Experimental Study on Flyash-Stabilized Expansive Soil

Sanjivani D. Nigade-Saha and B. V. S. Viswanadham

Abstract About 51.8 million hectares of India are covered with expansive black cotton soils. The expanding road network has compelled engineers to build roads over these weak soils. Constructing pavements on expansive subgrades involves a threefold problem of a poor supporting strata, heavy vehicular loading and lastly, scarcity of good-quality aggregate. Roads constructed on expansive soils incur large capital costs and maintenance costs. Flyash produced in several thermal power plants is largely unutilized. It can be used as a stabilizing material in the road pavements, as an alternative to replacement of locally available (substandard) materials, thereby reducing the problems associated with disposal of flyash, and also leading to economical constructions. Laboratory investigations were undertaken to study the stabilizing effect of locally available Class F-type flyashes, when used in combination with lime. Index tests to determine free swell index, linear shrinkage and pH along with detailed tests to determine UCS, CBR and heave were performed. The free swell and linear shrinkage were significantly reduced. UCS improved consistently with time. The soaked CBR test of LFA-treated samples indicate excellent improvement in strength and reduction in volume-change behaviour. The performance of the LFA treatment was largely affected by the type of flyash.

Keywords Expansive soil · Flyash-stabilized flexible pavements · Linear shrinkage · CBR · UCS · Heave

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1 Introduction

In India, about 51.8 million hectares of the land area (i.e. 16.6% of the total geographical area of the country) are covered with expansive black cotton soil. Almost 90% area of the two central states, viz., Maharashtra and Madhya Pradesh, and significant portions of adjoining states like Karnataka, Telangana, Gujarat and Rajasthan are covered with deposits of this expansive soil. These soils are unsuitable for construction either as fill material or as a subgrade as, in the presence of moisture, they exhibit undesirable engineering properties like low shear strength, low bearing capacity and very low penetration resistance. In addition, they also exhibit extensive volumetric changes. Due to their low strengths, such subgrades will require very thick pavement crusts. Also, pavements on such soils undergo large distress during service life, thereby requiring frequent maintenance. Thus, roads on expansive subgrades are problematic during the construction stage as well as the service life of the pavement, thereby incurring huge capital and maintenance costs.

The increased demands of electrical energy and availability of sufficient coal reserves have led to rise in number of coal-fired thermal power plants in the country. Indian coal has an ash content of 30–45%, thereby generating a very huge amount of flyash. In comparison with countries like Germany, Belgium and the Netherlands, where more than 95% of flyash generated is reportedly used, the level of utilization of flyash in India is low, thereby leading to large-scale accumulation of flyash. The unutilized flyash causes water and air pollution and also requires large areas of land for its disposal. As per report of Central Electrical Authority (CEA) New Delhi 2016, during the first half of the year 2015–16, about 83.64 million ton of flyash was generated, of which only 46.87 million ton flyash was utilized. The data regarding the modes in which flyash was utilized indicates that the percentage utilization was about 42% for manufacture of cement, 12.85% in flyash-based building products, 11.21% for land-reclamation, 10.91% for mine filling, etc., and only 4.87% in the construction of roads and embankments. There is a large potential of fly ash utilization in the road sector. Utilization of flyash in the road sector shall lead to savings of precious natural resources.

Beeghly (2003) has reported about 50% savings in construction costs due to reduction in material cost and 20% savings in maintenance costs due to permanent improvement of subgrade strength due to lime flyash (LFA) stabilization of the subgrade. 100% reduction in pavement costs against the option of undercutting and replacement of local soil has also been reported. The stabilizing effect of four different flyashes in stabilizing a highly expansive soil has been studied. All the Class F flyashes, when used in combination with lime, were effective in significant strength gain and reduction in volume-change behaviour of the expansive soil.

2 Materials

It is necessary to characterize the materials as the degree of improvement of subgrade strength is highly dependent on the physical and chemical properties of the treated soil and the stabilizer used. The physical and chemical properties of the untreated subgrade soil, various flyashes and activators used are presented in the following paragraphs.

2.1 *Expansive Soil*

The expansive soil for the present study is a black cotton soil that has been procured from a locality near Pune in the state of Maharashtra. The specific gravity of the soil sample was found to be 2.685. The activity of the untreated soil is 0.6. The free swell index was found to be 110%. Atterberg limits of the untreated soil were determined as per IS 2720 (Part V). The soil exhibited a liquid limit of 80% and plastic limit of 35%. Thus, the soil has a very high value of plasticity index of 45%. Since the plasticity index of the soil is greater than 35%, as per the recommendations of Little and Nair (2009), the soil will need treatment with any of the following stabilizers, viz.

(a) Lime
(b) Lime + cement
(c) Class F flyash + lime
(d) Class C flyash + lime

The grain size distribution curve is presented in Fig. 1. The soil can be classified as a clayey soil with very high plasticity (CH). The soil has more than 60.5% particles finer than 75 μm. Hence is unsuitable for being used as base material and can be used as a subgrade material only. The high value of free swell index indicates large volume changes in the presence of water, thereby posing threat of structural failure of the pavements laid on it.

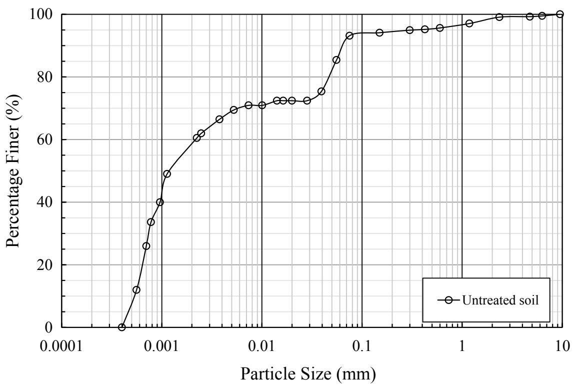

Fig. 1 Grain size distribution of untreated soil

Table 1 Properties of expansive soil

Property	Untreated soil
Liquid limit (%)	80
Plastic limit (%)	35
Plasticity index (%)	45
Gravel (>4.75 mm)	0.76%
Sand (0.075–4.75 mm)	6.11%
Silt (0.002–0.075 mm)	32.63%
Clay (<0.002 mm)	60.5%
Free swell index (%)	110

The index properties, swell characteristics, etc., of the untreated soil are summarized in Table 1.

The compaction characteristics of the black cotton soil were found by conducting a standard proctor test on the soil. As the soil was highly expansive, the soil was mixed with water and kept for 24 h prior to conducting the test. The untreated soil has OMC and MDD values of 35.5% and 12.66 kN/m^3. The soil was soaked at OMC and kept for 24 h and then compacted at MDD in the CBR mould. The soil has an unsoaked CBR value of 6.1% and a soaked CBR value of 1.5%. It is thus a weak subgrade.

2.2 Flyash

Pulverized fuel ash (PFA) is a waste product of thermal power plants. PFA extracted from the fuel gases by any suitable process like cyclone separation or electrostatic precipitation is called flyash. ASTM C 618-15 specifies two categories of flyash, viz. Class C and Class F. The Class F flyash is produced by the combustion of bituminous coal or anthracite. It contains less than 10% of CaO and hence possesses only pozzolanic properties. The Class C flyash is produced by the combustion of sub-bituminous coal or lignite. It contains more than 10% of CaO and possesses cementitious properties as well as pozzolanic properties.

Indian flyashes are generally of the Class F type. The flyashes available from the plants at Nashik, Dahanu, Ratnagiri and Surat were procured for the present study and are denoted as Flyash N, Flyash D, Flyash R and Flyash S, respectively. The physical characteristics of these flyashes are summarized in Table 2, and their grain size distribution curves are presented in Fig. 2.

Significant variation in the specific gravity, colour and physical appearance of flyash has been observed with change in source. Flyash D is a well-graded silty clay, light in colour and with small-sized soft lumps. Flyash N is a gap-graded sandy silt, grey in colour, with significant amount of black particles of unburnt coal, but without any lumps. Flyash R is light in colour and without any lumps. Flyash S is very dark in colour, with large-sized hard lumps. Both Flyash R and Flyash S are uniformly graded silty soils.

Table 2 Physical properties of flyash

Parameter	Flyash D	Flyash N	Flyash R	Flyash S
G_s	2.065	2.054	2.125	2.430
C_u	8	2.5	3.1	2.8
C_c	0.8	1.1	1.3	0.4
Fine sand (%)	17.4	40.2	6.0	14.2
Silt (%)	40.6	51.8	73.1	75.5
Clay (%)	42.0	7.8	20.8	10.0

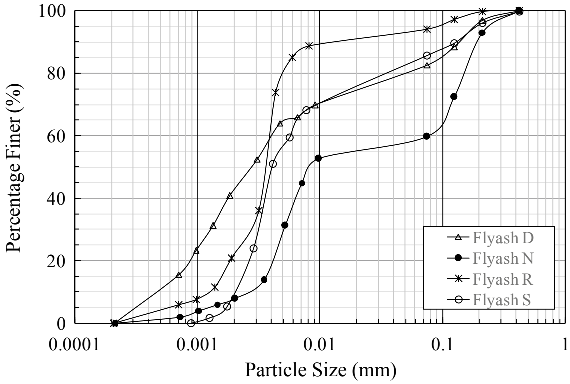

Fig. 2 Grain size distribution of flyashes

Flyash D and Flyash N show very low specific gravity of 2.065 and 2.054, respectively. A high value of specific gravity of 2.430 is observed for Flyash S, indicating the presence of heavy minerals.

The stabilizing effect of flyash is greatly affected by its' chemical composition. The chemical composition of the flyashes as determined by the XRF/ICP-AES technique is presented in Table 3. All flyash samples used in the present study were found to be of Class F type.

Table 3 Chemical composition of flyash

Parameter	Flyash D	Flyash N	Flyash R	Flyash S
CaO (%)	0.14	0.37	1.35	1.18
SiO_2 (%)	54.80	58.12	43.56	48.44
Al_2O_3 (%)	22.00	12.52	20.51	21.44
Fe_2O_3 (%)	10.80	13.22	12.50	12.18
MgO (%)	0.01	0.03	0.24	0.14
CaO/SiO_2 ratio	0.003	0.006	0.031	0.024
$SiO_2 + Al_2O_3 + Fe_2O_3$	87.60	83.85	76.57	82.05

A higher value of CaO indicates the presence of lime, thereby increasing the cementitious reactions. Flyash R and Flyash S have almost 1% higher lime content than Flyash D and Flyash N. The highest value of the CaO/SiO_2 ratio is found for Flyash R and is followed by Flyash S. Flyash D and Flyash N show very poor values of the CaO/SiO_2 ratio. Flyash D has the lowest values of CaO content and the highest value of combined content of $SiO_2 + Al_2O_3 + Fe_2O_3$.

2.3 Lime

Laboratory-grade quicklime was used. The lime is available in a fine-powdered form. The specific gravity of lime was found to be 2.070.

3 Test Procedures

Details of the tests like formulation of sample mix, procedure for preparing, storing and curing of samples and the various tests conducted are presented in following paragraphs.

3.1 Mix Design

The literature reviewed indicates that the amount of flyash used for stabilizing soils is generally up to 25%. Mishra et al. (2005) and Senol et al. (2006) have varied the percentage of flyash up to 20%. Cokca (2001) has reported the optimum percentage of flyash as 20%. Therefore, the percentage of flyash in the present study has been adopted as 20%.

The pH of the stabilized soil has been specified as 12.4, for sustaining the long-term pozzolanic reactions that result in strength gain and permanent improvement in stability. The optimum lime content, which is the lowest percentage of lime in soil that gives a pH of 12.4, was found on the basis of the pH procedure developed by Eades and Grim (ASTM D 6276-99a).

The pH of untreated soil was found to be 7.5. The results of the pH test as shown in Fig. 3 indicate that the optimum lime content of the soil is about 4%. It is decided to use a lesser percentage of lime in combination with the flyashes. Eight trial combinations with four different flyashes and 0% or 2% of lime as indicated in Table 4 were formulated and tested.

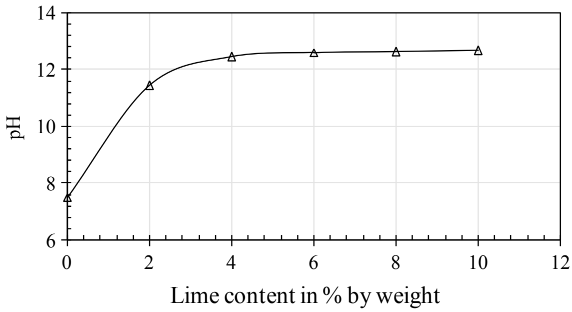

Fig. 3 Optimum percentage of lime from pH test

Table 4 Trial mix for laboratory tests

Proportion of soil:flyash:lime	Flyash D	Flyash N	Flyash R	Flyash S
80:20:0	D20	N20	R20	S20
78:20:2	D20L2	N20L2	R20L2	S20L2

3.2 Sample Storage and Curing

For uniform mixing of the stabilizers in powder form to the highly expansive soil, it was necessary that the moisture in the soil was uniformly distributed. Also during curing, the water content of the samples needs to be controlled. Therefore, special precautions were taken in preparation of the samples and their storage during the curing period. The amount of water as much close to the required moisture content as possible was added to the oven-dried soil and mixed thoroughly. The moist soil was then allowed to stand overnight in airtight polythene bags. The required quantity of stabilizer was then added to the soil and hand-mixed for about 8–10 min. Care was taken to break the clods/lumps that were formed during this process. The soils so prepared were immediately transferred to airtight bags to prevent loss of moisture. Blending of mix materials and casting of samples were done alternately to maintain constant time lag between blending and compaction.

After casting of samples, they were immediately transferred to airtight polythene bags and kept in a humid enclosure, as shown in Fig. 4. Storage and curing were done as per the protocol mentioned in the NCHRP report. Samples for UCS tests were prepared and cured in above-mentioned manner. Samples for CBR tests were compacted in CBR moulds immediately after adding stabilizers. The moulds were then placed in airtight polythene bags for required curing period. Samples for linear shrinkage tests were mixed and cured as mentioned above but cast into the moulds after required curing period. For free swell index tests, the stabilized soil was mixed and cured as mentioned earlier and then oven-dried.

Fig. 4 Storage of samples for curing

3.3 Test Programme

The test programme has been decided on the basis of ASTM D 4609-94, 'Standard Guide for Evaluating Effectiveness of Chemicals for Soil Stabilization'. The free swell test and the linear shrinkage tests are indicators of improvement in the volume-change characteristics. The UCS and CBR tests were conducted to assess the improvement in strength. The results of the soaked CBR tests show the effect of stabilization on moisture susceptibility.

4 Results and Discussion

Results of various tests conducted to assess the suitability of the different flyashes and LFA mix are discussed in the following paragraphs.

4.1 Free Swell Index and Linear Shrinkage

The potential of the expansive soil to expand on exposure to water can be assessed by the free swell index which is the increase in the volume of a soil, without any external constraints, on submergence in water. It can be determined as per IS: 2720 (Part XL). Linear shrinkage is the decrease in one dimension of a soil mass, expressed as a percentage of the original dimension, when the water content is reduced from the liquid limit to the shrinkage limit. The potential of expansive soils to shrink due to loss of water can be assessed by conducting the linear shrinkage test as per IS 2720 (Part XX). Table 5 lists the free swell index and linear shrinkage of the eight trial combinations.

Table 5 Free swell index and linear shrinkage of stabilized soil

Mix	Free swell index (%)	Linear shrinkage (%)
Untreated soil	110.0	21.1
D20	111.8	20.7
D20L2	88.9	14.3
N20	116.7	20.1
N20L2	50.0	13.9
R20	100.0	20.3
R20L2	80.0	13.5
S20	111.1	19.4
S20L2	80.0	12.3

The untreated soil showed a FSI of 110 indicating a critical degree of severity. However, on treatment with different types of flyash, the FSI increased slightly except for Flyash R, where a 10% reduction was noted. On treatment with LFA, the free swell index reduced by 20–30% approximately. In case of the LFA treatment with Flyash N, there was a very significant decrease in FSI, indicating the effect of its coarser particle size.

The linear shrinkage of untreated soil was 21.12%. After the test, the untreated soil samples were found in a crumbled state. The flyash-treated samples were warped longitudinally and exhibited significant linear as well as radial shrinkage. LFA-treated samples showed least distortion.

Treatment with all four types of flyash showed little reduction in linear shrinkage. However, in case of treatment with LFA, the linear shrinkage values reduced to 12.3–14.1%, which is a reduction of almost one-third of that of the untreated soil. Both the free swell index test and the linear shrinkage test indicate that LFA is an effective stabilizer to control volume change of expansive soil. The least effect in controlling the volume-change behaviour of the expansive soil was shown by the LFA treatment with flyash D.

4.2 Compaction Characteristics

The strength of the untreated as well as stabilized soil is assessed by conducting tests on the laboratory samples compacted to the in situ field conditions. Determination of the optimum moisture content and maximum dry density is therefore necessary. The addition of lime causes a change in the mineralogical structure of an expansive soil. It is reported that the OMC increases generally by 2–4% and even greater in case of highly expansive clays. The MDD has been reported to decrease typically by about 48–80 kg/cum on addition of lime. However, no general statement can be made about the modified relation between OMC and MDD of flyash-treated soils. The compaction characteristics of the treated and the untreated soil samples were determined as per IS: 4332 (Part III).

The untreated soil has OMC and MDD values of 35.5% and 12.66 kN/m^3, respectively. The soil treated with LFA showed a reduction in both MDD and OMC. The OMC and MDD of the LFA-treated soil were found to be 33.0% and 12.2 kN/m^3, respectively. For the flyash-treated soil, the OMC and MDD values were obtained as 31.0% and 13.35 kN/m^3, respectively.

4.3 Unconfined Compressive Strength

To assess the effectiveness of a stabilizer, various agencies have notified the unconfined compressive strength criteria. An improvement of 345 kPa has been specified in ASTM D4609-94. UCS samples of size 50 mm in diameter and 100 mm in height were cast at the optimum moisture content and maximum dry density using compression device and then were allowed to cure for duration of 7 days. Three samples each of every soil mix were tested in a UTM at a strain rate of 1.25 mm/min. The untreated soil showed ductile failure with bulging. The samples treated with flyash showed slight bulging at mid-height. The failure plane was well defined and inclined. The LFA-treated soil showed brittle failure with wide vertical cracks at the ends of the samples. The failure strain of the untreated soil reduced from 6.2% to about 1–1.5% in case of treated soil. The elastic parameters are listed in Table 6.

An improvement of 130–170 kPa above the strength of the untreated soil is achieved for flyash-treated soils, except for Flyash N, where a strength gain of 280 kPa was achieved due to stabilization The improvement in the UCS has been about 230 kPa for the LFA mix with Flyash R, whereas it is about 300–490 kPa in case of the LFA mix with other flyashes. The initial tangent modulus of the untreated soil improved from 3.3 MPa to about 25–40 MPa for the flyash-treated soil and to about 40–55 MPa for LFA-treated soil.

Table 6 Elastic parameters of flyash-/LFA-treated soil

Mix	σ_f (MPa)	Elastic modulus (MPa)		
		E_i	E_s	E_f
Untreated soil	0.098	3.29	3.18	1.58
7D20	0.25	38.80	24.80	20.34
7D20L2	0.40	55.23	39.57	42.45
7N20	0.38	36.80	33.49	25.13
7N20L2	0.44	53.31	40.82	35.16
7R20	0.24	25.12	22.31	18.76
7R20L2	0.33	38.78	31.36	29.26
7S20	0.27	24.15	18.75	17.58
7S20L2	0.59	56.52	46.38	37.31

Note The prefix '7' indicates 7 days of curing

In comparison with the flyash-treated soils, the LFA-treated soils have shown a very significant increase in the elastic parameters, which is in the range of the required strength gain, as specified in D 4609-94. It is therefore decided to carry further tests with LFA-treated soil.

Mishra et al. (2005) have reported retardation in the strength after 14 days of curing. Therefore, the improvement in the UCS over increased durations of curing was monitored. Samples were cured for 14 and 28 days with uniform conditions of humidity maintained for the entire duration of curing. The stress–strain plots of samples tested after 14 and 28 days of curing were compared with those cured for 7 days as shown in Figs. 5, 6, 7 and 8. A consistent increase in the failure stress values as well as the initial tangent modulus, with increase in duration of curing, is observed.

The UCS of the LFA-treated soil with Flyash D increased from 400 to 510 kPa and that of LFA-treated soil with Flyash N increased from 440 to 560 kPa. For the LFA-treated soil with Flyash R, the UCS value has increased from 330 to 630 kPa. The LFA-treated soil with Flyash S has shown the highest strength gain from 320 to 800 kPa. Thus, the soils treated with 2% lime and 20% of the four flyashes provide a 28-day UCS value between 0.51 and 0.8 MPa, which is adequate for a stabilized subgrade. After 28 days of curing, the initial tangent modulus was found in the range of 75–95 MPa as against 3.29 MPa of the untreated soil. The 1% secant modulus was obtained in the range of 45–65 MPa as against 3.18 MPa of the untreated soil. The failure strain for LFA-treated soils with either flyash N or Flyash R varied in the range of 0.75–1.25%. The LFA-treated soil with Flyash D showed lower failure strains varying between 0.65 and 0.95%. The LFA-treated soil with Flyash S failed at slightly higher strain values varying between 1.45 and 1.55%. Table 7 summarizes the elastic parameters.

The maximum UCS value is exhibited by the LFA-treated soil with Flyash S. The LFA-treated soil with Flyash R shows the highest values of 1% secant modulus and failure modulus. Flyashes with higher CaO content have shown better performance.

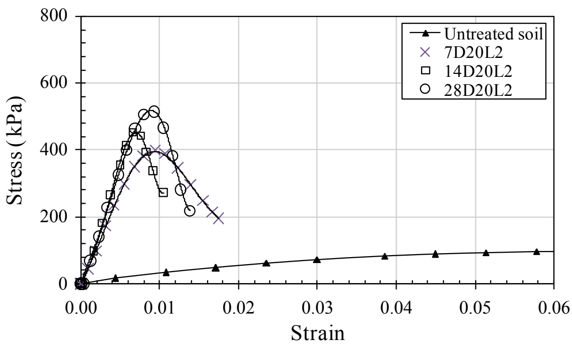

Fig. 5 Improvement in UCS of LFA-treated soil with Flyash D

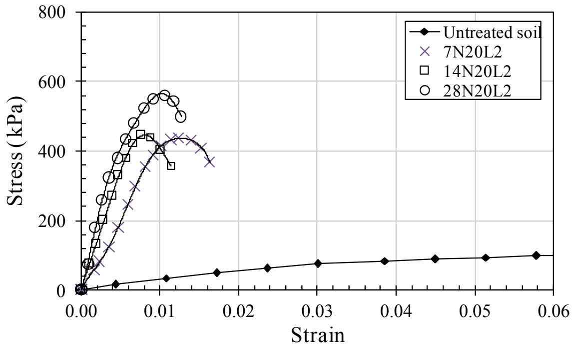

Fig. 6 Improvement in UCS of LFA-treated soil with Flyash N

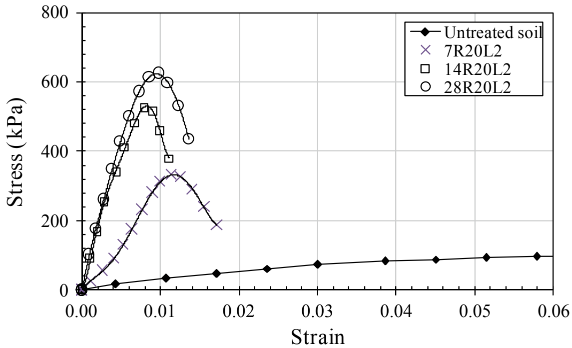

Fig. 7 Improvement in UCS of LFA-treated soil with Flyash R

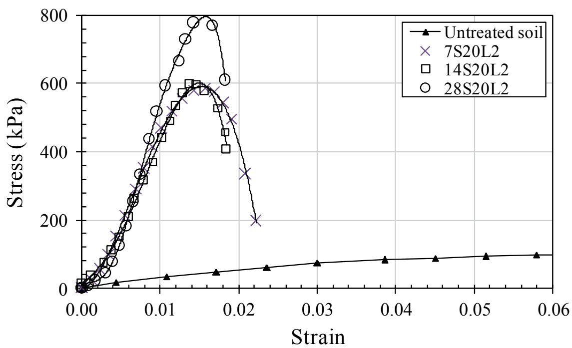

Fig. 8 Improvement in UCS of LFA-treated soil with Flyash S

4.4 California Bearing Ratio

The California bearing ratio is a very useful parameter in designing of flexible pavements. The LFA-treated samples were cured for 7 days and then soaked for 4 days with standard surcharge. The soaked CBR values and the % heave are listed in Table 8.

Table 7 Improvement in elastic parameters of LFA-treated expansive soil with curing

Mix	σ_f (MPa)	Elastic modulus (MPa)		
		E_i	E_s	E_f
7D20L2	0.40	55.23	39.57	42.45
28D20L2	0.51	74.27	48.91	55.25
7N20L2	0.44	53.31	40.82	35.16
28N20L2	0.56	93.15	55.67	52.62
7R20L2	0.33	38.78	31.36	29.26
28R20L2	0.63	82.04	62.26	63.90
7S20L2	0.59	56.52	46.38	37.31
28S20L2	0.80	81.39	55.15	51.80

σ_f: Stress at failure; E_i = initial tangent modulus; E_s = secant modulus at 1% strain; E_f = elastic modulus at failure

Table 8 CBR and heave of LFA-treated samples

Mix	CBR (%)	Heave (%)
Untreated soil	1.5	5.18
7D20L2	25.40	0.01
7N20L2	20.88	0.02
7R20L2	38.18	0.04
7S20L2	38.25	0.05

The LFA-treated soils with Flyash D and Flyash N gave a soaked CBR value between 21 and 25%. A very high value of CBR of 38% was obtained for both Flyash R and Flyash S. With longer duration of curing, the stabilizing effects are expected to be more prominent. The LFA treatment has reduced the heave from 5.25% to less than 0.05%, thereby reducing the moisture susceptibility.

5 Conclusions

Following conclusions can be drawn from the study:

- Class F-type flyashes are effective in stabilizing highly expansive soils only when used in combination with lime. The effectiveness of a flyash depends on its specific gravity, CaO content and CaO/SiO_2 ratio. Free swell index tests and linear shrinkage tests can be conducted to assess the effectiveness of various stabilizers.
- With LFA treatment of expansive soil, the UCS can be improved from 100 kPa to the range of 500–800 kPa, whereas the initial tangent modulus can be improved from 3 MPa to the range of 75–95 MPa. However, the failure strains are reduced to 1.0–1.5%.

- The heave of a soaked CBR sample is a better criterion than the free swell index to assess the swelling potential of a stabilized subgrade.
- The LFA treatment improved the soaked CBR values from 1.5% to the range of 20–40% and restricted the heave to 0.05%, thereby proving its suitability in treating expansive subgrades.

References

ASTM C 618-15 Standard specification for coal flyash and raw or calcined natural puzzolana for use in concrete

ASTM D 4609-94 Standard guide for evaluating effectiveness of chemicals for stabilization

ASTM D 6276-99a Standard test method for using pH to estimate the soil-lime proportion requirement for soil stabilization

Beeghly JH (2003) Recent experiences with lime-flyash stabilization of pavement subgrade soils, base and recycled asphalt. In: International ash symposium, University of Kentucky, Paper 46, pp 1–18

Central Electrical Authority, New Delhi (2017) Report on flyash generation at coal/lignite base thermal power stations and its utilization in the country for the 1st half of the year 2016–17 (Apr 2016–Sept 2016)

Cokca E (2001) Use of Class C fly ashes for the stabilization of an expansive soil. J Geotech Geo-Environ Eng ASCE 127(7):568–573

IS 2720(Part XX):1987 Methods of test for soils: determination of linear shrinkage. Bureau of Indian standards, New Delhi

IS 2720(Part XL):1977 Methods of test for soils: determination of free swell index of soils. Bureau of Indian standards, New Delhi

IS 4332(Part III):1967 Methods of test for stabilized soils: test for determination of moisture content-dry density relation for stabilized soil mixtures. Bureau of Indian standards, New Delhi

IS 4332(Part V):1970 Methods of test for stabilized soils: determination of unconfined compressive strength of stabilized soils. Bureau of Indian standards, New Delhi

Little DN, Nair S (2009) Recommended practice for stabilization of subgrade soils and base material. NCHRP Project 20-07 Final report, Transportation research board

Mishra A, Biswas D, Upadhyaya S (2005) Physico-mechanical behavior of self-cementing class C fly ash–clay mixtures. Fuel 84:1410–1422

Senol A, Edil TB, Bin-Shafique MS, Acosta HA, Benson CH (2006) Soft subgrades stabilization by using various fly ashes. Resour Conserv Recycl 46:365–376