Jurnal
Teknologi

Full Paper

EFFICACY OF MARBLE POWDER AS A STABILIZER FOR EXPANSIVE CLAY SUBGRADES

Suraj Nair[a], Abhishek Bagal[b], Tanishque Sarda[c], Paras Shah[d], Manoj Anaokar[e]*

[a]University of New South Wales, Australia (Former Undergraduate Student at NMIMS's MPSTME)
[b]Civil Engineer, Mumbai, India (Former Undergraduate Student at NMIMS's MPSTME)
[c]Adnani Enterprises Ltd., India (Former Undergraduate Student at NMIMS's MPSTME)
[d]Babson University, USA (Former Undergraduate Student at NMIMS's MPSTME)
[e]Mukesh Patel School of Technology Management & Engineering, Department of Civil Engineering, NMIMS, (Deemed to be University), Bhakti Vedant Swami Marg, JVPD Scheme, Vile Parle (West), Mumbai- 400 056, Maharashtra, India

Article history
Received
1 September 2024
Received in revised form
9 December 2024
Accepted
23 December 2024
Published Online
22 August 2025

*Corresponding author
manoj.anaokar@nmims.edu

Graphical abstract

Abstract

Expansive soils, characterized by significant volume fluctuations, pose detrimental effects on pavement performance through swelling and shrinking. A conventional stabilizer Lime has been studied extensively, and this research explores the viability of marble powder, rich in lime, as an alternative stabilizer in situations where pure lime availability is a constraint. Through X-Ray Diffraction tests, mineral composition changes were assessed in Unconfined Compressive Strength (UCS) Test samples, both uncured and 28-day cured, independently stabilized with marble powder and lime. The study evaluated the effects on key factors such as shear strength, swelling potential, and plasticity, influencing the engineering behavior of subgrade soils. Finite Element Analysis (FEA) using PLAXIS software was employed to evaluate vertical and lateral strains, crucial for understanding rutting and pavement fatigue life on this subgrade. Results revealed a 38.80% and 41.13% increase in the fatigue life of the 28-day marble-stabilized subgrade and lime stabilized soil, when compared with zero-day cured unstabilized soil. XRD analysis indicates that marble powder shows limited effectiveness in strength enhancement. Moreover, the rutting life of the 28-day cured marble-stabilized subgrade exhibited 557 times increase, and lime-stabilized subgrade showed 979 times increase compared to uncured unstabilized soil. While the improvement in fatigue and rutting life with marble powder was comparatively less than conventional lime stabilizer, the study concludes that marble powder is a viable stabilizer for expansive soils with low to medium expansiveness. It recommends further investigation of potential combinations of marble powder and lime for effective yet economical soil stabilization.

Keywords: Expansive clay subgrades, sustainable stabilizing materials, soil stabilization, lime, marble powder

1.0 INTRODUCTION

The economic development of any nation hinges on multiple factors, and the quality of pavement network stands out as a crucial element. In countries such as, Australia, Canada, Egypt, India, Israel, and the United States, a significant portion of land covered by black cotton soil faces issues related with this subgrade. Notably, states in India such as Gujarat, Maharashtra, Madhya Pradesh, Andhra Pradesh, Karnataka, and Chhattisgarh have approximately 20% of Indian land area occupied by black cotton soil. The expansive characteristics of this soil, marked by volumetric changes arising from seasonal moisture fluctuations, present a formidable challenge to the durability and lifespan of pavements. The consequential distress conditions necessitate frequent maintenance and premature reconstruction of pavements.

Expansive clay subgrades, particularly black cotton soils, require stabilization to mitigate swelling, decrease plasticity, and improve shear strength. Researchers globally have explored various stabilization methods, including mechanical approaches. However, studies indicate that compacting expansive soils to Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) results in the highest swelling pressure. Therefore, it is recommended to compact these soils at a slightly higher moisture content than OMC to achieve equilibrium moisture content, reducing swelling pressure [1]. With these challenges in mechanical stabilization, researchers have increasingly utilized chemical stabilization methods to modify properties such as Atterberg's limits, Free Swell Index (FSI), California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS), representing the shear strength of such clay soils. Conventional stabilizers like lime [2, 3], Fly Ash [4], and Cement [5, 6] have been employed. Some studies combine conventional stabilizers with other materials such as sugarcane molasses [7, 8] or zeolite [9]. Lime, specifically Calcium Oxide (CaO), has been identified as a key catalyst in this chemical stabilization process. Some researchers have also used rice husk ash or the combination of a combination of and marble powder [10, 11]. In regions like Rajasthan, India, where marble cutting is prevalent, marble dust waste constitutes about 20% of total marble usage [12]. Due to lime availability constraints, marble powder is being considered as a stabilizer. However, comprehensive scientific studies are essential before its widespread use. Therefore, this study aims to analyze the strength development over time and reductions in swelling and plasticity properties. The mineral composition changes at the end of a 28-day curing period for samples independently stabilized with marble powder and lime were studied. This study contributes to the body of knowledge by elucidating the role of marble powder as an alternative stabilizer in improving specific engineering properties of soil by studying their behaviour at micro-level and also carrying out the Finite Element Analysis using PLAXIS 3D software.

2.0 MATERIALS AND METHODOLOGY

2.1 Materials

2.1.1 Soil

Expansive Black Cotton (BC) Clay soil from Nashik, district of North Maharashtra in India is used for this study as this soil has typical Free Swell Index (FSI) of 100 that is according to IS 1498: 1970 the soil has 'High' degree of expansiveness and degree of severity is 'Critical'.

2.1.2 Stabilizers

a) Marble Powder

The marble powder, potential candidate as a stabilizer used in this study is procured from Nagpur. The chemical analysis of the marble powder was carried out to assess its chemical composition and the results of the analysis are presented in Table 1.

Table 1 Chemical Composition of Marble Powder

Chemical Compounds	Abbreviations	Amount (%)
Silicon Dioxide	SiO_2	5.47 %
Aluminum Oxide	Al_2O_3	0.38 %
Titanium Dioxide	TiO_2	0.009 %
Manganese Oxide	MnO	0.51 %
Calcium Oxide	CaO	35.38 %
Magnesium Oxide	MgO	13.43 %
Sodium Oxide	Na_2O	0.51 %
Potassium Oxide	K_2O	0.066 %
Ferric Oxide	Fe_2O_3	1.74 %
Loss on Ignition at 850°C for 1 hr.	-	42.5 %

b) Lime Powder

The lime powder, containing 99.7% CaO, was sourced from 'Powder Pack Chemicals' Borivali, Mumbai.

2.2 METHODOLOGY

2.2.1 Method for Design of Study and Data Analysis

The study is designed by initially conducting the laboratory testing to find out the original engineering properties of unstabilized soil. Thereafter, the effective percentages of stabilizers have been estimated by performing the atterberg's limits and it has been investigated that, which percentages of stabilizers provide more control on swelling and plasticity. Thereafter, the compaction and strength properties have been assessed for unstabilized and expanive soils stabilized each with lime and marble stabilizers at their effective percentages. The effect of curing on strength has been assessed. After that, the the X-Ray Diffraction (XRD) tests were performed on 28-day cured samples of unstabilized soils and samples of soils stabilized each with both the stabilizers with their effective percentages. This has been done to investigate the effect of mineralogical and morphological changes taking place due to the stabilization and to assess their effect on engineering behaviour of stabilized soils. Finite Element Analysis (FEA) was carried out to compare the effect of stabilization in each of the stabilizers on the vertical and lateral strains and on the rutting and fatigue life of pavements.

The data obtained from the results of the tests were compared in case of each of the stabilizers with that of unstabilized soil in order to investigate the improvement in engineering behaviour of soil. This comparison has also been done to assess the efficacy of marble powder stabilizer over the lime stabilizer, if the former is to be used as an alternative stabilizer to the later.

2.2.2 Laboratory Testing for Stabilized Soil Samples

In the next phase of the research investigation, the objective was to determine the effective percentage of marble powder and lime stabilizers. To achieve this, the Liquid Limit (LL) and Plasticity Index (PI) of expansive soils treated with both stabilizers were assessed through LL and PL tests. Therefore, Atterberg's limits, namely, Liquid Limit (LL) and Plastic Limit (PL) were also performed on the unstabilized soil [13], to estimate Plasticity Index (PI), a key element governing the design and life of pavements. After performing GSA and estimating plastic properties (LL and PI), the soil classification was carried out as per Indian soil classification system [14]. These tests were conducted on soils treated with varying proportions of marble powder as 18%, 20%, and 22% based on earlier studies which had observed as effective percentage of marble was about 20% [15]. The tests were also carried out on soils stabilized with 4%, 5%, and 6% lime. The stabilizers were added to the oven-dried expansive soil.

2.2.3 Laboratory Testing for Studying the Effect of Time on Strength of Expansive Soils

After obtaining the effective percentages of marble powder and lime stabilizer, it was planned to study the effect of time on UCS, that is, effect of curing period on the UCS of uncured unstabilized soil as well as the strength of soils stabilized with both the stabilizers. The samples were tested for curing periods of 0 days (uncured), 14 days and 28 days were decided for studying the effect of time on strength. The strength was assessed by performing UCS tests [16] on both unstabilized soil and soils stabilized with both the stabilizers. As soils are rolled in the field to Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) plus 2 % of moisture, the samples for UCS were moulded to the same densities and moisture content. Therefore, Standard Proctor Tests were performed in the laboratory to evaluate MDD and OMC for both unstabilized soils and soils stabilized with both the stabilizers.

2.2.4 X-Ray Diffraction Tests for Studying Minerology of Samples

It was decided to perform X-Ray Diffraction (XRD) tests on uncured unstabilized soil samples and on 28-Day cured soil samples stabilized with marble powder and lime for studying the morphological changes occurring in the soil samples due to stabilization.

The aim of XRD tests was to compare the results and study the mineralogical and morphological changes occurring post stabilization.

2.2.5 Numerical Analysis for Evaluating Strains to Estimate the Rutting and Fatigue Life of Pavements

To assess the effectiveness of a stabilizer, one common approach is to evaluate its impact on pavement performance. This evaluation typically involves comparing the fatigue life and rutting life of a pavement before and after stabilization. The Three-Layer Theory for pavement design utilizes the vertical compressive strain on the subgrade layer and the lateral tensile strain below the bituminous layer to estimate these parameters.

In this study, finite element analysis conducted with PLAXIS software was employed to obtain these strains. The rutting life and fatigue life of the pavement were estimated using Equation (1) and Equation (2), respectively. These estimates are expressed in terms of the pavement's capacity to withstand traffic over its design life, measured in Million Standard Axles (MSA).

The study compared the rutting life and fatigue life of pavements constructed on both unstabilized expansive subgrade soil and soils stabilized with marble powder and lime stabilizers. This comparison provides the insight about the effectiveness of the stabilization methods in enhancing pavement performance.

$$N_R=1.4100\text{x}10^{-08}[(1/\varepsilon_V)^{4.5337} \quad (1)$$

(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).

ε_v = Vertical compressive strain at the top of the subgrade calculated using PLAXIS 3D

$$N_f=0.5161 x C x 10^{-04} x[(1/\varepsilon_t)]^{3.89} x[(1/M_{RM})^{.0854} \quad (2)$$

(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 used in the bottom bituminous layer, selected as per the recommendations made in these guidelines. For Nashik the average highest annual temperature is 370 C as per the information from local district administration. Therefore, using Table 9.2 from IRC 37:2018 [17] the value of resilient modulus was estimated as 1700 MPa for the bitumen of Viscosity Grade VG30 to be used in the bituminous layer. Figure 1 shows the geometrical model used for Finite Element Analysis (FEM).

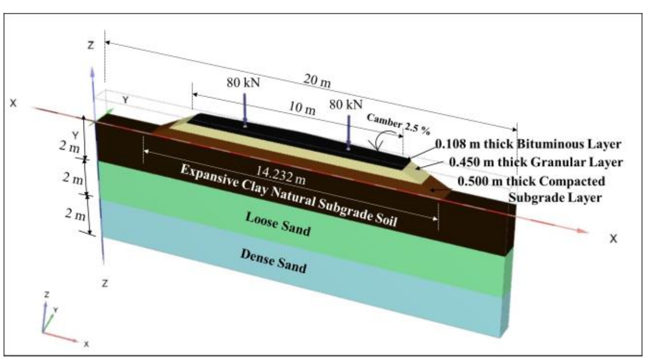

Figure 1 Geometrical Model for FEM

The pavement 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.

The model width is considered as 1 m long in the 'Y' direction. Therefore, the problem is plain strain problem. The stresses ε_v and ε_t are evaluated under the position of surface loads of the strains under each load for the respective levels was considered for evaluation of rutting and fatigue life of pavements. Thompson has presented the Equation [18] by Little Dallas [19] to evaluate the modulus of elasticity for lime on the top of subgrade layer and bottom of bituminous layer at the coordinates as shown in Figure 2. The average stabilized soil. The original equation by Thompson was in FPS system of units, researchers [3] have given the equation converted in IS units, is given in Equation (3),

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

Where, E = Elastic Modulus of Lime Stabilized Soil (kN/m^2)
UCS = Unconfined Compressive Strength of Lime Stabilized soil (kN/m^2)

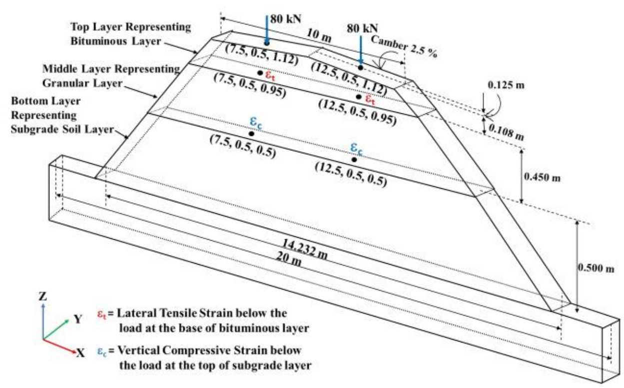

Figure 2 Stress-Strain Coordinates for FEM Model

In expansive clay stabilization using lime, cement or fly ash, the key element responsible for stabilization of expansive soil is generally lime, similarly, lime is the key element responsible for stabilization in marble powder stabilizer. It has beeen observed from Table 1 that, in natural unstabilized soil, some lime was present as its constituents. Therefore, it was considered to be appropriate to use Equation 3 in this study to evaluate the elastic moduli of lime stabilized soils in addition to unstabilized and marble powder stabilized soils.

2.2.6 Constitutive Models for FEA and Properties of Model Materials

The geological layers, including dense sand, loose sand, and subgrade soil, in PLAXIS were modelled using the 'Mohr-Coulomb Model.' The granular and bituminous layers containing aggregates were simulated using the 'Hardening Soil Model.'

Groundwater conditions in the soil strata were represented by the 'Van Genuchten Model' in PLAXIS. Three independent models were executed: Model 1 featured a compacted subgrade of uncured and unstabilized soil, Model 2 included a 28-day cured lime-stabilized soil compacted subgrade, and Model 3 involved a 28-day cured marble powder-stabilized subgrade. Table 2 presents the various properties of the unstabilized and stabilized subgrades whereas Table 3 shows the properties of geological strata and other components of model, serving as input parameters for Finite Element Analysis (FEA). The dry unit weight was determined from the Standard Proctor test conducted on both unstabilized soil and soils stabilized with lime and marble powder. Modulus of elasticity values were computed using Equation 3, with the Unconfined Compressive Strength (UCS) values for both unstabilized soil and soils stabilized with lime and marble powder. The modelling considered the 'Undrained A' condition, wherein both stiffness and strength parameters were assessed as effective stresses. Nashik district's average annual rainfall of 1100 mm, according to district administration data, was simulated using the precipitation function in PLAXIS. A time-dependent precipitation rate of 1.1 m/day was applied 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 as shown in Figure 3 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

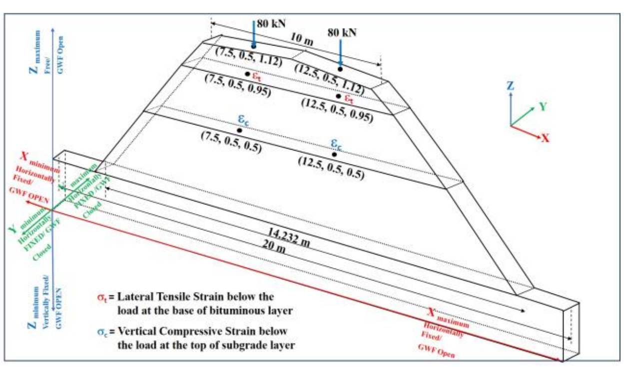

Figure 3 Boundary Conditions for Numerical Modelling

Ground Water Flow Boundary Conditions

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

Table 2 Model Components and Properties for Subgrade Soils

Components / Properties	Natural Subgrade	Uncured-Unstabilized Compacted Subgrade	28-Day Cured Lime Stabilized Subgrade	28-Day Cured Marble Powder Stabilized Subgrade
Dry Unit Weight obtained from Standard Proctor Test (kN/ m²)	14.50	15.00	15.5	16.40
Saturated Unit Weight (kN/ m²)	19.00	19.50	19.82	20.39
Void Ratio	0.95	0.82	0.761	0.665
Modulus of Elasticity (E) (kN/m²)	1.5×10^4	1.5×10^4	9.31×10^4	8.22×10^4
Poisson's Ratio (m)	0.35	0.35	0.35	0.35
Cohesion (C) (kN/ m²)	44	44	40	40
Angle of Internal Friction (f) (Degrees)	0	0	10	10
Type of soil	Sandy Clay Loam	Sandy Clay Loam	Silt-Loam	Silt-Loam
Type of Material Model	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}
Drainage Condition	Undrained 'A'	Undrained 'A'	Undrained 'A'	Undrained 'A'

Table 3 Model Components and Properties for Other Strata and Embankment

Components / Properties	Loose Sand	Dense Sand	Granular Layer Material	Bituminous Layer Material
Dry Unit Weight obtained from Standard Proctor Test (kN/ m^2)	19.00	19.5	18	24
Saturated Unit Weight (kN/ m^2)	21.50	22.00	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)	0.15	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 Laboratory Experimentation

3.1.1 Laboratory Testing for Unstabilized Soils

The Grain Size Analysis (GSA) carried out on the soil procured from Nashik for soil identification. The GSA results are shown in the Figure 4. For assessing the plasticity properties of soil Atterberg's Limits Tests were performed on unstabilized soil. The LL and PL values were observed as 55 %, and 31% respectively. The PI can be estimated as 24%.

With these values and from GSA, the soil obtained from Nashik was classified as Clay of High Plasticity (CH) as per IS soil classification system [14].

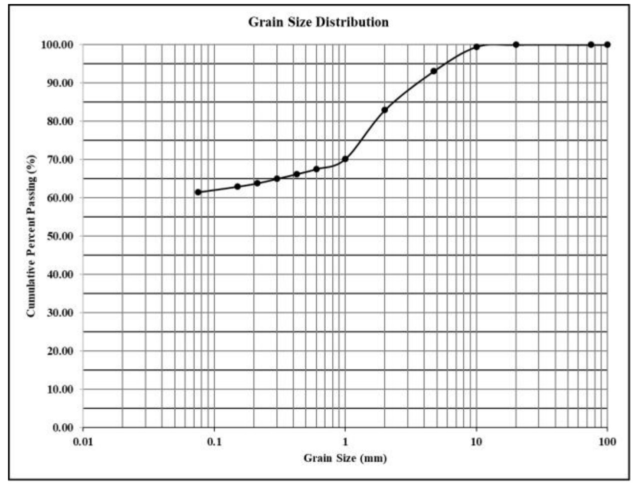

Figure 4 Grain Size Distribution of Natural Subgrade Soil

3.1.2 Laboratory Testing for Stabilized Soils

In the next stage it was decided to find out the effective percentage of stabilizers by estimating the values of LL and PI for different percentages of lime and marble powder and the percentage for which the reduction in plasticity is maximum, that is least LL and PI, was the effective percentage of stabilizer. The percentages of stabilizer for lime were 4 %, 5 % and 6 %, and those for marble powder were 18 %, 20 % and 22 %. The Atterberg's Limits for lime stabilized soils obtained were compared with those of unstabilized soil and presented in Figure 5. As it can be observed from the results, the effective percentage of lime stabilizer was 4 %. The Atterberg's Limits for marble powder stabilized soils obtained were compared with those of unstabilized soil and presented in Figure 6. As it can be observed from the results, the effective percentage of marble powder stabilizer was 18 %.

The LL of 55 % for unstabilized soil reduced to 48 % by using lime and reduced to 43 % by using marble powder. Therefore, the reduction in LL obtained by 4 % of lime is about 13 %, whereas that by 18 % of marble powder is 22 %.

PI of 25 % for unstabilized soil reduced to 12 % by using lime and reduced to 21 % by using marble powder. Compared to lime which has 6% of effective percentage, marble powder has effective percentage of 18 %. This is because lime is the common element in both for stabilizing the expansive soils. However, as shown in Table 1 marble powder has CaO content of 35 %, whereas lime is 99.7 % pure CaO.

Therefore, the reduction in PI obtained by 4 % of lime is about 52 %, whereas that by 18 % of marble powder is 16 %. Considering these results, it can be concluded that, the marble powder is less effective than lime stabilizer in reducing plasticity of expansive soil.

The Free Swell Index (FSI) test was then conducted [20] on unstabilized soil and on the soils stabilized with lime and marble powder at their effective percentages and the results obtained are presented in Table 4. The results indicated that, the FSI was reduced from 100 % for unstabilized soil to 10.5% for lime stabilized soil and reduced to 20 % for marble powder stabilized soil, that is, the reduction in FSI was 89.5 % for lime and that for marble powder stabilized soil the reduction in FSI was 80 %. Therefore, for reducing the swelling potential, lime is more effective as compared to marble powder, however, the reduction obtained by marble powder stabilizer is also considerable and therefore, marble powder can serve as a viable stabilizer candidate for swelling control.

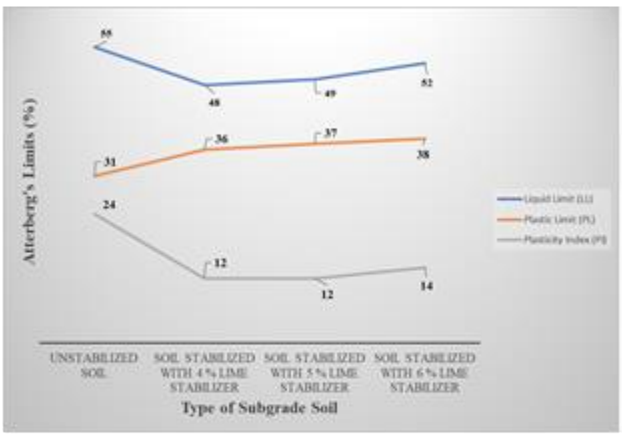

Figure 5 Atterberg's Limits for Lime Stabilized Soils

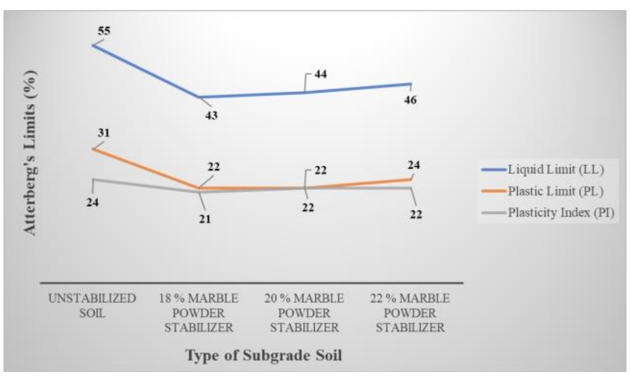

Figure 6 Atterberg's Limits for Marble Powder Stabilized Soils

Table 4 Free Swell Index of Unstabilized and Stabilized Soils

	Unstabilized Soil	4 % Lime Stabilizer	18 % Marble Powder Stabilizer
Free Swell Index (%)	100	10.5	20

3.1.3 Laboratory Testing for Studying the Time - Strength Relationship of Expansive Soil

Time - Strength relationships were studied by studying the effect of curing period on Unconfined Compressive Strength (UCS). The UCS tests were performed on unstabilized expansive soil samples and the soil samples stabilized with lime and marble powder with curing periods of 0 days, that is, uncured samples, 14 days and 28 days. The UCS samples were moulded at Maximum Dry Density (MDD) and at moisture content equal to Optimum Moisture Content (OMC) +2% of moisture, being expansive clay. The Standard Proctor tests were performed to evaluate the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of unstabilized and stabilized samples. The results obtained are shown in Table 5.

Table 5 MDD and OMC of Unstabilized and Stabilized Soils

	Unstabilized Soil	4 % Lime Stabilizer	18 % Marble Powder Stabilizer
MDD (kN/m^3)	14.81	15.21	16.09
OMC (%)	26.46	25.37	25.13

Three samples of UCS for each type of soil and for each period of curing were moulded. The average of the three results for respective stabilizer for respective period of curing was obtained and these results are shown in Table 6. Table 6 also shows the percentage improvement in UCS of stabilized soils over the UCS of unstabilized-uncured soil. It can be observed from Table 8 that, the 0-day, 14-day, and 28-day cured strength (UCS) of lime stabilized soil was 31 %, 44 % and 55 % respectively compared to that of uncured-unstabilized soil sample. The 0-day, 14-day and 28-day cured strength (UCS) of marble powder stabilized soil was 22 %, 33 % and 45 % respectively compared to that of uncured-unstabilized soil sample. It indicates that the rate of development of strength is less in case of marble powder stabilizer as compared to that of lime stabilizer. This is due to the fact that pure lime (CaO) causes direct reactions with the expansive soils, whereas, marble powder contains 35 % of CaO (Table 1). Due to this there is lesser growth development rate for marble powder stabilized soils.

Table 6 Percentage Improvement in UCS of Stabilized Soils over UCS of Uncured-Unstabilized Soil

Curing Period	Average UCS of Unstabilized Soil (kN/ m^2)	Average UCS of Lime Stabilized Soil (kN/ m^2)	Change in UCS of lime stabilized soil compared to Uncured Unstabilized Soil (%)	Average UCS of Marble Powder Stabilized Soil (kN/ m^2)	% Change in UCS compared to marble powder stabilized Uncured Unstabilized Soil (%)
0-Day (Uncured)	54	71	31	66	22
14-Day	59	77	44	72	33
28-Day	66	83	55	78	45

Therefore, it can be concluded that, if improvement in strength is the objective of stabilization, then, marble powder can be considered as an alternative to lime where the degree of expansiveness of the soil is not very high.

3.1.4 X-Ray Diffraction Tests

The X-ray diffraction tests were performed to understand the minerology of the expansive soil samples in uncured-unstabilized state and in stabilized state with both lime and marble powder stabilizers.

The results obtained by X-Ray diffraction tests for uncured-unstabilized expansive soil sample, 28-day cured lime stabilized soil sample and 28-day cured marble powder stabilized soil sample are shown in Figure 7, Figure 8, and Figure 9 respectively. 'PANalytical X'pert Highscore Plus' software was used for analyzing the data obtained from XRD. According to the 2θ value obtained on the x-axis, different minerals were calculated. The wavelength(λ) displays the peaks against the 'n' value on the y- axis. According to the standard patterns of peaks for different minerals, we can interpret the amount of different minerals present in the sample in terms of percentage.

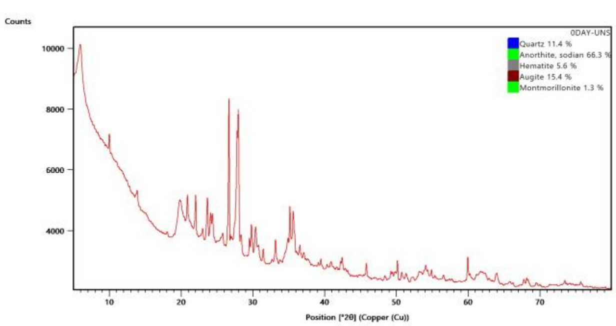

Figure 7 X-Ray Diffraction Results for Uncured-Unstabilized Soil Samples

Figure 8 shows the results of XRD for 28-day cured lime stabilized samples. It can be observed that, the primary constituent mineral in 28-day cured lime stabilized expansive soil was Andesine (68.2 %). Augite (19.3 %) and Quartz (9.0 %) were also present, even in this soil in significant amount; and Hematite (2.5 %) and montmorillonite (1 %) were the other minerals present in this soil. However, Anorthite Sodian present in unstabilized soil was not observed in lime stabilized soil and the Andesine in lime stabilized soil was not the constituent mineral of unstabilized soil.

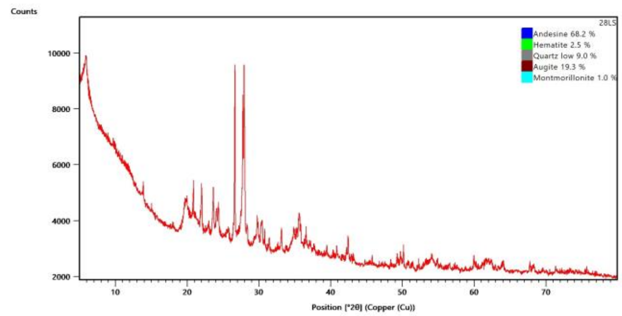

Figure 8 X-Ray Diffraction Results for 28-Day Cured Lime Stabilized Soil Samples

Figure 9 shows the results of XRD for 28-day cured marble stabilized sample. It has been observed that, the marble-stabilized sample, similar to the unstabilized soil, contain Anorthite Sodian (27.5%) and Anorthite (12.4 %) in the 28-day cured marble stabilized soil. However, it was in less amount (totalling to 39.9 %) as compared to that (66.3 %) in unstabilized soil. Andesine as observed in lime stabilized soil responsible for higher strength at 28-day strength is not observed in marble stabilized soil.

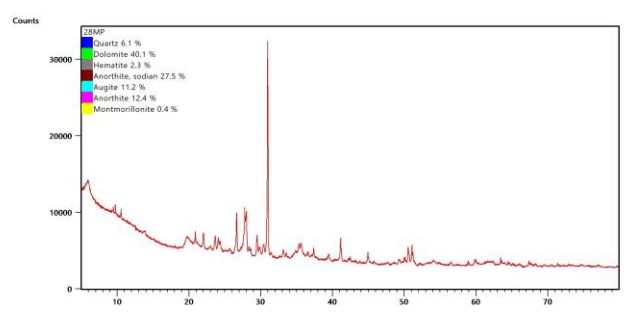

Figure 9 X-Ray Diffraction Results for 28-Day Cured Marble Powder Stabilized Soil Samples

The UCS samples for marble stabilized soil were more brittle in nature. Anorthite Sodian is used in manufacture of glass and ceramics resulted in brittleness of the UCS soil samples. Therefore, it can be concluded that, Andesine is the primary constituent mineral required for gain in UCS strength and Anorthite Sodian seemed to be responsible for the strength reduction in the marble stabilized soil. The other minerals present in marble stabilized soil were Augite (11.2 %), Quartz (6.1 %), Hematite (2.3 %) and Montmorillonite (0.4 %). Another major constituent mineral present in marble powder stabilized soil was Dolomite (40.1 %) which is generally rich in Calcium and Magnesium as marbles are produced due to the metamorphism of dolomite stones. Dolomite helps for improving UCS of clay soils and reducing the FSI [21]. However, the rate of strength gain in marble stabilized soils was not considerable as the Dolomite is present along with the Anorthite. Therefore, the marble powder stabilizer is not very effective in improving the UCS, although it was effective in significantly reducing the FSI (by 89.5 %) of the expansive soil.

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

The Equation 1 and Equation 2 were used to find out the rutting and fatigue life of a flexible pavement based on the three types of subgrades, namely uncured-unstabilized expansive soil subgrade, and 28-day cured subgrades stabilized with lime and marble powder. 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.

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

Type of Subgrade	Average vertical Compressive Strain	Percent Reduction in Vertical Strain in Stabilized Soil	Average lateral tensile Strain	Percent Reduction in Strain in Lateral Stabilized Soil
Uncured Unstabilized Expansive Clay Soil	0.000233	-	0.000298	-
28-Day Cured Lime Stabilized Expansive Soil	0.000056	75.97	0.000272	8.29
28-Day Cured Marble Powder Stabilized Expansive Soil	0.000063	75.12	0.000274	7.79

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 in terms of Million Standard Axles (MSA). The rutting and fatigue life of pavements founded on uncured-unstabilized subgrade and subgrades stabilized with lime and marble powder are shown in Table 8. It can be observed from the Table 7, that, there was considerable reduction of about 75 % in vertical strain in both lime and marble stabilized expansive soils.

However, Table 8 shows that, the increase in rutting life of pavement due to subgrade rutting was 641 times for lime stabilized subgrade and 376 times for marble stabilized subgrade as compared to unstabilized soil. This difference in increase rutting life of lime and marble powder stabilized subgrades could be attributed to the difference in their moduli of elasticity estimated using Equation 3, which governs their individual capacity to take the strains. The reduction in lateral tensile strains in pavement under the top bituminous layers was comparatively lesser as compared to the amount of reduction in vertical compressive strain acting at bottom subgrade level, because the stresses are always high in top layers of pavements and they go in reducing in lower layers. The reduction of about 8 % in lateral tensile strain was observed in both the stabilized expansive soils.

Table 4 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	4.15×10^8	-	2.55	-
28-Day Cured Lime Stabilized Expansive Soil	2.66×10^{11}	641	3.63	42
28-Day Cured Marble Powder Stabilized Expansive Soil	1.56×10^{11}	376	3.53	38

Considering the above discussion, it can be summarized that, if the objective of expansive soil stabilization is strength gain in UCS then, marble powder stabilizer is not a potential candidate as a stabilizer.

However, for reduction in plasticity, and swelling control which are the prime common objectives of the expansive soil stabilization, then marble powder is a good stabilizer candidate for soils having low to medium degree of expansiveness. Also, for the improvement in rutting and fatigue life of a flexible pavements founded on expansive soils the marble powder can be considered as a reliable alternative to lime stabilizer in case the availability of pure lime is a constraint.

4.0 CONCLUSION

After investigating the effect of marble powder and lime stabilizers on plasticity, swelling and strength gain with time as well as on fatigue and rutting life of pavements following conclusions are drawn:

The marble powder stabilizer reduced LL and PI of natural unstabilized expansive soil by 22 % and 16 % respectively as compared to lime stabilizer which reduced LL and PI by 13 % and 52 % respectively. Marble powder can therefore be used as an alternative stabilizer where plasticity reduction is the objective of stabilization.

The marble powder stabilizer reduced FSI by 80 % as against the reduction caused in FSI by the lime stabilizer of 89.5 %. Marble powder can therefore be used as an alternative to lime for the objective of swelling control in case of expansive soils with medium degree of expansiveness.

The X- Ray Diffraction Tests results revealed that, Dolomite rich in calcium and magnesium causes the strength gain with time however, Andesine the primary constituent mineral in lime stabilized soil to be seems responsible for gain in UCS is not observed to be formed in marble stabilized soil and Anorthite Sodian seemed to be responsible for the strength reduction in the marble stabilized soil. Therefore, where swelling and plasticity reduction is the objective of stabilizer 1ation there the marble powder is a potential candidate stabilizer for expansive soils, however, the efficacy of marble powder in increasing the strength is less as compared to lime stabilizer as the marble stabilized samples were observed to be brittle in nature.

The increase in UCS, over that of uncured-unstabilized expansive soils by using 28-day cured lime stabilized subgrade was 55 % as against the increase in UCS obtained by marble powder stabilizer was 45 % at the same curing period. Therefore, marble powder can be used as a dependable alternative if lime is not available.

The increase in the rutting and fatigue life of flexible pavements founded on expansive soils stabilized with marble powder was 376 times and 38 % respectively as compared to lime stabilized subgrades which resulted in increase of rutting and fatigue life of pavements by 641 times and 42 % respectively. This indicates that marble powder can satisfactorily contribute for improving the pavement durability as it results in improves the rutting and fatigue life a flexible pavement founded on expansive soils.

To summarize the conclusions, it can be stated that, the marble powder stabilizer can be considered as a reliable stabilizer for achieving the objectives of stabilization of expansive soils such as controlling plasticity and swelling, improving the strength of a subgrade (UCS), and increasing the rutting and fatigue life of a flexible pavements for improved durability of such pavements. The findings in this study therefore, support marble powder as a sustainable alternative where lime is less accessible, particularly for soils of low to medium expansiveness.

Acknowledgement

The authors would like to thank Mrs. Vidya Raul and Mr. Milind Sable, Lab Assistant, NMIMS' MPSTME for their continued help and cooperation during lab experimentation. We would also like to acknowledge Department of Earth Sciences, IIT Bombay for providing X-Ray Diffraction Testing facility for our research work.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

References

[1] Anaokar, M. and S. Mhaiskar. 2018. Evaluation of Swelling Control Parameters for Stabilized Expansive Soil Buffer Layers under Pavement Embankment. *International Journal of Engineering and Applied Sciences (IJEAS)*. 5: 79–85. https://doi.org/10.31873/IJEAS.5.1.33.

[2] Anaokar, M. and S. Mhaiskar. 2019. Numerical Analysis of Lime Stabilized Capping under Embankments based on Expansive Subgrades. *Heliyon*. https://doi.org/10.1016/j.heliyon.2019.e02473

[3] Anaokar, M. and S. Mhaiskar. 2020. Experimental and Numerical Assessment of Efficacy of Lime Stabilized Capping Material in Controlling Swelling Displacements within Flexible Pavement Embankments. *Heliyon*. 6. https://doi.org/10.1016/j.heliyon.2020.e04961.

[4] Gireesh Kumar, P. and S. Harika. 2021. Stabilization of Expansive Subgrade Soil by Using Fly Ash. *Materials Today: Proceedings*. 45: 6558–62. https://doi.org/10.1016/j.matpr.2020.11.469.

[5] Saride, S., A. J. Puppala, and Chikyala, S. R. 2013. Swell-Shrink and Strength Behaviors of Lime and Cement Stabilized Expansive Organic Clays. *Applied Clay Science*. 85: 39–45. https://doi.org/10.1016/j.clay.2013.09.008.

[6] Consoli, N. C., M. Tonini de Araújo, S. Tonatto Ferrazzo, V. de Lima Rodrigues, and C. Gravina da Rocha. 2021. Increasing Density and Cement Content in Stabilization of

Expansive Soils: Conflicting or Complementary Procedures for Reducing Swelling? *Canadian Geotechnical Journal*, 58: 866–78. https://doi.org/10.1139/cgj-2019-0855.

[7] Taye, B. and A. A. Araya. 2015. Stabilization of Expansive Clay Soil with Sugar Cane Molasses and Cement. *2nd International Conference on Transportation in Africa ICTA*. 1–13.

[8] Daniel, A. 2022. Evaluating the Durability of Expansive Subgrade Soils Stabilized with Molasses and Cement. [Internet]. Makerere University.

[9] Ahmadi Chenarboni, H., S. Hamid Lajevardi, H. MolaAbasi, and E. Zeighami. 2021. The Effect of Zeolite and Cement Stabilization on the Mechanical Behavior of Expansive Soils. *Construction and Building Materials*. 272: 121630. https://doi.org/10.1016/j.conbuildmat.2020.121630.

[10] Liu, Y., C. W. Chang, A. Namdar, Y. She, C. H. Lin, X. Yuan *et al.* 2019 Stabilization of Expansive Soil Using Cementing Material from Rice Husk Ash and Calcium Carbide Residue. *Construction and Building Materials*. 221: 1–11. https://doi.org/10.1016/j.conbuildmat.2019.05.157.

[11] Fentaw, M., E. Alemayehu, and A. Geremew. 2021. Experimental Study of Stabilization of Expansive Soil Using the Mixture of Marble Dust, Rice Husk Ash and Cement for Sub-Grade Road Construction: A Case Study of Woldia Town. *Journal of Civil Engineering, Science and Technology*. 12: 141–59. https://doi.org/10.33736/jcest.3977.2021.

[12] Kumar Sharma, A., N. Mishra, and L. Chaudhary. 2023. Effect of Adding Marble-Dust Particles (MDP) as a Partial Cement Replacement in Concrete Mix. *Materials Today: Proceedings*. https://doi.org/10.1016/j.matpr.2023.05.017.

[13] IS: 2720 (Part 5). 1995. Determination of Liquid and Plastic Limit. Bearau of Indian Standards, New Delhi, India. 1–16.

[14] IS 1498. 1997. IS 1498 Classification and Identification of Soils for General Engineering Purposes. BIS. 1–24.

[15] Zumravi, M. and E. A. E. Abdalla. 2018. Stabilization of Expansive Soil using Marble Waste PowdeR. *Second Conference of Civil Engineering in Sudan 2018, University of Khartoum, Sudan.*

[16] IS 2720 (Part 10). 1995. IS 2720 (Part 10)-1995: Determination of Unconfined Compressive Strength. Bearau of Indian Standards. 1–4.

[17] IRC-37. 2018. Guidelines for the Design of Flexible Pavements (Fourth Revision). Indian Roads Congress, New Delhi, India.

[18] Thompson,M. R. 1969. Engineering Properties of Lime-Soil Mixtures. *Journal of Materials, ASTM*. 4.

[19] Little, D. N. 1999. Evaluation of Structural Properties of Lime Stabilized Soils And Aggregates. National Lime Association. I: 1–97.

[20] IS: 2720 (Part 40). 1997. Determination Free Swell Index of Soils. *Bearau of Indian Standards, New Delhi, India*. 1–5.

[21] Mani Bharathi, A., P. T. Ravichandran, and K. D. Krishnan. 2019. Potential Use of Dolomite Hydrated Lime in Sustainable Strength Improvement of Clayey Soil. *Journal of Green Engineering*. 9: 489–50.