A study of multilayer soil-fly ash layered system under cyclic loading

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Abstract: In the present investigation, the cyclic load deformation behaviour of soil-fly ash layered system is studied using different intensities of failure load (I = 25%, 50% and 75%) with varying number of cycles (N = 10, 50 and 100). An attempt has been made to establish the use of fly ash as a fill material for embankments of Highways and Railways and to examine the effect of cyclic loading on the layered samples of soil and fly ash. The number of cycles, confining pressures and the intensity of loads at which loading unloading has been performed were varied. The resilient modulus, permanent strain and cyclic strength factor are evaluated from the test results and compared to show their variation with varying stress levels. The nature of stress-strain relationship is initially linear for low stress levels and then turns non-linear for high stress levels. The test results reveal two types of failure mechanisms that demonstrate the dependency of consolidated undrained shear strength tests of soil-fly ash matrix on the interface characteristics of the layered soils under cyclic loading conditions. Data trends indicate greater stability of layered samples of soil-fly ash matrix in terms of failure load (i) at higher number of loading-unloading cycles, performed at lower intensity of deviatoric stress, and (ii) at lower number of cycles but at higher intensity of deviatoric stress.

Keywords: *Layered soils, cyclic loading, triaxial tests, fly ash, shear strength*

Introduction

Coal based power plants not only produce of millions of mega-watts of power but also millions of tons of fly ash. Most of the coal based power plants were set-up with sole aim of power generation (Dhar, 2001). As a result of continuous disposal of ash, about 1000 million tons of ash is estimated as dumped in ash ponds in India and every year 100 million tons of ash is being added to this quantity which has already consumed about 40,000 hectares of precious land for storage that could have been used for agriculture or habitation (Murthy, 1998; Lamba et al, 2000). Besides the handling problems of huge quantity of ash, there are severe environmental concerns from rising dust from ash ponds to the near by areas whereby fly ash is present not only on dining tables but also in the lungs (Sivapullaiah, 2001). Environmentally safe disposal of large quantity of fly ash is not only problematic but also expensive. Keeping in view the gravity of the fly ash disposal problem, global efforts are mooted to utilize fly ash in bulk quantities. Despite these efforts, hardly 30% of produced ash on an average world over and less than 10% in India. To reduce the problem of disposal, efforts are being made to utilize the same. Bulk uses of fly ash are found in many geotechnical applications such as embankments, fill behind retaining walls. Reclamation fills and dams etc., due to its low unit weight, low compressibility and pozzolanic nature. B.R. Phani and Radhey S. Sharma (2004) studied that the plasticity, hydraulic conductivity and swelling properties of the blends (mix of fly ash and expansive soil) decrease and the dry unit weight and strength increase with an increase in fly ash content. The strength behaviour of fly ashes assumes importance in their use in geotechnical applications. Through the present paper, it has been demonstrated that the fly ash can be stabilized with clayey soil and used as fill material for land reclamation.

Fly ash, also known as pulverized ash, is a waste product of coal based thermal power plants. The Indian coal, having relatively low calorific value of 2500 to 3500 kcal/kg and with high ash content of about 45%, generates 70-75 million tones of fly ash in a year in India, which posses challenge for its safe disposal. The Delhi Metro Rail Cooperation (DMRC, 2005) has opted such an arrangement in its mass transit system for

Delhi. Though the DMRC has started using fly ash in layered combination with the locally available soil in embankments but there is no supporting research for the design of such embankments or prediction of its mechanical behaviour under loads. The detailed investigations are, therefore, necessary in order to understand the response of the layered system of soil and fly ash under repeated loads. The present work uses layered combination of fly ash and clayey soil. The advantage of using clayey soil is that it decreases the permeability, increases the density, reduces the compressibility and improves the shear strength characteristics of fly ash.

Cyclic loading is associated with most of the geotechnical problems, which includes mainly marine problems involving wave loading, pavement loading in the form of vehicular traffic, earthquake loading etc. The research on deformation behavior of soils under repeated loading dates back to 1950s. Seed (1956, 1958 and 1960) studied the effect of repeated loading on the strength and deformation of compacted clay and showed that repeated loading produced a gain of strength which suggests that a roadway grows with traffic (Seed et.al. 1995). The main factors controlling an embankment's performance is its deformation behaviour under loads. Diyaljee and Raymond (1982) established a procedure to predict the permanent deformation under long term repeated loading using the static stress-strain data and a minimum number of cycles of repetitive load test data. Probable conditions under cyclic loading are undrained and constant confining stress. Pumphery and Lentz (1986) tested Florida subgrade sand under repeated loading up to10 and 250 cycles and found that confining pressure did not cause significant changes in permanent deformation for low stress ratios (less than 0.60). However, a substantial decrease of permanent deformation was observed for large stress ratios. Several researchers (Allen & Thompson, 1974; Brown and Hyde, 1975) have explored the effect of variable (cyclic) confining pressure on the deformation of subgrade soils. Similar results for resilient and permanent strain were reported from cyclic and constant confining pressure tests, when the constant confining pressure was set to the average of the cyclic confining pressure (Brown & Hyde, 1975). This suggests that a fixed confining pressure could be used in repeated loading tests to get deformation data to simulate the cyclic confining effects of sub grade soils under moving vehicles. The cyclic shearing behavior of saturated clays has been addressed in numerous publications (Brown et al., 1975; Castro and Christian, 1976). Some investigators have suggested the relationships between moisture content, dry density, and the permanent axial strain accumulation that results from increasing number of load cycles (Li and Selig, 2001). Studies concerning fly ash utilization for soil stabilization have been conducted by many investigators. However, there is still a need to find new uses and to increase utilization so less ash will need to be deposited of. Its use as stabilizer clayey soils has not been investigated to an appreciable extent. Consoli et al. (2001) brought out the effects of compacted soil-fly ash-carbide lime mixtures on strength. Cocka (2001) suggested that the optimum fly ash used for stabilizing the expansive clay can be well assessed based on the swelling potential. He showed that the addition of fly ash to expansive clay reduces the swelling potential. There was only a slight decrease in swelling potential from 20 to 25% fly ash additions. The optimum fly ash content was found near 20%. The major technical issues in dealing with fly ash as geotechnical material are erosion and liquefaction for which some studies (Boominathan and Hari, 1999; Trivedi et al, 2000) are carried out previously. Sharma and Fahey (2003) studied that the deviator stress and deviatoric strain at yield reduced with increasing number of cycles for cemented sand due to progressive degradation of bond, which results in significant decrease in stiffness. Undrained triaxial tests are performed over a wide range of confining pressure and normalized cyclic stress.

In present work, an attempt is made to study the cyclic load deformation behaviour of layered system of soil and fly ash under various numbers of cycles and intensity of loads.

Layered soil

Although most of research activities have been concentrated on dealing with either single or mixed type of soil deposits occurring in natural conditions, but uneven availability of suitable geological material along with environmental constraints compels the use of multiple materials for the construction of embankment and pavement structures. The interaction between layers of material, having different elastic moduli and deformation behaviour, under cyclic loading has a major influence on how each layer and type of material behaves. The interaction of layers within a layered matrix affects its stress distribution, which in turn affects the total elastic and plastic strains developed within each material and hence their response to those stresses (Fleming and Rogers, 1995). The stress buildup ultimately leads to permanent deformation within the pavement. It has now been understood that the properties of an element within any one layer ofof material in a pavement structure will vary with the magnitude of the applied stress, the relative position of the element and the confinement provided to the thickness of the layer and the pavement structure as a whole (Fleming and Rogers 1995). Thus individual stress behaviour of each material together with the composite behaviour forms important part of the study under cyclic loading for a layered construction. Shroff et al (2004) studied to evaluate the failure mechanism of soil-fly ash composite mass under three point loading, triaxial loading condition and unconfined compression condition on cylindrical specimens. and proved that the soil-fly ash layered system can increase the value of cohesion (0 kPa to 69 kPa) and % failure strain value (9.5%).

A practical approach of utilization of fly ash in embankments is to have alternate layers of soil and fly ash for which no study is reported in literature. In the present study, a systematic laboratory investigation has been carried out by conducting a series of undrained cyclic triaxial compression tests on layered samples of soil and fly ash, under different intensities of deviatoric failure load and under varying confining pressures with a view to establish a relationship between shear strength parameters and cyclic loading conditions.

Resilient Modulus for Soils

Cracking of pavements, which result from excessive plastic and repeated elastic deflections, depend upon the resilient properties of the components of pavement. The Subgrade resilient modulus (M_r) is defined as the repeated maximum axial deviator stress (σ_d) divided by recoverable axial deformation (ε_r) that is $M_r = (\sigma_d \,/\, \varepsilon_r)$, which is an important characteristic of the multilayer pavement system. The AASHTO guide for design of pavement structures (AASTHO 1982) proposed the resilient modulus test to characterize roadbed soil.

Materials and Method

The soil is obtained from Aligarh located in Uttar Pradesh province of India whose properties are indicated in Table 1. The soil used in the study is cohesive having liquid limit and plastic limit as 32.5% and 22.5% with small angle of internal friction of 15^o.From the plasticity chart, it is confirmed that the soil is clayey silts. Such types of soils are not suitable for the construction of embankment of highways and railways due to its high compressibility and very low permeability. Whereas, fly ash is cohesion less ideal material whose angle of internal friction is about 26^o. Therefore several concentrated efforts are being made to understand the possible mechanisms governing behaviour of layered system of soil and fly ash under repeated loading in relation to shear strength.

The fly ash used in this investigation is procured from Dadri and Rajghat thermal power plants in India. Fly ash collected is dried, sieved through IS sieve 425 microns and stored in airtight containers in the laboratory. The chemical and physical properties of fly ash are given in Table 2. The fly ash used in the present study is classified

Table 1 Physical Properties of Soil

Specific gravity	2.7 at 28^{0} *C*
Natural water content	5.0%
Optimum moisture content	18.0%
Bulk unit weight	21.7 kN/m^3
Maximum dry density	18.4 kPa
Liquid limit	32.5%
Plastic limit	22.5%
Plasticity index	10.0%
Unit cohesion	68.0 kPa
Angle of internal friction	15.0^{o}
Soil classification as per *USCS*	Clayey silts with slight plasticity (*ML*)

Table 2 Properties of Fly ash

Chemical Properties		
Silica	(SiO_2)	60.03%
Alumina oxide	(Al_2O_3)	24.70%
Iron oxide	(Fe_2O_3)	9.46%
Loss on ignition	(*LOI*)	2.84%
Calcium oxide	(CaO_2)	2.29%
Magnesium oxide	(MgO_2)	0.26%
Sulpher trioxide	(SO_3)	0.40%
Potassium Oxide	(K_2O)	0. 20%
Sodium Oxide	(Na_2O)	0.30%
Physical Properties		
Specific gravity		1.98 at 28^{0} C
Natural water content		2.00%
Bulk unit weight		14.93 kN/m^3
Optimum moisture content		31.00%
Maximum dry Density		11.40 kPa
Percent finer than 75μ		45.00%
Fly ash Classification as per *ASTM C-618*		*Class F* - Non-self-cementing

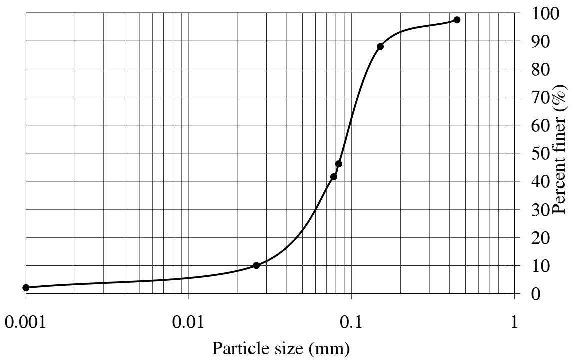

Fig. 1a Particle size distribution of fly ash

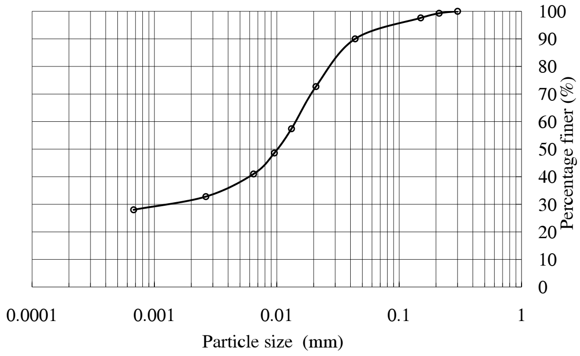

Fig. 1b Particle size distribution curve for clayey soil

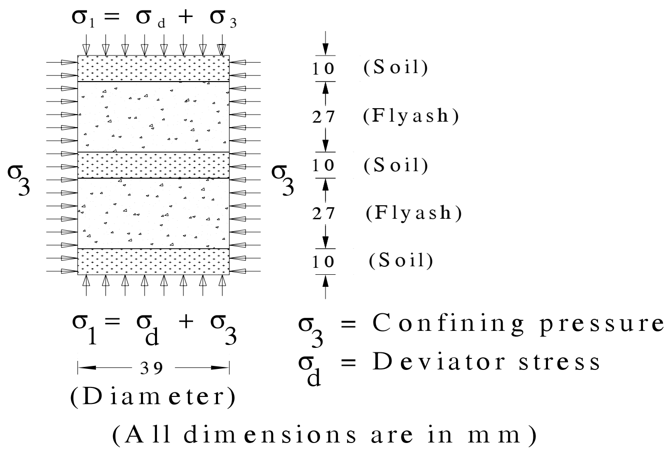

Fig. 2 Free body diagram of sample of soil-fly ash matrix

as Non-self-cementing; class F as per ASTM C-618. The optimum moisture content (OMC) of fly ash and soil using standard proctor compaction test was found to be 31% and 18% respectively. The particle size distribution curve of fly ash and soil are shown in Fig. 1a and 1b.

The triaxial specimens were prepared in a metal mould of 8.4 cm high and 3.9 cm in diameter and compacted in three equal layers. Each specimen of soil and fly ash was prepared at their corresponding OMC and statically compacted under the impact of 25 blows by a mini compactor of 100g weight by a free fall of 15 cm, imparting approximately 0.148 kgm^2/s^2 of energy. The layered system of soil and fly ash can be compacted in the field at their corresponding OMC to maintain nearly same density as done in the laboratory.

The size of the sample used was cylindrical, 8.4 cm high and 3.9 cm in diameter. In soil-fly ash matrix, there were alternate layers of soil and fly ash. The thickness of fly ash and soil were 2.7 and 1.0 cm respectively. The top and bottom layers in the specimen were that of soil, thus there were three soil and two fly ash layers The best option of number of soil and fly ash layers is 3 and 2 because the large amount of fly ash in two layers can be confined between three layers of soils. The binding effect of soil and fly-ash is also increased due to four interfaces of soil and fly ash layers as shown in Fig. 2. The gross unit weight of soil-fly ash matrix was maintained at 16.8±0.1 kN/m^3 for all the layered samples. All the samples have been prepared under similar

Table 3 Experiments performed on soil-fly ash matrix*

Number of cycles	Intensity of repeated load, I		
N	Set-1	Set-2	Set-3
10	25%	50%	75%
50	25%	50%	75%
100	25%	50%	75%

* Each set of experiment consists of three tests at confining pressure of σ_3 = 50, 100 and 150 kPa

conditions of compaction to maintain uniform density and good reproducibility. This arrangement of soil-fly ash matrix has been adopted keeping in view the fact that the fly ash cannot be placed at the top of embankments because it will then be exposed to the atmosphere causing the problems of erosion, water pollution like leaching owing to the existence of alkaline compounds and low shear strength due to its cohesion less nature. The details of cyclic tests on soil-fly ash matrix are given in Table 3.

A strain controlled triaxial shear test machine of 5000 kg with proving ring of 250 kg capacity is used for applying the axial load to the specimens of plain soil, plain fly ash and soil-fly ash matrix under non-cyclic loading as well as stress controlled cyclic loading. The tests were performed with a strain rate of 0.025 mm/minute under consolidated undrained conditions to simulate the actual ground cyclic conditions. Monotonic tests on plain fly ash and soil samples were carried out to explicitly develop a better understanding of the independent stress- strain behaviour of the constituent materials in the layered system in response to compressive loading and for critical comparison of various parameters.

There are nine sets of stress controlled cyclic load tests were perform as shown in table 3. One set of non-cyclic load test was also performed on this layered combination. Each set of tests was carried out at three different confining pressures, σ_3 = 50, 100 and 150 kPa. Thus a total number of thirty triaxial shear tests were performed including non-cyclic tests on plain soil, plain fly ash and soil-fly ash matrix. The intensity of load, I = 25%, 50% and 75% at which loading unloading of cycles was performed is the percentage of the deviator load at failure in non-cyclic loading condition. An equal time for loading and relieving, equal to one minute was adopted for all the cycles. After completing the desired number of cycles N, the deviator load was increased till failure of the specimen. The loading and unloading of samples under cyclic loads are shown in Fig. 3. The type of cyclic loading selected for the present study takes into account the worst condition of the pavements which receive normal traffic flow of lower load intensity during most part of their life (i.e. number of repetitions of loads of low intensity) but are subjected to a higher intensity of load cycle like the movement of battle tanks etc. (i.e. high magnitude of load), once in a life time. This type of alternative procedure of cyclic testing also described by Poulos, (1965) provides information on the loss/gain of shear strength due to cyclic loading by critically comparing the ratio of post-cyclic strength to static shear strength of the soils.

In another study employing a similar type of loading, conducted by Matthew et al. (2004), although the cyclic response was studied but the effect of each individual intensity of cyclic load was not studied, i.e. to say a set of desired cycles, was given in increments up to 5% axial strain,

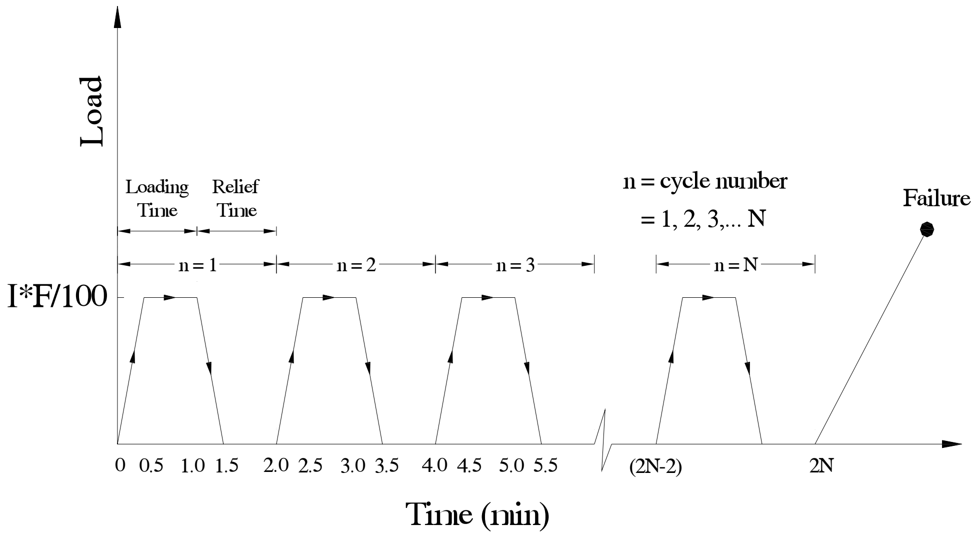

Fig. 3 Loading and unloading cycles

and then failed monotonically. But in this study, the effect of each individual intensity of failure load was studied up to different number of desired cycles and then failed monotonically. It is understood that for the practical implementation of the present study, for the design of highway pavements the value of load intensity, *I,* could be taken as the ratio of the traffic load intensity under normal traffic flow condition to the maximum expected traffic load. It is well understood that in such a loading subjecting similar samples to different intensities of cyclic stresses, *I,* the dependence of these strains on cyclic stress level can be plotted. The test of Thiers and Seed (1969) clearly indicates that for clays this loss of strength depends on the amount of cyclic strain relative to the static strain at failure.

In the present study, vertical axial compression of specimen with the change in the deviator load was recorded. A uniform failure criterion of peak deviator stress is adopted for all the samples during entire test range.

Mode of Failure

The failure of samples of plain soil is by bulging at the mid height of the specimen, but in case of samples of plain fly ash, a very distinct inclined crack appeared. For increasing intensity of loads, *I* and number of cycles, *N,* it is noticed that there is a sudden collapse of soil and fly ash layered samples due to breaking of cementitious compounds.

The following two different types of failure mechanisms were noticed in the layered samples of soil-fly ash matrix during the experiments:

Failure Mode 1: The failure occurred by bulging in the sandwiched layers of fly ash. The photographs of a sample taken before and after the testing are shown in Fig. 4. It is seen that many inclined shear failure planes appeared only in the sandwiched layers of fly ash in addition to tangential cracks from its radial bulging and the failure planes do not break the interfaces between soil and fly ash. This mode of failure was observed for samples that recorded an increase in the deviator stress at failure with increasing number of cycles (N), i.e. for samples tested for (a) all values of I and $N \leqq 50$, and (b) $I \leqq 25\%$ and $N > 50$.

Failure Mode 2: This failure mode also showed bulging at failure, but extended to a greater surface area. The photographs of a sample taken before and after the testing are shown in Fig. 5.

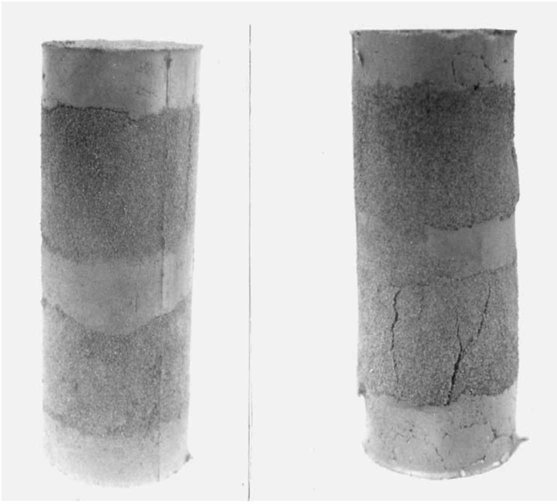

Fig. 4 Failure mode 1: Layered sample of soil-fly ash matrix before and after failure

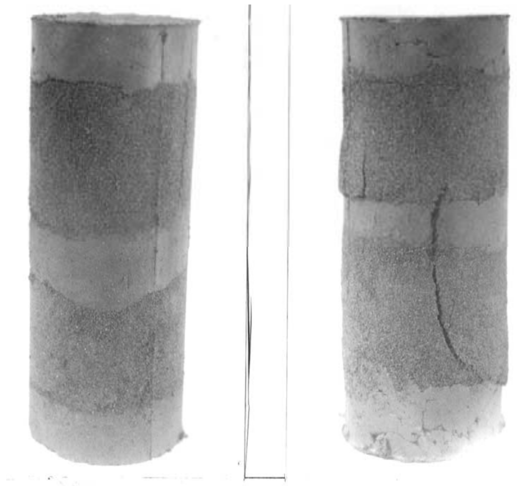

Fig. 5 Failure mode 2: Layered sample of soil-fly ash before and after failure

An inclined shear failure plane appeared passing through the layers of fly ash and extended to the layer of soil. It can be seen that after I >25% stress level comparatively large strains were recorded with number of cycles $N > 50$ indicating the possible collapse of the samples This type of failure occurs due to breaking of bond between the interfaces of soil and fly ash.

The difference observed in the two failure modes reflects the resistance of the different materials of the layered system to applied stresses. The crack formation in the samples initiated from the fly ash layer and extended to the soil layer as the load is increased. When either the intensity of load (I) is small or the number of cycles are small, there is gain in strength of the matrix due to the confinement of the fly ash layer due to which the failure of specimen is caused by the shear failure of fly ash layer which shows that the two layers behaved independently. Whereas, at higher intensity of load (I) and large number of cycles, the two materials start behaving as a single material due to which the shear failure cracks pass through both the materials in Failure Mode 2. It is therefore observed that there is some critical combination of intensity of load and number of cycles at which transition from Failure mode 1 to Failure mode 2 occurs. A large number of experiments will be required for indentifying these critical values. However, in the present study a wide range is observed for the transition phase.

Non-Cyclic Response

The variation of deviator stress with vertical axial strain for plain soil samples, plain fly ash and soil-fly ash matrix are shown in Figs. 6, 7 and 8 respectively. Each figure contains the results of three different values of confining pressures (σ_3). It was found from these figures that stress-strain behaviour of soil-fly ash matrix layered system resembles closely with that of plain soil under non-cyclic loading conditions. It was also observed from these figures that the increase in confining pressure results in stiffening of soil, fly ash as well as soil-fly ash matrix and hence results in the increase of ultimate deviator stress and ultimate strain. The magnitude of increase is considerably higher for plain fly ash as compared to plain soil that shows significant effect of confining pressure (σ_3) in fly ash. The ultimate deviator stress as well as the ultimate vertical axial strain of plain fly ash is considerably less than that of plain soil at the same confining pressure. It is seen from these figures, that the ultimate deviator stress of soil-fly ash matrix at 50 kPa confining pressure is slightly less (~6.0%)

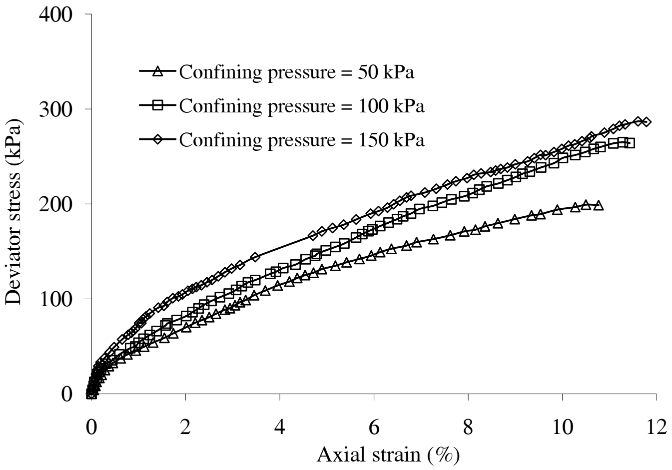

Fig. 6 Stress-strain diagram of plain soil

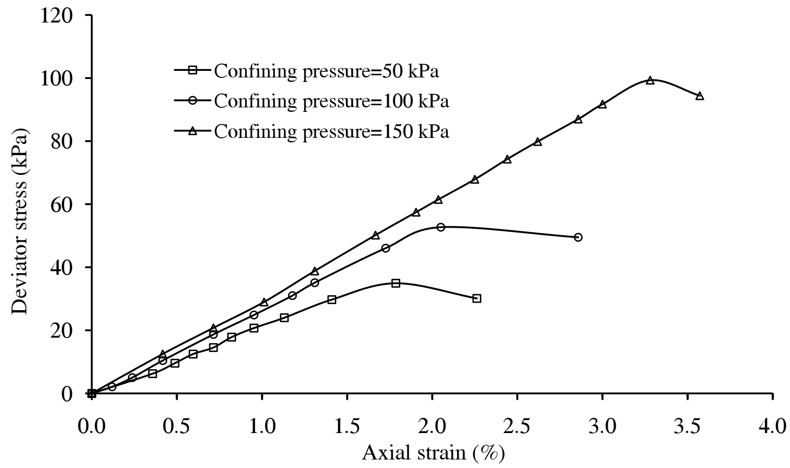

Fig. 7 Stress-strain diagram for plain fly ash

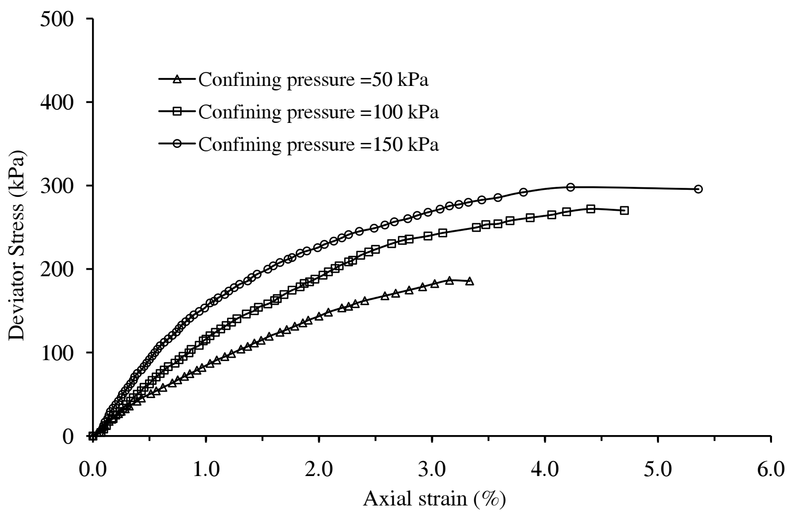

Fig. 8 Stress-strain diagram of layered sample for N=0

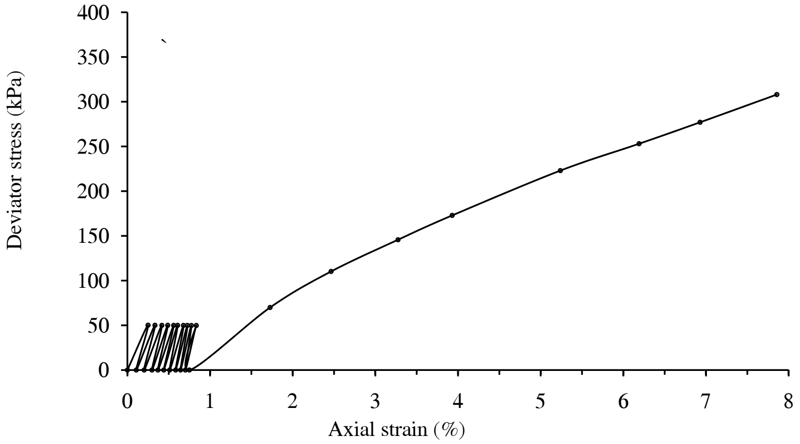

Fig. 9 Stress-strain diagram of soil-fly ash layered system
(Intensity of cyclic loading, I = 25%, Confining pressure = 50 kPa, Number of cycles, N = 10)

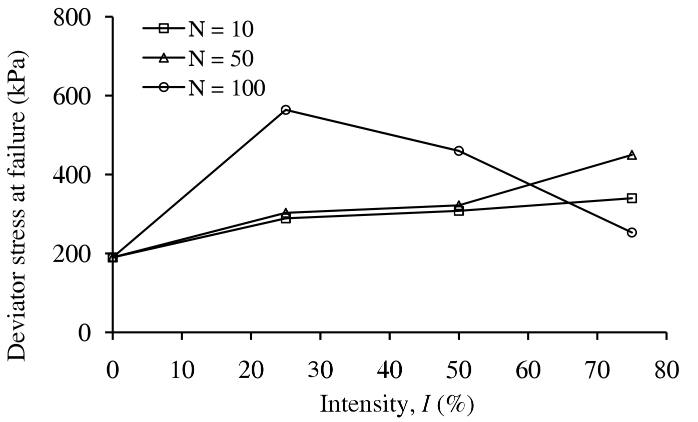

Fig. 10 Variation of deviator stress at failure with change in I for σ_3 = 50 kPa

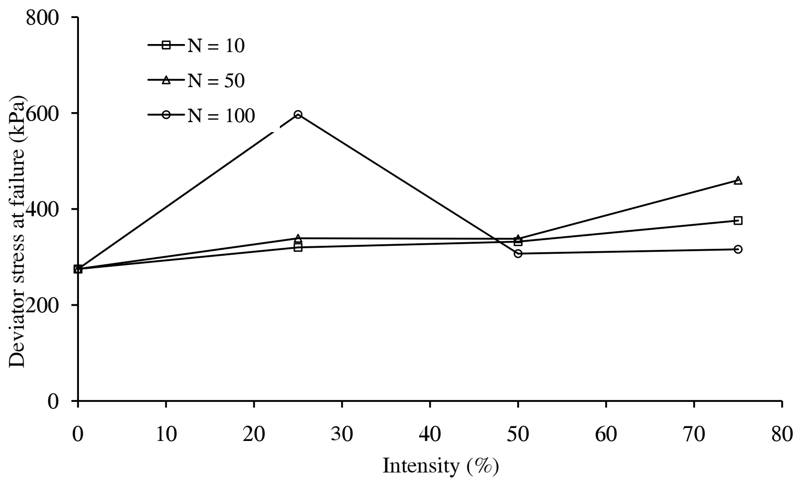

Fig. 11 Variation of deviator stress at failure with change in I for σ_3 = 100 kPa

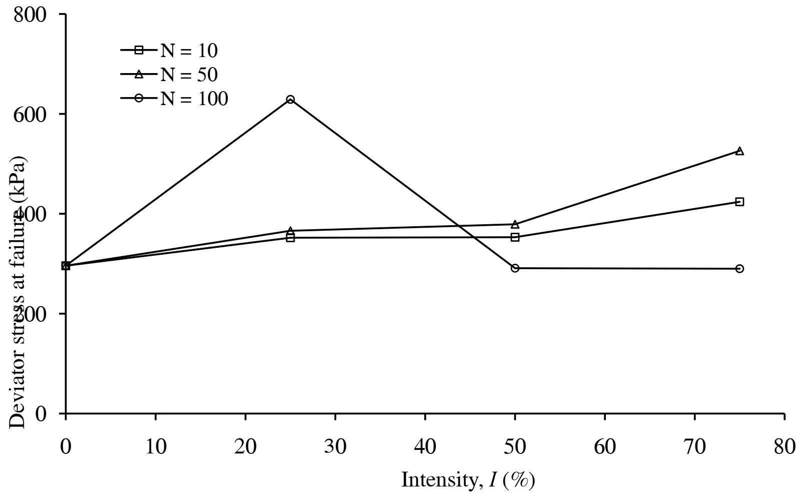

Fig. 12 Variation of deviator stress at failure with change in I for σ_3 = 150 kPa

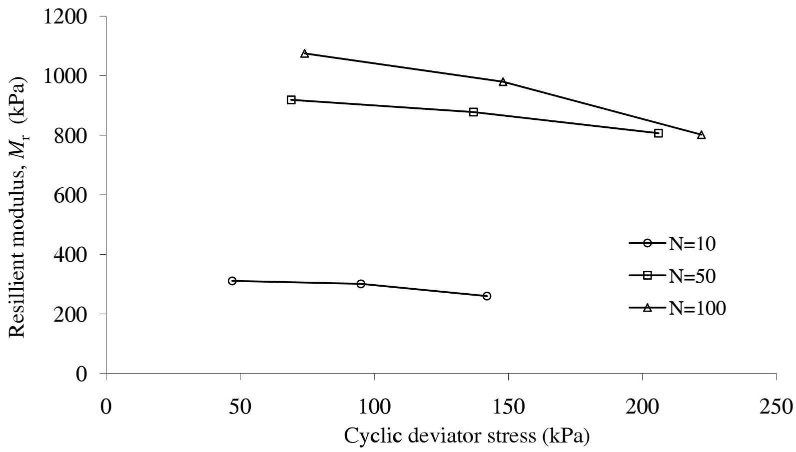

Fig. 13 Resilient modulus variation

than the corresponding value of plain soil, whereas at higher confining pressure the ultimate deviator stress of soil-fly ash matrix is slightly more (~3.0%) than their corresponding values of plain soil. The failure strains of soil-fly ash matrix are comparatively higher than the corresponding values of plain fly ash and lower than plain soil. The fly ash is an inert and cohesion less material due to which it does not possesses strength property on its own as it reduces the interlocking effect at lower strain and plain clayey soil is cohesive and fails at larger strain due to its strength property. The soil-fly ash matrix thus fails at some intermediate strain value.

Cyclic Response

Influence of Parameters *I* and N

The stress-strain variation observed during the actual loading adopted in the study is shown in Fig. 9. The variations of deviator stress at failure of soil-fly ash matrix with change in the intensity, *I,* for three different values of confining pressures (σ_3) are shown in Figs. 10 to 12. Each figure shows the results of three different values of N =

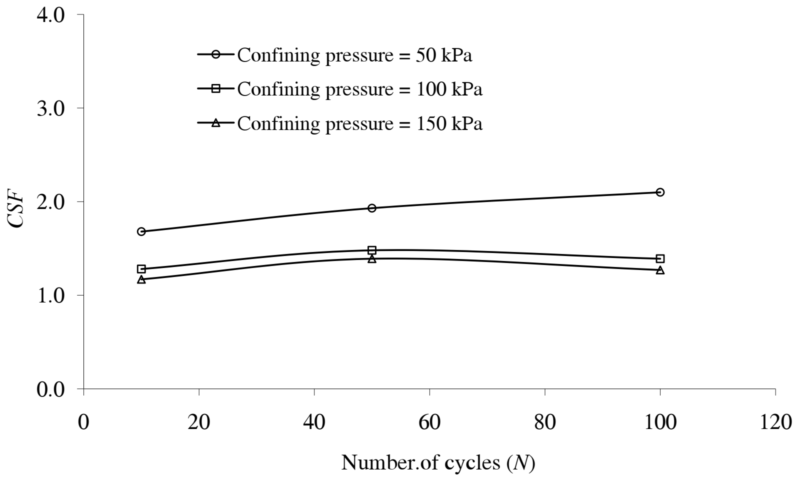

Fig. 14 Relation between cyclic strength factor (CSF) and N

10, 50, 100 and I = 25%, 50%, 75%. It is seen from these figures, that for N = 10 and 50, deviator stress at failure increases with increase in the value of I; whereas for N = 100, it increases initially and then decreases. It was also noticed that the deviator stress at failure for a given number of cycles, N and intensity, I, increases with increase in confining pressure with only one exception of N = 100 and I = 50%. It is seen from the figures that deviator stress at failure increases with increase in I for low values of N (= 10 to 50) for all confining pressures, whereas at higher value of N (= 100), it increases up to I = 25% and then decreases. It seems that the cyclic loading with low value of I acts as compactive effort thus improving its strength, whereas, cyclic loading with higher value of I causes damage which gets accumulated with increase in number of cycles.

It has been observed from the plots that for N = 50 at lower values of I = 25%, there is increase in deviator stress at failure for all confining pressures, and this increase is significant at higher values of I. At moderate I = 50%, there is some increase in deviator stress at failure for low confining pressures, σ_3 = 50 kPa, whereas there is almost no change at higher confining pressures, σ_3 =100 and 150 kPa. At higher values of I = 75%, there is small increase in deviator stress at failure initially when N increases, and then it falls down. It has been also seen from the plots that at higher values of N = 100, there is decrease in deviator stress at failure when intensity, I, is increased beyond 25%. Maximum value of deviator load at failure was obtained for N = 100 at I = 25% and under a confining pressure, σ_3 = 150 kPa, which is approximately 20% more than the non-cyclic value i.e. at I = 0. Maximum decrease in failure deviatoric stress with increasing number of cycles is obtained for samples tested under maximum intensity of load I = 75% under all the three confining pressures used for N = 100. These samples have also shown comparative increase in their permanent strain levels as shown in Fig. 12.

It can be concluded from the above discussion that intensity of load, I, plays an important role in this layered combination with larger variations observed in failure stress at higher intensities of failure load. It is also observed that the critical level of intensity, I, for this layered combination which represent onset of instability in terms of failure load seems to lie between I = 25% to 50%.

Resilient Modulus (M_r) and Cyclic Strength Factor (CSF)

The resilient moduli of the samples were calculated from the last cycle (n = N) for each cyclic test. The plot showing variation of resilient modulus (M_r) along with the cyclic deviator stress level in Fig.13 clearly indicates an inverse

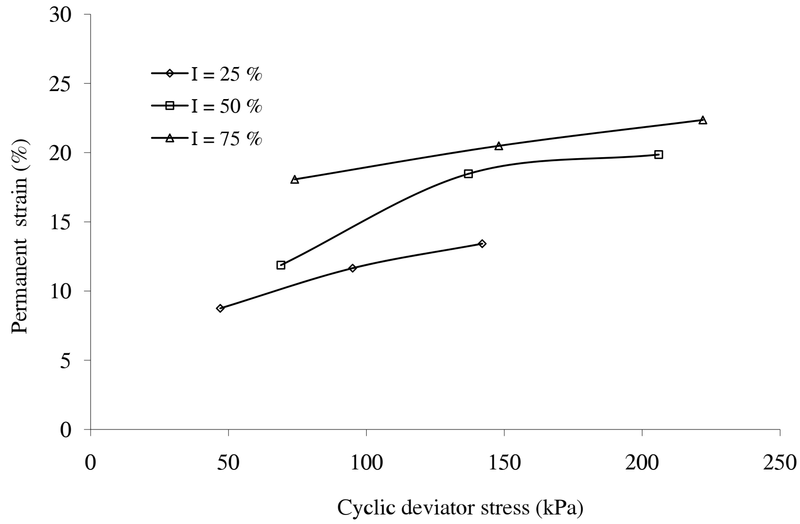

Fig. 15 Plot showing variation of permanent strain and cyclic deviator stress

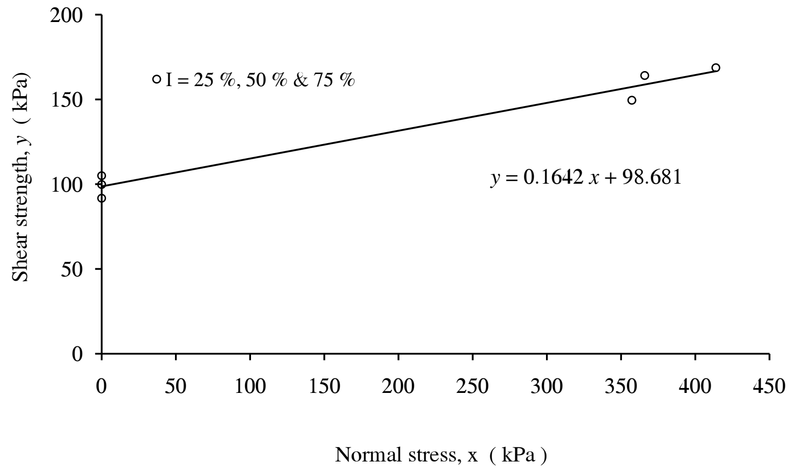

Fig. 16 Failure envelop for soil-fly ash matrix (N=10)

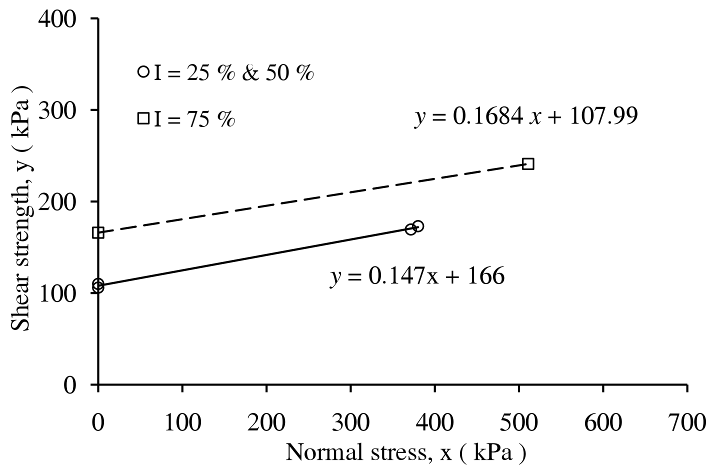

Fig. 17 Failure envelop for soil- fly ash matrix (N=50)

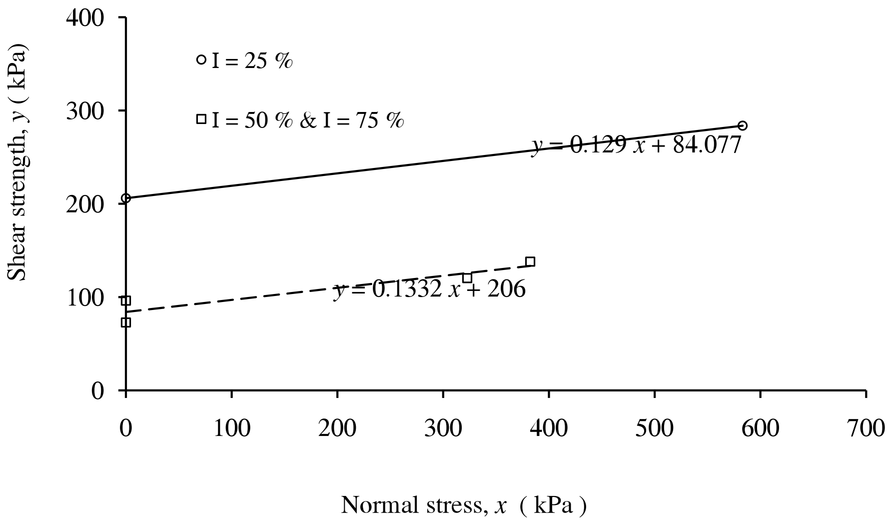

Fig. 18 Failure envelop for soil-fly ash layered system (N =100)

stress dependency, i.e. an increase in cyclic deviator stress level has shown a fall in modulus values, with the maximum value of Mr being obtained at I = 25% for N = 100. The modulus value used in the plot indicates average value of three confining pressures used in the study σ_3 = 50, 100, 150 kPa. The pattern obtained above is similar to as shown by Li and Selig (2001) for sub grade soils under traffic loading.

The cyclic strength factor (CSF) of the layered samples, which is defined as the ratio of post-cyclic strength (obtained after desired number of cycles, N) to static shear strength up to failure of the samples were evaluated and compared graphically. CSF values representing an average value for three intensities, *I,* are plotted against number of cycles, *N,* as shown in Fig. 14. The plot clearly shows that the increase in strength over static strength due to number of cycles, *N,* is higher at low confining pressure of 50 kPa while at higher confining pressure (σ_3 = 100, 150 kPa) the increase is marginal. The lower increase in strength or CSF at 100 and 150 kPa of confining pressure clearly demonstrates the prominent effect of confinement on strength of samples, in particular at 150 kPa pressure.

Permanent Strain Variation

Permanent strains of the sample representing average of the three values of σ_3, that were calculated relative to complete failures of samples were plotted against cyclic deviator stress as shown in Fig. 14. It is observed from the plot that larger strains were obtained for samples under maximum intensity of load (I = 75%) showing the fact that intensity of cyclic load, *I,* has an exclusive role during the cyclic loading of the samples. These samples have also registered a fall in their deviatoric stress levels with increase in number of cycles, N as shown earlier in Figs. 10 - 12. On comparing the graphs of Figs. 10, 11, 12 and 15, a comparative instability is observed to occur at higher intensities of load (I = 75%), with the development of higher permanent strains and early failure of samples.

Shear Strength Parameters

The failure envelopes of soil-fly ash matrix for different values of N have been plotted in Figs. 16 to 18. A Mohr-Coulomb failure equation has been proposed for different cases. The equation is of the type:

$$\tau_f = c + \sigma_n \tan\phi \qquad (1)$$

Where,
c = unit cohesion, ϕ = Angle of internal friction, σ_n = Normal strength and τ_f = Shear strength.

There is no any significant influence of the parameter, I, for N = 10, (Fig. 15) perhaps because of lesser number of cycles and therefore, a common shear strength envelope have been plotted in this figure.

The shear strength parameters of the envelope are: c = 98.7 kPa, $\phi = 9.32^o$.

The shear strength envelope for I = 25% and I = 50% for N = 50, is almost the same (Fig. 16), therefore, a combined shear strength envelope has been plotted in the figure for these two values of I, whereas for I = 75% a separate shear strength envelope has been drawn. The shear strength parameters obtained are:

$c = 108.0$ kPa, $\phi = 9.55°$ for $I \leqq 50\%$
$c = 166.0$ kPa, $\phi = 8.36°$ for $I > 50\%$

Two shear strength envelopes for N = 100, are considered, one for I = 25% and another combined for I = 50% and 75% whose values are close to each other (Fig. 17). The shear strength parameters obtained are:

$c = 206.0$ kPa, $\phi = 7.58°$ for $I < 50\%$
$c = 84.0$ kPa, $\phi = 7.35°$ for $I \geqq 50\%$

Conclusions

Performance based approach of pavement design using analytical methods incorporate laboratory measurements of resilient modulus and resistance to permanent deformation of the subgrade and foundations as an important parameter of investigation nowadays. This aspect of analysis was kept in concern while drawing the conclusions from the present study. On the basis of the tests conducted in this study, the following main conclusions are drawn:

- Resilient Modulus values calculated for different cyclic stress levels and under varying number of cycles show an inverse stress dependency whereas permanent strains show a linear stress dependency. Cyclic strength factor defined for the test results appears to provide an appropriate index for evaluating the performance of layered system under cyclic loading.

- The development of permanent strains appears to govern largely the stress-strain behaviour of layered sample of soil-fly ash matrix under cyclic loading. A value of applied cyclic deviator stress (Intensity, I) above which the onset of permanent deformation becomes unstable is shown to occur above 50% deviator stress at failure. The cyclic loading at intensity of load, $I \geqq 50\%$ lead to instability of soil-fly ash matrix, whereas lower intensity of load (I = 25%) helps in improving its shear strength characteristics. The experimental investigation substantiates the use of fly ash in layered combination with clayey type of soil under lower number of cycles with high value of intensity of load (I) and for higher number of cycles with lower value of parameter, I.

- The study shows that the value of deviator stress at failure and cohesion continuously increases with the increase in the number of cycles, N for lower values of I ($I \leqq 25\%$) in soil-fly ash matrix under cyclic loading conditions that signifies the good performance of this combination under lower percentages of failure stress levels. At lower intensity of load and higher number of cycles, the strength of layered system of soil-fly ash matrix increases due to interlocking of fly ash particles and binding effect of interfaces of soil and fly ash layers. Further studies need to be done on such layered arrangement employing fly ash as one of the constituent material for its mass scale utilization to explicitly understand its response under varying cyclic loading conditions.

- The Mohr-Coulomb equation derived form the experimental data looks to provide reasonable first order accuracy. The results form the studies could be utilized in the development of an advanced constitutive model based on theory of elasto-plasticity.

- Furthermore as being a totally new area of research, the results form this study can be used as a preliminary basis for advanced level researches.

- Clay and fly ash, which are usually, considered undesirable materials for embankment applications when used independently have been converted into useful materials by their layered combination.

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