A study on dynamic small-strain shear modulus of fly ash stabilized expansive soil

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Abstract. The shrink-swell property exhibits in expansive soils mainly due to the presence of montmorillonite mineral. This leads to sudden change in strength and stiffness of soil underneath the foundation and ultimately causes premature failure of structure. An experimental program was carried out to study the swelling and stiffness characteristics of black cotton soil by inclusion of class F fly ash. The percentage of fly ash were varied between 2% to 20%. A series of bender element tests were performed to study the dynamic properties of fly ash stabilized soils at different curing periods. It has been found that, the curing period does not influence the small modulus of fly ash stabilized specimens. However, small strain shear modulus of soil increases with increasing fly ash percentage in BC soil. Whereas, the free swell index decreases with increasing fly ash content in BC soil. A generalized equation is proposed to describe modulus reduction behavior of soils with respect to different fly ash content.

Keywords: shear wave, bender element, clayey soil

1 Introduction

Black cotton (BC) soils are the clay which exhibits shrink-swell properties, cracking and over-consolidation characteristics etc. strongly linked to its soil water characteristics curve [1]. The problems associated with the soils located in central India with semiarid climatic region are well known to the geotechnical engineers. One of the method for controlling the volume change parameter is the inclusion of some admixtures which is most effective and commonly used technique. On the other hand, increasing energy demand resulted in the production of fly ash as a by-product from the coal dependent power plants. Fly ash is an alkaline material composed of non-crystalline silicate, iron oxides and aluminum and also some microcrystalline materials along with free lime and unburnt carbon etc. [2]. Disposal of such material requires highly skilled workers and large area of land which creates serious environmental concerns.

India is a one of the largest fly ash producing country with 73 billion tons of coal reserve. Out of which 50% fly ash is being used by cement producing industries. Despite that,

large amount of fly ash still remains unused. Studies have been done so far to improve the swelling characteristics of expansive soils using lime, geopolymer, rice husk ash, stone dust and fly ash etc. based on unconfined compression test, compaction test and CBR test respectively before in-situ application [3]. However, very few studies have been undertaken to study the dynamic properties of fly ash treated expansive soils. Small strain stiffness of geomaterials based on shear wave velocity measurement is more sensitive to the moisture content. Dynamic properties of soils are very much important in the design of pavement structures, buildings and dams subjected to seismic loading [4].
The objective of this paper is to study the small strain stiffness characteristics of expansive soils by inclusion of class F fly ash varying from 2 to 20% using bender element test. The soils specimens were compacted at maximum dry density corresponding to optimum moisture content. Similarly, swelling potential at different fly ash contents were studied and compared with small strain stiffness parameters. A generalized equation is proposed to describe modulus reduction behavior of soils with respect to different fly ash content.

2 Experimental Investigations

2.1 Materials

The soil tested for this study were sampled from Vidarbha region of India. Table 1 shows the physio-mechanical properties of expansive soil. The soil classified according to AASHTO and the Unified Soil Classification System (USCS) is A-7-6 and CH respectively. Further, the soil sample was examined for its compaction characteristics [5,6] to obtain the maximum dry density corresponding to its optimum moisture content. The standard proctor test was conducted by replacing the soil with different fly ash percentage as 2, 4,8… up to 20%. The compaction curve for all the cases are presented in Fig. 1. The composition of fly ash varies from place to place due to quality of coal and operational characteristics of industry. Fly ash obtained from Sipat Thermal Power Plant, India was used in this study. The fly ash was characterized and classified as per [5] as Class F.

Table 1. Physio-mechanical parameters of expansive soil.

Properties	**Value**
Specific gravity	2.66
Dry density (kN/m^3)	21.4
Liquid limit (%)	69
Plastic limit (%)	35
OMC (%)	21.4
D50 (mm)	0.051
FSI (%)	90
C’ (kPa)	33
Φ (°)	19.3

Table 2 shows the physio-chemical properties of fly ash obtained from the chemical composition using X-ray fluorescence test. The cylindrical soil specimen having aspect ratio as 2 were prepared using cylindrical mould of size 50 mm diameter and 100 mm length. All the soil specimens were prepared at optimum moisture content corresponding to its known dry density using results of compaction curve and Fly ash was added to the soil in varying percentage by weight from 2 to 20% to perform bender element test.

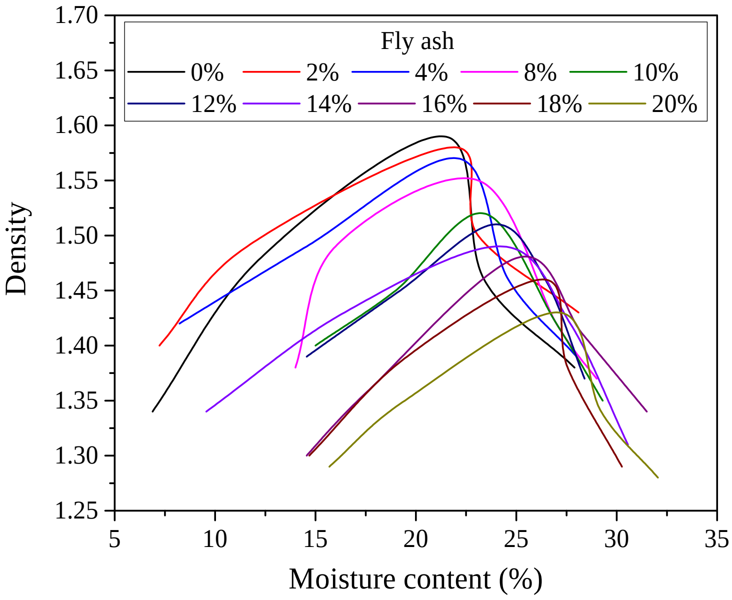

Fig. 1. Compaction characteristics of soil specimen at different fly ash content.

Table 2. Physio-chemical properties of class F fly ash

Properties	Fly ash % wt
Specific Gravity	2.09
Specific Surface Area	368.6 m2 /kg
Particle Size Distribution	37–420 [illegible]
Median Particle Size	152.4 [illegible]
SiO_2	50.36
Al_2O_3	24.69
Fe_2O_3	7.45
CaO	7.59
K_2O	0.79
MgO	1.26
Na_2O	0.06
TiO_2	1.45
SO_3	0.09
P_2O_5	0.54
Loss on Ignition	5.09

2.2 Experimental Test Setup

The test setup consists of a transmitter and a receiver bender element to transmit and to capture the electromechanical shear wave through the soil specimen [7]. Fig. 2 depicts the schematic of experimental setup adopted for the present study. The transmitter element is excited using single cycle sinusoidal transverse motion using frequency pulse generator and the response of the transmitter is recorded at the receiver bender element located at another end of specimen on oscilloscope and data is further processed through the computer. A filter amplifier attached to the receiver element helps to filter and amplify the received waveforms to read accurately. The wave travel time was then calculated by knowing the tip-tip distance between transmitter and receiver.

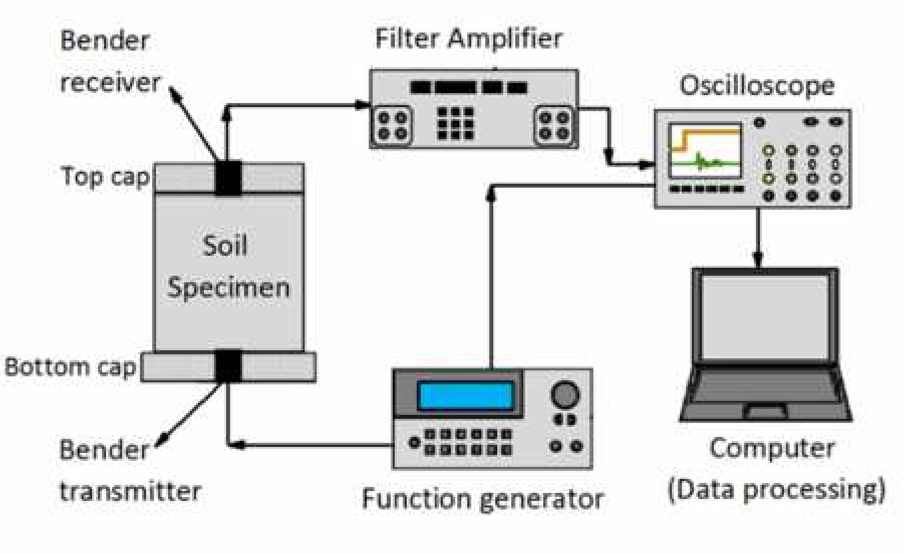

Fig. 2. Schematic of experimental setup

3 Result

Received waveforms were interpreted by adopting the most popular time domain method as peak to peak of received and transmitted signals as shown in Fig. 3. The shear wave velocity and the small strain shear modulus can be measured as

$$V_s = {}^{L_{tt}}/_{\Delta t} \quad (1)$$

$$G_{max} = \sqrt{{}^{V_s}/_{\rho}} \quad (2)$$

where, V_s is the shear wave velocity, L_{tt} is the tip to tip length between transmitter and receiver, Δt is the time required to travel the waveform from transmitter to receiver and ρ is the density of the soil specimen respectively [8].

The shear wave velocity using bender element test is determined in untreated and treated soil specimens using Eq. 1 and the small strain shear modulus is determined using Eq. 2.

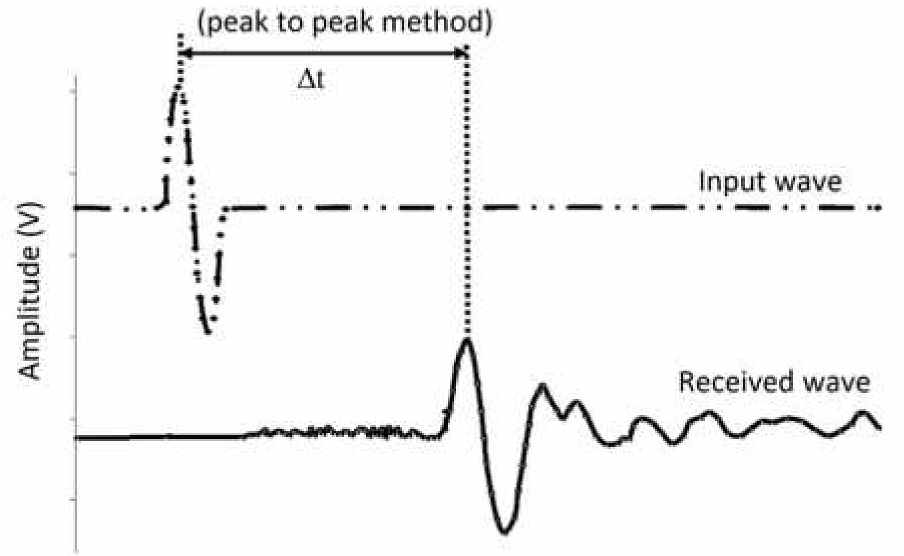

Fig. 3. Interpretation technique for transmitted and received waveforms

3.1 Effect of fly ash percentage on free swell index (FSI)

Fig. 4 shows the effect of addition of fly ash on the swelling characteristics of black cotton soil. Increase in the fly ash percentage results in the decreased free swell index. It is noteworthy to mention here that, the replacement of 20 % fly ash can reduces the free swelling index of black cotton soil by 20% from the initial value of 90%.

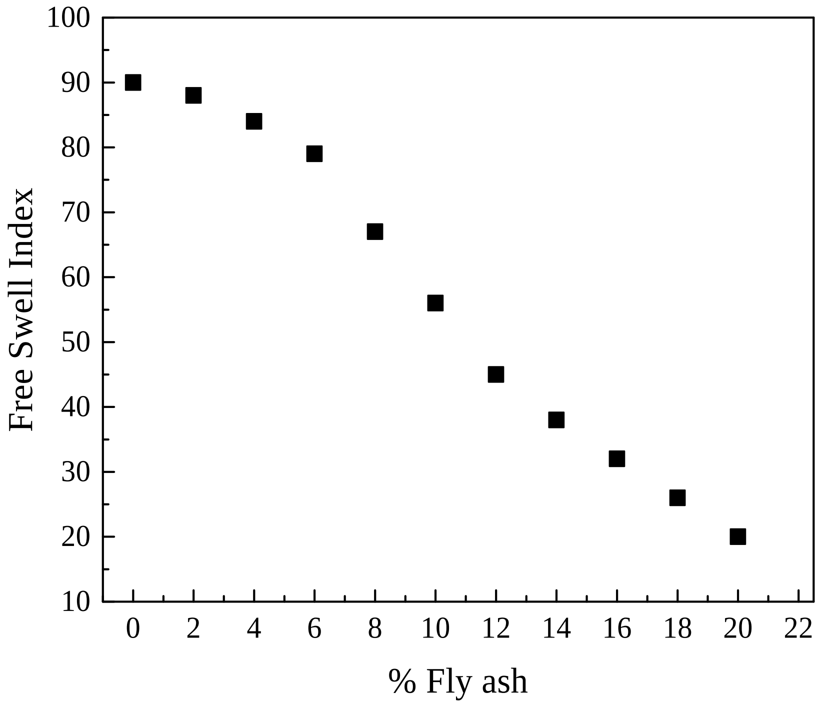

Fig. 4. Effect of fly ash inclusion on free swell index of soil

Table 3. Percentage deviation in modulus value at different fly ash content and curing time.

% fly ash	Shear modulus, G_{max} (MPa)		% Deviation	Shear modulus, G_{max} (MPa)	% Deviation	Shear modulus, G_{max} (MPa)	% Deviation
	1 day	3 days		7 days		28 days	
0	90	90	*0.00*	92	*2.22*	97	*7.77*
2	101	103	*1.98*	105	*3.96*	111	*9.90*
4	135	137	*1.48*	141	*4.44*	145	*7.41*
6	184	183	*-0.54*	192	*4.35*	191	*3.80*
8	209	210	*0.48*	219	*4.78*	225	*7.66*
10	250	248	*-0.80*	259	*3.60*	269	*7.60*
12	289	293	*1.38*	299	*3.46*	312	*7.96*

14	326	327	*0.31*	336	*3.07*	341	*4.60*
16	345	350	*1.45*	359	*4.06*	371	*7.54*
18	379	380	*0.26*	389	*2.64*	405	*6.86*
20	400	395	*-1.25*	418	*4.50*	435	*8.75*

This indicates the drastic change in the performance of fly ash treated soil. The similar behavior was observed in previous studies, which implies the usefulness of the replacement of expansive soil with soil waste material such as fly ash [1,9].

3.2 Effect of fly ash addition on small strain shear modulus of soil

Figure 5 establishes the relation between small strain shear modulus of black cotton soil with addition of different fly ash fractions at different curing periods. However, no such effect was observed for the curing time. Table 3 represents the percentage deviation in shear modulus value at different fly ash content and curing time. Curing period of three days period indicates very less increase in the modulus as 0.5 to 1%. On the other hand, 7 days curing period expresses increment from 2 to 4%. However, 28 days curing improves the modulus value up to 8% which is very less effective.

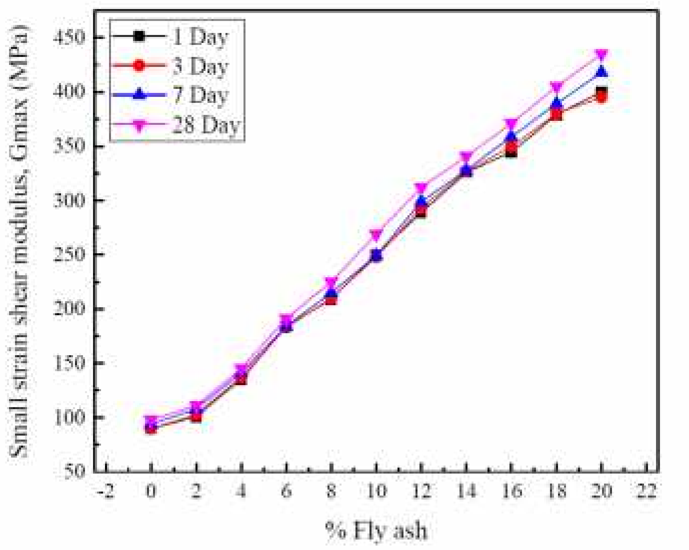

Fig. 5. Small strain shear modulus variation with fly ash inclusion at different curing periods

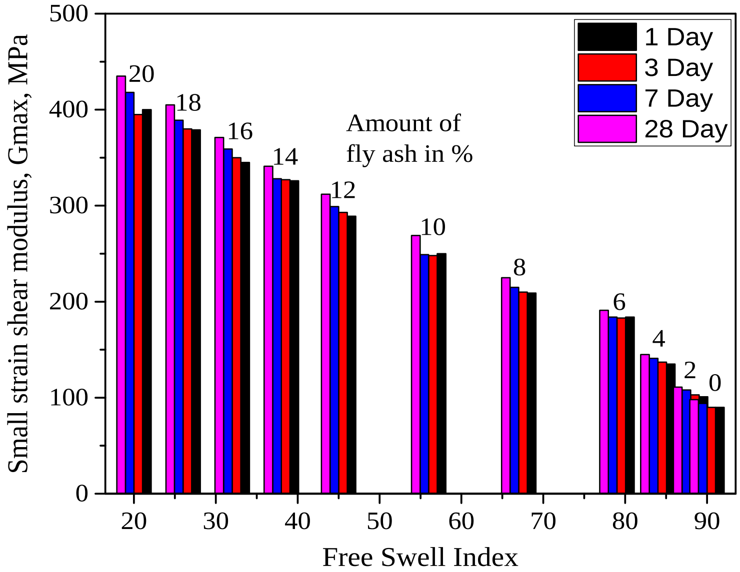

Fig. 6. Combined effect of swelling characteristics of fly ash treated soil on small strain shear modulus with curing period

Fig. 6 establishes the relation between free swell index and small strain shear modulus for black cotton soil with different fly ash percentage and different curing periods. The reduction in FSI results in higher shear modulus whereas increase in the fly ash content leads to the increased modulus [3]. However, the inclusion of fly ash rises the water consumption which makes this method uneconomical which must be consider while applying to field. Although, a simple equation has been developed to represent the small strain stiffness degradation of fly ash treated soil using arithmetic model in regression analysis (R^2=0.99) as

$$G_{max} = 52\, FSI^{0.65} \tag{3}$$

where, FSI is the free swell index.

4 Conclusion

The present study is performed to investigate the dynamic properties of fly ash treated black cotton soil. A significant portion of black cotton soil was replaced with fly ash and characterized in the laboratory for different index properties including proctor compaction. All the samples were conditioned using free swell index test. Further, the bender element tests were performed on soil specimens treated with different fly ash content.

The outcome from the present study enables to understand the behavior of the soil to the shear stress at small strain range. Some of the concluding remarks from the present analysis are as follows

- The inclusion of fly ash from 0 to 20% in black cotton soil decreases the free swell index from 90% to 20%.
- The small strain shear modulus reduction was observed with reduction in fly ash content in BC soil.
- The curing period does not spring up the stiffness of fly ash treated soil significantly.
- The method is quite useful and effective however, the amount of moisture content required also increases with increased fly ash content, which must be consider during in-situ field practices.

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