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Research article

Experimental and numerical assessment of efficacy of lime stabilized capping material in controlling swelling displacements within flexible pavement embankments

Manoj Anaokar [a,*], Sharad Mhaiskar [b]

[a] NMIMS, Mukesh Patel School of Technology Management & Engineering, Department of Civil Engineering, Bhakti Vedant Swami Marg, JVPD Scheme, Vile Parle (West), Mumbai 400056, Maharashtra, India
[b] SVKM's NMIMS (Deemed to be University), V. L. Mehta Road, Vile Parle (West), Mumbai 400056, Maharashtra, India

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ABSTRACT

The performance of flexible pavements constructed on embankments founded on expansive clay subgrade is greatly affected by the distress caused in these embankments as they are subjected to swelling displacements. These are caused by the volume changes in expansive subgrade soil due to moisture variation. The authors have suggested the technique of 'C'-shaped lime stabilized capping in their earlier studies which is useful for controlling swelling displacements within the expansive subgrade. In the present study, the authors have attempted to assess the efficacy of the capping material itself for controlling swelling displacements at the top and bottom of embankment which is directly responsible for improving the performance of pavements on these embankments. This assessment is carried out with respect to stiffness and reduction in permeability of capping material. Stiffness of the buffer layer controls swelling displacements within the embankment under flexible pavement and the reduced permeability of the capping will control moisture variations and the corresponding pavement distress. The stiffness assessment is carried out through laboratory Unconfined Compression Strength (UCS) tests for modulus estimation by curing the samples for short-term and long-term strength gain. Assessment of permeability reduction is carried through the study of permeability of expansive soils after lime stabilization. Swelling displacements are estimated using Finite Element Analysis (FEA) of the numerical model. The experimental and numerical analysis results indicate that with the increased modulus and reduced permeability of the buffer layer material the swelling displacements at the top and bottom of pavement embankment have reduced. This will help in improving the performance of pavement constructed on the embankment founded on the expansive subgrade.

1. Introduction

Even the cautiously designed structures are subjected to distress conditions and the funds invested in the construction of these structures go in vain due to the large seasonal volume changes occurring in the supporting founding expansive soils. Various investigators have used different stabilizing materials and techniques in their research work to control the expansiveness of the expansive soil for improving the performance of the structures founded on such soils. Lime stabilization and fly ash stabilization techniques are quite popular among the researchers. In experimental approach fly ash stabilization has been studied [1] to assess the effect of such stabilization on plasticity, hydraulic conductivity and swelling properties. Some investigators have even studied [2] the stabilization of fly ash itself with lime and gypsum. The effect of lime stabilization on different engineering properties of expansive soils is studied by several investigators [3, 4, 5] over several years through an experimental approach. Some of the investigators [6] have adopted the approach of Soil Water Characteristics Curve (SWCC) to study relation of the components of the curve namely, saturated gravity water content, residual water content, air entry value and the slope of the curve with matric suction and attempted to interpret the effect of improvements in these components on the properties of soil like water holding capacity with varying percentages of lime. In another study researchers [7] observed the increase in water retention capacity due to a reduction in pore size after lime stabilization. Many other researchers [8] have adopted the numerical approach for studying the volume changes and displacements in expansive soils. In another study [9] variation in suction and settlements during shrinkage of expansive soils is studied to evaluate

* Corresponding author.
E-mail addresses: manoj.anaokar@nmims.edu, anaokarm@yahoo.co.in (M. Anaokar).

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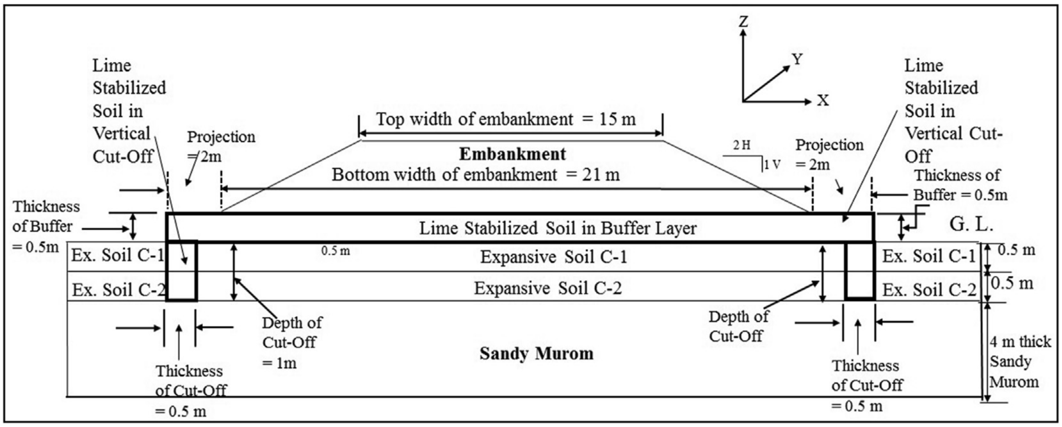


Figure 1. 'C'-shaped protective capping under pavement embankment.

the performance of horizontal moisture barriers using software Abaqus. The results indicate that the performance depends on soil properties and climatic conditions. Deflection measurement on pavement embankments under varying traffic loads cycles is studied in another research study [10] using software PLAXIS 2D. Another study [11] performs the computations of deformations and groundwater flow conditions with time-dependent boundary conditions to assess the stability of embankment slopes using software PLAXIS 2D.

From literature, it is observed that the lime stabilization technique is better and a widely successfully used technique over the years as compared to the other techniques using other stabilizing materials. In lime stabilization, whether, the experimental approach, SWCC approach or numerical approach is adopted, the technique involves the complete volume stabilization of expansive soil up to active zone depth of 1–1.5 m within which the volume changes are normally taking place. This is not cost-effective as large amount of lime (CaO), is required to cause effective stabilization. Therefore, a cost-effective and easy to use technique is necessary which can be adopted on-site with the available equipment on-site like graders, rotavators, etc. for mixing the lime efficiently up to the complete depth. However, this equipment can only carry out mixing effectively up to 0.3 m–0.5 m depth. Considering this need, the authors suggested in their earlier studies [12] a new technique of 'C'-shaped lime stabilized capping by stabilizing the locally available expansive soil (Figure 1). This cap is of the shape of the English letter 'C' and is formed by the horizontal buffer layer and the vetical Cut-offs as shown in Figure 1. The thickness of capping suggested in that study was 0.5 m and it was observed that the swelling displacements within the expansive clay subgrade soil below the embankment were controlled using this technique. However, it is felt necessary to study the effect of this capping on the displacements at the top and bottom of the pavement embankment itself which actually carries the flexible pavements. Distress in pavements is due to the swelling displacements at top and bottom of the embankments supporting flexible pavements. Therefore, controlling these displacements will help to reduce the distress.

The present study, therefore, assesses the efficacy of the capping itself by laboratory experimentation and numerically analyzing the capping material for assessing the role of the stiffness of the buffer layer in reducing the swelling displacements at the top and bottom of the embankment. The details of the materials used in the study are presented in the following section.

2. Materials and methods

The nost widely occurring type of expansive soil available in India, known as black cotton soil, is used in this study. Quick lime is used for carrying out lime stabilization. The material details are presented in the following sections.

2.1. Materials

2.1.1. The expansive black cotton soil

Ahmednagar in Central Maharashtra predominantly consists of expansive clay called Black Cotton Soil. The soil samples were collected from the three locations, termed as location 'A', 'B' and 'C' as shown in

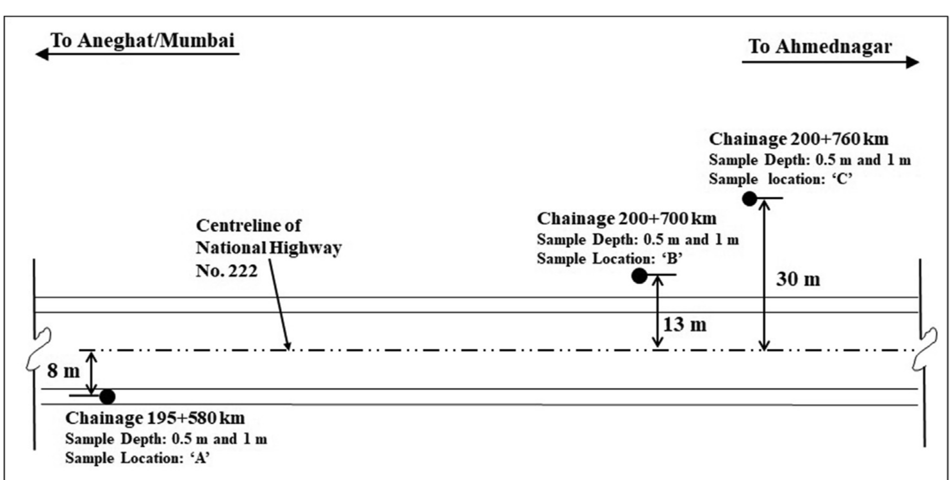


Figure 2. Location plan for soil samples.

Table 1. Basic properties of unstabilized expansive soil samples (Anaokar and Mhaiskar [12]).

Properties	Soil A-1	Soil A-2	Soil B-1	Soil B-2	Soil C-1	Soil C-2
IS Soil Classification	CH	CH	CH	CH	CH	CH
AASHTO Classification	A-7-5	A-7-5	A-7-6	A-7-6	A-7-6	A-7-6
LL (%)	99	78	66	71	93	89
PI (%)	63	44	38	45	66	63
SL (%)	18	23	20	21	11	12
FSI (%)	188	66	111	90	138	180
MDD (kN/m^3)	14.02	14.22	15.01	17.07	15.89	16.09
OMC (%)	24	32	27.5	27.5	22.5	19.5
Swelling Pressure at OMC (kN/m^2)	1 76.52	68.65	137.29	88.26	156.91	245.17
Swelling Pressure at OMC+2% (kN/m^2)	73.55	31.38	16.67	6.37	13.73	29.42

Figure 2. These locations are the same locations as in earlier studies [12], which are situated along the National Highway No.222. This location was selected because normally distress in pavements is observed in this region. The samples were collected from the depths of 0.5 m and 1 m because the color of the sample was changing at 0.5 m. The samples from locations A, B, and C were, therefore, termed as A-1, A-2, B-1, B-2, C-1 and C-2 respectively. All these soil samples are classified as Highly Plastic Clay Soils (CH) as per Indian Standard (IS) soil classification. As per Group Index Method soil samples 'A-1' and 'A-2' belong to the group A-7-5 and 'B-1', 'B-2' and 'C-1', 'C-2' belong to the group A-7-6. After 1 m the soil available at the site has been observed as yellowish-brown sandy Murrum.

2.1.2. Stabilizing material

The quick lime powder was used for the stabilization of the expansive soil. It is 100% lime (CaO). CaO is obtained by calcination of the lime stone, which is a calcareous rock of sedimentary type consisting of mineral calcite ($CaCO_3$).

3. Methodology

3.1. Introduction

This section is divided into two sub-sections. The first subsection presents the methodology adopted for laboratory experimentation. The second subsection discusses the details of numerical modeling carried out for validating the results obtained from laboratory experimentation.

3.2. Methodology for laboratory experimentation

As the soil belongs to the same location from the earlier studies, the basic properties like index properties comprising of Atterberg's Limits and Grain Size Analysis, the compaction properties, that is, Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) and the Swelling Pressure (SP) magnitudes are considered from the earlier studies [12]. They are reported in Table 1. The results in Table 1 indicate that the soils are highly plastic clay soils having medium to high degree of expansiveness as per IS 1498–1997 [13]. As the swelling pressure varies depending on the moisture content and it is maximum at OMC and reduces at OMC+2 % [14], therefore, the magnitudes of swelling pressure at these two moisture contents are reported in Table 1.

The optimum percentage of lime of 5% is worked out in earlier studies [1] in the laboratory by comparing the results of Free Swell Index (FSI) and Atterberg's Limit Test results at different percentages of lime as 0% (unstabilized soil), 2 %, 4 % 5% and 6%. At 5% lime, the plasticity was reduced as Liquid Limit (LL) and Plasticity Index (PI) values have been observed to reduce and the Shrinkage Limit (SL) values for the soil samples have been observed to increase.

In the present study, this percentage of lime, that is, 5 % was then used for molding samples for UCS, and consolidation tests. Consolidation test data is used to obtain the permeability. As it was necessary to assess the effect of lime stabilization on improvement in elastic moduli (obtained from UCS), and, on reduction in permeability. It was necessary to evaluate these properties in case of unstabilized as well as lime stabilized soils. Therefore, in the present study, UCS (as per IS 2720 Part 10–1995) [15] and consolidation tests (as per IS 2720 Part 15–1997) [16] were performed in both unstabilized and lime stabilized states on all the six expansive soil samples. For both these tests in unstabilized and lime stabilized states the samples were molded to MDD and OMC+2% of the corresponding states because the soils will be compacted in the field corresponding to these densities and moisture contents. For calculating the elastic moduli of the materials Dallas Little [3] in his report submitted to National Lime Association, USA, has referred to Thompson's equation [17] for evaluating modulus 'E' from Unconfined Compressive Strength (UCS) value. Thompson developed this correlation between UCS and Elastic Modulus based on generalized stress-strain plot for lime stabilized expansive clays. Thompson's equation in SI form is given below:

$$E(kN/\ m^2) = 68810 + 124\ (UCS,\ kN/\ m^2) \tag{1}$$

For studying the effect of curing period on the increase in UCS and also on the elastic moduli the UCS was obtained in unstabilized states and lime stabilized states by adding 5% of lime to expansive soils UCS tests were performed on the samples cured for 0 days (unstabilized), 3 days, 7 days, 14 days, 28 days, 45 days and 90 days. The moduli obtained from this laboratory experimentation are later used in the FEA of the numerical model in order to study the effect of modulus on the swelling displacements at the top and bottom of pavement embankment. Laboratory consolidation tests were performed on all the six soil samples in unstabilized and lime stabilized states and the permeabilities of the soils are obtained from the consolidation test data. The methodology for the numerical modeling is presented in the following section.

3.3. Methodology for numerical modelling

3.3.1. Introduction

The efficacy of the capping is assessed in the present work to confirm the swelling displacements are controlled at the top and bottom of pavement embankment. The effect of stiffness of buffer layer on displacments is also assessed at the top and bottom of buffer layer which is the horizontal componenet of the capping. The assessment of effect of capping is carried out through FEA for the numerical model simulating the two physical states and comparing the swelling displacements in these two states when the soil becomes wet during monsoon. One state is unstabilized state when the embankment is based directly on the expansive subgrade (called as Unstabilized Road Model, '*URM*') and the other state is stabilized state when the embankment is based on the 'C'-shaped capping serving as a buffer layer between the embankment base and the expansive subgrade (called as Stabilized Road Model, '*SRM*').

The effect of stiffness of the buffer layer on the displacements is assessed by by comparing the *SRM*s in two ways. Initially, by varying the

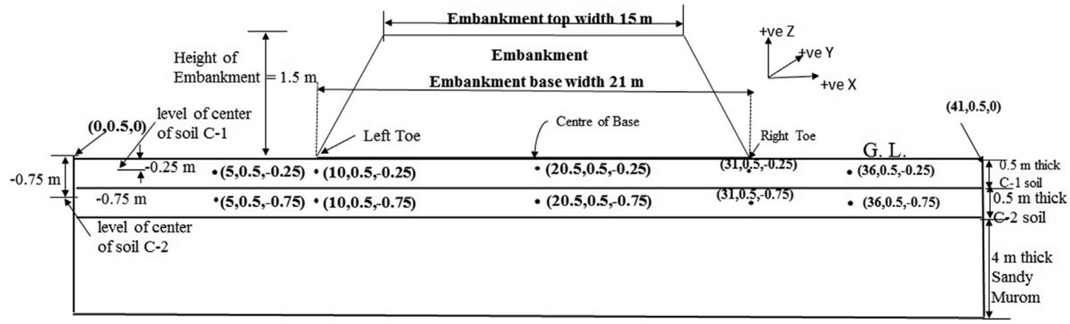


Figure 3. Coordinates of the nodes for swelling displacements in URM Anaokar and Mhaiskar [12].

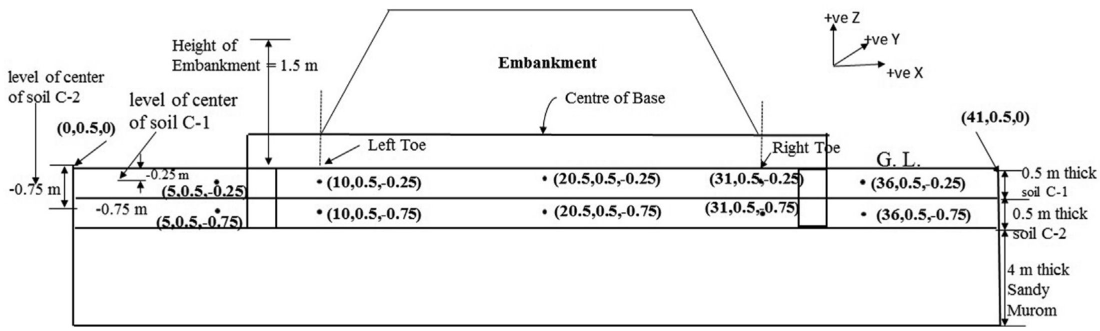


Figure 4. Coordinates of the nodes for swelling displacements in SRM.

thickness of buffer layer and then by varying the modulus of the buffer layer.

The basic aim of the capping having a buffer and vertical cut-off as its components is to provide a control on volume changes in expansive subgrade caused by moisture variations. Laboratory experimentation indicates that, the improved properties of the capping material will control the swelling displacements in expansive subgrade thereby controlling the swelling displacements in embankmens carrying pavements. Therefore, it is necessary to validate the efficacy of the proposed 'C'-shaped capping model itself, to assess directly the control on volume strains caused within the protected capping zone under the embankment after the construction of capping. The details of the numerical model with capping considered for FEA are as shown in Figure 1.

3.3.2. Constitutive models

Software PLAXIS 3D is used to carry out FEA of the numerical model in unstabilized and stabilized states for simulating *URM* and *SRM*. There are different material models available in PLAXIS 3D for simulating soils. They include Linear Elastic Model (LEM), Mohr-Coulomb Model (MCM), Hardening Soil Model (HSM), Soft Soil Model (SSM), etc. The elastic behavior of soil is non-linear and therefore, the model doesn't have the required features for simulating soils such as expansive soil. MCM is the most used model in earlier studies to simulate expansive soil. Some investigators have used the HSM [18] and SSM [10] to simulate expansive soil. The present work involves the stiffness study. However, the HSM doesn't distinguish between large stiffness at small strains and reduced stiffness at engineering strain levels. Therefore, the stiffness parameters are required to be selected in accordance with the dominant strain levels in the application and the correct dominant strain level needs to be identified for avoiding the incorrect output results [19]. Excavation is involved in the present work in the staged construction of the numerical model and the SSM is not recommended in soft soil problems since the model hardly supersedes the MCM in unloading problems [19]. Considering these issues MCM is used in the present study to simulate the expansive soil. However, MCM itself doesn't have the capability to cause the swelling strains in the soils. Therefore, the volume strain feature available in the software PLAXIS 3D is used with a positive value of volume strain is given as input in positive 'Z' direction to simulate the upward swelling. These volume strains are used to simulate the swelling in Monsoon Phase that is Phase 6. This value of swelling strain is obtained from the laboratory consolidation tests by noting down the swelling strain when the sample is allowed to swell under the seating load. The percentage of increase in sample thickness in laboratory test due to swelling compared with the original height of the sample is taken as the swelling strain. These values of volume strain are given in Table 4. Van Genuchten hydraulic model is used for simulating the the ground water conditions.

3.3.3. Boundary conditions

The soil volume considered for numerical modeling is 41 m long along the 'X' axis, 1 m wide along the 'Y' axis. Figures 3 and 4 show the dimensions of the model components and the coordinates of the nodes for the swelling displacements at the top and bottom of the embankment for pavement for *URM* and *SRM* respectively.

Boundary conditions for displacements are as follows:

The model is considered in the X-Z plane. The 'X' axis is horizontal and the 'Z' axis is vertical. X_{min} and X_{max} boundaries are horizontally fixed. As the software is 3D, therefore, 1 m width has to be considered along the 'Y' axis. Therefore, the problem is plane strain approximation. Both Y_{max} and Y_{min} are considered as horizontally fixed. Z_{min} is vertically fixed whereas boundary Z_{max} is kept free for allowing swelling in the vertically upward direction.

Boundary conditions for groundwater conditions are as follows:

Only Y_{min} and Y_{max} boundaries are considered as closed, which means no flow can take place along the 'Y' axis. All other boundaries X_{min}, X_{max}, Z_{min} and Z_{max} are kept open, that means the moisture movements can take place along 'X' and 'Z' directions.

Table 2. Curing Period-UCS Relation for Soils (UCS in kN/m^2).

Period of Curing (Days)		0	3	7	14	28	45	90
Soil A-1	Without Lime	101.01	116.70	141.22	152.00	122.58	73.55	26.48
	With Lime	129.45	246.15	254.97	297.14	355.98	387.36	513.87
Soil A-2	Without Lime	130.43	139.25	151.02	164.75	105.91	92.18	36.28
	With Lime	138.27	187.31	302.04	355.98	377.56	469.74	537.40
Soil B-1	Without Lime	86.30	109.83	117.68	121.60	62.76	63.74	112.78
	With Lime	124.54	276.55	302.04	320.68	510.93	567.81	605.07
Soil B-2	Without Lime	94.14	61.78	108.85	107.87	59.82	36.28	18.63
	With Lime	151.02	195.15	244.19	268.70	487.39	543.29	576.63
Soil C-1	Without Lime	55.90	76.49	81.40	108.85	104.93	94.14	16.67
	With Lime	159.85	170.64	217.71	325.58	435.42	516.81	538.39
Soil C-2	Without Lime	55.90	87.28	106.89	180.44	115.72	105.91	31.38
	With Lime	130.43	262.82	296.16	360.88	558.98	569.77	589.38

Table 3. Comparative results of permeability for the unstabilized and the lime stabilized soils.

Soil Sample	A-1	A-2	B-1	B-2	C-1	C-2
Permeability of Unstabilized Soil (cm/s)	4.17×10^{-6}	6.38×10^{-6}	5.05×10^{-6}	5.00×10^{-6}	4.32×10^{-6}	4.01×10^{-6}
Permeability of Lime Stabilized Soil (cm/s)	7.38×10^{-7}	3.25×10^{-6}	1.58×10^{-6}	1.38×10^{-6}	8.19×10^{-7}	4.78×10^{-7}
Reduction in permeability (%)	82	49	69	72	81	88

4. Results and discussion

4.1. Introduction

Initially, the results of laboratory experimentation are presented and discussed. Thereafter the results of suctions and vertical displacements obtained from FEA are presented and discussed for assessing the efficacy of the material of the 'C'-shaped capping in reducing the swelling displacements if any at the top and bottom of the pavement embankment.

4.2. Results and discussion on laboratory experimentation

The capping material should have an increased modulus for the buffer layer so as to provide a firm levelled surface below the base of the embankment. The UCS tests have been performed on the samples moulded at a density equal to MDD and moisture content equal to OMC+2% as it can be observed from earlier studies [14] that we get the reduced swelling pressures when the soils are compacted at a moisture content of OMC+2%. The results of UCS in unstabilized and stabilized states (lime content 5 %) for different curing periods are reported in Table 2.

The UCS has been performed on specimens of all the soils. The samples were cured by preserving the moisture in them by sealing the samples in self-sealing polythene bags and wrapping these bags with moist cloth. This will maintain the humidity surrounding the bag preserving the moisture loss from the samples. The samples were cured for 0-day (that is tested on the same day as moulded), 3days, 7 days, 14 days, 28 days, 45 days and 90 days.

From the results of UCS in Table 3, it can be observed that the Unconfined Compressive Strength improves on lime stabilization with an increase in the curing period. UCS of unstabilized uncured soil is 55.90 kN/m^2. This increases to 159.85 kN/m^2 on stabilization. On curing UCS of stabilized soil increased by about 3 times and further increased by 1.36, 2.03, 2.72, and 3.23 times, respectively after 7, 14, 28 and 45 days. Therefore, the buffer layer will be having more strength to resist the volume changes which may occur in expansive subgrade soil below the embankment by providing a relatively rigid surface under the embankment base.

Therefore, the capping material is observed to efficiently fulfil the requirements of reduced permeability and increased strength so as to act as a moisture barrier and provide a level surface of increased modulus under the pavement embankment to resist the swelling strains if any.

The permeability of the soil is observed from the consolidation test data. The consolidation tests were performed in both unstabilized and lime stabilized states. The results of the permeability are presented in Table 3.

The results in Table 3 indicate that there is a reduction in permeabilities after lime stabilization. From theses results, it can be stated that

Table 4. Numerical model properties.

Layer and Soil Details	γ_d (kN/m^2)	γ_{sat} (kN/m^3)	c (kN/m^2)	φ (Deg-rees)	E (kN/m^2)	E_{OED} (kN/m^2)	ν (ratio)	Volume strain representing Swelling Strain (%)	Type of Analysis
γ_O-C-1	15.89	20.01	47.07	6	8.048×10^4	1.083×10^5	0.3	3.23	Undrained 'A'
γ_O -C-2	16.09	19.91	52.96	7	8.194×10^4	1.103×10^5	0.3	1.81	Undrained 'A'
γ_i C-1	13.73	18.64	33.89	5	7.721×10^4	1.039×10^5	0.3	0.16	Undrained 'A'
γ_i C-2	13.24	18.15	33.89	5	7.721×10^4	1.039×10^5	0.3	0.10	Undrained 'A'
(LS_7) C-1	15.4	19.52	108.85	7	9.58×10^4	1.29×10^5	0.3	0.08	Undrained 'A'
(LS_{28}) C-1	15.4	19.52	217.71	7	1.23×10^5	1.65×10^5	0.3	0.08	Undrained 'A'
(LS_{45}) C-1	15.4	19.52	258.41	7	1.33×10^5	1.789×10^5	0.3	0.08	Undrained 'A'

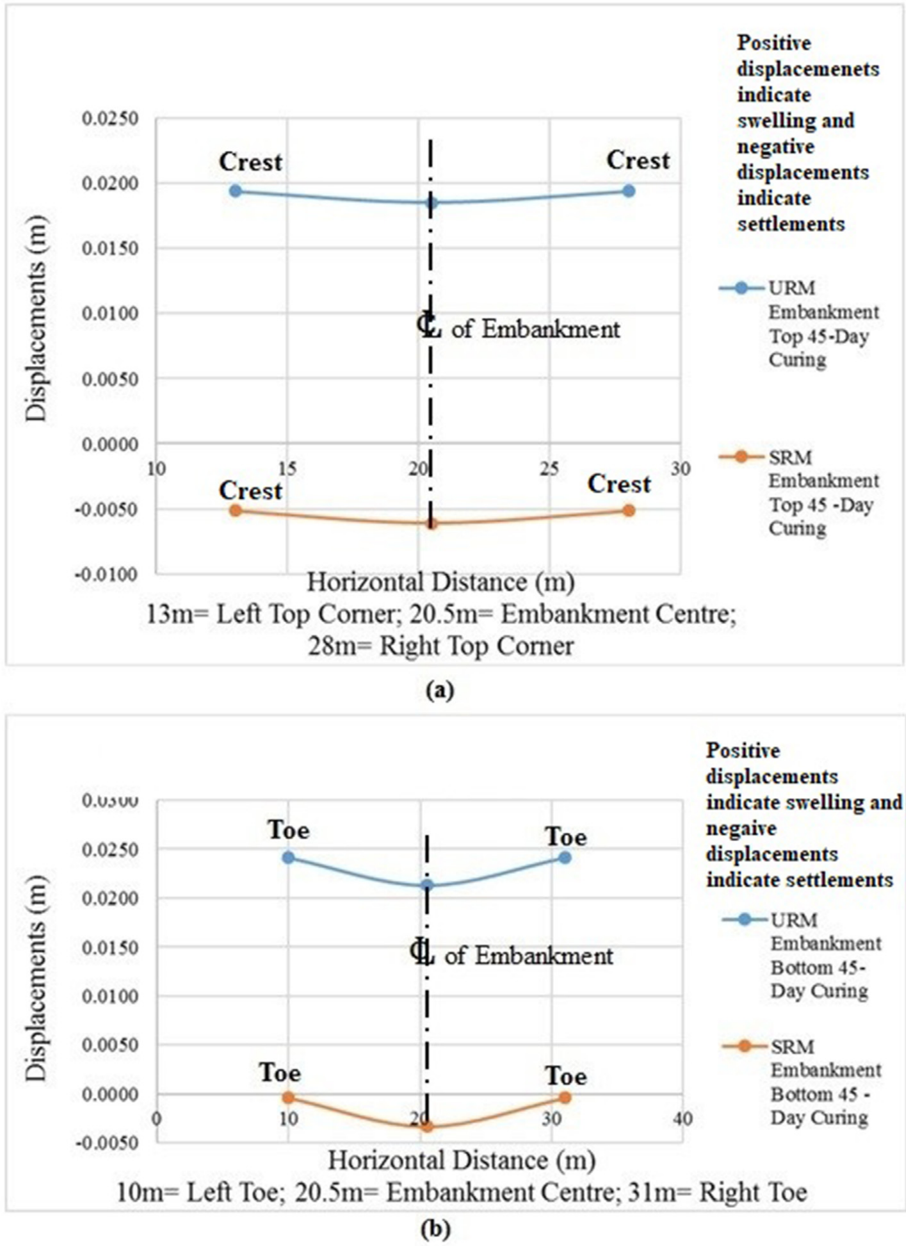


Figure 5. Comparitive Results of Displacements between URM and SRM. (a) At Crest of Embankment. (b) At Toe of Embankment (Buffer Layer: Projection = 2 m, Thickness = 0.5 m; Vertical Cut-off depth = 1 m and Thickness = 0.5 m).

the capping material for buffer and especially in vertical cut-offs has about 80% reduced permeability in case more expansive soils A-1, C-1 and C-2. This will help to reduce the moisture variations within the capping zone thereby reducing the volume strains in expansive subgrade within this zone. In turn, this will help to reduce the swelling displacements within the embankment. This statement is validated by assessing the swelling displacements at the top and bottom of the embankment.

4.3. Results and discussion on numerical modelling

4.3.1. Introduction

Laboratory experimentation results indicate that the strength of UCS is increasing after 45-Day curing and therefore, the capping or the buffer layer within the capping will have increased elastic modulus which will help to reduce the swelling displacements within the embankment at its top and bottom. However, in field conditions, the load system is complex as there are many parameters involved such as weight of embankment, modulus of the capping material, moduli of the expansive clay subgrade, etc. Therefore, FEA carried out for the numerical model simulating the field conditions in case of a physical model. The properties of soils used as input parameters for numerical model are discussed in the subsequent section and are presented in Table 4. As discussed in methodology after applying these loading, swelling and moisture conditions to the numerical model, the results obtained are shown in the figures in the following sections along with the discussion on it.

4.3.2. Properties of numerical model

Modulus corresponding to 45-day curing is considered for considerable gain in UCS. Location ‘C’ has expansive soils which are most swelling amongst the expansive soils at locations ‘A’, ‘B’ and ‘C’ as shown in Figure 2. Therefore, the model is considered to be constructed at location ‘C’ on the expansive soil layer C-1 underlain by another expansive soil

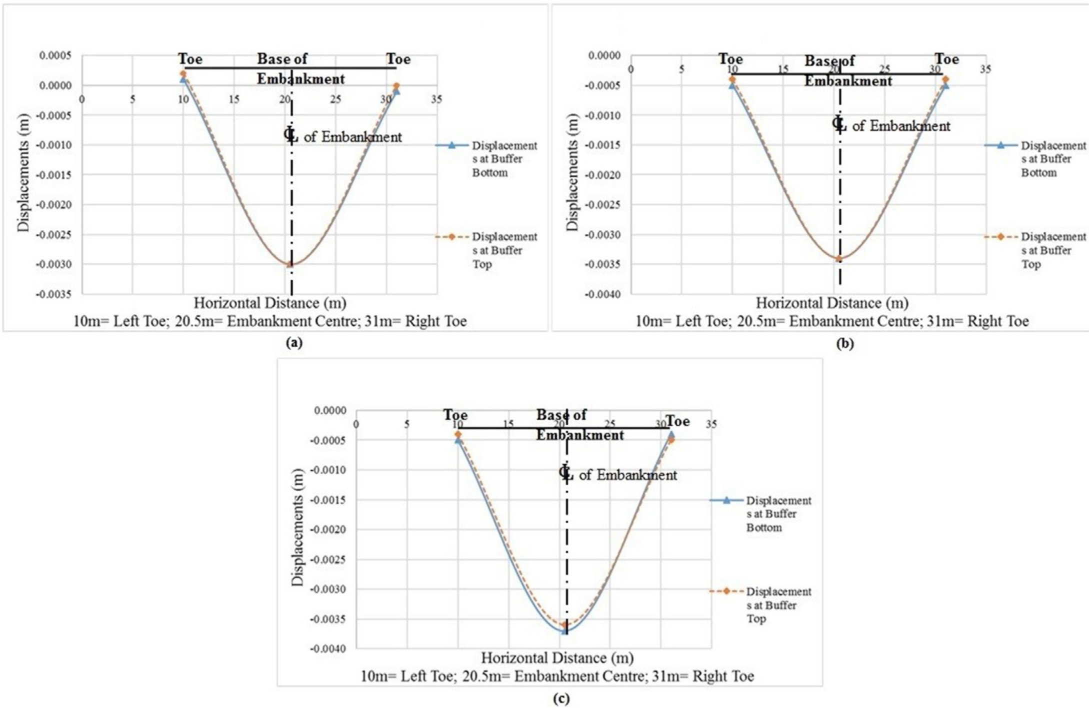


Figure 6. Effect of Buffer Thickness on Displcements at Top and Bottom of Buffer Layer. (a) Displacements when buffer thickness = 0.3 m. (b) Displcements when buffer thickness = 0.5 m. (c) Displcements when buffer thickness = 0.7 m. (Buffer Layer: Projection = 2 m; Vertical Cut-off depth = 1 m and Thickness = 0.5 m).

layer C-2. The thickness of each layer as obtained from field data is 0.5 m and the sandy Murrum thickness is considered as 4 m as observed in the field.

In the earlier studies [20], it has been observed that the void ratio varies from 0.8 in summer to 1.2 after rains in monsoon and as void ratio increases, swelling pressure reduces. Due to seasonal variations in moisture throughout the year as there are variations in amount of swelling it will result in the corresponding variations in void ratio. Therefore, considering the average conditions, it is assumed that the void ratio reaches a value between '0.8' and '1.2' i.e. equal to unity. The unit weights, permeability and swelling pressure for the expansive subgrade soil within the capping zone are estimated from laboratory results corresponding to the void ratio of '1' [12].

The conventions and symbols used in Table 4 are as follows:

γ_O-C-1 and γ_O -C-2 are the Unit weights of unstabilized expansive soil layers C-1 and C-2 respectively Outside capping during Monsoon; γ_i -C-1 and γ_i -C-2 are the unit weights of unstabilized soils C-1 and C-2 respectively inside the capping zone at Void Ratio = 1; LS_7, LS_{28}, and LS_{45} indicate the Lime Stabilized Soil C-1 at MDD and OMC+2% cured for 7,

γ_d = Dry Unit Weight of soils; γ_{sat} = Saturated Unit Weight of soils; c = cohesion; φ = angle of friction; E = Young's Modulus; E_{OED} = Oedometer Modulus; ν = Poisson's ratio.

4.3.3. Assessment of effect of capping over the swelling displacements in flexible pavement embankment

The present study has been undertaken with an objective to control the swelling displacements in flexible pavement embankment because these displacements are responsible for causing the distress in the pavements by reducing their performance and life. In that sense, magnitudes of swelling displacements are the performance indicators. Considering this, it has been decided to compare the results of displacements at the top and bottom of an embankment when the embankment rests directly on the expansive subgrade (URM) with the corresponding displacements at top and bottom of embankment when it rests on the buffer of 'C'-shaped capping. The comparative results for URM and SRM for the swelling displacements at the top and bottom of the embankment are shown in Figure 5 (a) and (b) respectively.

Discussion on comparative results in Figure 5 is presented below:

Figure 5 (a) indicates that the swelling displacements under the Left Top Corner (X = 13 m); Centre (X = 20.5 m), and Right Top Corner (X = 28 m) in SRM are lesser both at top and bottom indicating the positive role of the buffer or capping in reducing pavement embankment distress.

Figure 5 (b) indicates a similar comparison for the bottom of the embankment and it also shows that the swelling displacements at the bottom of pavement embankment are controlled when the lime stabilized capping is provided under the embankment as a buffer layer between expansive subgrade and base of the embankment.

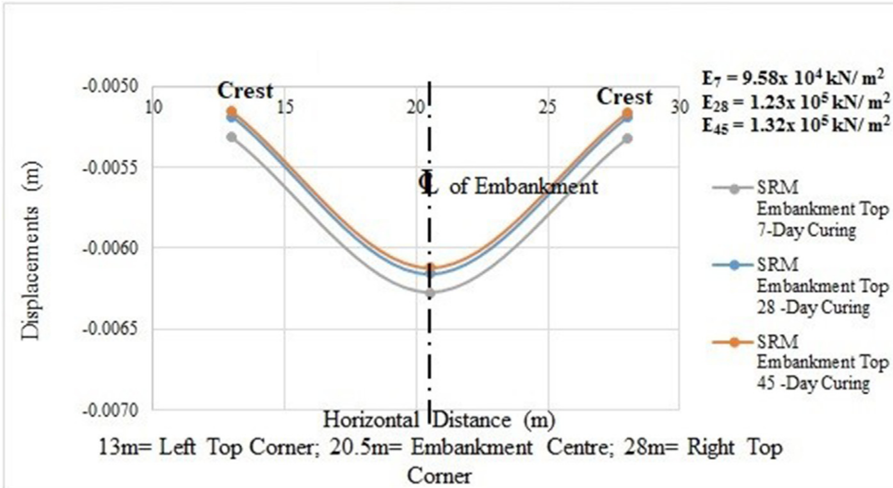
4.3.4. Study of buffer stiffness by variation in buffer thickness

For studying the effect of variation in buffer layer thickness on buffer stiffness, the three cases have been considered, viz., 0.3 m, Buffer thickness of 0.5 m, and 0.7 m.

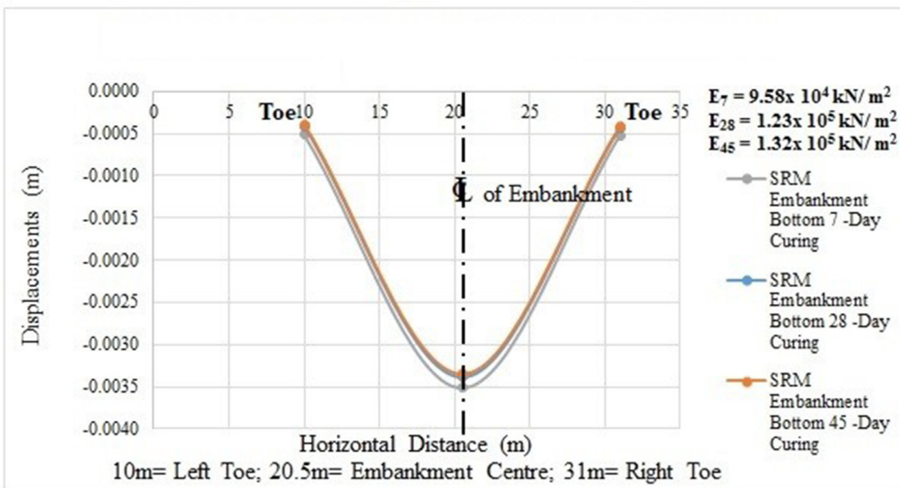
The comparison of displacements in Figure 6 (a) through (c) corresponding to different buffer thicknesses indicates the following:

The displacements above and below the buffer are negative, i.e. settlements. Irrespective of the buffer thickness, displacements at the top and bottom of the buffer layer at the corresponding nodes, both under the toes (left and right) and the centre, are equal. Therefore, it can be inferred that the buffer layer is sufficiently stiff so that the swelling displacements are restricted to the zone within the capping and are not propagated above.

A buffer thickness of 0.5 m is preferable, since 0.3 m is too thin from practical point of view and 0.7 m does not give any additional benefit compared to 0.5 m. Also, it satisfies the requirement of IRC-36 of replacement of expansive soil below the embankment base up to a depth of 0.5 m by providing a lime stabilized buffer layer. This buffer also takes care of the IRC-37 recommendation of the buffer layer under the base of the embankment. Under the centre of the embankment, the settlements increase in all the cases as compared to those at toes. This is can be attributed to the fact that under the centre of the embankment the buffer



(a)



(b)

Figure 7. Effect of Variation in Modulus on Displacemnts (a) At Top of the Embankment. (b) At Bottom of the Embankment. (Buffer Layer: Projection = 2 m, Thickness = 0.5 m; Vertical Cut-off depth = 1 m and Thickness = 0.5 m).

is subjected to a greater magnitude of the load as compared to those under the toes.

Therefore, it can be inferred that the buffer thickness of 0.5 m is sufficiently stiff to resist the volume strains generated in the expansive subgrade below the buffer layer.

4.3.5. Study of buffer stiffness by variation in elastic modulus of buffer

Another factor directly influencing the buffer stiffness in resisting the swelling strains from the expansive subgrade is the elastic modulus of the buffer or lime stabilized capping material itself. The modulus of this layer is varied based on curing periods of 7-Day (Short-term), 28-Day and 45-

Table 5. Assesment of stresses in capping.

Sr. No.	Stress Points	Location	Mean Effective Stresses $(\sigma'_1 + \sigma'_3)/2$ (kN/m^2)	Effective Vertical Normal Stresses ($\sigma'_{z\text{-}z}$) (kN/m^2)	Presence of Tensile Stresses
1)	1336	Left Top Corner of Capping	-102.40	-133.02	Not Present
2)	1341	Left Bottom Corner of Capping	-91.79	-128.97	Not Present
3)	2164	Right top Corner of capping	-101.10	-132.59	Not Present
4)	2136	Right Bottom Corner of capping	-91.40	-126.95	Not Present
5)	2792	Centre of Buffer Layer at Top	-89.91	-125.77	Not Present
6)	2783	Centre of Buffer Layer at Bottom	-91.66	-128.35	Not Present
7)	3528	Left Vertical Cut-off outside	-93.09	-106.78	Not Present
8)	6428	Left Vertical Cut-off inside	-78.95	-81.16	Not Present
9)	5136	Right Vertical Cut-off inside	-90.88	-106.59	Not Present
10)	5142	Right Vertical Cut-off outside	-56.90	-75.44	Not Present

Day (long-term) and the resulting UCS (Strength gain). The displacements are estimated at the top and bottom of the embankment. The results of these are shown in Figure 7 (a) and (b).

Following observations have been recorded:

Figure 7 (a) and (b) indicate that the displacements are negative, i.e. settlements at the top and bottom of the pavement embankment. The settlements are found to reduce with increase in modulus. Settlements corresponding to 45 – Day curing are shown in the figures.

In comparison to those of URM, the settlements in the case of SRM are lesser at both top and bottom indicating the positive role of the buffer or capping in reducing pavement embankment distress.

It can be concluded from the above discussion that, the 'C' –shaped lime stabilized capping formed by using locally available expansive soil as suggested in this study can control the swelling occurring at the top and bottom of the embankment on which the pavements are constructed. Therefore, the distress and hence the performance in the flexible pavements can be controlled if this technique is adopted on pavement project sites, where the pavement embankments are founded on the expansive subgrades.

4.3.6. Assessment of safety of capping against stresses developed in capping

The safety of the 'C'-shaped capping is assessed against failure due to stresses. Normally the corners of capping, centre of buffer along its length and centre of vertical cut-offs along its depth are the possible critical points where stress concentrations can be high. Therefore, at these points the mean effective stresses, effective vertical normal stresses ($\sigma'_{z\text{-}z}$) and tension cut-off points representaing the failure points due to tension are assessed for the stress magnitudes. The results are presented in Table 5.

In PLAXIS 3 D the negative Principal stresses indicate the compressive nature of the stresses. It can be observed in Table 5 that the stresses at the locations mentioned above are compressive as they have negative sign. This indicateds that, the capping is not subjected to tensile stresses. This is confirmed from the results of tension cut-off points as such points are not observed at these locations. The magnitudes of the compressive stresses at these locations shown in Table 5 indiate that they are lesser than the cohesion (258.41 kN/m^2) which is the shear strength parameter of the expansive clay subgrade soil obtained from UCS. Also, the modulus (1.33×10^5 kN/m^2) of the lime stabilized expansive soil mentioned in Table 4 is sufficiently high to resists these stresses developed at these locations. Therefore, The capping is also safe against compressive stresses.

5. Conclusions

Based on the experimental and numerical studies following conclusions are drawn:

Experimental Studies:

1) Laboratory experiments indicate that, permeability of lime stabilized capping soil reduces by more than 80 % due to lime stabilization.
2) UCS of unstabilized soil C-1 (55.90 kN/m2) increases by almost three times on lime stabilization and, further, on curing for 45 days, increases by 3.23 times. Therefore, elastic modulus also increases linearly proportionately.
3) Experimental studies indicate the feasibility of developing a suitable material with requisite strength and imperviousness, for the capping in the proposed method, to effectively control swelling in expansive subgrade as well as pavement embankment.

Numerical Studies:

4) Numerical validation of capping behaviour using experimentally obtained parameters show that, 'C-shaped' capping fulfils its intended objective of reduction in swelling displacements.
5) The proposed capping in the case of SRM is observed to restrain swelling displacements significantly as compared to URM at the top and bottom of pavement embankment. This may be attributed to the increased modulus of capping due to stabilization. Based on the study it is proposed that the capping be constructed during summer and cured for 45 days.
6) The buffer layer performs its role of controlling swelling displacements effectively. A thickness of 0.5 m is found to be appropriate for this purpose. This is borne out by the observation that the displacements above and below the buffer layer are almost same and there is substantial reduction of swelling at the top and bottom of the pavement embankment as well as within the expansive subgrade due to capping.
7) The capping is safe against tensile or compressive stresses.
8) Therefore, it can be concluded that the methodology of providing 'C' shaped lime stabilized capping suggested by authors is effective for reducing the distress in embankments by a reduction in swelling of expansive subgrade soils.

Declarations

Author contribution statement

Manoj Anaokar: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Sharad Mhaiskar: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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