength of Lime Stabilized soil (kN/ m^2)

In the context of stabilizing expansive clay with lime, cement, or fly ash, lime typically serves as the crucial element for stabilization, for cement and fly ash stabilization as well. Additionally, even in the case of natural, unstabilized soil, a certain amount of lime is naturally present in expansive soil. Hence, it was deemed appropriate for this study to utilize Equation 3 to assess the elastic moduli of lime-stabilized soils, as well as unstabilized and marble powder-stabilized soils.

2.2.5 Constitutive Models for FEA and Properties of Model Materials

The geological layers, comprising loamy sand, sand, and subgrade soil in PLAXIS software, were represented using the 'Mohr-Coulomb Model.' The granular and bituminous layers with aggregates were simulated using the 'Hardening Soil Model.' Groundwater conditions in the soil strata were modelled in PLAXIS software using the 'Van Genuchten Model.' Four distinct models were run: Model 1 featured a compacted subgrade with uncured-unstabilized soil, Model 2 had 28-day cured cement-stabilized subgrade, Model 3 involved 28-day cured lime-stabilized subgrade, and Model 4 simulated 28-day cured fly ash-stabilized subgrade. Table 3 outlines the components of the model and their properties, serving as input parameters for Finite Element Analysis (FEA). Dry unit weights were determined from laboratory Standard Proctor Tests. The modulus of elasticity for unstabilized soil represented by a typical value for black cotton soil, while values for stabilized soil were computed using Equation 3. The 'Undrained A' condition, was considered in the modelling where both stiffness and strength parameters were evaluated as effective stresses. The average annual rainfall of 550 mm in Ahmednagar district was considered as per the data obtained from district administration. The precipitation was simulated using the precipitation function in PLAXIS. It is a time-dependent function for simulating precipitation. The precipitation was applied at a rate of 0.55 m/day over a two-day period.

2.2.7 Boundary Conditions

The length of numerical model in 'Y' direction is considered as unity and stress-strains are considered in 'X' and 'Z' direction.

The boundary conditions for displacements and ground water flow conditions are as follows:

Displacement Boundary Conditions

$X_{Minimum}$ = Horizontally fixed, $X_{maximum}$ = Horizontally fixed, $Y_{Minimum}$ = Horizontally fixed, $Y_{maximum}$ = Horizontally fixed, $Z_{minimum}$ = Vertically fixed, and $Z_{maximum}$ = Free

Ground Water Flow Boundary Conditions

$X_{Minimum}$ = Open, $X_{maximum}$ = Open, $Y_{Minimum}$ = Closed, $Y_{maximum}$ = Closed, $Z_{minimum}$ = Open, and $Z_{maximum}$ = Open

The laboratory experimentation program was executed based on theoretical framework and the numerical analysis was carried out using the model properties given in Table 2 and Table 3.

Table 2 Properties of Natural and Stabilized Subgrades

Components / Properties	Natural Subgrade	Uncured-Unstabilized Compacted Subgrade	28-Day Cured Cement Stabilized Subgrade	28-Day Cured Lime Stabilized Subgrade	28-Day Cured Fly Ash Stabilized Subgrade
Dry Unit Weight obtained from Standard Proctor Test (kN/ m^2)	15.00	16.09	16.68	16.48	16.28
Saturated Unit Weight (kN/ m^2)	19.44	20.13	20.51	20.38	20.25
Void Ratio	0.8	0.678	0.617	0.638	0.658
Modulus of Elasticity (E) (kN/m^2)	1.5×10^4	1.5×10^4	1.07×10^5	9.73×10^4	8.06×10^4
Poisson's Ratio (μ)	0.35	0.35	0.35	0.35	0.35
Cohesion (C) (kN/ m^2)	44	44	40	40	40
Angle of Internal Friction (ϕ) (Degrees)	0	0	10	10	10
Type of soil	Sandy Clay Loam	Sandy Clay Loam	Silt-Loam	Silt-Loam	Silt-Loam
Type of Material Model	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb	Mohr-Coulomb
Permeability (k) (m/day)	8.64×10^{-3}	8.64×10^{-3}	8.64×10^{-5}	8.64×10^{-5}	8.64×10^{-5}
Drainage Condition	Undrained 'A'	Undrained 'A'	Undrained 'A'	Undrained 'A'	Undrained 'A'

Table 3 Properties of Geological Strata and Construction Materials

Components / Properties	Sand	Loamy Sand	Granular Layer Material	Bituminous Layer Material
Dry Unit Weight obtained from Standard Proctor Test (kN/ m^2)	19.00	19.00	18	24
Saturated Unit Weight (kN/ m^2)	21.50	21.86	20	24
Void Ratio	0.5	0.4	0.95	0.4
Modulus of Elasticity (E) (kN/m^2)	6 x 10^4	9 x 10^4	E_{50}=500x10^3 EOD=283.6x 10^3 E_{ur}=1.5 x 10^6	E_{50}=2x10^6 EOD=2x 10^6 E_{ur}= 6 x 10^6
Poisson's Ratio (m)	0.2	0.15	0.2	0.2
Cohesion (C) (kN/ m^2)	0	0	-	-
Angle of Internal Friction (f) (Degrees)	28	36	-	-
Type of soil	Sand	Sand	Course	-
Type of Material Model	Mohr-Coulomb	Mohr-Coulomb	Hardening Soil	Hardening Soil
Permeability (k) (m/day)	0.9992	0.8256	864	0
Drainage Condition	Drained	Drained	Drained	Undrained 'B'

3.0 RESULTS AND DISCUSSION

3.1 Basic Properties of Unstabilized Expansive Soils

It has been observed from the Grain Size Analysis results along with LL and PI results that the soil was clay having high plasticity and as per IS soil classification it is highly plastic clay soil (CH). The FSI of the soil has been observed as 100 %. The basic properties of unstabilized subgrade soil which have been observed are given in Table 4.

Table 4 Basic Properties of Unstabilized Subgrade Soil

Test Description	Results
LL (%)	81
PL (%)	25
PI (%)	56
FSI (%)	100
IS Soil Classification	CH

From Table 4, it can be observed that, the degree of expansion of the soil is high and degree of severity is critical according to IS 1498-1970 and the subgrade soil is expansive clay subgrade.

3.2 Estimation of Effective Percentages for Stabilizers

The results obtained after the tests for LL, PL and FSI on the Fly Ash, Cement and Lime stabilized expansive soils are presented in Figure 3(a) through Figure 3(c). The results in Figure 3(a) for Fly Ash stabilizer indicate that out of the five percentages of Fly Ash namely 20 %, 24%, 28 %, 29% and 30% the plasticity and swelling properties have been reduced maximum at 28 % of Fly Ash. Figure 3(b) for cement stabilizer indicates that out of the five percentages of cement namely 8%, 10%, 12%, 13% and 14%, PI and FSI values have been minimum at 12% of cement. Figure 3(c) for lime stabilizer indicates that out of the five percentages of lime namely 4%, 5%, 6%, 7% and 8% LL, PI and FSI values have been minimum at 6% of lime.

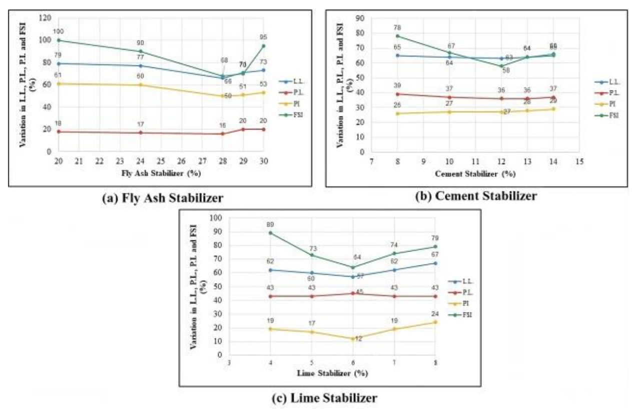


Figure 3 Variation of Plastic and Swelling Properties with Percent Stabilizer

The reduction in plasticity and swelling for Fly Ash, Cement and Lime stabilizer has then been compared at their effective percentages as 28 %, 12 % and 6% respectively with the unstabilized soil properties and comparative results are presented in Figure 4.

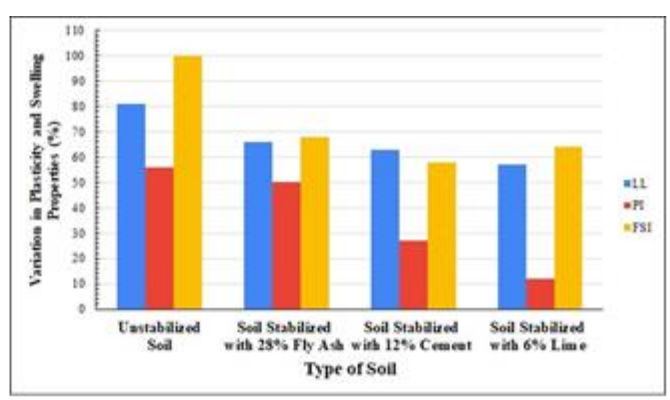


Figure 4 Efficacy of Conventional Stabilizers in Reducing Plasticity and Swelling of Unstabilized Expansive Soil

It can be observed from Figure 4 that the decrease in LL as compared to that of unstabilized soil has been 19 %, 22 % and 30 % respectively for fly ash, cement, and lime, whereas the decrease in PI is 11 %, 52 % and 79 % respectively for these stabilizers. Therefore, lime is the most effective in reducing plasticity of expansive soils as maximum decrease in plasticity of expansive soil is observed in case of lime stabilized expansive soil.

3.4 Effect of Stabilizers on Compaction Prosperities

The light-weight compaction tests were performed on these stabilized soils with their respective effective percentages of stabilizers. The results obtained in the tests are presented in Table 5 along with the results of the same test for unstabilized expansive soil.

Results of the Table 5 indicate that, the MDD has been increasing insignificantly (1% to 3%) with a significant reduction in OMC (8% to 31%) on stabilization.

Table 5 Compaction Properties of Expansive Soils in Unstabilized and Stabilize States

Type of Soil	MDD (kN/m^3)	Increase in MDD of Stabilized Soils over Unstabilized Soil (%)	OMC (%)	% Reduction in OMC of Stabilized Soils over Unstabilized Soil (%)
Unstabilized Soil	16.09	-	22.67	-
Fly Ash Stabilized Soil	16.28	1.18	15.62	31.10
Cement Stabilized Soil	16.68	3.67	19.73	12.97
Lime Stabilized Soil	16.48	2.42	20.82	8.16

3.5 Effect of Stabilizers on UCS Increase of Unstabilized Uncured Expansive Soils with Time of Curing

The samples for UCS have been molded at these MDD and OMC+2 % and cured for 28 days to study the effect of curing period on UCS. The results of UCS are presented in Table 6. The UCS results of uncured unstabilized soils were compared with the UCS results for stabilized soils cured for 28 days. It was observed from Table 6 that, there is an increase in UCS on curing the samples. The increase in UCS of 28-day cured stabilized samples was observed as about 5, 4 and 2 times for cement, lime and fly ash stabilized soil samples respectively. This increase can be attributed to the pozzolanic reactions taking place in stabilized soil samples.

Table 6 Comparison of UCS of Unstabilized and Stabilized Soils at 28-Day Curing

Type of Sample	UCS at 28-day curing (kN/m^2)	Increase over 28-Day UCS of Unstabilized Soil
Unstabilized Soil	61	-
Cement Stabilized Soil	308.30991	5 times
Lime Stabilized soil	229.48229	4 times
Fly Ash Stabilized soil	95	2 times

3.6 Effect of Stabilizers on Microstructure of 28-Day Cured Expansive Soils in Unstabilized and Stabilized States

It was decided to study the expansive soil samples stabilized with the three conventional stabilizers cured for 28 days using Environmental Scanning Electron Microscope (ESEM) and Energy Dispersive Spectroscopy (EDS). The objective of conducting ESEM and EDS has been, to study the morphology and associated chemical composition of the samples after curing responsible for the gain in UCS for 28-day cured samples.

The Figure 5 (a) through Figure 5 (l) show the ESEM images for unstabilized, fly ash stabilized, lime stabilized and cement stabilized samples. It can be observed from Figure 4 (a) that, unstabilized soil has most rough and heterogeneous surface. The roughness and the heterogeneity have been observed to reduce gradually in fly ash stabilized soil (Figure 5 (d)), lime stabilized soil (Figure 5 (g)) and cement stabilized soil (Figure 5 (j)) respectively. Figure 5 (b), Figure 5 (e), Figure 5 (h) and Figure 5 (k) show the crack widths measured with Imagej software in case of unstabilized and stabilized soils. It can be observed that, maximum crack of 0.127 mm is observed in unstabilized soil (Figure 5 (b)) and it goes on reducing in fly ash stabilized soil (0.122 mm) in Fig. 5 (e), lime stabilized soil (0.049 mm) in Figure 5 (h) and further reduction takes place in cement stabilized soil to 0.025 mm as observed in Figure 5 (k). It can be observed that the porousness of the surface goes on reducing from unstabilized soil (Figure 5 (c)), to fly ash stabilized soil (Figure 5 (f)), lime stabilized soil (Figure. 5 (i)) and it is least in case of cement stabilized soil (Figure 5 (l)).

ESEM images from Figure 5 and UCS results from Table 5 need to be considered together for studying the pattern of UCS gain in case of three stabilizers. In the initial reactions during stabilization, the clay particles agglomerate (flocculate) to impart friability to the mixture reducing plasticity of soils, in which lime seems to be more effective as seen from Figure 4, where the reduction in PI is maximum for Lime.

The long term pozzolanic reactions taking place due to the gel formations because of the calcium silicate and aluminum silicate. Also, amount of silica and alumina in the unstabilized or stabilized soils play a major role in deciding the strength gain with time because of pozzolanic reactions. It can be observed from Table 1 that, calcium in the form of CaO in the natural unstabilized soil, fly ash, lime and cement is 15.98%, 1% to 3%, 100% and 60% to 67% respectively. Therefore, as lime has highest calcium it was most effective in the initial reactions causing reduction in plasticity. However, for UCS gain with time pozzolanic reactions was observed to be the governing factor. Table 1 shows that, percentage of silica and alumina is highest in fly ash (61% to 64% and 21% to 27% respectively). However, the fly ash being ‘F’ class fly ash, it has low CaO percentage of 1% to 3%. As the silica gel is highly porous, give rise to reduction in overall strength [21], [22]. Considering the higher percentage of silica and lower percentage of calcium, the efficacy of the reactions to cause the stabilization is least in fly ash with least UCS among the three stabilizers as it is evident from the ESEM results. The morphological improvement is not much in the form of smoothness and homogeneity in case of fly ash stabilized soil.

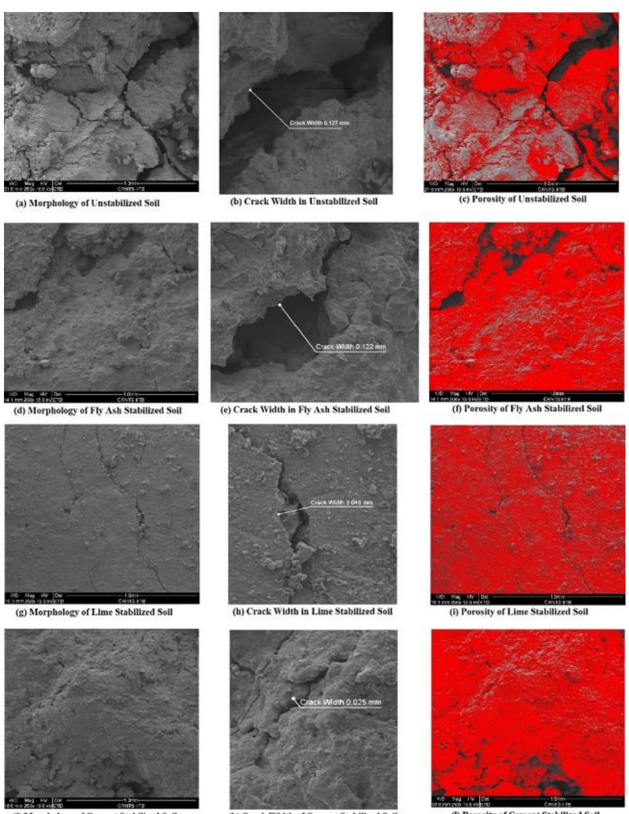


Figure 5 ESEM Images for 28-Day Cured Unstabilized and Stabilized Soils

It can be inferred from the above discussion that, as a stabilizer the lime is more effective in controlling the plasticity of soil and cement is more effective in increasing shear strength in the form of UCS. However, based on present costs of the stabilizers, per kg of stabilizer in the Indian markets, if purchased in bulk quantity, are as follows - fly ash is Rs. 2 per kg, lime is Rs. 4 per kg and cement is Rs. 6 per kg. Even though the fly ash is cheapest among all the three stabilizers, however, the effective percentages of stabilizers required for causing the reactions are in the range of 25% to 30% for ‘F’ class fly ash (which is predominantly available in India), 8% to 12% for cement and 4% to 6% for lime. Considering this analysis, it can be inferred that, if very large gain in strength is not the requirement, then for significant strength gain with considerable reduction in plasticity and swelling the lime stabilizer can be considered as the most effective and economical candidate as an expansive soil stabilizer. Lime will help to reduce the volume changes of expansive subgrade soil economically. The conclusions of this study have been presented in the subsequent section.

3.7 Numerical Analysis for studying the Rutting and Fatigue Life of Flexible Pavement

Equation 1 and Equation 2 were utilized to determine the rutting and fatigue life of a flexible pavement across four subgrade types: uncured and unstabilized expansive soil subgrade, and 28-day cured subgrades stabilized with cement, lime, and fly ash. The average vertical compressive strains required to estimate rutting life were worked out by averaging the strains on the top of subgrade layer under each 80 kN load (Standard Axle) at the coordinates as shown in Figure 2. Similarly, the average lateral tensile strains required to estimate fatigue life were worked out by averaging the strains below the bituminous layer under each 80 kN load at the coordinates as shown in Figure 2. These strains are shown in Table 7. As per the Indian code, IRC -37:2018, the rutting and fatigue life of pavement is expressed in terms of load carrying capacity of a pavement during its design life expressed in Millions Standard Axles (MSA). The rutting and fatigue life of pavements founded on uncured-unstabilized subgrade and subgrades stabilized with cement, lime and fly ash are shown in Table 8. It can be observed from the Table 6, that, there was considerable reduction of about 78 % in vertical strain in both cement and lime stabilized expansive soils and also 75 % reduction in case of fly ash stabilized soil. However, as observed from Table 8, the increase in rutting life of pavement due to subgrade rutting was 1136 times for cement, 769 times for lime stabilized subgrade and comparatively lesser increase of 371 times in case of fly ash stabilized subgrade as compared to unstabilized soil. This difference in increase rutting life of cement, lime and flay ash stabilized subgrades could be attributed to the difference in their individual capacity to take the strains because of the difference in their moduli of elasticity, namely, 1.07 x 10^5 kN/ m^2 for cement, 9.73 x 10^4 kN/ m^2 for lime and 8.06 x10^4 kN /m^2 for fly ash stabilized subgrade. The reduction in lateral tensile strains in pavement under the top bituminous layers was comparatively lesser to the amount of reduction in vertical compressive strain acting at the bottom subgrade level, because the stresses are always high in top layers of pavements and they go on reducing in lower layers. The reduction of about 9 % in lateral tensile strain was observed in both cement and lime stabilized expansive soils it was about 8% in fly ash stabilized soil as shown in Table 7.

However, it can be observed from Table 7 that, the increase in fatigue life of pavement was 46 % and 43 % for cement and lime stabilized subgrades whereas it was 37 % for fly ash stabilized subgrade as compared to unstabilized soil.

Considering all this discussion, it can be summarized that, if the objective of expansive soil stabilization is strength gain then, fly ash stabilizer is not a potential candidate as a stabilizer.

Table 7 Vertical Compressive and Lateral Tensile Strains at the Interphases of Layers

Type of Subgrade	Average vertical Compressive Strain	% Reduction in Vertical Strain in Stabilized Soil	Average lateral tensile Strain	% Reduction in Strain in Lateral Stabilized Soil
Uncured Unstabilized Expansive Clay Soil	0.000236	-	0.000297488	-
28-Day Cured Cemnt Stabilized Expansive Soil	0.0000500	78.81	0.000269678	8.94
28-Day Cured Lime Stabilized Expansive Soil	0.0000545	78.64	0.000271212	8.51
28-Day Cured Fly Ash Stabilized Expansive Soil	0.0000640	75.00	0.000274235	7.62

However, for soils with low degree of expansiveness and where availability of fly ash is in abundance, or availability of lime is a constraint then the fly ash can be a considered as a satisfactory alternative as a stabilizer.

Table 8 Rutting Life and Fatigue Life of Flexible Pavement Founded on Unstabilized and Stabilized Subgrades

Type of Subgrade	Rutting Life of Flexible Pavement due to Subgrade Rutting (MSA)	Increase by number of times in Rutting Life in Stabilized Soil	Fatigue Life of Flexible Pavement due to Fatigue in Top Bituminous Layer (MSA)	% Increase in Fatigue Life in Stabilized Soil
Uncured Unstabilized Expansive Clay Soil	3.92 x 10^8	-	1.84	-
28-Day Cured Cement Stabilized Expansive Soil	4.45 x 10^{11}	1136	2.70	46
28-Day Cured Lime Stabilized Expansive Soil	3.01 x 10^{11}	769	2.64	43
28-Day Cured F Stabilized Expansive Soil	1.45 x 10^{11}	371	2.53	37

3.8 Future Scope for the Research Study

For the future studies, the stabilization of expansive soils can be studied with some new stabilizers like marble powder using the similar approach for the research studies as it contains higher percentage of lime and availability of pure lime is becoming a critical issue day by day. Also, expansive soil from some other locations can be studied for such stabilization with more number of sample size.

4.0 CONCLUSION

After investigating the effect of cement, lime, and fly ash stabilizers on plasticity, swelling and strength gain with time following conclusions are drawn:

1) The effective percentages for fly ash, cement, and lime observed in this study are 28%, 12% and 6% respectively.

2) The ability of fly ash to reduce swelling and plasticity is least among the three stabilizers as it reduced FSI by 32 %, LL by 19 % and PI by 11 %

3) Cement was observed as the most effective stabilizer in reducing the FSI of the expansive soil to a maximum extent of 42% and was the most effective stabilizer for increasing strength increasing the UCS by

a maximum extent of 5 times as compared to that of unstabilized-uncured expansive soil.

4) Lime was the most effective stabilizer for reducing plasticity as it reduced the LL and PI to a maximum extent of 30 % and 79 % respectively.

5) ESEM results indicate that, more homogeneous and denser matrix can be achieved with cement stabilization which is responsible for maximum strength gain with time among the three stabilizers.

6) This study concludes that cement is the most effective stabilizer for Black Cotton soils, as it has significantly improved UCS, and controlled swelling followed by lime which reduces plasticity and swell potential, making them viable options for different engineering applications.

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Conflicts of Interest

The author(s) declare(s) that there is no conflict of interest regarding the publication of this paper.

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