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EXPANSIVE SOILS: PROBLEMS AND REMEDIAL MEASURES

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ABSTRACT

Expansive soil is a worldwide problematic soil that causes extensive damage to civil engineering structures. Expansive soils of India are highly argillaceous, very fine-grained, possesses unique capacity to hold water, swell when wetted and exert high swelling pressures when confined. Various problems associated with these soils are: structural problems through differential movement of the structure resulting in severe damage to the foundations, buildings, roads, retaining walls, canal linings and movement of soils on unstable slopes. On the other hand, in India, nearly 150 million tonnes of fly ash is being generated annually posing dual problem of environmental pollution and difficulty in disposal, which calls for establishing strategies to use the same effectively and efficiently. In this paper, a brief review has been made about possible pre & post construction solutions, and fly ash stabilization of expansive soils has been studied in detail. Test specimens were prepared with expansive soil using a range of fly ash contents (by dry weight of the soil) at $0.95\gamma_{dmax}$ and Optimum moisture content and subjected to different tests with out and with curing time. Based on favorable results, it is concluded that the fly ash can be successfully used not only as an effective stabilizer, but also as an engineered construction material. *Thus the main objective of present study was a two-fold: First, to overcome problems posed by expansive soils by choosing a suitable ground improvement technique and second, to avoid the tremendous environmental problems caused by large scale dumping of fly ash by its economical and environmentally beneficial utilization in various Geotechnical applications.*

KEYWORDS: Expansive soil, Solid waste, Environmental pollution, Waste utilization, Ground improvement.

INTRODUCTION

Expansive soil is a worldwide problematic soil that causes extensive damage to civil engineering structures. Documented evidence is available of the existence and problems associated with expansive clays having occurred in countries like India, Africa, Australia, USA and in Canada. The origin of these soils is yet not fully known. It is generally ascribed to long continued surface action on rocks like Deccan traps and Peninsulas of gneisses of a basic composition. Their formation /occurrence on granite, shale, basalt, sand stone, slates, lime stone, basic volcanic ash, calcareous aluminum has also been recognized. Expansive soils of India, popularly known as black cotton soils, have been subjected to extensive research. Expansive soils are also known as “Swelling Soils”, “Heaving Soils”, and “Volume Changing Soils”. Semi-arid, hot climate and poor drainage conditions, low lying regions and flood plains are usually associated with the formation of expansive or black cotton soils [Holtz and Gibbs1954, Jones et al. 1773, Humad1977, Mir 2001]. Differential thermal analysis and X-ray diffraction pattern analysis have shown that montmorrillonite is the predominant clay mineral in black cotton soil [Roy and Char 1969, Sridharan and Rao 1973, Lunkad 1977, Kate 2005]. In INDIA, these soils are also known as “**REGUR SOILS**”, which are highly argillaceous, somewhat calcareous, very fine-grained, possesses unique capacity to hold water, very plastic, swell when wetted and exert high swelling pressures when confined. When wet, they have a gooey texture and easily stick to the soles of shoes. When dry, they shrink and crack appears on the ground that often forms a hexagonal pattern, like the bottom of a dried-up pond. The effects of black cotton soils on man-made structures continue to be a major problem worldwide. On account of these adverse engineering properties it has posed numerous foundation problems, and therefore, are of special engineering interest. Various problems associated with these soils are: structural problems through differential movement of the structure resulting in severe damage to the foundations, buildings, roads, retaining walls, canal linings and movement of soils on unstable slopes. On the other hand, in India, more than 150 million tonnes of fly ash is being generated annually posing dual problem of environmental pollution and difficulty in disposal, which calls for establishing strategies to use the same effectively and efficiently. There exists a vast scope of utilization of fly ash in Geotechnical constructions like lightweight embankments, road sub-bases and structural landfill as a replacement to conventional earth material and cement. Therefore, researchers and field engineers around the world are engaged in understanding the behavior of expansive soils and in solving these associated problems and to find out ways and means for economically and environmentally beneficial utilization of fly ash. To overcome these problems, various improvement techniques have been used to improve expansive soils for a safe design of structures. Many researchers [e.g. Pandian and Mir 2002, Mir and Pandian 2003, Mir et al. 2004, Phanikumar and Sharma 2004, Mir and Sridharan 2013, Mir 2015], have investigated successful stabilization of expansive soils and improvement in shear strength. Saha and Pal [2012], Phanikumar and Sharma [2007], Mir and Sridharan [2014] have studied experimentally the compressibility behavior of expansive soils stabilized with fly ash and reported significant improvement in compressibility characteristics of expansive soils.

In this paper, a brief review has been made about possible pre & post construction solutions, and fly ash stabilization of expansive soils has been studied in detail to investigate immediate & long term behavior of fly ash modified expansive soils. In this study, test specimens were prepared with expansive soil using a range of fly ash contents (by dry weight of the soil) at $0.95\gamma_{dmax}$ and Optimum moisture content and subjected to different tests with out and with curing time. The index and engineering properties of fly ash stabilized specimens were evaluated. Reactions that occur in the soil-fly ash mixture result in lower water contents, higher shear strength, and lower compressibility. Hence based on favorable results, it is concluded that the fly ash can be successfully used not only as an effective stabilizer, but also as an engineered construction material. *Thus the main objective of present study was a two-fold: First, to overcome problems posed by expansive soils by choosing a suitable ground improvement technique and soil stabilizing agent, and second, to avoid the tremendous environmental problems caused by large scale dumping of fly ash by its economical and environmentally beneficial utilization in various Geotechnical applications.*

PROBLEMS ASSOCIATED WITH EXPANSIVE SOILS

Expansive soil is an expensive material. Expansive soils occurring above water table undergo volumetric changes with changes in water content [Katti 1979, Nelson and Miller 1992]. Increase in moisture content in expansive soils causes the following effects.

1. Expansive soils expand and contract due to change in moisture content of the soil, causing structural Problems through differential movement of the structure resulting in severe damage to the foundations, buildings, roads, retaining walls, canal linings etc. Figure 1 illustrates the kind of typical damage that a structure resting on an expansive soil may suffer. The amount by which the ground can swell and/or shrink is determined by the water content in the near-surface zone. However, it may be noted that swelling and shrinkage are not fully reversible processes, and the effects of high shrink–swell potential can cause severe damage to various structures constructed on or in these expansive soils.

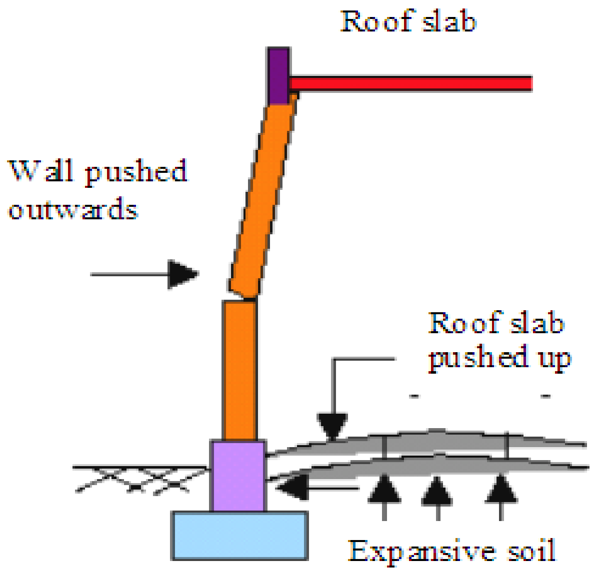


Fig 1: Effects of swelling on a structure.

2. A second effect of expansive soils is the additional horizontal pressure applied to foundation walls in basements and crawl spaces. Increased water content in the soils adjacent to the foundation wall will cause the soils to expand and increase the lateral pressure on the foundation wall. If the foundation wall does not have sufficient strength, minor cracking, bowing or movement of the wall may occur. Serious structural damage or failure of the wall may also occur.

3. A third effect associated with claystone (a type of expansive soils) is the movement of soils on unstable slopes. Expansive claystone soils found as a layer under a more rigid top layer of soils, become unstable as the moisture content increases, allowing the claystone and top layers of the soil to move. If the soil is located on a slope, the top layer of soil can creep. Consequently, a house with an inadequate foundation built on unstable slopes can be subjected to creeping of the structure down slope or to failure of the structures in a landslide.

PREVENTIVE DESIGN CONCEPTS

For safe and stable construction of engineering structure on expansive soils, the following preventive design concepts play a vital role.

Pre-Construction Solutions

Prior to building the structure, a soil test of the site should be performed to ensure that the soils are stable or to determine the approximate effect the soils will have on the structure.

This will assist in determining if the soils are capable of property supporting the structure. In addition, information on the soils can ensure that the foundation is designed to withstand the effects of the existing soil conditions, and assist in the development of plans for long-term maintenance.

Post-Construction Solutions

For structures affected by expansive soils, movement can be prevented by providing various methods of underpinning (to prevent vertical movement and / or sliding) and /or reinforcing of the foundation walls (to withstand lateral pressure).

Special foundation

Deep piers and footings, and in more recent years use of rigid (waffle-type or post-tensioned) slabs, are the principal preventive techniques for safe design of building foundations (Fig. 2).

Fill blanket

Replacement of the influential upper few feet of expansive bedrock with a blanket of stable compacted fill can control damage by eliminating the most unstable zone and stabilizing the water content of the deeper rock. Bedrock stratigraphy, fill thickness, permeability, expansivity and structural design are all factors to be considered in this preventive design approach (Fig. 3).

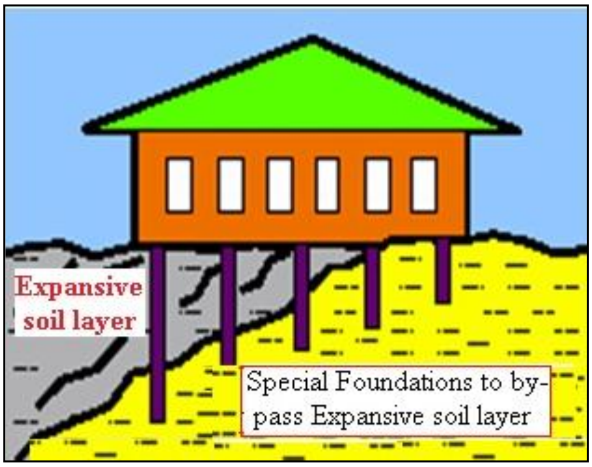


Fig. 2. Special foundation in expansive soils against failures in expansive soils

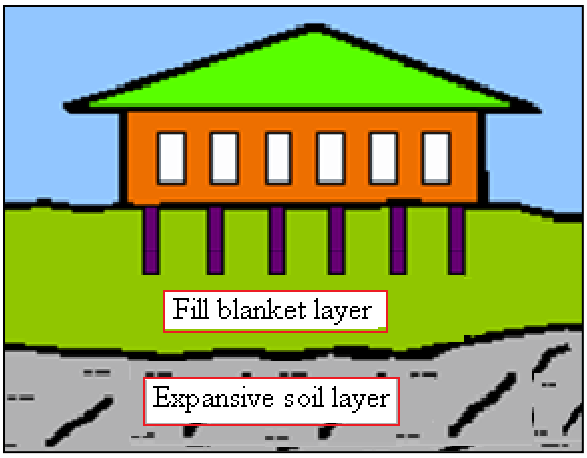


Fig. 3. Fill blanket as preventive measure against failures in expansive soils

NEED FOR STABILIZATION OF EXPANSIVE SOIL

Expansive soil is known for its undesirable characteristics of high swelling and shrinkage. The inherent high swelling and shrinkage characteristics of black cotton soils cause considerable damage to the structures built on or with them. Admixing stabilizers (fly ash in the present case) can modify these undesirable properties. Hence, using fly ash for improvement of soils has a two-fold advantage. First, to avoid the tremendous environmental problems caused by large scale dumping of fly ash, and second, to reduce the cost of stabilization of soils and bulk utilization of fly ash.

FLY ASH AS AN ADDITIVE IN SOIL STABILISATION

Fly ash disposal and utilization shall continue to be an important area of national concern due to India's dependence on thermal power generation for its energy supply. The importance and urgency of utilization of the 150 MT of fly ash being produced annually is a well-known fact. Fly ash is a versatile material with many applications in the construction industry. However, only about 20% fly ash produced in the world is utilized in variety of applications and the rest is dumped as a waste material posing serious health and environmental problems. In fact it was this palpable and real sense of urgency which resulted the taking up of the Mission project for “the safe utilization and disposal of fly ash”.

MATERIALS AND METHODS

For the present study, expansive soil was collected from Davengere District of Karnataka State and two fly ashes namely, Badarpur fly ash - BFA (from Badarpur thermal power station UP), and Neyveli fly ash - NFA (from Neyveli thermal power station Tamil Nadu) are used. These two fly ashes were chosen for this study as they represent the extreme cases based on calcium content among many Indian fly ashes. The physical properties of the expansive soil and the two fly ashes used in this investigation are listed in Table 1 whereas Table 2 reports the chemical analysis of oven dried expansive soil and the two fly ashes. Different percentages of expansive soil were added to Badarpur fly ash and Neyveli fly ash and their index properties were determined. Standard Proctor compaction tests, consolidation tests and strength tests were carried out on the so obtained expansive soil – fly ash mixes. Specimens with fly ash were cured for 7 days and 28 days and subjected to Consolidation and unconfined compression strength tests. All the samples were prepared as per standard procedures [IS: 1498, IS: 2720 (part 1 &3)] and compacted at $0.95\gamma_{dmax}$ and corresponding water content on the dry side of optimum. The test program is given in Table 3.

Table 1: Properties of materials used.

Properties	Expansive soil	BFA	NFA
Fine and size (%)	10	10	10
Silt size (%)	27	87	85
Clay size (%)	63	3	5
(%)age finer 75µ m	90	90	90
Coeff. of uniformity	---	6.7	1.1
Coeff. of curvature	---	1.5	0.8
Sp. Gravity, G	2.71	2.18	2.64
Liquid limit, (%)	84	50	40
Plastic limit, (%)	25	NP	NP
Shrinkage limit, (%)	8.3	36	38
PI=LL-PL (%)	59	NP	NP
PI (A-line)	47	22	15
PI (U-line)	68	38	29
Clay mineral type	Montt.	NA	NA
Classification	CH	SM	SM
Free swell index (%)	65	---	---
Swelling pr. (kPa)	280	---	---
Maximum dry density (kN/m^3)	14.4	10.6	12.6
OMC (%)	28.6	38	33

Table 2: Chemical analysis for expansive & fly ashes.

Comp. (by wt. %)	Expansive soil	BFA	NFA
SiO_2	49.2	57.5	36.5
Al_2O_3	24	33	41
Fe_2O_3	5.8	4.8	4.5
TiO_2	0.7	1.4	1.4
CaO	0.4	0.5	9.00
MgO	0.4	0.2	3.8
K_2O	0.12	0.4	0.1
Na_2O	0.1	0.2	0.4
LOI*(900 ^{o}C)	18.1	1.5	3.5
Clay mineral	Montmorillonite	---	---
Free Lime	---	---	3.2
*: LOI-loss on ignition, BFA: Badarpur fly ash; NFA: Neyveli fly ash			

Table 3: Experimental Program for expansive soil-fly ash Mixtures.

Expansive Soil-BFA mixes			**Expansive Soil-NFA mixes**		
Expansive soil (%) (G=2.71)	**Badarpur fly ash, BFA (%) (G=2.18)**	**G_{mix}***	**Expansive soil (%) (G=2.71)**	**Neyveli fly ash, NFA (%) (G=2.64)**	**G_{mix}**
100	0	2.71	100	0	2.71
80	20#	2.58	90	10	2.70
60	40	2.47	80	20	2.70
40	60	2.37	60	40	2.68
20	80	2.27	40	60	2.67
0	100	2.18	20	80	2.65
0	100$	2.18	0	100	2.64

#: 20BFA = 20% BFA (BFA-by weight) + 80% expansive soil and so on

$: 8.5 % of lime (CaO) was added to BFA to make it at par with NFA in terms of lime content.

***: Specific gravity of composite soil sample** (e. g. soil +fly ash) is computed as:
or expansive soil (G=2.71) - Badarpur fly ash (G=2.18) ratio of 80:20 for total mass of mix, M =100g (80g of soil + 20g of fly ash), the specific gravity of this soil-fly ash mixture is calculated as: $\mathbf{G_{mix}=M/(V_s+V_f)}$.
V_s= Volume of expansive soil sample = 80/2.71 (cc) and V_f = Volume of fly ash = 20/2.18 (cc)
[$G_s=\gamma_s/\gamma_w$, $\gamma_s=G_s$ ($\gamma_w=1$), $V=M/\gamma_s=M/G_s$, γ_s = M/V = soil particle density of mix.
Therefore, $G_{mix}= M/(V_s+V_f)$ & (V_s+V_f) =V].
Likewise, the specific gravity of other samples of soil-fly ash mixtures is calculated in the same manner.

RESULTS AND DISCUSSIONS

The properties, which are of greatest important in the characterization of a material to be used as a resource material include are physical properties, index properties and engineering properties. The test results are described as below.

Specific gravity

The specific gravity of natural soils ranges from 2.65 to 2.80. The specific gravity of expansive soil and fly ashes was determined as per relevant standard procedures [IS: 2720-part 4] and test values are given in Table 1. It is seen that Badarpur fly ash possesses low specific gravity. Hence, low specific gravity and a relatively uniform grain size distribution, resulting in low unit weight will result in lower earth pressure leading to savings. Specific gravity values for soil-fly ash mixes is computed as per experimental program as given in Table 3.

Effect of fly ash on water holding capacity of expansive soil

Atterberg limits such as liquid limit, plastic limit and shrinkage limit represent the water content limits of fine grained soil at different consistency states are extensively used in geotechnical engineering. Atterberg limit tests were conducted as per relevant standard procedure [IS: 2720-part-5, IS: 2720-part-6]. Effect of fly ash on liquid limit, plastic limit, shrinkage limit and plasticity index of expansive soil is illustrated in Fig. 4.

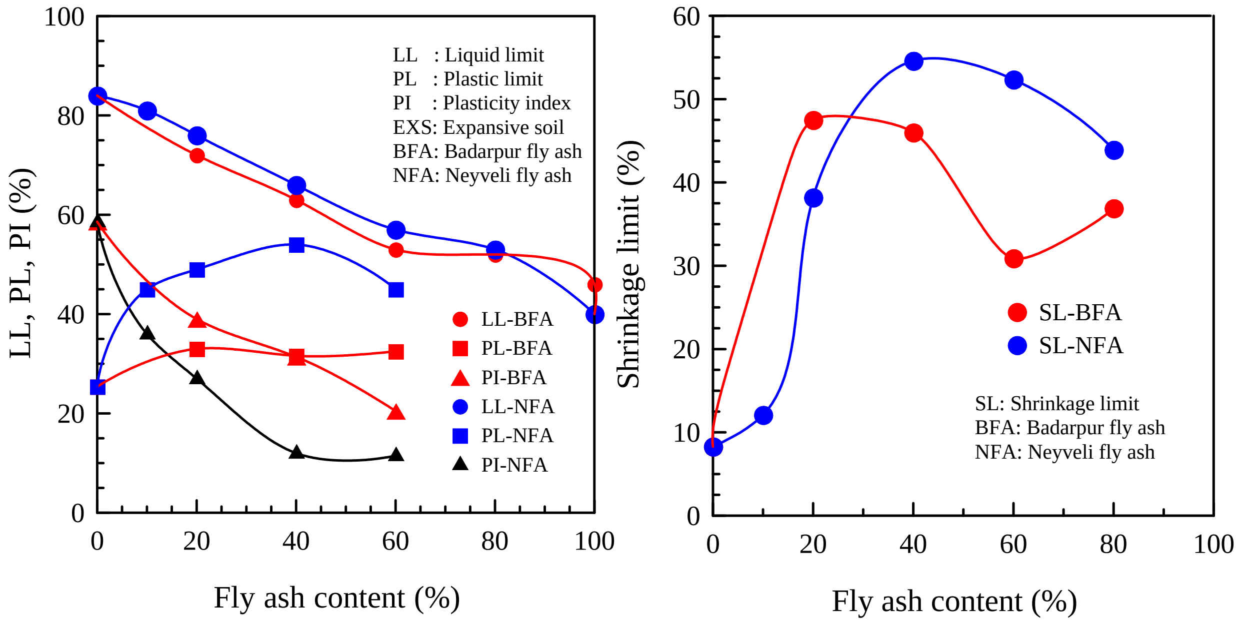


Fig 4: Effect of fly ashes on index properties of expansive soil.

The values of liquid limit, plastic limit and shrinkage limit are useful in the classification of soils. They also provide an overall idea for the engineering properties of the soils. The liquid limit (air dried) values of the expansive soil and fly ashes are 84 %, 50% and 40% respectively. However, fly ashes are inert material and possess liquid limit due to their fabric characteristics, which possess cenospheres and due to water holding capacity. Shrinkage limit values are 8%, 36% and 38% for expansive soil, BFA and NFA respectively. The liquid limit of the expansive soil decreased with an increasing amount of stabilizer. This is understandable since fly ashes are coarse grained compared to expansive soil resulting in the dilution of the liquid limit. Furthermore, they are inert and hence, even their finer fractions do not contribute to the liquid limit values. The liquid limit of fly ashes is exhibited due to the flocculated structure of the fly ashes and not due to the plasticity characteristics. Addition of 10% of Neyveli fly ash has changed the classification of expansive soil from CH to MH, MH-ML. The trends of variation exhibited by plastic limit plasticity index are also on the same expected lines. The increase in plastic limit on addition of fly ash is due to lime content imparted to the soil from fly ash, which causes reduction in the diffuse double layer thickness and flocculation of the clay particles, and substitution of finer soil particles with coarser fly ash particles. Plasticity index is a good indicator of swelling potential. The swell potential of the treated soil is often of great importance for modified sub-grades.

Engineering Properties

The engineering properties of expansive soil are very much influenced by the factors like source of the method of collection of the soil samples etc. The various engineering properties are described as below.

Effect of fly ashes on compaction characteristics

Compaction improves the engineering properties of foundation material so that the required shear strength is obtained, while decreasing the shrinkage, permeability, and the compressibility characteristics. The results of compaction tests [IS: 2720-part 7] carried out on expansive soil and fly ashes are illustrated in Fig. 5.

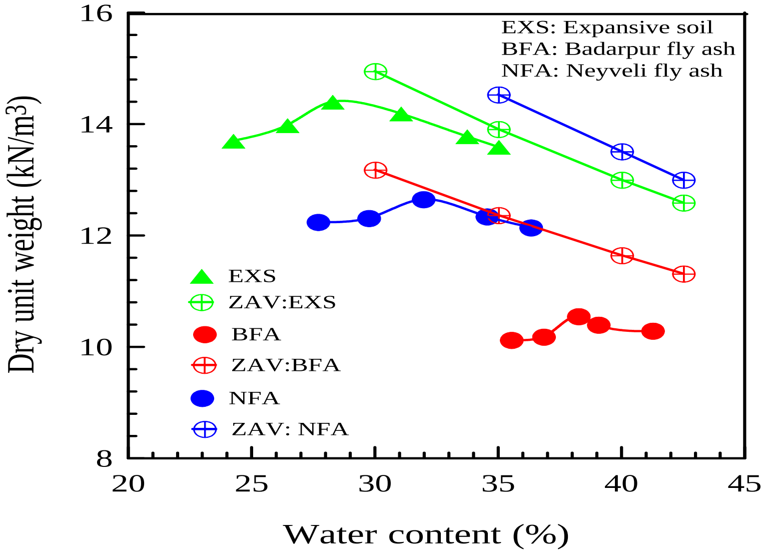


Fig 5: Compaction curves for expansive soil and fly ashes.

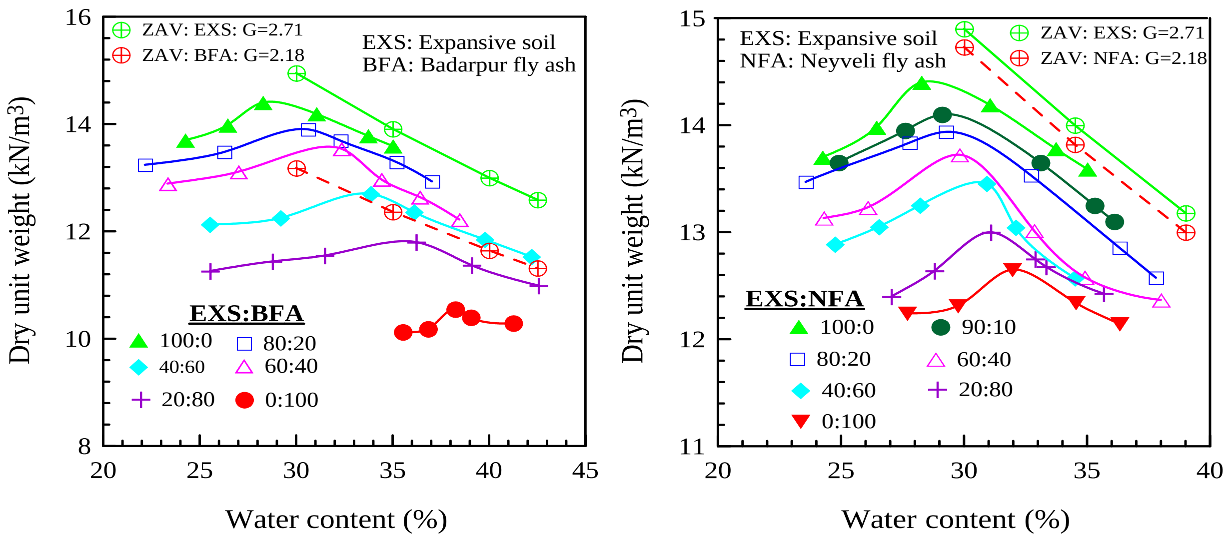
Compared to expansive soil, fly ashes exhibit lower dry density and higher optimum moisture content. The increase in optimum moisture content is due to the presence of hollow cenospheres in fly ashes as well as increase in surface area of solids. The increase in optimum moisture content can also be attrubuted on account of additional water held within the flocs resulting from flocculation due to lime and the fly ash reaction. Decrease in dry density is because of low specific gravity due to large cenospheres [Pandian, et al. 1998] and poor gradation of fly ash, and the immediate formation of cemented products, which reduce the dry unit weight of the treated soil. The reduced dry unit weight reduces the swell shrinkage potential of the compacted expansive soils. Hence, in order to appreciate the real degree of compaction, the effect of variation of specific gravity has been normalized with reference to soil (G_{std} = 2.65). Normalized dry unit weight-normalized water content plots not only helps in overcoming the effect of widely varying specific gravity, but also facilitates proper comparison of the compaction characteristics of fly ashes with those of soils without any change in the shape of the compaction curves. Thus, the conventional dry density-water content values are modified in terms of normalized dry density and normalized water content which accounts for the large variation in specific gravities of fly ashes using the following equations.

Normalized dry density, $\gamma_{dn} = \gamma_d * G_{std} / G_m$ (I)

Normalized water content, $w_n = w * G_m / G_{std}$ (II)

Where, G_m = specific gravity of the material,
G_{std} = Standard specific gravity with respect to which the values are normalized,
γ_d = density of the material and w = water of the material.

Figure 6 (ab) shows the compaction curves for expansive soil-fly ash mixes. From Fig. 6 (ab), it is also seen that with the addition of small amount of expansive soil to the fly ash, γ_{dmax} of the composite sample increases with a decrease in OMC. The increase in γ_{dmax} can be mainly attributed to the improvement in gradation of the fly ash and increase in the specific gravity of soil-fly ash composite sample. It may also be noted that the specific gravity of the two expansive soil and NFA are almost of the same order (NFA: 2.64 as against 2.71 of expansive soil). Because of the increased resistance offered by the fly ash, which is a coarser and uniformly graded material, γ_{dmax} obtained is lesser than the γ_{dmax} of expansive soil.



(a). Expansive-Badarpur fly ash mixes **(b). Expansive-Neyveli fly ash mixes**

Fig. 6 Compaction curves for expansive soil fly ash mixes.

Effect of fly ashes on swelling and compressibility characteristics

In the present study, the swelling potential for expansive samples treated with fly ash was determined from the one dimensional consolidation test [ASTM D4546-90]. Marked changes were observed in the compression behavior for soil-fly ash mixes. Figure 7 shows the variation of collapse-swell with pressure for different curing periods. The reduction in swelling pressure [IS: 2720-part 40, IS: 2720-part 41] of expansive soil can be attributed to the reduction of amount of suction consequent upon addition of fly ash. It is seen that 10% NFA is the optimum content to reduce swelling characteristics compared to 40% BFA.

Consolidation occurs more rapidly in uniformly graded/coarse grained soils than in silty-clay/clay due higher void ratio and greater permeability. The geotechnical engineer plays a vital role in predicting the magnitude and rate of settlement of foundations due to structural loads. The soil samples were prepared by compacting at 0.95 γ_{dmax} and corresponding water content on dry side of optimum (OMC and MDD by standard Proctor test) and tested in a fixed ring consolidometer using brass rings of 60mm diameter and 20mm height [IS: 2720-part 15]. The compressibility characteristics viz, compression index, which gives the magnitude of settlement and coefficient of consolidation, C_v which gives the rate of settlement are determined by a standard consolidation test [Sridharan et al. 1987]. Figure 8 shows the compressibility curves for cured samples for one week and 7 days. It can also be seen that with increase in curing time, the compressibility decreases. This is due to the cementation bonds which are formed between free lime and reactive silica and thereby improving the compressibility characteristics of the expansive soil. It is seen that cured samples resist the external load very effectively. The load – compression curves are much flatter. Fly ash alone gives much lesser compression. It is also observed that compressibility increases with increase in effective consolidation pressure and as fly ash content increases, compression index decreases. Also, due to cation exchange reaction, an increase in the flocculation and aggregation causes a chemically induced preconsolidation effect, which increases the vertical effective yield stress and reduces the compressibility characteristics.

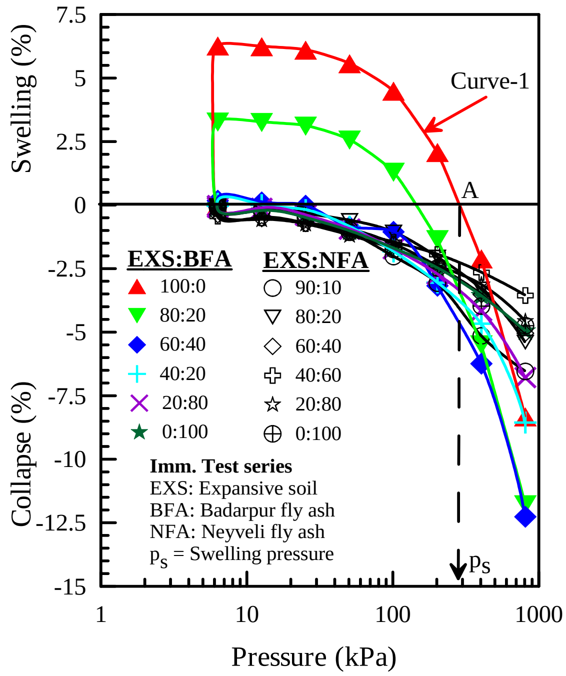


Fig. 7. Variation of collapse-swell potential of expansive soil with addition of fly ashes.

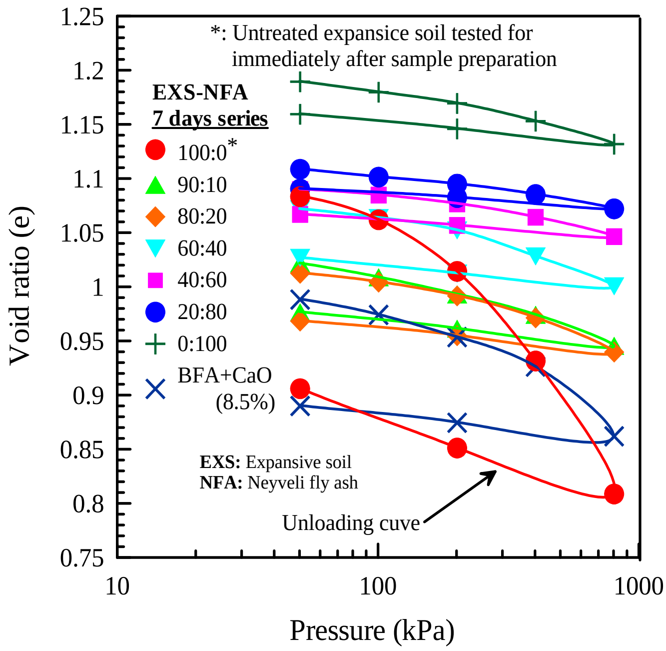


Fig. 8. e-logσ´ plot for soil-fly ashes mixes for 7 days curing period.

Effects of stabilization on the unconfined compressive strength of black cotton soil

In some special cases, as for checking the short-term stability of foundations and slopes where the rate of loading is fast but drainage is very slow, one of the most common tests is the unconfined compression test. Unconfined compression strength test is the simplest and quickest test for determining the shear strength of cohesive soils. The strength of clayey soil can be altered by the addition of fly ash. The soil-fly ash samples were prepared [IS: 2720-part 10] and compacted at 0.95γ_{dmax} and corresponding water content on dry of optimum and tested in an unconfined compression testing machine. The unconfined compressive strength (ucs) of expansive soil decreases continuously with an increase in the percentage content of Badarpur fly ash for both, immediate and higher curing periods. This is because, in absence of pozzolanic reactions, fly ash behaves just like silt, and can decrease the ucc strength of soil. It is further observed that the addition of 8.5 % lime does not affect the ucs strength of Badarpur fly as much because of non-availability of reactive silica. However, ucs of expansive soil is increased due to pozzolanic affect class C Neyveli fly ash. The variation of ucc strength of expansive soil with various percentages of fly ashes at different curing periods is also shown in Figs. 9 and 10.

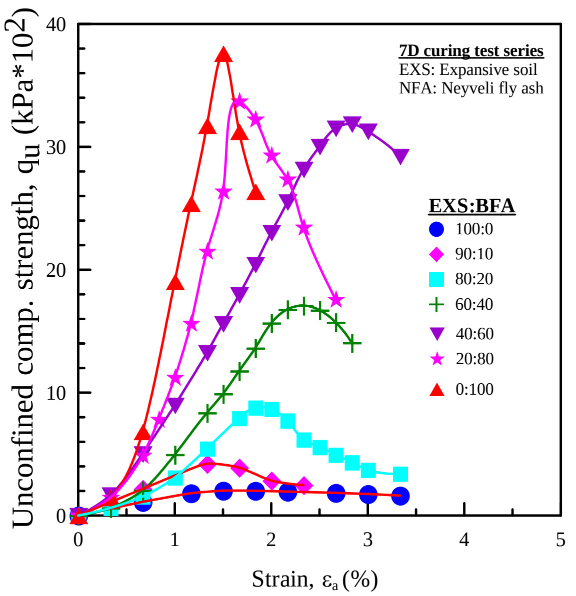


Fig 9. Stress-strain plot for 7D test series.

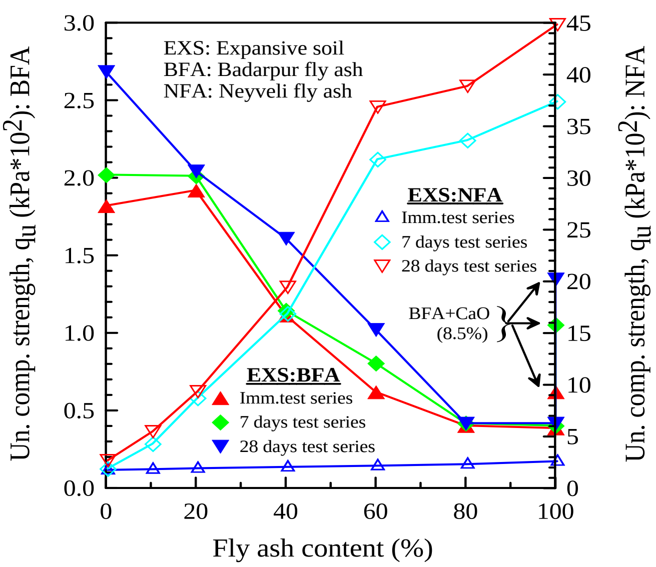


Fig 10. Variation in "ucs" with fly ashes.

CONCLUSIONS

Based on the test results obtained, the following conclusions can be made.

1. The index properties of expansive soil are significantly altered by the addition of fly ashes. The extent of variation depends on the particle size distribution, free lime content and pozzolanic reactivity of the fly ash.
2. The compacted density of soil fly ash mixes is low compared to BC soil alone that will be beneficial since a lower density will result in lower earth pressure leading to savings.
3. It has been observed that 10 % of Neyveli fly ash is the optimum amount required to minimize the swell potential compared to 40 % of Badarpur fly ash.
4. The unconfined compressive strength of soils can be increased by addition of reactive fly ash. Fly ashes alter the strength of expansive soil significantly by pozzolanic reactions that increase the strength and by reduction in cohesive strength of clayey soils by the silty nature of fly ash particles.
5. The study brings out the bulk and effective utilization of fly ash, on one hand affords a means of disposing off the power plant by product without adversely affecting the environment and on the other hand proves to be an effective admixture for improving an expansive soil.

REFERENCES

1. ASTM D4546-90, "Standard test methods for one-dimensional swell or settlement potential of cohesive soils", Annual Book of ASTM standards, American society for testing and materials, Philadelphia, www.astm.org.
2. Holtz, W. G. and Gibbs, H. J., "Engineering properties of expansive clays", Transaction of American Society of Civil Engineers, 1954; 121: 641-677.
3. Humad, S., "Lime pile stabilization of Black cotton soil", Proc. of the 1st National Symposium on Expansive Soils, HBTI-Kanpur, India, 1977; 4-1 to 4-8.
4. IS: 1498-(1970), "Classification and identification of soils for general engineering purposes", BIS, New Delhi.
5. IS: 2720-part 1 (1980), "Indian Standard Code for preparation of soil samples", Bureau of Indian Standards, New Delhi.
6. IS: 2720-part 3(1) (1980), "Method of test for soils: Determination of specific gravity of fine grained soils", BIS, New Delhi.
7. IS: 2720-part 4 (1985), "Method of test for soils: Determination of grain size distribution", BIS, New Delhi.
8. IS: 2720-part 5 (1985), "Method of test for soils: Determination of Atterberg limits", BIS, New Delhi.
9. IS: 2720-part 6 (1972), "Method of test for soils: Determination of shrinkage factors", BIS, New Delhi.
10. IS: 2720-part 7 (1980), "Method of test for soils: Determination of water content-dry density relation using light compaction", BIS, New Delhi.
11. IS: 2720-part 40 (1977/2002), "Method of test for soils: Determination of free swell index for fine grained soils", BIS, New Delhi.
12. IS: 2720-part 41 (1977/2002), "Method of test for soils: Determination of swelling pressure of soils", BIS, New Delhi.
13. IS: 2720-part 15 (1986), "Method of test for soils: Determination of consolidation properties", BIS, New Delhi.
14. IS: 2720-part 10 (1973), "Method of test for soils: Determination of shear strength parameter by unconfined compression test", Bureau of Indian standards, New Delhi.
15. Jones, Jr., D. Earl & Holtz, Wesley G., August, "Expansive Soils-The Hidden Disaster" Civil Engineering-ASCE., 1973; 49-51.
16. Kate, J.M. (2005), "Strength and volume change behavior of expansive soils treated with fly ash", Geo Frontiers-2005, ASCE, Geotechnical Special Publication.

17. Katti, R. K. (1979), "Search for solutions to problems in black cotton soils", Indian Geotechnical Journal, 1st IGS Annual Lecture (Dec-1978); 9(1): 1–80.
18. Lunkad, S. K. (1977), "The effect of soil genesis and expanding layered lattice mineral on the engineering index properties of residual soil of Malwa Plateau", Procc. First Nat`l Sym. on Expansive Soils, Kanpur.
19. Mir B. A. (2001), "*The effect of fly ash on the engineering properties of black cotton soils*", M. E. Thesis, Department of Civil Engineering, IISc, Bangalore – 560 012.
20. Mir, B. A. and Pandian N. S. (2002), "Fly Ash – As an additive for stabilization of soils", Procc. of International Workshop and Conference on Construction Management and Materials (CONMAT-2003), pp. 739-750, I.I.T. Khargpur.
21. Mir, B. A., Shah, M. Y. and Pandian, N. S. (2004), "Fly ash – As a cementitious Material", Proceedings of the National Conference on Materials and Structures (MAST-2004); 1: 90 – 94, NIT Warangal (AP).
22. Mir, B. A. & Sridharan, A. (2013), "Physical and compaction behavior of clay soil-fly ash mixtures", Journal of Geotechnical and geological Engineering, 2013; 31 (4): 1059-1072.
23. Mir, B. A., "Effect of fly ash on swelling potential of BC soil", Proceedings of Indian Geotechnical Conference on Geotechnical Advances and Noval Geomechanical Applications, IIT Roorkee, 2013; 120(1): Theme 4, pp. 1-9.
24. Mir, B. A. and Sridharan, A., "Volume change behavior of clayey soil–fly ash mixtures", International Journal of Geotechnical Engineering, 2014; 8(1): 72-83.
25. Mir, B. A. "Some studies on the effect of fly ash and lime on physical and mechanical properties of expansive clay", International Journal of Civil engineering-Trans. B: Geotechnical Engineering – Geotechnique, 2015; 13(3&4B): 203-212.
26. Nelson and Miller, J.D. (1992), Expansive soils: Problems and Practice in Foundation and Pavement Engg, John Wiley Publication.
27. Pandian, N. S., Rajasekhar, C. and Sridharan, A., "Studies of the specific gravity of some Indian coal ashes, Journal of testing and evaluation", JTEA, 1998; 26(3): 177-186.
28. Pandian N.S. and Mir, B.A. (2002), "Compaction behavior of fly ash–BC soil mixes", Proceedings of Indian geotechnical conference, 2002; N. I. T. Allahabad, 1: 261–264.
29. Phanikumar BR, Sharma RS, "Effect of fly ash on engineering properties of expansive soil", J Geotech Geoenviron Eng., 2004; 130(7): 764–767.
30. Phanikumar BR, Sharma RS, "Volume change behavior of fly ash-stabilized clays", J Mater Civ Engg., 2007; 19(1): 67–74.

31. Roy, S. and Char, A. N. R., "Engineering characteristics of black cotton soils as related to their mineralogical composition", Procc. Sym. on Black Cotton Soils, college of Military Engineering, Poona, 1969; 17.
32. Sridharan, A. and Rao, G. V., "Mechanisms controlling volume change of saturated clays and the role of the effective stress concept", Geotechnique, 1973; 23(3): 359-382.
33. Sridharan, A., Murthy, N. S. and Prakash, K., "Rectangular hyperbola method of consolidation analysis", Geotechnique, 1987; 37(3): 355-368.