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Sustainable soil stabilization of expansive soil subgrades through lime-fly ash admixture

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Abstract

Expansive soils, known for their significant volume changes with moisture variation, pose severe challenges for construction and pavement integrity. This study investigates the stabilization of expansive subgrade soils using a lime-fly ash mixture, aiming to enhance engineering properties and reduce associated risks. Soil samples from Nashik, Maharashtra, India, were analyzed for their geotechnical properties, revealing high plasticity and expansive nature. The study utilized different proportions of lime-fly ash mixtures to assess improvements in the stabilized soils' Unconfined Compressive Strength (UCS) and California Bearing Ratio (CBR). Laboratory tests, including granulometry, SEM, and XRF, indicated significant changes in the soil's physical and chemical composition. The stabilization process showed a marked reduction in the Free Swell Index (FSI) and swelling pressure attributed to flocculation. The optimum mix ratio of 1:4 (lime: fly ash) demonstrated the most substantial improvement, with UCS increasing to 224 kPa and CBR values reaching 8%. Additionally, the elastic modulus of the stabilized subgrade showed considerable enhancement, indicating better load-bearing capacity and durability. A flexible pavement design was implemented on both untreated and treated subgrades, demonstrating a 28% cost reduction for the stabilized section. This research underscores the effectiveness of using a sustainable lime-fly ash blend in mitigating the challenges posed by expansive soils, offering a cost-effective and environmentally friendly solution for road construction. The findings provide a robust framework for engineers to improve the stability and longevity of pavements on expansive soils.

Keywords Soil Stabilization · Fly ash · Lime · Expansive Soil · Strength and durability · Geotechnical properties

1 Introduction

Expansive soil, often referred to as shrink-swell soil, exhibits considerable changes in volume due to variations in moisture content. Comprised mainly of clay minerals, this soil type expands upon absorbing water and contracts when it dries [1, 2].

The expansive nature of this soil presents complex geotechnical and engineering challenges, necessitating the use of specialized foundation design and construction techniques. These techniques are crucial in mitigating the potential risks associated with the dynamic behavior of expansive soil [3]. The subgrade materials, which are the underlying soil or ground strata beneath a road pavement, often lack the necessary load-bearing capacity to maintain the pavement's structural integrity and withstand vehicular traffic loads. This requires modification and re-engineering to enhance their

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load-supporting capabilities. Expansive soils, in particular, can cause premature deterioration, leading to the early failure of the pavement structure.

While many approaches have been explored, practitioners dealing with the challenges of expansive soil often find soil substitution and stabilization the preferred options [4]. These methods have proven effective in mitigating the risks associated with expansive soil. However, it is noteworthy that replacing problematic soil with higher-quality borrowed soil can significantly increase construction costs. Therefore, the avenue of modifying soil through stabilization techniques has progressively attracted the attention of engineers over time [5].

Engineers tend to favor physicochemical modification techniques to enhance durability when faced with expansive soils. This approach involves managing the volume changes caused by swelling, shrinking, and consolidation by bolstering strength-related qualities over an extended period [6]. Typically, chemical stabilization is the method of choice to achieve this goal using traditional or non-traditional agents, which helps to reduce the plasticity index, increase the size of soil particles, mitigate their tendency to swell and shrink and enhance their cementation properties [7].

Common traditional materials like lime, cement, and type C fly ash, which are high in calcium, are often utilized in construction. Many research studies have assessed the efficacy of traditional supplements in strengthening expansive soil [8–10] and have shown that these conventional materials have stand-alone stabilizing capabilities.

Considered the most suitable method for the chemical stabilization of expansive soils, lime has been shown to modify soil behavior by reducing plasticity index, swelling, and compressibility properties while enhancing compressive and shear strengths [11]. The impact of molding water content on the geotechnical properties of lime-stabilized expansive soil was investigated in [12]. The study demonstrated that increasing lime content reduces the maximum dry density and specific gravity while increasing the optimum moisture content, void ratio, and unconfined compressive strength (UCS), with maximum strength observed at the optimum moisture content. The impact of $Na_2SO_4$and $CaSO_4{\cdot}2H_2O$ on the UCS of clayey soils stabilized with lime and natural pozzolana indicates that sulfate ions interact with alumina, silica, calcium, and hydroxyl ions to produce ettringite, resulting in the degradation of stabilized clayey soils [13, 14]

Ordinary Portland cement (OPC) and lime have been the primary chemical additives used in construction for over a century [15, 16]. The stabilization of road pavement subgrade has been expensive and environmentally unsustainable because of the high levels of carbon dioxide (CO_2) released during cement production [17]. However, using a sustainable non-traditional stabilizer in road subgrade stabilization will enhance the engineering properties of expansive subgrade materials while reducing environmental effects and overall construction costs [18].

Using fly ash (FA) alone is limited by its low calcium content, slow pozzolanic reaction, and insufficient binding agents, while lime alone struggles with non-cohesive soils, can cause sulfate-induced heave, and has a high carbon footprint. The fly ash-lime mixture synergistically enhances the pozzolanic reaction, accelerates strength gain, improves soil binding, and works across various soil types. Additionally, it utilizes industrial waste, reduces landfill disposal, and lowers material costs, making it a more effective and sustainable solution for soil stabilization.

The application of FA and lime individually in stabilizing weak soils has been studied extensively; however, the combined application of lime-fly ash has not been dealt with in detail, particularly fly ash with weak cementation properties. Some studies showed the effective use of class F fly ash using cement and lime as activators in amended highway base material [19].

This laboratory study assessed the improvement in engineering properties achievable by stabilizing expansive subgrade soils with a lime-fly ash blend. The study included UCS and CBR tests to evaluate the bearing strength of the stabilized soils as working platforms during subgrade construction. A flexible pavement design was implemented on expansive soil, both with and without stabilization, using lime-fly ash. The cost analysis indicated a 28% reduction in subgrade costs for the stabilized section.

2 Materials

Soil samples for this study were gathered from three pits at depths ranging from 0.5 to 1.5 m. These samples comprised dark brown soil, commonly called Black Cotton (BC) soil. The sampling took place in Nashik, Maharashtra, India, located between 19°35′ and 20°50′ north latitude and 73°16′ and 74°56′ east longitude, near the River Godavari [20]. Undisturbed soil samples were collected from three sites adjacent to a proposed city road, with black clayey soil observed from the surface down to a depth of 2.5 m [21].

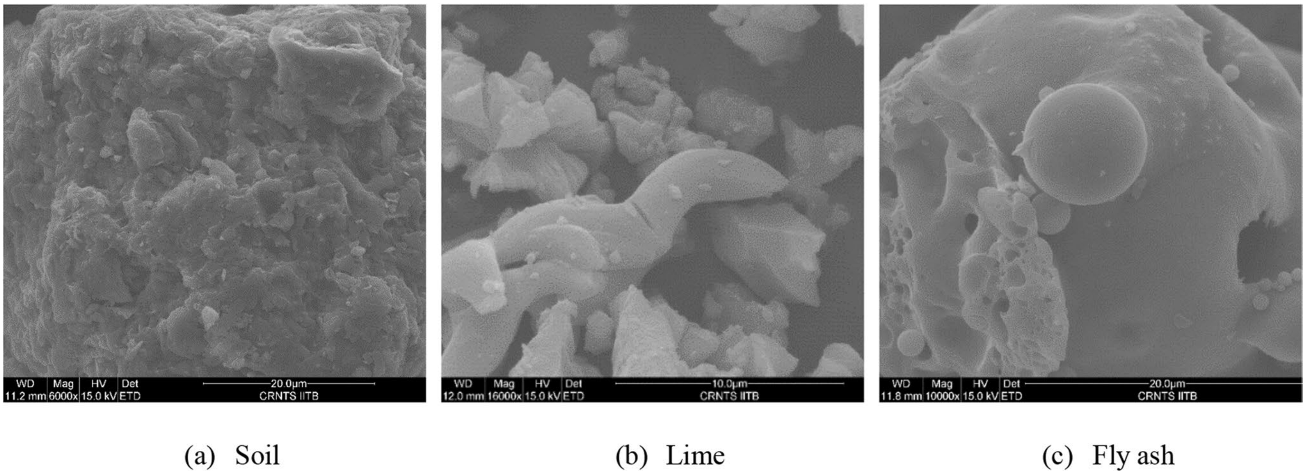

Fig. 1 SEM images (**a**) Soil (**b**) Lime (**c**) Fly Ash

Table 1 Chemical composition of material used

Chemical composition	Soil (%)	Lime (%)	Fly ash (%)
SiO_2	48.50	4.6	54.9
TiO_2	1.48	0.009	2.25
Al_2O_3	20.46	0.49	31.7
Fe_2O_3	15.73	0.10	3.4
MnO	0.14	0.002	2.51
MgO	4.38	0.22	0.43
CaO	9.60	90	0.74
Na_2O	1.54	0.06	2.52
K_2O	3.29	0.002	1.55

The specific gravity (Gs) of soil was determined using a specific gravity bottle per IS 2720 Part 3 Sect. 1 guidelines [22], with kerosene employed instead of water due to the soil's high affinity for water. The average Gs was found to be 2.63. Dry sieve analysis as per. IS 2720 (Part 4) [23] indicated a grain size distribution of 5% sand, 35% silt, and 61% clay. The consistency analysis as per liquid limits (LL) varied from 66 to 69%, and the plasticity index (PI) ranged from 32 to 35%. According to the Unified Soil Classification System (USCS), the clay is classified as high plasticity (CH). The cation exchange capacity (CEC) of soil, a measure of its ability to retain cations that neutralize the negative charge of soil particles, was 27.6 meq/100 g. Compaction characteristics give a Maximum Dry Density (MDD) of 1.52 gm/cc and an Optimum Moisture Content (OMC) of 26%. The pH value was determined to be 8.1 using a digital pH meter (CHEMILINE), indicating slight alkalinity. Prakash and Sridharan (2004) [24] proposed that a free swell test classified the clay as low swelling with a free swell ratio (FSR) of 75%.

Surface analysis of all materials used was conducted using Scanning Electron Microscopy (SEM) at the Sophisticated Analytical Instrument Facility (SAIF), Indian Institute of Technology Bombay. The SEM analysis was performed under dry conditions to minimize the effect of moisture on the soil's microstructure and texture. The SEM image in Fig. 1 (a) reveals that soil has fine flocculent structures, resulting in a higher surface area that enhances water interaction and absorption.

The chemical composition of all the materials was determined using X-ray fluorescence (XRF). The chemical composition of the soil, as shown in Table 1, is primarily composed of silicon dioxide (SiO_2) at 48.50%, aluminum oxide (Al_2O_3) at 20.46%, and iron oxide (Fe_2O_2) at 15.73%, which contribute to its expansive nature and dark color.

The fly ash was procured from a thermal power station located in Eklahara, Nashik, and was dark grey, insoluble in water, with a pH of 7.9. The fly ash analyzed contains 54.9% SiO_2, 31.7% Al_2O_2, and 3.4% Fe_2O_2, indicating strong pozzolanic properties and making it suitable as a supplementary cementitious material. With only 0.74% CaO, it is classified as Class F fly ash, typically requiring an activator like lime for effective use in soil stabilization. SEM images of fly ash (Fig. 1c) typically reveal spherical particles with smooth surfaces, indicative of high-temperature coal combustion.

These cenospheres range from a few micrometers to over 100 µm, contributing to excellent flow properties. The images also show irregular particles and porous structures, increasing the surface area for pozzolanic reactions.

This study used a typical commercial hydrated lime with a 90% CaO content and other oxides. SEM images of hydrated lime (Fig. 1b) typically show a highly crystalline structure with plate-like and irregularly shaped particles.

3 Laboratory testing programme

The laboratory testing aimed to examine the change in index and engineering properties and soil swelling behavior caused by the admixture of lime and fly ash.

The fly ash, lime, and expansive soil were dried for 24 hours in an oven at 40°C. The proportions of lime, fly ash, and expansive soil in the lime-fly ash-soil mixtures were determined based on their respective dry weights and the total mixed dry weight of the three components. By the guidelines of IRC: SP: 89 [25], trial mixes were prepared using lime-fly ash ratios of 1:2, 1:3, and 1:4, as presented in Table 2.

In these designations, "LF" stands for Lime-Fly ash, the first two digits represent the ratio (e.g., 02 for 01:02, 03 for 01:03, and 04 for 01:04), and the last part (A1, B1, C1) differentiates the specific mixture within each ratio.

The required amounts of lime, fly ash, and expansive soil were measured and combined in their dry state for all mixtures. Subsequently, these dry mixtures were mixed with the appropriate amount of water, determined by their optimum moisture content. The mixing process was conducted manually to ensure homogeneous mixtures at each stage.

Each soil mixture was subjected to a light compaction test following the procedure laid down by IS 2720 (Part VIII) [26]. MDD and OMC values were scaled out from the plots and used for further experimentation.

Unconfined Compressive Strength (UCS) is a suggestive strength criterion to decide the optimum mix proportion of lime-fly ash mixes and structural layer coefficients of the bases and sub-bases in pavement design. Samples were prepared at Proctor densities corresponding to OMC for each mix proportion, cured for seven days at 100% relative humidity, and controlled at room temperature. Strength was determined by crushing cylindrical samples (38 mm in length and 76 mm in diameter) at a constant strain of less than 2%. The test was terminated when the load decreased with increasing strain or at 15% strain was reached.

The CBR test was carried out following the guidelines of (IS 2720, Part XVI) [28]. Samples were prepared at MDD and OMC from Proctor results and cured for seven days with soaking of 4 days.

The free swell index (FSI) is expressed as follows [29]

$$FSI(\%) = \frac{V_w - V_k}{V_k} \quad (1)$$

where V_W and V_k are the soil volumes in water and kerosene,

The swelling pressure of the composite samples was measured by conducting a constant-volume swell test [21, 30, 31].

The constant volume method uses a main frame, a load cell, a floating ring-type oedometer, and a digital readout unit (Fig. 2). This test is carried out on soil and stabilized soil with various proportions of lime-fly ash mixtures. The procedure begins by placing the samples within the consolidation ring into the oedometer cell. The cell is then placed in the loading device, and a seating load of 5 N is applied to ensure no gap between the metal bar connected to the load cell and the upper cap on the sample. The soil sample is saturated with water and given 24 h to swell. After this time, the amount of

Table 2 Legend and proportion of the mixture

Ratio	Notation	Sample designation	Proportion by parts		
			Lime	Fly ash	Soil
01:02	A	LF02-A1	2.5	5	92.5
01:03	A	LF03-A1	2.5	7.5	90
	B	LF03-B1	4	12	84
	C	LF03-C1	5	15	80
01:04	A	LF04-A1	2	8	90
	B	LF04-B1	3	12	85
	C	LF04-C1	4	16	80

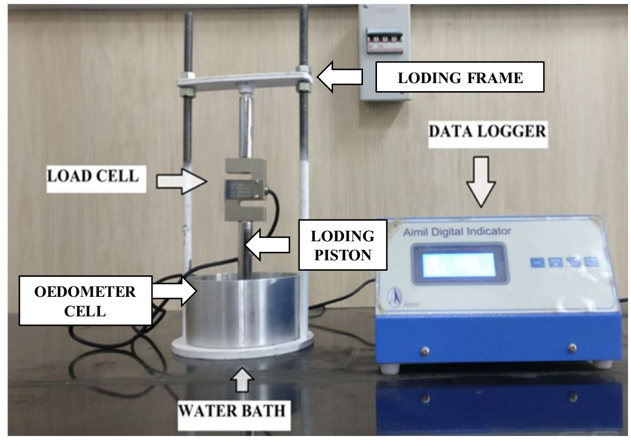

Fig. 2 Swell Pressure Measurement apparatus

swelling is measured, and the initial force of 5 N is subtracted from this value. The remaining force is then divided by the cross-sectional area of the soil sample to find the swelling pressure.

4 Results and discussion

4.1 Compaction characteristics

The study investigates the influence of lime and fly ash on soil's MDD and OMC. Results show that as the proportion of lime and fly ash increases, MDD decreases while OMC increases. The pure soil sample exhibits an MDD of 1.52 g/cc and an OMC of 26%. Adding lime and fly ash, MDD decreases progressively, reaching a minimum of 1.38 g/cc for the LF04-C1 sample. Conversely, OMC increases to 27.4% for the same sample. These changes can be attributed to the lower specific gravity of lime and fly ash and the increased moisture demand. Thus, incorporating lime and fly ash results in lighter, more moisture-absorbent soil mixtures.

4.2 Plasticity

Figure 3 depicts the effect of the lime-fly ash blend on the liquid limit (LL) and plastic limit (PL) of soil, which decreased as the blend proportion increased. However, the immediate effect of more inert fly ash contributes to an increase in a coarser fraction, which leads to a decrease in LL. However, the PL of the soil–lime–fly ash mix increased with the increased percentage proportion of the lime-fly ash blend. The main reason for this effect was the substitution of smaller soil particles with larger fly ash particles.

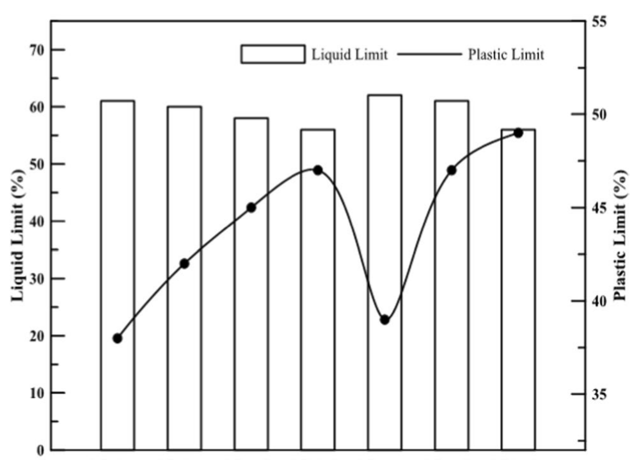

Fig. 3 Variation of liquid limit and plastic limit for different proportions of lime–fly ash in Soil

The increase in fly ash content from 5% to 7.5% results in a decrease in the LL from 61 to 60 and an increase in the PL from 38 to 42. This indicates that higher fly ash content contributes to improved soil stabilization by reducing LL and increasing PL. Similarly, with the lime content fixed at 4%, increasing the fly ash content from 12 to 16% leads to a decrease in LL from 58 to 56 and an increase in PL from 45 to 49. This consistent trend demonstrates that increasing fly ash content leads to reduced LL and enhanced PL, further promoting soil stabilization.

The consistent decrease in the LL and increase in the PL resulting from increasing fly ash content while keeping lime content constant highlights the positive impact of higher fly ash content on soil stabilization. The observed effects are mainly due to the higher fly ash content. This content improves soil stabilization by enhancing the LL and PL through cation exchange. When added to the soil, lime releases Ca + + ions that facilitate cation exchange in the clay minerals. This causes the soil to flocculate and reduces the thickness of the diffuse double layer.

4.3 Swelling behavior

The study investigates the effects of lime and fly ash stabilization on the Free Swell Index (FSI) and swelling pressure of expansive soils. The results shown in Table 3 show that increasing the proportions of lime and fly ash significantly reduces both FSI and swelling pressure. Mixtures with higher lime and fly ash content, such as LF03-C1 and LF04-C1, exhibit the lowest F.S.I. values (55% and 54%) and swelling pressures (72 kPa and 70 kPa). When lime is added to soil, it liberates Ca + +, which promotes cations exchange in the clay mineral, flocuting the soil and decreasing the swelling properties of the soil [32].

4.4 Unconfined compression strength (UCS)

Table 3 shows the measured values of UCS at different mixture proportions. An increase in fly ash content in the blend decreases UCS while the cementation properties of lime increase the UCS. This increase in UCS is attributed to pozzolanic reactions. Studies have reported an increase in UCS and a decrease in P.I. with the addition of lime [33].

4.5 California Bearing Ratio (CBR)

As depicted in Table 3, the value increased as the proportion of lime increased in the blend. Only in the 01:02 blend proportion did the CBR value increase by 43% compared to virgin soil. A maximum CBR value of 28% has been recorded for the blend proportion of 01:03, wherein the lime proportion was four parts. The trend shows increased CBR as both fly ash and lime proportions increased. The increase in C.B.R. values with higher proportions of lime and fly ash is due to cation exchange and pozzolanic reactions, which stabilize the soil by flocculating clay minerals and forming additional cementitious compounds, thereby improving the soil's load-bearing capacity. A minimum value of CBR obtained for 01:02 blend proportion with lime content of 2.5 parts was 7%.

Table 3 Effect of lime-fly ash on engineering properties of soil

Proportion	Sample designation	FSI (%)	Swell Pressure (kPa)	MDD g/cc	OMC %	UCS (kPa)	CBR (%)
01:00	Soil	75	147	1.52	26	175	4
01:02	LF02-A1	70	121	1.50	26.2	213	7
01:03	LF03-A1	68	98	1.48	26.4	329	8
	LF03-B1	60	85	1.45	27	592	17
	LF03-C1	55	72	1.40	27.2	707	28
01:04	LF04-A1	67	120	1.47	26.2	224	8
	LF04-B1	61	95	1.44	26.8	404	13
	LF04-C1	54	70	1.38	27.4	624	24

4.6 Elastic modulus of stabilized soils (Es)

Elastic modulus is a good indicator of the strength of sub-grade/sub-base. The experimental determination of Es for blended soil was not part of the scope of the present study. However, empirical relations suggested by IRC SP 37 were used to determine the Es of Subgrade and subcase (assumed thickness of 200 mm):

$$Es = 0.2 \, x \, h^{0.45} x \, E_1 \quad (2)$$

where Es is the elastic modulus, h is the thickness of the sub-base layer, and E1 is the modulus of the subgrade layer in MPa. IRC SP 37[25] suggested following relationship between E1 and CBR

$$E_1 = 10.79 \, x \, CBR \ \ldots\ldots\ldots\ldots \ (\text{if CBR} < 5\%) \quad (3)$$

$$E_1 = 17.6 \, x \, CBR^{0.64} \ldots\ldots\ldots\ldots \ (\text{if CBR} > 5\%) \quad (4)$$

Table 4 shows that the elastic modulus of only Soil increased from 43.04 to a Maximum of 148.49 MPa for different blend proportions. Also, for the sub-base, it increases from 93.40 to 322.25 MPa respectively. It shows a gradual increase in the elastic modulus with the increase in lime content with fly ash.

5 The design of flexible pavement

Flexible pavement design by the Indian Road Congress (IRC)[34] method involves an inclusive evaluation of existing designs, incorporating design charts and a pavement catalog within the code. Consider the ratio of fly ash and lime as 1:3, where CBR values range from 8 to 28%, and as per the IRC, CBR should range between 2 to 8%, accommodating design traffic ranging from 1 to 150 million standard axles (MSA), with an average annual pavement temperature of 35 °C. The layer thicknesses are fine-tuned based on stage construction requirements, facilitating the selection of designs tailored to specific traffic and soil conditions. Design traffic is determined by considering Subgrade CBR values and the cumulative number of standard axles.

This methodology quantifies traffic in terms of the cumulative number of standard axles (8160 kg) the pavement will bear over its 15 year design life. Factors considered include initial traffic measured in Commercial Vehicles Per Day (CVPD), traffic growth rate, designated lifespan, and the Vehicle Damage Factor (VDF). Distribution of commercial traffic across the carriageway is also factored in, with initial traffic estimates based on 7-day, 24 h classified traffic counts for existing roads and projections for new roads based on potential land use and existing traffic patterns. In the absence of sufficient data, an average annual growth rate of 7.5% is recommended.

Pavement design life spans were set at 15 years for arterial roads, 20 years for expressways and urban roads, and 10 to 15 years for other road categories. The Vehicle Damage Factor (VDF) is crucial for converting commercial vehicle axle loads into standard axle-load repetitions, varying based on axle configuration, loading, terrain, road type, and region. Distribution factors for different road types are outlined, with assumptions made until reliable data is available.

Table 4 Effect of lime-fly ash mixture on modulus of elasticity

Ratio	Sample designation	Design CBR (%)	Modulus of Elasticity of Subgrade (Es) (MPa)	Modulus of Elasticity of Sub-base (E1) (MPa)
01:00	Soil	4	43.04	93.40
01:02	LF02-A1	7	61.15	132.70
01:03	LF03-A1	8	66.60	144.54
	LF03-B1	17	107.89	234.15
	LF03-C1	28	148.49	322.25
01:04	LF04-A1	8	66.60	144.54
	LF04-B1	13	90.87	197.21
	LF04-C1	24	134.54	291.97

The flexible pavement design process in this study involves a comprehensive approach. Initial traffic is set at 300 CVPD in both directions, with a chosen design life of 15 years and a growth rate factor of 6%. The cumulative standard axle load (CSA) is determined using a formula, resulting in a value of 11.33 million standard axles (MSA). Geometric parameters for embankment stability and load distribution comply with guidelines from the Ministry of Road Transport and Highways (MORTH)[33] and the Indian Road Congress (IRC).

The design of pavement layers requires precise calculations, especially considering factors like the California Bearing Ratio (CBR) and the subgrade's resilient modulus (Mr). In untreated subgrade soil, the CBR value is typically around 4%. However, when treated with a Lime and Fly Ash blend in a 1:4 proportion, this value can increase significantly, reaching up to 8%. The impact of this blend, as detailed in Table 4, is substantial.

This difference in CBR values directly affects the total pavement thickness, which has implications for construction costs, durability, and long-term performance. The improved CBR values after adding lime and fly ash highlight the effectiveness of soil stabilization techniques. Not only do these materials enhance the subgrade's strength, but they also contribute to environmental sustainability by utilizing waste resources efficiently.

Design parameters, following Indian standard technical specifications such as IS 2720: Part 8 and 16, [26, 28] are crucial for ensuring the structural integrity and functionality of the pavement throughout its design life. Treated subgrades with higher CBR values experience reduced potential for pavement distress, including issues like rutting and cracking under heavy traffic loads. This approach aligns well with modern engineering practices, prioritizing optimized material use, improved performance, and reduced environmental impact, making it a sustainable choice for road infrastructure development. Table 5 depicts the design components and design parameters used in this study.

The data shows that the thickness of the treated sub-base granular layer was reduced from 295 to 200 mm for the untreated subgrade, as indicated in Table 6. Moreover, the base thickness for untreated and treated subgrade cases decreased from 250 to 175 mm without adversely affecting the pavement system's structural properties. The subgrade calculation's resilient Modulus (Mr) was considered as per IRC: 37 2018[34].

5.1 Cost analysis for lime & Fly ash

In accordance with the instructions of the National Highway Authority of India (NHAI) 2020., the rate of the materials used for the cost analysis is obtained from the Schedule of Rates (SoR). Table 7 presents the material cost comparison of the two choices used in the current study for a 1 km stretch of 2-lane roadway with heavy traffic characteristics. Using compacted expansive soil as a subgrade is the first choice, and another is the application of expansive soil combined with the 01:04 ratio under dry conditions (1 part lime & 4 parts of flyash). While wet mix macadam is utilized to lay the base, closely graded material (Grading I) is employed to construct a granular sub-base. Constructing a pavement requires higher thicknesses of the base course and sub-base course to provide adequate drainage facilities, increasing the construction cost. Therefore, the present study attempts to estimate the pavement construction cost with and without a stabilizer. From the analysis, it is observed that the soil is treated with lime and fly ash treatment.

Table 5 Design calculation for pavement design

Embankment design components*	Design parameter values
Initial traffic (CVPD)#	300 (sum of both directions)
Design life	15
Growth rate factor	6%
Cumulative Standard Axle Load of the Selected Vehicle (CSA)	365(NFD [1 + r] (m + n)-1}/r = 11.33msa
The top width of the embankment	7.5 m
Carriageway	3.75 m
Height of embankment	2.0 m
Side slope	2H: 1 V
The bottom width of the embankment	15.5 m
Side slope earth over the thickness	1.0 m
Length of embankment	1000 m

*Design criteria are as per MORTH [35];

#Average number of commercial vehicles per day (rural roads); IRC: 37 2018[34]

Table 6 Calculating thickness values of the pavement layers for untreated and treated subgrade

CBR %	CSA (million standard axle)	Total pavement thickness (mm)	Granular sub-base, (mm)	Granular base course (mm)	Dense bituminous macadam binder course (mm)	Bituminous concrete surface course (mm)	*Mr (MPa)	Type of Sample
4	11.33	755	295	250	160	50	50	Untreated
8	11.33	550	200	250	40	60	50	01:03 (LF04-A1)

Table 7 Estimation of cost of construction using untreated and treated soils

	Pavement components	Quantity	Rate (INR*)	Amount (INR*)
	Providing earthwork in embankment with approved materials	1000 × 10.01x0.5 = 5005 m3	757.00	37,88,785.00
Untreated Soil C.B.R. 4%	Construction of granular sub-base by providing close-graded Material, spreading in uniform layers	1000 × 8.42x0.295 = 2483.9 m3	1,804.00	44,80,955.60
Treated Soil lime & Fly Ash. 8%		1000 × 8.61x0.2 = 1722 m3	1,804.00	31,06,488.00
	Wet mix macadam: laying, spreading, and compacting graded stone aggregate to wet mix macadam	1000 × 3.75x0.25 = 937.5 m3	2,045.00	19,17,187.50
	Prime coat: providing, applying primer coat with bitumen emulsion	1000 × 3.75 = 3750 m2	33.00	1,23,750.00
	Providing, applying tack coat on the prepared surface	1000 × 3.75 = 3750 m2	18.00	67,500.00
Untreated Soil CBR 4%	Dense bituminous macadam: proving and laying dense bituminous macadam using crushed aggregates of Grading II,	1000 × 3.75x0.04 = 150 m3	9,664.00	14,49,600.00
Treated Soil lime & Fly Ash. 8%		1000 × 3.75 × 0.04 = 506.25 m3	9,664.00	33,75,000.00
	Bituminous concrete:—providing and laying bituminous concrete using crushed aggregates of grading II	1000 × 375x0.05 = 187.5 m3	10,599.00	19,87,312.50
	Cost of lime	1000 × 10x0.1	10	640000
	Transportation cost of Fly ash per metric ton		120	120
	Summarized total cost in Indian rupees			
	Untreated Soil INR.1,81,63,891.00	Treated Soil with Lime & Fly ash INR. 1,30,80,743.00		

Cost Reduction 28%

(INR*) Indian Rupees

As the thickness of the surface course remains the same in both techniques, it is not considered in the cost analysis. The cost analysis shows that there is a saving of 28% per km length of road pavement under heavy traffic characteristics. Pavement construction is more economical than untreated soil. (see Table 7). Furthermore, the analysis reveals that compared to the embankment constructed with lime and fly with a (1:4A, LF04-A1) ratio is cost-effective.

6 Conclusions

This study showed that adding a blend of lime and fly ash impacts soil index, engineering properties, and swelling behavior. The untreated soil had low structural capabilities and was unsuitable for constructing bases, subcases, or embankments. However, incorporating fly ash and lime decreased the soil's plasticity index, resulting in a better-quality soil mix.

As the mixture proportion increased, the free swell index decreased, which indicates that the blend reduced the soil's swelling potential. UCS showed different trends depending on the mixture composition. Increased fly ash content decreased UCS while adding lime increased UCS. The CBR value also increased with an increase in the proportion of lime in the blend. The elastic modulus of the stabilized soils increased with the increase in lime content with fly ash, indicating a gradual increase in the strength of the sub-grade/sub-base.

The construction cost savings of flexible pavement under heavy traffic characteristics are computed to be about 28% per km of road length when natural soil stabilized with lime and fly ash is used as a subgrade.

The long-term effects of the mixture on soil stability and durability, as well as the potential environmental impacts of fly ash, require further investigation. It's important to note that our study's reported UCS and CBR values are based only on unsoaked samples, which is a limitation. The use of soaked UCS and CBR values is more critical for assessing soil stabilization performance under wet conditions.

Overall, this study's findings provide valuable insights into the use of a lime-fly ash mixture for soil stabilization and can be helpful for engineers and researchers in designing and constructing sustainable infrastructure.

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Author contribution M.E. and S.P. have formulated methods and concepts of work. T.S. collected materials, conducted experimental work, and prepared the first draft.

Data availability The authors confirms that all data generated or analysed during this study are included in this published article.

Declarations

Competing interests The authors declare no competing interests.

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