Second ASCE India Conference on "Challenges of Resilient and Sustainable Infrastructure Development in Emerging Economies" (CRSIDE2020)

March 2-4, 2020

Strength and Durability Characteristics of Fly Ash Admixed Black Cotton Soil

***Chethan B A [a], A U Ravi Shankar [b], Raghuram K Chinnabhandar [c] and Avinash H T [d]**

[a] Research Scholar, NITK Surathkal, Civil Engineering Department, Mangaluru - 575025, India,
chethanba@gmail.com
[b] Professor, NITK Surathkal, Civil Engineering Department, Mangaluru - 575025, India,
aurshankar@gmail.com
[c] Research Scholar, NITK Surathkal, Civil Engineering Department, Mangaluru - 575025, India,
raghuramkchinnabhandar@gmail.com
[d] Research Scholar, NITK Surathkal, Civil Engineering Department, Mangaluru - 575025, India,
avinashmng@gmail.com

***Abstract*—Black cotton soil (BCS) encountered during the construction of roads usually will be replaced by good quality earth. Increased construction activities and scarcity of suitable quality materials enforce to stabilize weak soils by using marginal materials. Laboratory investigations were performed on BCS by admixing marginal material Class F fly ash (FA) procured from a thermal power plant. Mechanical characteristics of BCS such as Unconfined Compressive Strength (UCS), California Bearing Ratio (CBR), Split Tensile Strength (STS) and Flexural Strength (FS) were evaluated at varying dosages of FA (0, 5, 10, 15, 20, 25, and 35%) and various curing periods (0, 3, 7, 28, 60, and 90 days). Predominantly FA has modified the plasticity characteristics of BCS with the increase in dosages. Because of minimal calcium oxide content available in FA for the pozzolanic reaction, the UCS variations of the mixes were dominated by the availability of moisture in the specimen at the time of testing. Even though CBR is as high as 25% under unsoaked condition, on soaking, most of the cured mixes have lost their strength and reached a value close to 2%. Cured and soaked cylindrical samples have shown low STS (i.e., around 10 kPa). Low moisture contents were observed in the middle of 4 days soaked specimens due to a low moisture penetration rate. Low FS values were found for all mixes. All samples tested for wet-dry (WD) cycles of durability test failed within 5 hours of soaking in water. A significant increase in the volume of the specimens was observed during the thawing cycle of freeze-thaw (FT) durability test when enclosed in absorptive felt pads. On freezing of absorbed water, samples have developed cracks due to the formation of ice crystals, lead to the disintegration with increased cycles. No significant chemical changes were observed in the FA admixed and cured BCS, justifying the poor performance under high or low moisture contents. Hence, the FA used in the investigation cannot suit the requirements as a stabilizer for BCS.**

***Keywords*—Stabilization, Class F fly ash, Black cotton soil, UCS, CBR**

I. Introduction

Black cotton soil (BCS) covers around 20% of Indian subcontinent viz. entire Deccan Plateau, Western Madhya Pradesh, portions of Rajasthan, Bundelkhand region in Uttar Pradesh, and some areas of Andhra Pradesh and Karnataka. Because of the black color and usefulness in growing cotton, it is named BCS (Malik & Priyadarshee, 2018). Rainwater, water and sewer line leakages, low evaporation rates can lead to high water content conditions in this soil. This soil tends to swell with the increase in water content, hence, termed as expansive soil. Enormous volume change of expansive soil is due to the presence of Montmorillonite clay mineral (Chen, 1975). Along with shrink-swell behavior, it has low strength and low permeability.

Pavement structures constructed on expansive soils show signs of cracks, with settlement or uplift, hence making them unsuitable for use. Whenever road alignments pass over weak and soft ground, then good quality earth obtained from borrow pits is used for the construction of subgrades. However, the depletion of good quality material enforces engineers to use in-situ soils by improving their properties. BCS alone is unsuitable for the subgrades, and hence the necessity of soil stabilization comes into the picture.

Coal-based thermal power plants are the source of a large quantity of FA in India. Burning of anthracite/bituminous coal produces class F FA, whereas burning of sub-bituminous coal produces class C FA. Disposal of unused FA creates an enormous amount of environmental stress. FA is an inexpensive binder used for soil stabilization compared to

---

* Corresponding author: **Chethan B A, chethanba@gmail.com**

cement and lime (Association, 2003). Binders like lime, cement, and FA can chemically stabilize the soils at low cost (B. S. R. Kaniraj & Havanagi, 2000; S. R. Kaniraj & Havanagi, 1999; Keshawarz & Dutta, 1993; Parsons & Kneebone, 2005; Sridharan, Prashanth, & Sivapullaiah, 2016). Massive structures like dams, embankments, retaining wall backfills, subgrade, base, sub-base consume an ample amount of FA. Usage of FA in the construction improves the strength characteristics along with diminishing the disposal problems. Some FA finds applications as a partial replacement in the production of Portland cement concrete, but a significant portion ends up in landfills. Class F FA is an effective stabilizer for pavement subgrades, and soils with weak bearing capacities (Acosta, 2002; Vishwanathan, Saylak, & Estakhri, 1997). Expansive soil stabilized by the admixtures like FA controls its volume change behavior (Kehew, 1995).

In the chemical stabilization, the chemical reaction of the FA in the presence of water binds the soil solids, thereby increasing the strength and stiffness of the soil. Siliceous and aluminous pozzolanic materials present in class F FA can only form cementitious compounds when they chemically react with calcium oxide in the presence of moisture (Cockrell & Leonard, 1970). Cementing potential (Janz & Johansson, 2002) of FA is indicated by CaO/SiO_2 ratio. The addition of FA to the soil reduces the water content. Reduction in water content diminishes the pozzolanic effect of FA. The CaO content greater than 10% and CaO/SiO_2 ratio between 0.5 to 0.8 resulted in remarkable UCS improvement of organic soils (Tastan, Edil, Benson, & Aydilek, 2011). The addition of 20% class C FA has depleted plasticity index, swelling potential of expansive soil due to the flocculation of clay particles induced due to time-dependent pozzolanic reaction (Cokca, 2001). CBR of soil-fly ash mixes increases with an increase in FA content but decreases with an increase in compacting water content (Edil, Acosta, & Benson, 2006). The addition of FA decreased the liquid limit and plasticity index and increased the CBR and UCS (Nicholson & Kashyap, 1993).

The objective of this study are (1) to determine stabilization potential of class F fly ash on soft soil (2) to quantify UCS, CBR, STS and FS improvements or variations (3) to study the behavioral changes of specimens under WD and FT durability tests (4) to investigate the dominating factors affecting the stabilization process, such as FA percentage, water content, and formation of pozzolanic gel.

II. Materials and Methods

A. Materials

Soil: Black cotton soil used in the study was collected from Chikkamagaluru, Karnataka, India. The geotechnical properties of the BCS are determined according to IS codes of practice and tabulated in Table 1. From the wet sieve analysis, it was observed that a significant amount of particles were of silt and clay size. Hence, the soil is classified as fine grained soil according to IS 1498-1970 (BIS 1970).

Table 1: Black cotton soil properties

Test properties	Value	
Specific gravity, G	2.56	
Gravel (%)	2	
Sand (%)	26	
Silt and clay (%)	72	
Liquid limit (%)	57	
Plastic limit (%)	29	
Shrinkage limit (%)	23	
Type of compaction	Standard Proctor	Modified Proctor
Unit weight (kN/m^3)	16.10	18.05
OMC (%)	22.2	16.0
CBR Unsoaked (%)	8	12
CBR Soaked (%)	2	2
UCS (kPa)	401	1141

FA: Marginal material used in the present study is FA obtained from M/s Udupi Thermal Corporation Ltd., Karnataka, India. The chemical properties of FA are tabulated in Table 2. SEM and EDAX images of FA are depicted in Figures 8a, 8b, and elemental quantification is provided in Table 4. The principal constituent of FA is SiO_2. The amount of CaO is minimal; hence, as per ASTM C618 2008, it is classified as Class F FA.

B. Methods

The soil procured was oven-dried, pulverized, and stored in airtight containers. Soil-Fly ash (SFA) mixes were prepared by varying FA dosages from 5, 10, 15, 20, 25, and 35%, which are represented with Mix ID's M1 to M6, respectively. Influences of these FA dosages on Atterberg limits, standard and modified compaction characteristics of SFA mixes were identified.

B.1. Unconfined Compressive Strength Test

UCS tests were conducted on soil and SFA mix specimens prepared following relevant Indian standards. Soil and FA were mixed based on a dry mass basis according to both standard and modified compaction densities. Mixes prepared at OMC were then compacted in stainless steel mould to obtain cylindrical specimens of 38 mm diameter and 76 mm height (aspect ratio of 2). The specimens were extruded by using a hydraulic jack. Prepared samples were weighed and kept in a desiccator for the specified curing period to maintain 100% relative humidity. After 3, 7, 28, 60, and 90 days of curing, the specimens were taken out of desiccator and weighed before subjecting to the UCS test. One set of samples was tested immediately after preparation to know UCS strength at OMC. The significance of curing time, variation in moisture content, and chemical reactions on UCS were analyzed.

B.2. California Bearing Ratio Test

CBR test specimens were prepared based on standard and modified compaction characteristics to assess the strength of the soil. Selected SFA mixes (M1, M2, and M3) with 5, 10, and 15 % FA were tested under unsoaked (prevailing short duration dry state during summer) and soaked (prevailing wet state during the rainy season) conditions. Before testing, specimens were cured at 25^0C and 100 % relative humidity for 0, 3, 7, and 28 days in the mould by sealing them in plastic wrap for finding unsoaked CBR. Four days of soaking of specimens was done after curing to simulate the worst possible moisture conditions arising at the site. Both unsoaked and soaked CBR strength tests were conducted to know the dropdown in CBR on soaking. This dropdown in the CBR value is represented by using a parameter "CBR Reduction Factor (CBR RF)" calculated using the following formula.

$$\text{CBR RF} = \frac{\text{Unsoaked CBR}}{\text{Soaked CBR}}$$

B.3. Split Tensile Strength Test

Traffic load and differential settlements will cause tension in the subgrade layer of roads. Direct measurement of the tensile strength is a tedious process. After the completion of the soaked CBR test, the specimens were extruded carefully from CBR moulds by using sample extruder to avoid soil loss. Extruded samples were tested diametrically to find their split tensile strength (STS) based on the Brazilian tensile test, which is generally known as an indirect tensile strength test (Das, Yen, & Dass, 1995; Franklin & Dusseault, 1989). The plane surface of specimens remains vertical during the load application. In this investigation, specimens of 10 cm diameter and 10 to 12.7 cm height were used. After testing, representative soil samples were obtained from the top, middle, and bottom portions of specimens to find the variation of moisture content along the depth on four days of soaking. The tensile strength of the cylindrical specimen is calculated using the following formula.

$$f_{ct} = \frac{2P}{\pi Dt}$$

Where, P = Failure load, D = Diameter of the specimen, and t = Thickness of the specimen.

B.4. Flexural Strength Test

Combined tensile and compressive strength of stabilized soil can be effectively determined by using a flexural strength test (Natt & Joshi, 1984). FS is an important parameter to judge the suitability of soil subgrades for the pavements. Beam specimens of size 7.5X7.5X30 cm were prepared with selected SFA mixes (M1, M2, and M3) comprising of 5, 10 and 15% FA content and cured for 0, 3, 7, and 28 days by sealing in plastic wraps. Flexural strength test (FST) was carried out on cured of SFA beam specimens by a third point loading system complying with Indian standards.

$$f_{ct} = \frac{Pl}{bd^2}$$

Where, P = Failure load, l = Span length, b = Average width of the sample, and d = Average depth of the sample.

B.5. Durability Test

UCS specimens of SFA mixes were subjected to 12 wet-dry (WD), and 12 freeze-thaw (FT) cycles of durability tests confirming to ASTM D 559 and ASTM D 560 standards. The deterioration of 28 days desiccator cured specimens was carefully examined to simulate the performance under cyclic seasonal changes and adverse weather conditions. Specimens were tested until the weight loss exceeded 14% or till completion of 12 cycles. Volume change of each sample is calculated by recording the dimensional variations exhibited on the absorption of water by capillary action and its subsequent freezing in the FT test or by intake of water on immersion and controlled drying in WD test.

Soil, FA, selected SFA mixes were subjected to chemical analysis. SEM images, EDAX patterns are used to know the modifications after 90 days curing period.

III. Results and Discussion

A. Chemical Properties

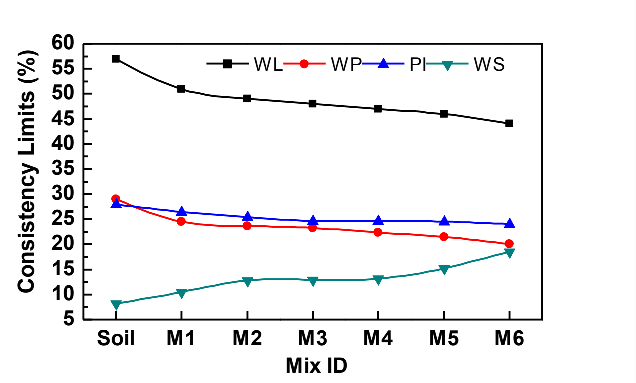
Both soil and fly ash are having major SiO_2 components, followed by Al_2O_3 and Fe_2O_3. Stabilized and cured mixes after 90 curing days have not shown any considerable variation in these pozzolanic components. Meager CaO/SiO_2 ratio for the fly ash and M1 to M3 combinations showed that the pozzolanic reactions are not governing the strength characteristics.

Table 2: Chemical properties of soil, fly ash and mixes

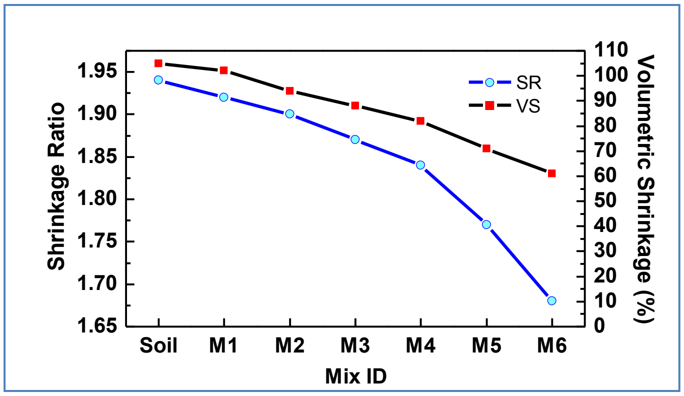
Oxides (%)	Soil	Fly ash	Mix M1	Mix M2	Mix M3
pH	8.24	10.7	8.55	8.77	8.99
Conductivity	1.085	1.052	1.493	1.049	1.349
SiO_2	75.4	70.5	70.8	67.1	71.4
Fe_2O_3	2.64	1.84	2.35	2.39	2.62
Al_2O_3	7.06	10.98	9.79	8.85	10.08
Chloride	0.027	0.014	0.018	0.02	0.018
CaO	0.008	0.003	0.008	0.007	0.006
MgO	0.0003	0.0011	0.0006	0.0019	0.0014
SO_3	0.16	0.15	0.16	0.07	0.07

B. Consistency limits

An increase in the percentage of FA has resulted in a decrease in the liquid limit and plastic limit of soil. Even though the shrinkage limit has increased marginally with the low FA amendment, a remarkable increase was found only above 20% dosage. Shrinkage ratio and volumetric shrinkage were depleted substantially with an increase in FA content. Therefore, the higher fly ash amendment depicts the improvement in resistance to the extreme volume changes and improvement in the plasticity characteristics of BCS, which is the primary concern from construction point of view.



1(a)



1(b)

Fig. 1: Variation of Consistency limits with fly ash dosages

C. *Compaction Characteristics*

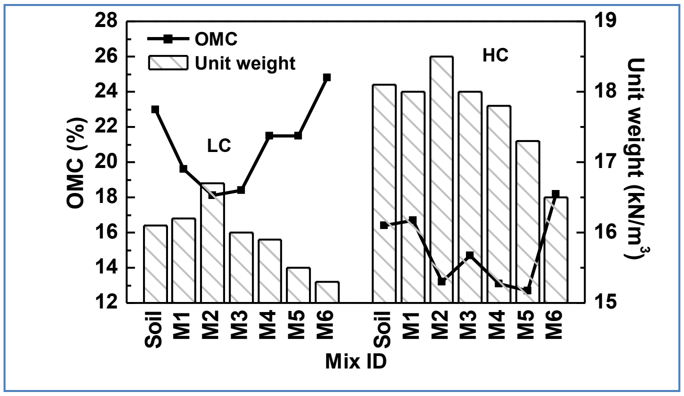


Fig. 2: Influence of FA percentage on compaction characteristics of SFA mixes

Standard and Modified Proctor's compaction tests were conducted at different dosages of FA to determine the variation in OMC and MDD of SFA mixes. Figure 2 shows the variation of these parameters. For the BC soil MDD's of 16.1 and 18.1 kN/m^3 was obtained at OMC's of 22.9% and 16.4%, respectively, corresponding to standard and modified compactions. SFA mixes have shown peak MDD's of 16.5 and 18.5 kN/m^3 at OMC's of 18.1% and 13.2% respectively, corresponding to standard and modified compactions at 10% FA content due to closer packing of SFA mix by filling up of void spaces. Further increase of FA content beyond 10% has resulted in the dropdown of MDD of SFA mixes, attributed due to the addition of low specific gravity FA in the soil. The replacement of higher specific gravity soil particles by low specific gravity fly ash particles resulted in the dropdown in the unit weight of mixes. A decrease in the OMC of SFA mixes attributed due to the non-plastic nature of FA and the absence of free lime in it, which may attract more water for hydration reaction (Vikas Malik, Aakash Priyadarshee 2018). IRC(2007) suggests the use of material with density >1.64g/cc (16.10 kN/m^3) for the subgrade. Hence, all SFA mixes with modified compaction and few mixes with standard compaction satisfy this criterion. However, the blends with higher FA content have remarkably lost their plasticity characteristics and showed low shrinkage properties, hence the UCS test is conducted on all SFA mixes.

As the dosage of fly ash increased, the effort or energy required for the preparation of mix is relatively lower in comparison with soil. But, as the dosage of fly ash increased, the rebound effect has increased during the compaction, making it more resistant to densify. At higher fly ash dosages, dust nuisance has aggravated, which may be a severe concern regarding environmental pollution during construction. The mixes having higher fly ash dosage have shown relatively flat (low-intensity peaks) compaction curves. Whereas, BCS and SFA mix having a low FA dosage have shown bumpy (high-intensity peaks) compaction curves. Hence, there is a minimal variation in the density of SFA mixes with high FA content.

D. *Unconfined Compressive Strength*

UCS variation for different FA dosages and curing periods of 0, 3, 7, 28, and 90 days for standard and modified compaction are depicted in Figures 3a and 3b, respectively. The moisture content of the specimens after curing was determined by recording the mass. The specimens kept in the desiccator could not retain the OMC with the curing period, due to the absorption/evaporation of water by/from the UCS specimen. This variation in moisture content has resulted in saturation or drying up the sample, further causing a change in lubrication and cohesion between soil and FA particles. The UCS of SFA mixes mainly depended upon the cured specimen's moisture content at the time of testing. In general, the increase in moisture content above OMC has resulted in the depletion of UCS and vice-versa. Specimens prepared by standard compaction showed low UCS due to low compactive energy when compared to high UCS obtained in modified compaction with higher compactive energy. Hence, the UCS was found to be higher for denser mixes. The highest UCS of 1106 and 1436 kPa was observed for 60 days cured SFA mixes corresponding to standard and modified compactions, respectively. A higher dosage of FA caused the depletion of UCS due to the loss of bonding between soil and FA particles. Too much moisture loss has resulted in drying up and powdering of specimens at higher FA content. The high moisture content tends to soften the sample, resulting in low UCS.

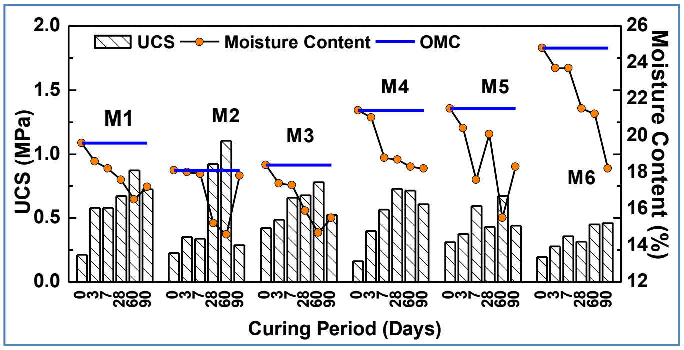


Fig. 3a: Influence of curing period and moisture content on UCS of SFA mixes under standard compaction

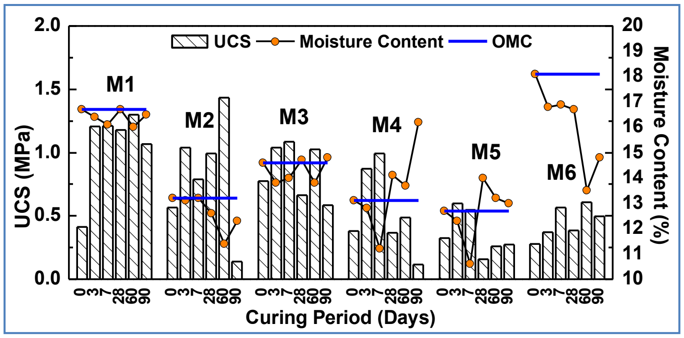


Fig. 3b: Influence of curing period and moisture content on UCS of SFA mixes under modified compaction

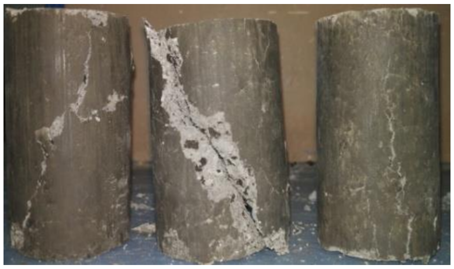


Fig. 3c: Tested UCS samples

E. California Bearing Ratio

Variation of unsoaked, soaked CBR, and CBR reduction factors of SFA mixes with 5, 10, and 15% FA dosages are depicted in Figures 4a and 4b. Black cotton soil has shown meager soaked CBR value, which is not preferable for pavement construction. Hence, it may be amended with marginal materials to improve strength. With the increase in the curing period, unsoaked CBR has found to increase till seven days of curing for most of the SFA mixes. Further increase in curing period till 28 days has resulted in the dropdown of unsoaked CBR, which may be due to the higher water content at the surface of compacted soil specimen, as observed in the case of UCS specimens. Unsoaked CBR has increased as high as 18% and 26% corresponding to standard and modified compactions, respectively. But further four days soaking has made SFA mixes so weaker that most of the CBR's were approaching near to 2%. On curing, specimens with modified compaction got higher CBR due to higher density. During soaking, the SFA mixes have absorbed water due to the formation of a diffused double layer of water around the hydrophilic clay or silt particles, resulted in the softening of specimens, leading to the higher CBR reduction factor. Hence, the fly ash amendment is not having any significant influence on the soaked CBR of SFA mixes.

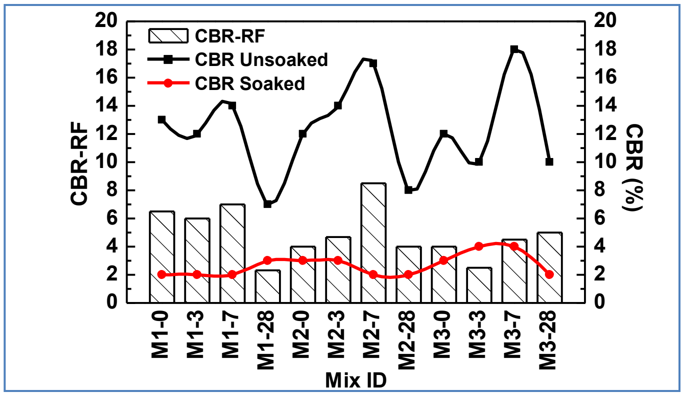


Fig. 4a: Variation of CBR of SFA mixes under standard compaction

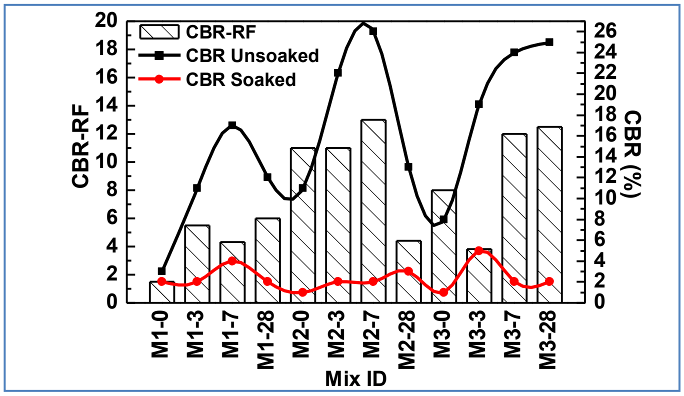


Fig. 4b: Variation of CBR of SFA mixes under modified compaction

F. Split Tensile Strength

Table 3 shows the variation in the moisture content of cured and four days soaked of STS samples of M1, M2, and M3 SFA mixes. Extracted soaked specimens of CBR were subjected to the STS test; hence the moisture content was on the wet-side of OMC representing weaker condition. The absorption of water is more at the exposed surfaces. Due to the presence of fine particles of soil and FA, the compacted CBR specimens lead to lower permeation of water towards the center, which is evident from the variation of moisture content across the depth of the sample. Much lower values of STS obtained can be related to the rainy season strengths of the mixes arising due to subgrade submergence. All SFA specimens did not pass a minimum STS of 469 kPa for the subgrade application (Osinubi 2000).

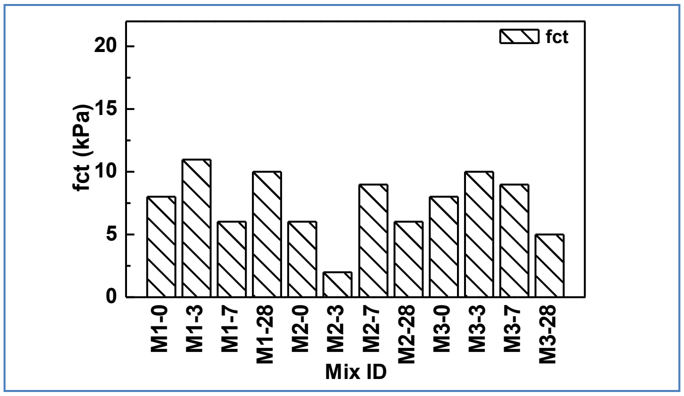


Fig. 5a: Variation of the Split tensile strength of SFA mixes under standard compaction

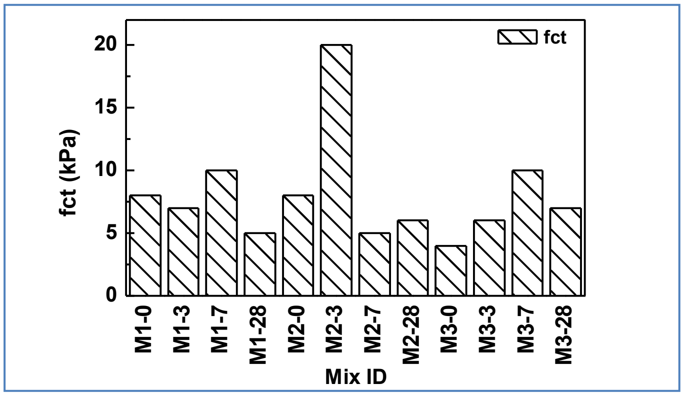


Fig. 5b: Variation of the Split tensile strength of SFA mixes under modified compaction

Table 3: Moisture content variations across the depth of the Split tensile strength SFA samples

	Standard compaction			Modified compaction		
	Moisture Content (%) @,					
Mix ID	Top	Middle	Bottom	Top	Middle	Bottom
M1-0	28.2	26.9	27.0	28	25.2	29.1
M1-3	28.5	24.5	23.7	29	24.4	31.2
M1-7	29.1	23.9	26.8	27	23.7	29.5
M1-28	29.1	25.6	29.6	30	24.5	27.6
M2-0	28.1	24.7	27.1	30	23.2	26.7
M2-3	29.4	24.4	26.5	31	27.2	31.6
M2-7	25.1	21.3	25.1	31	23.2	27.4
M2-28	33.9	24.3	29.8	26	23.1	30.3
M3-0	32.4	25.9	26.4	32	25.6	27.0
M3-3	28.2	23.8	24.8	26	23	29.0
M3-7	24.8	22.9	25.0	28	22.5	26.3
M3-28	33.6	25.4	32.6	30	22.4	29.3

Fig. 5c: Split tensile strength test

G. Flexural Strength

All stabilized mixes amended with FA have developed few shrinkage cracks due to moisture loss. Due to meager pozzolanic reactions, the beam specimens were not much resistant to applied loads and failed at low modulus of rupture values, as shown in Figure 6a. Hence, these mixes were not capable of resisting the flexural stresses, which are well correlated with the small split tensile strength values.

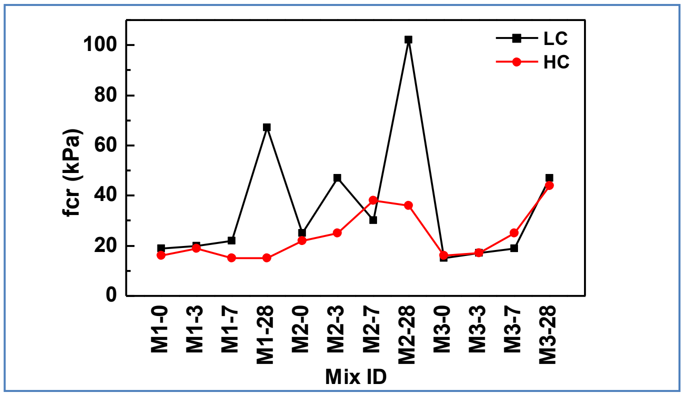


Fig. 6a: Variation of the flexural strength of SFA mixes under standard and modified compaction

Fig. 6b: Flexural strength test

H. Durability

UCS samples cured for 28 days when subjected to the WD durability test failed during the first wetting cycle. These samples have shown expansion and subsequent disintegration with material loss. Samples with a high FA amendment have failed quickly due to low cohesion between particles. Whereas, the specimens with low fly ash content have taken more time for disintegration due to high cohesion between particles. It is evident from the test that a meager pozzolanic reaction that might have happened due to the reactive materials present in the FA is not able to withstand the expansion of the specimen due to the formation of a diffused double layer around the soil particles.

The specimens, when tested for FT cycles, during initial freezing, have not shown any identifiable dimensional variations. But on subsequent thawing, due to the absorption of water available from felt pads, the specimens have exhibited growth in volume (10 to 35%) and softening. Higher volume changes were observed for samples prepared using modified compaction, with low OMC, and due to higher water absorption. These specimens with high volume changes could not sustain under the brush strokes.

Fig. 7a: Deteriorated WD samples after wetting cycle

Fig. 7b: Soil loss of WD sample after wetting cycle

Fig. 7c: Swelling of a sample after thawing cycle

I. SEM Image and EDAX Results

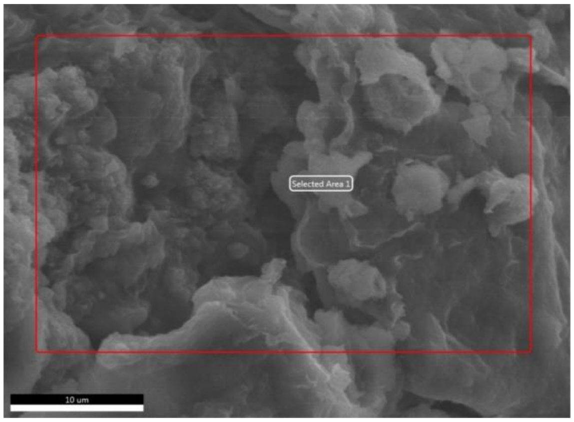


Fig. 8a: SEM Image of Mix M2

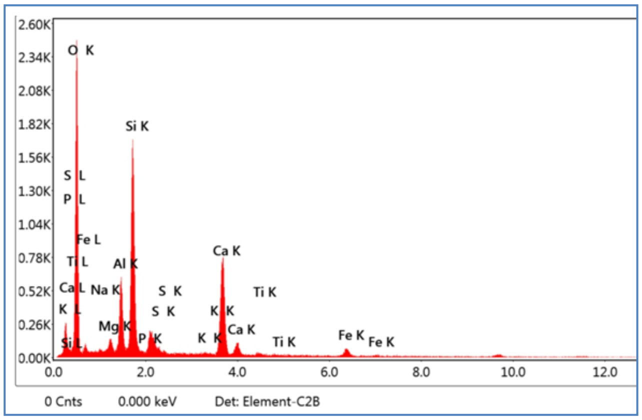


Fig. 8b: Spectrum of elements and oxides in Mix M2 after 90 days curing

Table 4: Quantification of elements in Mix M2 after 90 days curing

Element	Weight %	Atomic %
O K	55.81	71.73
NaK	0.72	0.65
MgK	1.74	1.47
AlK	6.26	4.77
SiK	15.59	11.41
P K	0.64	0.43
S K	0.94	0.60
K K	0.34	0.18
CaK	14.59	7.48
TiK	0.62	0.27
FeK	2.75	1.01

SEM image was obtained for 90 days cured Mix M2 with 10% FA shows the presence of montmorillonite clay mineral in the form of a flake-like structure. This clay mineral is responsible for swell-shrink behaviour, moisture variations, and strength variations, as observed from different tests. Darker areas show the air voids. Spherical particles show the unreacted FA, indicting its inertness. Elemental quantification shows the presence of oxides, which were further identified by the chemical analysis. The presence of Titanium oxide is responsible for the black colour of the soil.

IV. Conclusions

Fly ash amendment has a beneficial effect on the control of plasticity characteristics of black cotton soil. Higher fly ash dosages resulted in the reduction of the volumetric changes. At the same time, a high dosage of fly ash caused the loss of cohesion of mix, leading to the ease of mixing and moulding.

The density of mixes increased up to 10% fly ash amendment due to filling up of void spaces. But, a further increase in dosage reduced the unit weight due to the replacement of more massive soil particles by lighter fly ash particles.

The variation in moisture content mainly dominated UCS of all the mixes. Higher the cured moisture content lower is the UCS and vice versa. The pozzolanic reaction offered by the fly ash is so meager that it has no significant effect on any of the strength values. Hence, the presence of moisture at the time of testing also should be given due consideration to account its influence on strength parameters.

The amendment of fly ash has the least effect on the soaked CBR, split tensile strength, and the flexural strength of the soil. The strength loss is higher when the samples were soaked. The low strength values depict the inefficiency of the stabilizer for pozzolanic reactions under the wet conditions in the case of CBR and durability tests.

All the stabilized mixes completely disintegrated during the first wetting cycle during the WD durability test. Whereas, the absorption of moisture has resulted in volume growth of samples during thawing. Further freezing has resulted in the development of shrinkage cracks due to the growth of ice crystals, leading to quick disintegration of samples on subsequent FT cycles.

From this laboratory investigation, it was concluded that Class F fly ash having low CaO content itself lacks self cementitious properties, hence unable to withstand the strength loss on moisture variations of black cotton soil-fly ash mixes. However, it improves plasticity characteristics along with reducing shrinkage. Therefore cementitious compounds may be added to this for further improvements.

Abbreviations

BCS – Black cotton soil

CBR – California bearing ratio

CBR RF – CBR reduction factor

FA – Fly ash

FS (fcr) – Flexural strength

FT – Freeze-Thaw

HC – Modified compaction

LC – Standard compaction

PL – Plastic limit

SFA – Soil-Fly ash

SL – Shrinkage limit

SR – Shrinkage ratio

STS (fct) – Split tensile strength

UCS – Unconfined compressive strength

VS – Volumetric shrinkage

WD – Wet-Dry

WL – Liquid limit

References

[1] Acosta, H. A. (2002). *Stabilization of soft subgrade soils using fly ash*. University of Wisconsin--Madison.

[2] Association, A. C. A. (2003). *Fly ash facts for highway engineers*. US Department of Transportation, Federal Highway Administration.

[3] ASTM C618. (2008). Standard specification for coal fly ash and raw or calcined natural pozzolan for use in concrete. In *American Society of Testing and Materials*. Pennsylvania, USA: West Conshohocken.

[4] ASTM D 559-96. (2003). Standard test methods for wetting and drying compacted soil-cement mixtures. *Conshohocken, PA (USA)*.

[5] ASTM D560-03. Standard test methods for freezing and thawing compacted soil-cement mixtures.

[6] Chen, F. H. (1975). Foundations on Expansive Soils, Elsevier Scientific Publication Company.

[7] Cockrell, C. F., & Leonard, J. W. (1970). Characterization and *Utilization Studies on Limestone Modified Flyash* (Vol. 60). Coal Research Bureau, West Virginia University.

[8] Code, I. S. IS 1498–1970. *Classification and identification of soils for general engineering purposes (first revision)*.

[9] Code, I. S. IS 2720 (Part 5)–1985. *Determination of liquid limit and plastic limit (second revision)*.

[10] Code, I. S. IS 2720 (Part 7)–1980. *Determination of water content, dry density relation using light compaction (second revision)*.

[11] Cokca, E. (2001). Use of class c fly ashes for the stabilizationof an expansive soil. Journal of Geotechnical and Geoenvironmental Engineering, 127(7), 568–573.

[12] Das, B. M., Yen, S. C., & Dass, R. N. (1995). Brazilian tensile strength test of lightly cemented sand. *Canadian Geotechnical Journal*, *32*(1), 166–171.

[13] Edil, T. B., Acosta, H. A., & Benson, C. H. (2006). Stabilizing Soft Fine-Grained Soils with Fly Ash. Journal of Materials in Civil Engineering, 18(2), 283–294. https://doi.org/10.1061/(asce)0899-1561(2006)18:2(283)

[14] Franklin, J. A., & Dusseault, M. B. (1989). Rock engineering.

[15] IS 2720-16. (1987). Methods of Test for Soils, Part 16: Laboratory Determination of CBR.

[16] IS 4332-6: Methods of test for stabilized soils, Part 6: Flexural strength of soil-cement using simple beam with third-point loading.

[17] IS: 2720-Part 3. (1980). Methods of Test for Soils–Determination of Specific Gravity.

[18] IS: 2720-Part 6. (1972). Indian Standard Methods of Test for Soils: Determination of Shrinkage Factors.

[19] Janz, M., & Johansson, S.-E. (2002). The Function of Different Binding Agents in Deep Stabilisation: Report 9. Linkoping, Sweden, Report 9(July), 44.

[20] Kaniraj, B. S. R., & Havanagi, V. G. (2000). Progress of coa l f ly a sh fertil izer. *Journal of Geotechnical and Geoenvironmental Engineering, 127*(July), 15–16.

[21] Kaniraj, S. R., & Havanagi, V. G. (1999). Compressive strength of cement stabilized fly ash-soil mixtures. Cement and Concrete Research, 29(5), 673–677. https://doi.org/10.1016/S0008-8846(99)00018-6

[22] Kehew, A. E. (1995). Geology for engineers and environmental scientists. Pearson College Division.

[23] Keshawarz, M. S., & Dutta, U. (1993). Stabilization of south Texas soils with fly ash. FLY ASH FOR SOIL IMPROVEMENT. ASCE GEOTECHNICAL SPECIAL PUBLICATION NO. 36.

[24] Malik, V., & Priyadarshee, A. (2018). Compaction and swelling behavior of black cotton soil mixed with different non-cementitious materials. *International Journal of Geotechnical Engineering, 12*(4), 413–419. https://doi.org/10.1080/19386362.2017.1288355

[25] Natt, G. S., & Joshi, R. C. (1984). Properties of cement and lime-fly ash stabilized aggregate. *Transportation Research Record*, *998*, 32–40.

[26] Nicholson, P. G., & Kashyap, V. (1993). Flyash stabilization of tropical Hawaiian soils. FLY ASH FOR SOIL IMPROVEMENT. ASCE GEOTECHNICAL SPECIAL PUBLICATION NO. 36.

[27] Parsons, R. L., & Kneebone, E. (2005). Field performance of fly ash stabilised subgrades. Proceedings of the Institution of Civil Engineers-Ground Improvement, 9(1), 33–38.

[28] Sridharan, A., Prashanth, J. P., & Sivapullaiah, P. V. (2016). Effect of fly ash on the unconfined compressive strength of black cotton soil. Proceedings of the Institution of Civil Engineers - Ground Improvement, 1(3), 169–175. https://doi.org/10.1680/gi.1997.010304

[29] Standard, I. (2010). IS: 2720 (Part X)-1991 (2006) Methods of Test for Soils: Part 10 Determination of Unconfined Compressive Strength. *India: Bureau of Indian Standards*.

[30] Standard, I. 2720 (Part 8). 1983. *Methods of Test for Soils: Determination of Water Content–Dry Density Relation Using Heavy Compaction*.

[31] Tastan, E. O., Edil, T. B., Benson, C. H., & Aydilek, A. H. (2011). Stabilization of Organic Soils with Fly Ash. *Journal of Geotechnical and Geoenvironmental Engineering*, *137*(9), 819–833. https://doi.org/10.1061/(asce)gt.1943-5606.0000502

[32] Vishwanathan, R., Saylak, D., & Estakhri, C. (1997). Stabilization of subgrade soils using fly ash. *Ash Utilization Symposium. CAER, Kentucky*, 204–211.