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# Some studies on the effect of fly ash and lime on physical and mechanical properties of expansive clay

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***Abstract***

*Fly ash is one of the most plentiful and versatile of the industrial by-products. At present, nearly 150 million tonnes of fly ash is being generated annually in India posing dual problem of environmental pollution and difficulty in disposal. This calls for establishing strategies to use the same effectively and efficiently. However, it is only in geotechnical engineering applications such as the construction of embankments/dykes, as back fill material, as a sub-base material etc., its large-scale utilization is possible either alone or with soil. Soil stabilization can be achieved by various means such as compaction, soil replacement, chemical improvement, earth reinforcement etc. Usually, in the case of clay soils, chemical improvement is commonly most effective since it can strengthen the soil, to remove its sensitivity both to water and its subsequent stress history. Among chemical means or additives, fly ash/lime provides an economic and powerful means of improvement, as demonstrated by the significant transformation that is evident on mixing with heavy clay. In the present investigation, different percent fly ashes (10%, 20%, 40%, 60% & 80%) were added to a highly expansive soil from India by dry weight of the natural soil, and subjected to various tests. The important properties that are necessary for using fly ash in many geotechnical applications are index properties, compaction characteristics, compressibility characteristics, permeability and strength. Based on test results, it has been found that 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 problematic/marginal soils and improving their engineering properties for safe construction of Engineering Structures.*

**Keywords:** *Solid waste material, Waste management, Expansive soils, Soil Stabilization, Environmental problems, Physical & mechanical properties.*

## 1. Introduction

Due to rapid urbanization and huge population increase particularly in developing countries around the world, there is scarcity of good construction sites as well as construction materials. Hence, there is lot of pressure on Structural and Geotechnical Engineers to use marginal/weak soils for construction of various infrastructures. On the other hand, due to set-up of various industrial units, lot of waste materials is produced every day, which need to be disposed-off or used in various construction activities in a scientific way to avoid any environmental or health problems. Among various such solid wastes, Fly ash is one of such solid waste material produced in burning of coal in thermal power stations in India and around the world during electricity generation process. The current generation of fly ashes from more than 100 thermal power stations in India is more than 150 million tones per year.

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With a very small utilization of less than 10 % of fly ash produced currently, the ash deposit is expected to become alarming due to limited space available for fly ash disposal near most of the thermal power stations, and the tremendous environmental problems being caused by large scale dumping of fly ash and the health hazards posed if not managed properly. Thus, this calls for strategies to encourage and establish technologically feasible, cost effective and environment friendly disposal methods and one such attempt is the bulk utilization of fly ash for stabilization of soils in various geotechnical engineering applications to use the same effectively and efficiently instead of open dumping [1].

Expansive soil (generally known as Black Cotton soil in India) is found in the semi-arid regions of the world and is in abundance where the annual evaporation exceeds the precipitation. Black cotton soil deposits experience large volume changes on exposure to climates with alternate wet and dry seasons, which result in distress to the structures founded on or with them. [2-4]. Black cotton soils, though primarily belong to the fine-grained group of soils and are classified as clays mostly, have gained significant importance due to their peculiar behavior of volume change (Fig. 1). Since expansive soils exhibit inherent swell-shrink properties, therefore, a careful study of all aspects of these problematic soils will be of great importance. On the other hand, utilization of fly ash reduces the quantity of waste material to be disposed-off and avoids associated environmental problems. In India, about 100 thermal power stations are using bituminous coal (with ash content > 30 %) producing enormous quantities of ash as waste material. Combustion of sub bituminous coal produces a fly ash (Class C) that has self-cementing characteristics and has been used in earthwork applications to improve the mechanical properties of soils for more than 20 years [5]. Among soils, black cotton soil is problematic and hence fly ash is tried as a stabilizer to enhance its engineering properties and also helps in reducing surface encrustation, which is a problem in red soils [6-8].

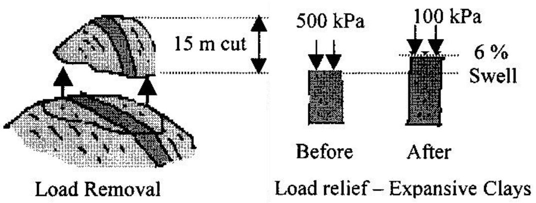



**Fig. 1(a)** Volume change of BC Soil due to removal of load

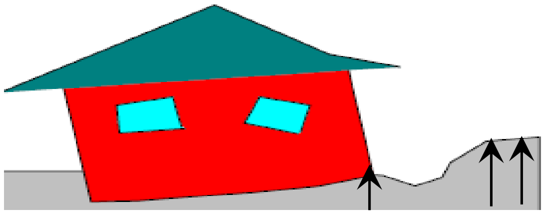


**Fig. 1(b)** Localized heave due to drainage problems

Soil stabilization or soil improvement can be achieved by various means such as compaction, soil replacement, chemical improvement, earth reinforcement etc. Usually, in the case of clay soils, chemical improvement is commonly most effective since it can be used to change the nature of the material, strengthen the soil to remove its sensitivity both to water and its subsequent stress history. Among chemical means or additives, fly ash/lime provides an economic and powerful means of improvement, as demonstrated by the significant transformation that is evident on mixing with heavy clay [9-11].

Development of adequate network of Roads/Railways is of vital importance in the socio-economic development of the country. The quantum of materials required for filling low lying areas as well as for constructing Roads/Railway embankments and building foundations are usually large and there is a shortage of topsoil in most urban areas. Hence, Fly ash has great potential for important uses in various constructions like lightweight embankments [12-13], valley fills [14], road pavements [15] and structural landfill as a replacement to conventional earth material (Fig. 2a-b). Soil-fly ash and soil-lime-fly ash mixes have proved to be very effective and economical for use in base and sub-base layers of pavement systems. Dispersive soils, which are highly susceptible to erosion, on mixing with fly ash and curing for a sufficient period of time not only become resistant to erosion but also gain in strength [16]. Uppal and Dhawan [17] reported that mixtures of lime and fly ash are useful for stabilisation of various soils (CL, ML, SC & CH). Fly ash can provide an adequate array of divalent and trivalent cations ($Ca^{2+}$, $Al^{3+}$, $Fe^{3+}$, etc.) under ionised conditions that promote flocculation of dispersed clay particles. Many researchers, e.g. [18-21] have reported successful stabilization of expansive soils with admixtures such as lime and fly ash, which controls the potential of soils for a change in volume, and improves the strength of soils. Strength behavior of expansive soil stabilized with fly ash and lime has been studied by the several researchers e. g. [22-27], while as many other researchers e. g. [28- 31] have reported the volume change behavior of expansive soil stabilized with fly ash and lime. Thus, expansive soils can be potentially stabilized effectively by using fly ash. Therefore, in the present investigation, an attempted has been made to study the behavior of soil-fly ash mixes with different percent fly ashes. In this study, high-calcium (Class C- Neyveli fly) and low-calcium (Class F-Badarpur fly ash) fly ashes in different proportions (10%, 20%, 40%, 60% & 80%) were added to Black cotton soil from India by dry weight of the natural soil, and subjected to various tests. Based on test results, it has been found that 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 problematic/marginal soils and improving their engineering properties for safe construction of Engineering Structures.

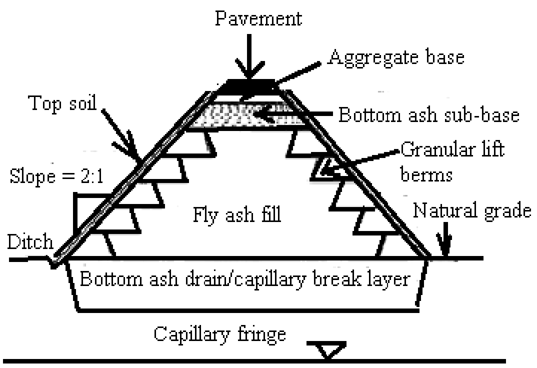



**Fig. 2 (a)** Fly ash in embankment

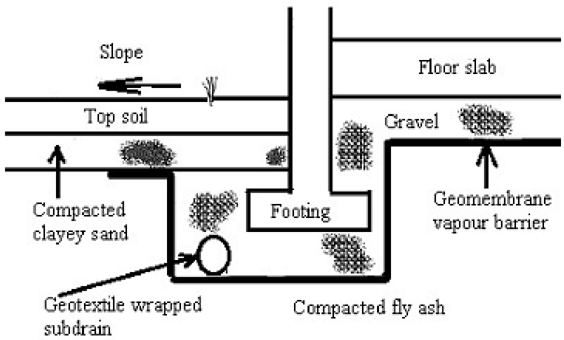



**Fig.2 (b)** Building foundation using fly ash

## 2. Materials, Experimental Program and Methodology

### *2.1. Black cotton soil*

In the present investigation, black cotton soil was collected from Davengere District of Karnataka State. The BC soil was chosen for this study because it possesses low strength and inherent high swelling and shrinkage characteristics

### *2.2. Fly ashes*

In the present investigation, two fly ashes - Badarpur fly ash (Class F) and Neyveli fly ash (Class C) have been chosen for evaluating the effect of fly ash on volume change behavior of BC soil and its bulk stabilization for its effective use. These two fly ashes were chosen for this study as they represent the extreme cases based on calcium content among many Indian fly ashes. Class F fly ash -low lime (CaO) fly ash with $SiO_2 + Al_2O_3 + Fe_2O_3 > 70\%$ - ASTM [32] is normally produced from burning anthratic or bituminous coal. It has pozzolanic properties, but little or no cementious properties. Class C fly ash - high lime (CaO) fly ash with $SiO_2 + Al_2O_3 + Fe_2O_3 > 50\%$ - ASTM [32] is normally produced from burning lignite or sub-bituminous coal and in addition to having pozzolanic properties, possesses autogenous cementitious properties. Class C fly ashes have more a glassy structure (calcium aluminate) and minor constituents of crystalline compounds, which are highly reactive. Therefore, Class C fly ashes are more reactive than Class F fly ashes.

### *2.3. Lime*

In this study, commercially available hydrated lime was used as an additive to Badarpur fly ash to make it at par with Neyveli fly ash in terms of lime content.

### *2.4. Experimental programme and sample preparation*

In the present investigation, different percent fly ashes (10%, 20%, 40%, 60% & 80%) were added to a highly expansive soil, e.g. BC soil from India by dry weight of the natural soil, mixed thoroughly and subjected to various tests. The important properties that are necessary for using fly ash in many geotechnical applications are index properties, compaction characteristics, compressibility characteristics, permeability and strength. All the samples were prepared as per standard procedures [33-34] and compacted at $0.95\gamma_{dmax}$ and corresponding water content on the dry side of optimum. Experimental program for various BC soil-fly ash mixes is given in Table 1.

**Table 1** EXPERIMENTAL PROGRAM FOR BC SOIL-FLY ASH MIXTURES

| **BC Soil-Badarpur fly ash mixes** | | | **BC Soil-Neyveli fly ash mixes** | | |
|---|---|---|---|---|---|
| **BC Soil (%) (G=2.71)** | **Badarpur fly ash, BFA (%) (G=2.18)** | **$G_{mix}$*** | **BC 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% BC 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:

For BC 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 soil sample = 80/2.71 (cc) and $V_f$ = Volue of fly ash = 20/2.18 (cc)

[$G_s=\rho_s/\rho_w$, $\rho_s=G_s$ ($\rho_w$=1), $V=M/\rho_s=M/G_s$, $\rho_s$ = 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.

### *2.5. Testing methodology*

Laboratory tests were carried out on the BC soil, and the two fly ashes, which include soil classification, chemical analysis, specific gravity, Atterberg limits, Proctor compaction tests, free swell, consolidation tests and unconfined compression strength tests by following standard laboratory procedures. The physical and index properties of the BC soil and the fly ash used in this investigation are listed in Table 2 whereas Table 3 reports the chemical analysis of oven dried BC soil and the fly ash respectively.

**Table 2** Properties of BC soil & fly ash

| | Property | BC Soil | BFA* | NFA** |
|---|---|---|---|---|
| **Particle sizes/ soil grading** | Clay size (%) | 63 | 03 | 00 |
| | Silt size (%) | 27 | 90 | 89 |
| | Fine sand (%) | 10 | 07 | 11 |
| | Coeff. Of uniformity, $C_u$ | --- | 6.3 | 1.4 |
| | Coeff. Of curvature, $C_c$ | --- | 0.95 | 0.9 |
| | Suitability Number, $S_n$ | --- | >50 | >50 |
| | Specific gravity, G | 2.71 | 2.18 | 2.64 |
| **Index properties** | Liquid Limit, LL (%) | 84 | 45 | 40 |
| | Plastic Limit, PL (%) | 25 | NP$ | NP$ |
| | Shrinkage Limit, SL (%) | 8 | 36 | 38 |
| | Plasticity Index, PI (%) | 59 | --- | --- |
| | Plasticity Index –$A_{line}$, $PI_A$ (%) | 47 | 18 | 15 |
| | Plasticity Index –$U_{line}$, $PI_U$ (%) | 68 | 33 | 29 |
| | Clay mineral | Mont. | NA | NA |
| | Classification | CH | ML | ML |
| | **Free swell ratio (%)** | 65 | 0.75 | 1.2 |
| | **Swell pressure (kPa)** | 280 | --- | --- |
| | Optimum moisture content, OMC (%) | 29 | 38 | 33 |
| | Std. Proctor max$^m$ dry unit wt., $\gamma$ (kN/m$^3$) | 14.4 | 10.6 | 12.6 |

* : BFA- Badarpur fly ash, **: NFA- Neyveli fly ash, $: NP-Non-plastic

CH: Inorganic clayey soil of high plasticity

ML: Inorganic silts and very fine sands, rock flour, silty or clayey fine sands with slight plasticity

*2.4.1. Particle size analysis*

The particle size distribution analysis [35-36] for BC soil and fly ashes [37] is carried out as per relevant codal procedures. The particle size distributions curves for these materials are shown in Fig. 3. Particle size distribution analysis revealed that the BC soil contained about 63% clay size particles (< 2µm), and that fly ashes are mainly silt dominated (Table 2). The grain size distribution curves for Badarpur fly ash and Neyveli fly ash are poorly graded sandy silt (SM) of uniform size.

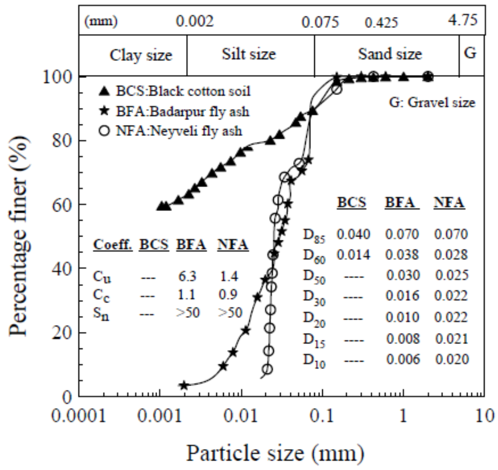



**Fig. 3** Particle size distribution curves for BC soil and Fly ashes

*2.4.2. Chemical analysis*

The chemical analysis of BC soil and fly ashes were performed in accordance with ASTM [38]. The chemical composition of BC soil and the two fly ashes (Neyveli & Badarpur fly ashes) is given in Table 3. The main constituents of the BC soil and both fly ashes are silica (as $SiO_2$), alumina (as $A1_2O_3$), and iron oxide (as $Fe_2O_3$). The $SiO_2$ + $A1_2O_3$ + $Fe_2O_3$ fraction of the both fly ashes is more than 80% of its total content, which can be classified as a silica-aluminous fly ashes. The chemical analysis shows Neyveli fly ash to contain 9% CaO and Badarpur fly ash to contain 0.5% CaO. The main constituent of the clay mineral of BC soil is montmorillonite. According to ASTM [32] classification, only Neyveli fly ash can be classified as Class C fly ash and Badarpur fly ash falls under Class F.

**Table 3** CHEMICAL ANALYSIS FOR BC SOIL & FLY ASH

| Composition (by wt. %) | BC 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 | Mont | --- | --- |
| Free Lime | --- | --- | 3.2 |

^: LOI-loss on ignition

*2.4.3. Specific gravity*

The specific gravity of BC soil and fly ashes were in accordance with ASTM [39]. The specific gravities of black cotton soil, Badarpur fly ash and Neyveli fly ash are 2.71, 2.18 and 2.64 respectively. It is noted that the specific gravity of fly ashes vary significantly compared to natural soils. The specific gravity of most fly ashes is low compared to soils because of the presence of cenospheres [40]. The generally low specific gravity of fly ash resulting in low unit weight as compared to soils is an attractive property for its use (such as a backfill material for retaining walls, as embankment material) in geotechnical engineering applications. Since the specific gravities of the fly ashes vary over a wide range (i.e., 2.18 – 2.64), the specific gravity of the soil-fly ash mixtures will also vary between 2.18 and 2.71. The specific gravity of soil-fly ash mixtures is calculated in proportion of ratios of soil-fly ash mixtures. For example, for BC soil-Badarpur fly ash ratio of 80:20, the specific gravity of this soil-fly ash mixture is calculated as:

$$G_{mix} = G_{BC\ soil}*0.8 + G_{BFA}*0.2 = 2.71*0.8+2.18*0.2 = 2.604 \quad (1)$$

Similarly, the specific gravity of other samples of soil-fly ash mixtures is calculated in the same manner (see Table 2).

*2.4.4. Consistency limit tests*

Consistency limits such as liquid limit, plastic limit and shrinkage limits for the BC soil and fly ashes were determined in accordance with ASTM [41-42]. The liquid limit of BC soil, Badarpur fly ash and Neyveli fly ash are 84%, 50% and 40%, respectively. The BC soil may be classified as clay with high liquid limit (CH) from its plasticity chart. The fly ashes exhibit liquid limits due to their fabric and not due to plasticity characteristics. Since fly ashes are essentially silt sized and non-plastic, plastic limit of fly ashes alone cannot be determined easily. Therefore, Cone penetrometer apparatus is used for determination of fly ashes and other silt dominated soils. The shrinkage limit for BC soil, BFA and NFA is 8%, 36% and 38% respectively.

*2.4.5. Compaction characteristics*

The optimum moisture content (OMC) and the maximum dry density (MDD) of the BC soil and the fly ashes were determined using the Standard compaction test [43]. Figure 5 shows the compaction curves for the materials used. The values of OMC and MDD obtained are 28.3% and 14.4 kN/$m^3$ respectively for the BC soil; 38.2% and 10.6 kN/$m^3$ respectively for Badarpur fly ash and 31.95% and 12.6 kN/$m^3$ respectively for Neyveli fly ash. It is seen that compared to BC soil, fly ashes exhibit lower dry unit weight and higher optimum moisture content due to the presence of large and hollow cenospheres in fly ashes and a relatively uniform grain size distribution. The compaction curves for BC soil-fly ash mixes are also shown in Fig 5.

*2.4.6. Free swell test*

The free swell testing method was used to determine the swelling potential of the test specimens [44]. In the field of geotechnical engineering, the swelling nature of soils is quantified using free swell ratio (FSR) [45-46], which is defined as:

$$FSR = \frac{V_d}{V_k} \quad (2)$$

where: $V_d$ = the equilibrium sediment volume of 10g of oven dried soil in 100ml jar containing distilled water, and $V_k$ = the equilibrium sediment volume of an identical soil sample in kerosene.

In the present study, the values of free swell ratio (FSR) obtained are 6.5, 0.75 and 1.2 for BC soil, Badarpur fly ash and Neyveli fly ash respectively. It is seen that fly ashes have very low values of FSR indicating negligible degree of expansivity or swell potential.

*2.4.7. One dimensional compression test*

The swelling potential [$\delta H/H_o$, ($H_o$ = initial height of specimen)**]** and swelling pressure of the BC soil were determined using one dimensional compression tests [47]. The specimens were inundated with water and allowed to swell against a seating pressure of 6.25kPa. The dial gauge readings were recorded until the specimen reached a constant swollen height ($\delta H$ = Dial gauge Divn.*0.002). After equilibrium was attained, a pressure increment ratio of 1 was used for next pressure applications (up to 800kPa). Each pressure increment was maintained for 24 hours and dial gauge readings were recorded during consolidation process with time. Addition of fly ash to BC soil decreases the free swell index, swell potential and swell pressure. There is a considerable reduction in the swelling potential as the amount of fly ash-added increases. With duration of curing, swelling potential/pressure further decreases. It has been observed that 10 % of Neyveli fly ash (Class C fly ash) is the optimum amount required to minimize the swell potential compared to 40 % of Badarpur fly ash (Class F fly ash).

*2.4.8. Unconfined compression tests*

Essentially, the unconfined compression test is a special case of the triaxial compression test of soils where the compression and shear strengths of a soil prism, or cylinder, are measured under zero lateral stress ($\sigma_2 = \sigma_3 = 0$). The unconfined compression test is the simplest and quickest test for determining unconfined compressive strength of the cohesive soils. The shear strength of cohesive soils (cohesion) is taken as equal to half the compressive strength. These values are used for checking the short-term stability of foundations and slopes, where the rate of loading is fast. In the present study, the unconfined compression tests were conducted BC soil-fly ash specimens as per ASTM [48] for *"Immediate" test series* and for "*7 and 28 Days" curing series* under a constant strain rate of 0.625 mm/min**.** In both cases, the test specimens of height 7.6cm and diameter 3.8cm were prepared by statically compacting the mixtures in a mould at 0.95 $\gamma_{dmax}$ and corresponding water content dry side of optimum. The specimen was centrally placed on the lower plate of UCT machine and motor was switched on. The readings of proving ring divisions (for vertical load) and compression dial gauge readings (for axial strain) were taken at regular intervals of strain dial gauge reading. Loading was continued until three or more consecutive readings of the load dial gauge showed a decreasing or a constant value or a strain of 20 % has been reached. The load readings were plotted against deformation and the point of failure was identified. The failure was noticed by bulging phenomenon in the case of BC soil and as brittle failure for fly ashes. For 7 and 28 Days curing test series, samples were prepared as described above for each series and were cured in a desiccator at 100 % humidity. The samples were removed from the desiccator at the end of the required curing periods and tested for unconfined compressive strength as per the standard method as described before. The effect of increasing the fly ash content on the unconfined compressive strength of BC soil was investigated.

## 3. Results and Discussion

### *3.1. Effect of fly ash stabilization on index properties*

Effects of fly ash on liquid limit, plastic limit, shrinkage limit and plasticity index of BC soil are shown in Fig. 4. The liquid limit of the BC soil decreased with an increasing amount of stabilizer. This is understandable since fly ashes are coarse grained compared to BC 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 BC soil from CH to MH, MH-ML.

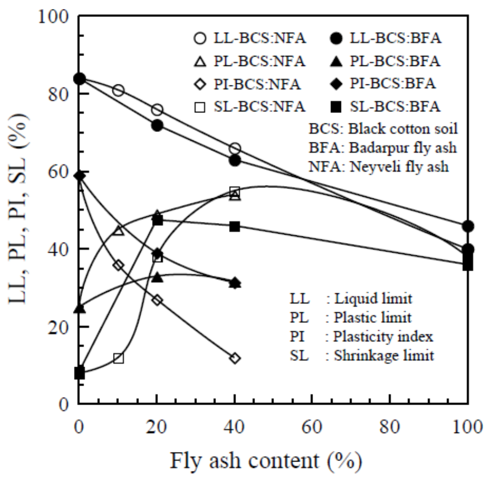



**Fig. 4** Effect of fly ash on index properties of BC soil

The trends of variation exhibited by plastic limit, shrinkage limit and 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. The value of shrinkage limit is used for understanding the swelling and shrinkage properties of cohesive soils. Shrinkage limit is important for stabilized fly ash used as liners. Cracking can lead to the development of secondary permeability. Shrinkage cracking also plays an important role if fly ash is used in rigid pavements. It is also seen that shrinkage characteristics are rapidly enhanced by increasing fly ash content of 40%. However, there is marginal decrease in shrinkage limit with higher increments of fly ash content. Test results show that the shrinkage limit of the resulting BC soil–fly ash mixture increases mainly due to the flocculation of clay particles caused by the free lime present in the fly ash and also due to the substitution of finer particles of black cotton soil by relatively coarser fly ash particles. Addition of 20 % fly ash with BC soil enhances the shrinkage limit of the soil samples from 8 to 36 % for BC soil–Badarpur fly ash composite samples and from 8 to 47 % for BC soil–Neyveli fly ash composite samples (Fig. 4). Since fly ashes are silt sized and non-plastic, plastic limit and shrinkage limit of fly ashes alone could not be determined.

### *3.2. Effect of fly ash stabilization on compaction characteristics of BC soil*

Density is an important parameter because it determines the load, which a structural fill will apply to itself and to its foundation, and because it influences the permeability, stiffness and strength of fill, thus affecting the settlement and ultimate stability. The results of compaction tests carried out on BC soil fly ash mixes are shown in Fig. 5 (a-b). Compared to BC soil, fly ashes exhibit lower dry density and higher optimum moisture content. The increase in OMC is due to the presence of hollow cenospheres in fly ashes as well as increase in surface area of solids and its poor gradation. Decrease in dry density is because of low specific gravity due to large cenospheres and a relatively uniform grain size distribution, resulting in low unit weight. It is also seen that with the addition of small amount of BC soil to the fly ash, $\gamma_{dmax}$ of the composite sample increases with a decrease in OMC. The increase in $\gamma_{dmax}$ 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 BC soil and NFA are almost of the same order (NFA: 2.64 as against 2.71 of BC soil). Because of the increased resistance offered by the fly ash, which is a coarser and uniformly graded material, $\gamma_{dmax}$ obtained is lesser than the $\gamma_{dmax}$ of BC soil. Since the water contents of fly ash and soil are different (i.e., 33% for Neyveli fly ash as compared to 29% for BC soil), OMC increases with increase in fly ash content. The increase in optimum moisture content is probably on account of additional water held within the flocs resulting from flocculation due to lime and the fly ash reaction. The effect of fly ashes on OMC and MDD of BC soil is illustrated in Fig. 6(a-b).

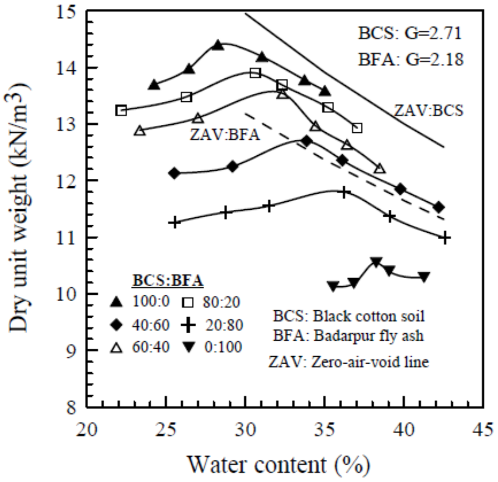



**Fig. 5(a)** Effect of Badarpur fly ash on compaction characteristics of BC soil

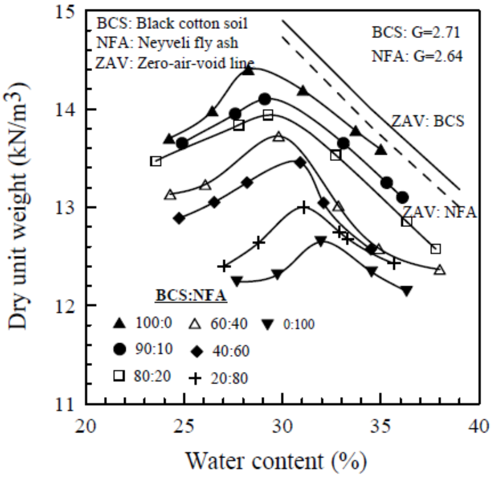



**Fig. 5(b)** Effect of Neyveli fly ash on compaction characteristics of BC soil

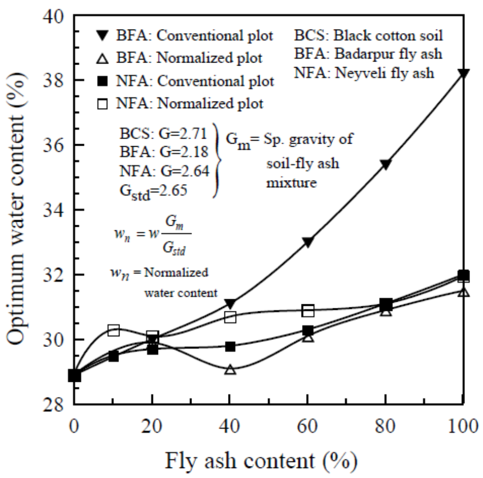



**Fig. 6(a)** Effect of fly ashes on OMC of BC soil

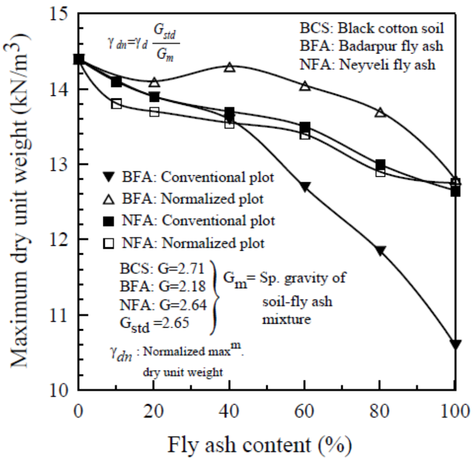



**Fig. 6(b)** Effect of fly ashes on MDD of BC soil

### *3.3. Effect of fly ash stabilization on compressibility characteristics of BC soil*

The compressibility characteristics compression index, which is used to determine the magnitude of settlement and the coefficient of consolidation, $C_v$ which is used to calculate the rate of settlement are determined by a standard procedures. For fly ashes with age-hardening properties, including most "high lime" fly ashes from lignite or sub-bituminous coals, the age hardening can reduce the time rate of consolidation, as well as the magnitude of the compressibility. Consolidation tests were conducted on BC soil-fly ash specimens immediately after sample preparation and also cured for 7 days and 28 days respectively. Figure 7 (a-b) shows the variation of percent swell and swell pressure with pressure for different curing periods. From Fig. 7a, it is seen that as the percent fly ash content increases, the swell potential shows considerable decrease. The interaction between clay particles that is necessary for swelling is reduced quite effectively by the addition of non-plastic fly ash particles. It is also observed that with an increase in the curing time, both swelling as well as compression potential is reduced. Hydrated lime (CaO) of 8.5% is added to BFA to make it at par with NFA in terms of lime content. But it does not proved beneficial since BFA is non-pozzolanic in nature. Point A in Fig. 7b represents the swelling pressure of BC soil (280kPa). Figure 8(a-b) shows variation of compression index with increasing pressure for BC soil-fly ash mixes for immediate, 7days and 28 days test series. It is seen that NFA decreases compression index of BC soil tremendously compared to BFA due to its pozzolanic effect. This is due to the cementation bonds which are formed between free lime and reactive silica and thereby improving the compressibility characteristics of the BC soil.

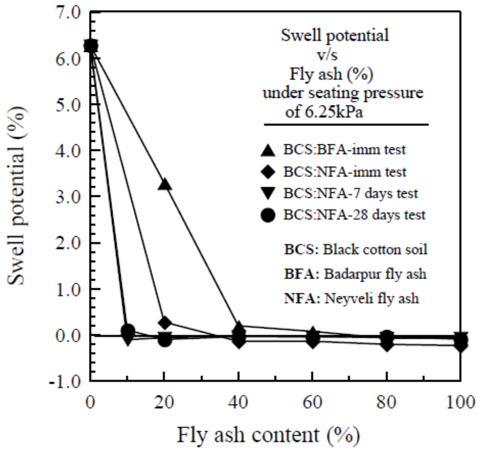



**Fig. 7(a)** Effect of fly ashes on swelling characteristics of BC soil

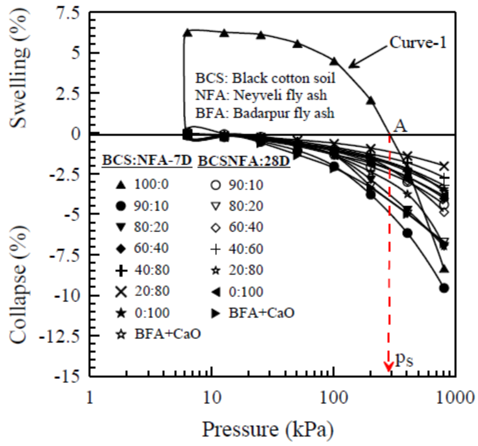
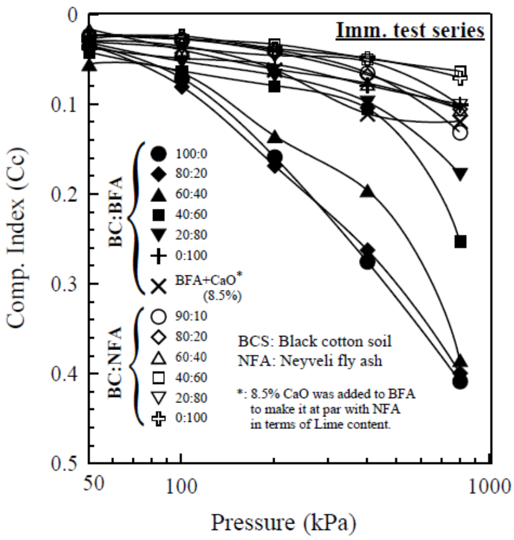
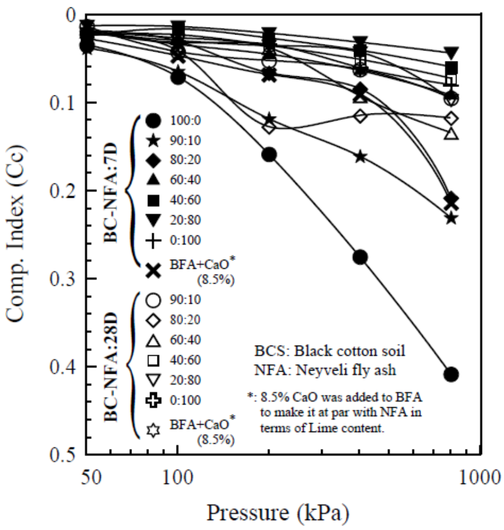



**Fig. 7 (b)** Effect of Neyveli fly ash on swelling & collapse characteristics of BC soil




(a) Immediate test series




(b) After curing 7 & 28 days

**Fig. 8** Effect of fly ash on comp. index of BC soil

### *3.4. Effect of fly ash stabilization on permeability behaviour of BC soil*

Permeability (k) is an important parameter in designing the liners to contain leachate migration. Figure 9 (a-b) shows effect of addition of fly ash on permeability behavior of BC soil with pressure for immediate, 7days and 28 days test series. It is seen that the values of k for fly ashes are typically in the range of the coefficient of permeability of non-plastic silts and addition of fly ash has reduced permeability of BC soil tremendously resulting in good draining material. Test results reveal that at the same effective vertical stress, the treated soil specimen has higher permeability than the untreated clay. This implies that at the same depth below the ground surface, the treated clay will show a higher void ratio than the un-treated soil specimen.

With increase in percent fly ash, void ratio and permeability of the composite samples increase. This indicates that the addition of fly ash to fine grained soils makes it granular leading to higher coefficient of permeability. The plasticity of fine-grained soils is reduced and workability increased. At lower consolidation pressure, Badarpur fly ash exhibits higher permeability values. At higher consolidation pressures, the order of permeability is almost same for both the fly ashes. This is because the reduction in the pore space available for flow for Badarpur fly ash is more compared to Neyveli fly ash with increasing consolidation pressures.

### *3.5. Effect of fly ash stabilization on the unconfined compressive strength of black cotton soil*

In this study, uunconfined compression tests were conducted on BC soil-fly ash specimens immediately after sample preparation and also cured for 7 days and 28 days respectively. The test results have shown that the effect of fly ash is mainly through pozzolanic reactivity and the silty character of fly ash and many factors of fly ash such as reactivity, free lime content and silty nature influence the strength of soil. Effect of BFA and NFA on stress-strain behavior of composite soil specimens is illustrated in Figs. 10 (a-c) and Figs. 11 (a-c) whereas effect of fly ash on unconfined compression strength (ucs) of BC soil is shown in Fig. 12 for immediate, 7days and 28 days test series respectively. The variation of ucs of BC soil with various percentages of Neyveli fly ash at different curing periods is also shown in Fig. 13. On addition of small amounts of fly ash (10%), the immediate ucs strength of BC soil remains essentially unaffected, whereas there is a significant increase in the ucs strength for 7 days curing period and a marginal increase for 28 days curing period. This is due to the influence of pozzolanic reaction between fly ash and free lime, which dominates the influence of silty fly ash particles, and all the cementitious compounds are developed within 7 days curing period. The variation in ucs of different fly ashes can be explained effectively based on the reactive silica and free lime content. Hence this is of vital importance for field engineers from time and economical point of view.

## 4. Summary and Conclusions

Following are some of the broad conclusions deduced from the present study:

The stabilization of the problematic soil such as black cotton soil with fly ash is an effective means of chemical stabilization of soils. It is seen that the index and engineering properties of BC soil are significantly altered by the addition of fly ashes.

Both high-calcium and low-calcium fly ashes can be recommended as effective stabilizing agents for improvement of BC soil. However, the Class C fly ash has more pozzolanic effect compared to Class F fly ash in soil stabilization.

Since fly ash is a freely draining material, it can be used in the construction of embankments etc. leading to its bulk utilization.

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.

With increase in per cent fly ash and curing time, compression index and the coefficient of consolidation gets reduced and stability increases.

With increase in percent fly ash, void ratio and permeability of the composite samples increase. The plasticity of fine-grained soils is reduced and workability is increased.

The unconfined compressive strength of soils can be increased by addition of reactive fly ash. Fly ashes alter the strength of BC soil significantly by pozzolanic reactions that increase the strength. For fly ashes with higher reactivity, the effect of pozzolanic reactions over-rides the effect of silty behavior and vice versa for low reactive fly ash. It is further observed that the addition of 8.5 % lime does not affect the ucs of Badarpur fly as much because of the non-availability of reactive silica.

The use of pozzolznic fly ash in ground improvement is an effective means of waste management, and it is particularly useful for reducing the porosity of blended soils. The study brings out the bulk and effective utilization of fly ash as an engineered construction material. Hence, the recycling/utilization of fly ash have the advantage of using an industrial waste by-product without adversely affecting the environment or potential land use.

## References


[1] Ghais A, Abadi A. Fly ash utilization in soil stabilization, Proceedings of the International Conference on Civil, Biological and Environmental Engineering (CBEE-2014), Istanbul (Turkey), 2014, pp. 76-78.

[2] Chen FH. Foundations on expansive soils, Elsevier, Amsterdam, The Netherlands, 1975.

[3] Holtz WG, Gibbs HJ. Engineering properties of expansive clays, Transaction of American society of civil engineers, 1954, No. 121, pp. 641-677.

[4] Gromko GJ. Review of expansive soils, Journal of Geotechnical Engineering Division, ASCE, 1974, Vol. 100, pp. 667-787.

[5] Ferguson G. Use of self-cementing fly ashes as a soil-stabilizing agent, Proceedings of Session on Fly Ash for Soil Improvement, ASCE, Geotechnical Special Publication, 1993, Vol. 36, pp. 1-14.

[6] Mir BA. Effect of fly ash on the Engineering Properties of BC soils, ME. Thesis, Department of Civil Engineering IISc, Bangalore, 2001.

[7] Zha F, Liu S, Du Y, Cui K. Behavior of Expansive Soils Stabilized with Fly Ash Natural Hazards, Springer, 2008, Vol. 47, pp. 509-523.

[8] Bose B. Geo-engineering properties of expansive soil stabilized with fly ash, EJGE, Bund J, 2012, Vol. 17, pp. 1339-1353.

[9] Cokca E. Use of class C fly ash for the stabilization of an expansive soil, Journal of Geotechnical and Geoenvironmental Engineering, 2001, No. 7, Vol. 127, pp. 568-573.

[10] Bhuvaneshwari S, Robinson RG, Gandhi SR. Stabilization of expansive soils using fly ash, Fly Ash India - Fly Ash Utilization Programme (FAUP), TIFAC, DST, New Delhi, 2005, pp. 5.1-5.10.

[11] Nalbantoglu Z. Effectiveness of Class C fly ash as an expansive soil stabilizer. Construction and Building Materials, Elsevier Ltd, 2014, Vol. 18, pp. 377-381.

[12] Martin JP, Collins RA, Browings JS, Biehl FJ. Properties and use of fly ashes for embankments, Journal of Energy Engineering, 1990, No. 2, Vol. 166, pp. 71- 85.

[13] Rajakumar C, Meenambal CT. Effect of coal ash in the stabilization of expansive soil for the pavement, International Journal of ChemTech Research, 2015, No. 1, Vol. 8, pp. 170-177.

[14] Turgeon R. Fly ash fills a valley, Civil Engineering, ASCE, New York, 1988, pp. 58-67.

[15] Ahmed NAK, Damgir RM, Hake SL. Effect of fly ash and rbi grade 81 on black cotton soil as a sub grade for flexible pavements, International Journal of Innovations in Engineering and Technology, 2014, Issue 1, Vol. 4, pp. 124-130.

[16] Indraratna B, Nutalaya P, Kuganenthira N. Stabilization of a dispersive soil by blending with fly ash, Quarterly Journal of Engineering Geology & Hydrogeology, 1991, Vol. 24, pp. 275-290.

[17] Uppal HL, Dhawn PK. A resume on the use of fly ash in soil stabilization, Road Research Papers, 1968, Vol. 95, pp. 1-12.

[18] Puppala AJ. Fibre and fly ash stabilization methods to treat soft expansive soils, Geotechnical Special Publication, 2001, Vol. 112, pp. 136-145.

[19] Kate JM. Strength and volume change behavior of

expansive soils treated with fly ash, GeoFrontiers-2005, ASCE, Geotechnical Special Publication, pp. 1-15.
[20] Gourav D, Kumar D, Priyadarshee A. Effect of fly ash on the properties of black cotton soil: a review, International Journal of Advanced Technology in Engineering and Science, 2015, Special Issue No. 02, Vol. 03, pp. 596-604.
[21] Pandian NS. Fly ash characterization with reference to geotechnical applications, Journal of the Indian Institute of Science, 2004, Vol. 84, pp.189-216.
[22] Sridharan A, Prashanth JP, Sivapullaiah PV. Effect of fly ash on the unconfined compressive strength of black cotton soil, Proceedings of the ICE – Ground Improvement, 1997, No. 3,Vol. 1, pp. 169-175.
[23] Kumar A, Walia BS, Bajaj A. Influence of fly ash, lime and polyester fibers on compaction and strength properties of expansive soil, Journal of materials in Civil Engineering, 2007, Issue 3, Vol. 19, pp. 242-248.
[24] Saha S, Pal SK. Influence of fly ash on unconfined compressive strength of soil and fly ash layers placed successively, Electronic Journal of Geotechnical Engineering, 2013, Vol. 18, pp. 1593-1602.
[25] Satyanarayana K, Hemanth PVV, Praveen SP, Kumar SBV. A study on strength characteristics of expansive soil-fly ash mixes at various molding water, International Journal of Recent Technology and Engineering, 2013, No. 5, Vol. 2, pp. 145-149.
[26] Verma SK, Maru S. Behavioral study of expansive soils and its effect on structures–a review, International Journal of Innovations in Engineering and Technology, 2013, No. 2, Vol. 2, pp. 228-238.
[27] Mir BA, Sridharan A. Physical and compaction behavior of clay soil-fly ash mixtures, International Journal of Geotechnical and geological Engineering, 2013, No. 4, Vol. 31, pp. 1059-1072.
[28] Phanikumar BR, Nagareddayya S, Sharma RS. Volume change behavior of fly ash- treated expansive soils, Proceedings of the 2nd International Conference on Civil Engineering, Indian Institute of Science, Bangalore, India, 2001, Vol. 2, pp. 689-965.
[29] Phanikumar BR, Sharma RS. Volume change behavior of fly ash-stabilized clays, Journal of Materials in Civil Engineering, 2007, pp. 67-74.
[30] [30] Phanikumar BR. Effect of lime and fly ash on swell consolidation and shear strength characteristics of expansive clays: A comparative study, Journal of Geomechanics and Geoengineering: An international Journal, 2009, No. 2, Vol. 4, pp. 175-181.
[31] Mir BA, Sridharan A. Volume change behaviour of clayey soil–fly ash mixtures, International Journal of Geotechnical Engineering, 2014, No. 1, Vol. 8, pp. 72-83.
[32] ASTM C618-12a, Standard Specification for Coal Fly Ash and Raw or Calcined Natural Pozzolan for Use in Concrete, ASTM International, West Conshohocken, PA, 2012, www.astm.org.
[33] ASTM D421-85. Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants, ASTM International, West Conshohocken, PA, 2007, www.astm.org.
[34] ASTM D2217-85. Standard Practice for Wet Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants, ASTM International, West Conshohocken, PA, 1998, www.astm.org.
[35] ASTM D2487-06. Standard procedure for classification of soils for engineering purposes, Annual Book of ASTM Standards, American society for testing and materials, Philadelphia, West Conshohocken, PA. www.astm.org, 2006, Vols. 04-08.
[36] ASTM D422-63 (2007)e2. Standard Test Method for Particle-Size Analysis of Soils, ASTM International, West Conshohocken, PA, 2007, www.astm.org.
[37] ASTM D5239-12. Standard Practice for Characterizing Fly Ash for Use in Soil Stabilization, ASTM International, West Conshohocken, PA, 2012, www.astm.org.
[38] ASTM C311/C311M-13, Standard Test Methods for Sampling and Testing Fly Ash or Natural Pozzolans for Use in Portland-Cement Concrete, ASTM International, West Conshohocken, PA, 2013, www.astm.org.
[39] ASTM D 854-14, Standard Test method for specific gravity of soil solids. Annual Book of ASTM Standards, American Society for Testing and Materials, Philadelphia, Vol. 04.08, 2014, www.astm.org.
[40] Pandian NS. Rajasekhar C, Sridharan A. Studies of the specific gravity of some Indian coal ashes, Journal of Testing and Evaluation, JTEA, 1998, No. 3, Vol. 26, pp. 177-186.
[41] ASTM D4318-10E1. Standard test methods for liquid limit, plastic limit, and plasticity index of soils, Annual Book of ASTM Standards, American society for testing and materials, Philadelphia, 2010, www.astm.org.
[42] ASTM D427-04. Test Method for Shrinkage Factors of Soils by the Mercury Method, ASTM International, West Conshohocken, PA, 2004, www.astm.org.
[43] ASTM D698-12e2. Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort, ASTM International, West Conshohocken, PA, 2012, www.astm.org.
[44] ASTM D4546-14. Standard Test Methods for One-Dimensional Swell or Collapse of Soils, ASTM International, West Conshohocken, PA, 2014, Vol. 04.08, www.astm.org.
[45] Sridharan A, Prakash K. Classification procedures for expansive soils, Proceedings of the Instution of Civil Engineering (UK), 2000, Vol. 143, pp. 235-240.
[46] Mir BA. Effect of fly ash on swelling potential of bc soil, Proceedings of Indian Geotechnical Conference (IGC-2013), Roorkee, 2013, Theme No. 4, Paper No. 120, pp. 1-9.
[47] ASTM D2435/D2435M-11. Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading, ASTM International, West Conshohocken, PA, 2011, www.astm.org.
[48] ASTM D2166/D2166M-13. Standard Test Method for Unconfined Compressive Strength of Cohesive Soil, ASTM International, West Conshohocken, PA, 2013, www.astm.org.