50th IGC

50th INDIAN GEOTECHNICAL CONFERENCE
17th – 19th DECEMBER 2015, Pune, Maharashtra, India
Venue: College of Engineering (Estd. 1854), Pune, India

A COMPARATIVE STUDY ON GEO-TECHNICAL CHARACTERISTICS OF SEDIMENTED AND COMPACTED FLY ASH BED TREATED WITH LIME COLUMN

S.P.Singh[1], N.Roy[1], S.Sangita[2], A.Pani[3]

ABSTRACT

Fly ash is a solid waste, generated by thermal power plants where coal is used as fuel. The disposal of fly ash has become a grave menace to the eco-system as it gives rises to a lot of problems such as shortage of disposal land, leaching of heavy and trace elements and dusting of atmospheric air. In order to get rid of these problems, this waste material is being used in several construction processes such as structural fills for low lying areas, embankment and subgrade for highways, backfill in retaining structures, mine stowing etc.. From the time immemorial fly ash has been used in various construction processes in order to save the conventional earth material. However, this fly ash possesses a very poor bearing capacity and high compressibility for which it is not suitable to be used in construction processes. By a though study of research work, it has been convinced that use of lime column is a slow yet effective method which improves the strength and stability of fly ash. This paper highlights the effect of lime column in improving the geo-technical characteristics of sedimented and compacted fly ash bed by simulating a field condition as closely as possible

In the present experimental investigation, large scale laboratory models of sedimented and compacted fly ash beds were prepared and a lime column was installed at the center of the beds in order to facilitate in-situ stabilization. The test set up consists of a large circular galvanized iron tank of 105 cm diameter and 120 cm height open at the top with a drainage arrangement at the base. In order to prepare the fly ash bed, about 1 tonne of fly ash sample was used and the amount of water required for the flow-able fly ash slurry was determined from step-by-step water addition, and mixing of fly ash. The optimum moisture content without bleeding of water from fly ash was based on eye judgment and it was found to be 75%. The slurry was prepared at this moisture content and placed in the tank. Before placing slurry in the test tank, a cylindrical steel casing of 10cm dia and 100cm height , wrapped with fiber mesh of small aperture was placed at the middle of test tank. In addition to this, fly ash beds were also prepared at MDD and OMC value. For this about 1 ton of fly ash sample was taken and compacted to maximum dry density (1.16g/cc) at optimum moisture content (38.7%). After mixing, the sample was placed in the tank by 10 equal layers and tamped with a large hammer so that the compacted fly ash sample could be placed uniformly throughout the tank. Before placing the sample in the test tank, the bottom of the test tank was

[1]Professor, Civil Engineering Department, NIT Rourkela, India, spsingh@nitrkl.ac.in
[2]M.Tech Student,Civil Engineering Department, NIT Rourkela, India, sushreesangita87@gmail.com
[3]Ph.D Student, Department of Civil Engineering, NIT Rourkela, India, 514ce1009@nitrkl.ac.in

filled with a filter bed of highly permeable material such as sand up to a height of 10cm . After placing the fly ash sample, the lime column was installed at the center of the test tank by pouring thick slurry of hydrated lime. The quantity of lime required for installing the lime column was 10kg. After the installation of lime column, the fly ash beds present in the test tank was saturated in order to facilitate in-place stabilization**.**

After the curing periods of 30, 90, 180 and 365 days, the samples were collected to study the improvement in various properties such as water content at saturation, dry density, unconfined compressive strength, and hydraulic conductivity. The samples were collected from different radial distances like 5 cm, 15cm, 25cm, and 35 cm and at various depths of 10 cm, 30 cm, 50 cm and 70 cm. In order to study the hydraulic conductivity of stabilized fly ash specimens, the samples were collected by using molds of 10cm diameter and 15 cm height. Then the samples were safely transferred into the permeability mould and the test was conducted in a constant head permeameter. A thin sampling tube of 36mm diameter and 78mm height was inserted in the test tank at required locations and the specimens were collected for unconfined compression tests. The density and moisture content of fly ash for different predetermined locations and positions were also determined by collecting undisturbed samples the bed. Enough care was taken in the process of insertion of sampler into the ash bed to obtain least disturbed samples for the representative testing. Similar procedure was adopted for sampling corresponding to different stabilization periods.

The lime column method was found to be effective in increasing the unconfined compressive strength and reducing hydraulic conductivity of fly ash deposits along with modifying other geotechnical parameters including water content, density. A comparative study showed that the dry density and strength of compacted fly ash bed is much higher than the sedimented fly ash bed whereas the hydraulic conductivity value of the samples collected from compacted fly ash bed is less than that of sedimented fly ash bed. Thus, the in-place stabilization by lime column technique has been found to be effective in increasing the unconfined compressive strength and reducing hydraulic conductivity of ash deposits in addition to modifying other geotechnical parameters including water content and dry density.

Keywords: Fly ash, lime column, stabilization, pozzolanic reaction, unconfined compressive strength, hydraulic conductivity

50th IGC

50th INDIAN GEOTECHNICAL CONFERENCE
17th – 19th DECEMBER 2015, Pune, Maharashtra, India
Venue: College of Engineering (Estd. 1854), Pune, India

A COMPARATIVE STUDY ON GEO-TECHNICAL CHARACTERISTICS OF SEDIMENTED AND COMPACTED FLY ASH BED TREATED WITH LIME COLUMN

S. P. Singh, Professor, Department of Civil Engineering, NIT Rourkela, Odisha, Email-spsingh@nitrkl.ac.in
N.Roy, Professor, Department of Civil Engineering, NIT Rourkela, Odisha, Email-nroy@nitrkl.ac.in
S. Sangita, M.Tech Student, Department of Civil Engineering, NIT Rourkela, sushreesangita87@gmail.com
S. Samantasinghar, Ph.D Student, Department of Civil Engineering, NIT Rourkela, 514ce1007@nitrkl.ac.in

ABSTRACT: This paper highlights the effect of lime column in improving the geotechnical characteristics of sedimented and compacted fly ash. In this experimental investigation, large scale laboratory models of sediment and compacted fly ash beds were prepared with a centrally installed lime column simulating a field condition as closely as possible. After the curing periods of 30, 90, 180 and 365 days, the undisturbed fly ash specimens were collected from different radial distances and depths to study the improvement in various properties such as water content, dry density, unconfined compressive strength, and hydraulic conductivity. From the test results, it was found that lime column treatment is an effective means of increasing the unconfined compressive strength and reducing hydraulic conductivity of fly ash deposits along with modifying other geotechnical parameters including water content, density and shear parameters. A comparative study showed that the strength and dry density of stabilized fly ash specimens collected from compacted fly ash are much higher than that of sediment fly ash bed whereas the hydraulic conductivity value was found to be less in the samples collected from the compacted fly ash bed than that of sedimented fly ash beds.

INTRODUCTION

Coal based thermal power plants (TPPs) has been the backbone of a country due to its major contribution in electricity generation for the developmental purposes. With a stock of 70 billion tonnes fossil fuel reserve, majority of TPPs (84%) are run on coal. About 260 million tonnes (MT) of coal (65% of annual coal produced in India) is being used by TPPs which ultimately results in generation of enormous quantity of fly ash in the country. At present, over 165 MT of fly ash is being generated by TPPs as a by- product of coal combustion and is predicted to cross 225 million tonnes by the year 2017. With the increase in generation of fly ash, its disposal has become a major issue for thermal power plants as it creates a lot of problems like shortage of usable land, increase in disposal cost, leaching of noxious heavy metals and dusting of atmospheric air. In order to get rid of disposal and dusting problem, this waste material is being used in several construction processes such as structural fills for low lying areas, embankment and subgrade for highways, backfill in retaining structures, mine stowing etc. as a replacement to conventional earth material. However, unstabilized fly ash is not suitable for construction works due to low bearing capacity and high compressibility. So in order to transform it into a promising construction material, suitable stabilization method should be adopted so that it can be used in various construction processes. In-situ stabilization of pond ash is an attractive idea to bring about improvement in the geotechnical properties. Out of several techniques, lime column treatment seems to be the best alternative for in-situ stabilization pond ash as it is less time consuming as well as cost-effective. By a thorough study of the previous research works, it is convinced that lime column treatment is a sluggish yet effective method which converts the waste fly ash into a desirable and sustainable construction material.

LITERATURE REVIEW

A good number of literatures are available on successful application of lime column in stabilizing the soft soil. For instance, Barnes et al. [1] presented both laboratory and field test results of in-place stabilization of waste phosphatic clays using lime column. Results of their study showed a significant increase in shear strength in the stabilized clay specimens. Hardianto and Ericson [8] successfully used lime column in stabilizing phosphatic clays ponds. The in-situ test results show that there is a reduction in plasticity as well as permeability and increase in strength, through hydration and pozzolanic reaction. Ghosh and Subbarao [3] modified class F fly ash with lime as well as combination of lime and gypsum and found a significant reduction in hydraulic conductivity with an increase in the curing period. Gupta et al. [6] presented the results of field trials for improvement of soft soils. Lime to water ratio of 30% was applied to study the efficacy of lime column in improving soft soil. The embankment made with black cotton soil was modified with lime columns and pressure injection of lime slurry and found that both techniques resulted in significant improvement in strength and settlement characteristics. Ghosh and Subbarao [4] studied the microstructural developments of a low-lime fly ash modified with 6 and 10% lime and 1% gypsum through X-ray diffraction, differential thermal analysis, scanning electron microscopy, and energy-dispersive X-ray microanalysis tests to gain information on the fly ash-lime interaction and found a substantial change in strength gain and reduction in hydraulic conductivity. Tonoz et al. [13] studied the strength of the soil surrounding the lime-column. Most of their results showed that the soil strength increased near the column to a distance up to 2 to 3 times of the column diameter in radial direction. Chand and Subbarao [2] reported the effectiveness of in-place treatment of an ash deposit by hydrated lime column. Ghosh and Subbarao [5] studied shear strength characteristics of a low lime class F fly ash modified with lime alone or in combination with gypsum and found a significant gain in unconfined compressive strength. Muntohar [11] presented laboratory scale model test results of soft clay stabilized with lime column technique. The lime-column of 50 mm in diameter (D), and the depth was 200 mm is used. The CPT results showed that the installation of LC affected the soil strength to a depth of 4xD beneath the bottom of LC and the water content of soil decreased near the LC, but beyond the distance of 4D in radial direction the water content remained its original value. Moghal and Sivapullaiah [10] presented the effects of addition of lime and lime along with gypsum on the compressibility behavior of two class F fly ashes. Raju [12] showed the effectiveness of vibro techniques in stabilizing the fly ash deposits. Wilkinson et al. [14] showed the applicability of lime slurry pressure injection (LSPI), stabilization technique for improving the geotechnical properties of problematic soils. Kokusho et al. [9] applied heavy compaction method (HCM) for compacting fly ash deposit. Kishan et al. [8] found a reduced value of hydraulic conductivity in fly ash due to addition of lime and/or gypsum with increase in curing period.

Scanning thorough the previous research works; it is perceived a limited attempt has been made to study the efficacy of lime column in improving the geo-technical characteristics of fly ash. So in this experimental investigation, an effort has been made to study the efficacy of lime column in improving various properties of fly ash such as water content, dry density, shear strength parameters, unconfined compressive strength, and hydraulic conductivity by preparing large scale laboratory models.

MATERIALS

Fly Ash

The fly ash used in the experimental work was procured from RSP Rourkela. Its physical properties and chemical composition are given in Table1.The major constituents of fly ash are silica, alumina and iron. Calcium present in the fly ash is less than 20%. So, according to ASTM specification C 618-89 (1992), this fly ash belongs to a Class F category.

Lime

The commercially available superior grade quick lime was used to prepare lime column.

Table 1 Properties of RSP fly ash

Physical properties of Fly ash		Chemical composition	
Properties	Value	Constituents	Percentage
Specific gravity	2.44	SiO_2	59.2
Dry density	1.16 gm/cc	Al_2O_3	17.9
OMC	38.7%	Fe_2O_3	9.5
Liquid limit	56.8%	CaO	3.2
Cu and Cc	8.34 and 2.08	MgO	1.3
Cohesion	0.04 kg/cm^2	SO_4	1.2
Angle of internal friction	44^0	Unburnt Carbon	7.0
Hydraulic conductivity at sedimented and compacted condition	1.02X10^{-4} cm/sec and 4.25X10^{-5}	Others	0.7

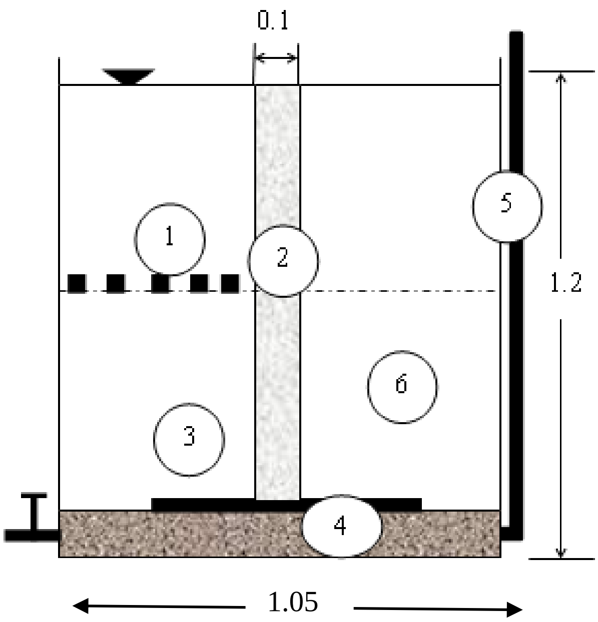
METHODOLOGY

Preparation of Sediment and Compacted Fly Ash Beds

Figure. 1 shows the test set up for sedimentation of ash slurry which consists of a large circular galvanized iron tank of 105cm diameter and 120cm height open at the top with a drainage arrangement at the base. About 1 tonne of fly ash sample was used and the amount of water required for the flow-able fly ash slurry was determined from step-by-step water addition, and mixing of fly ash. The optimum moisture content without bleeding of water from fly ash was based on eye judgment and it was found to be 75%. The slurry was prepared at this moisture content and placed in the tank. Before placing slurry in the test tank, a cylindrical steel casing of 10cm dia and 100cm height wrapped with fiber mesh of small aperture was placed at the middle of test tank. In addition to this, fly ash beds were also prepared at MDD and OMC value. For this about 1 ton of fly ash sample was taken and compacted to maximum dry density (1.16g/cc) at optimum moisture content (38.7%). After mixing, the sample was placed in the tank by 10 equal layers and tamped with a large hammer so that the compacted fly ash sample could be placed uniformly throughout the tank. Similar arrangements were also made here for placing the lime column.

Installation of Lime Column

At the end of the initial sedimentation period of one month, the lime column was installed at the center of the ash beds. The quantity of lime required for installing the lime column was 10kg. The required quantity of lime was taken and it was divided into10 equal parts after placing each part, the layers are tamped with a small hammer. Thus, a lime column of 10 diameter and 100cm height was installed at the middle of the ash beds.

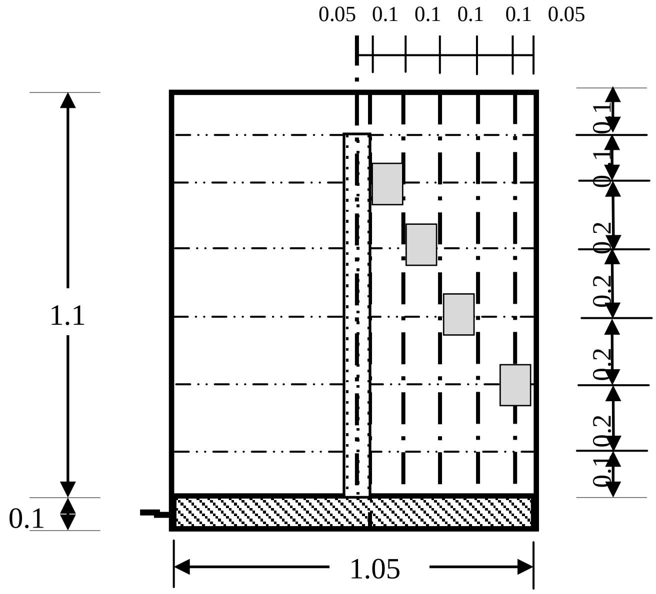


1-Temperature sensors, 2-Lime column
3-Base plate, 4-Sandbed, 5-Stand pipe
6-Fly ash bed

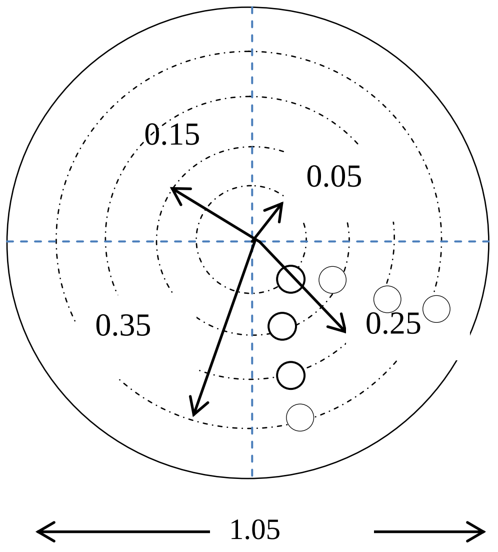
Fig. 1 Details of test tank and it's components

Sampling Program and Testing

The samples were collected from various radial distances such as1 5cm, 25 cm, 35cm, and 45cm as well as depths like 10cm, 30cm, 50cm, 70cm, and 90cm after 30, 90, 180 and 365 days of installation of the lime column and various properties such as water content, dry density, unconfined compressive strength, and hydraulic conductivity were determined. The details of sampling locations for are presented in (Figure 2).



(a)



(b)

Fig. 2 (a) Elevation **(b)** Plan of the test tank showing locations for collection of samples for determination of hydraulic conductivity

All dimensions are in m

Permeability Test

The permeability test of the cured specimens was performed according to the procedure prescribed in IS: 2720 (Part-17; 1986) in a constant head permeameter. In order to know the hydraulic conductivity of stabilized fly ash specimens, the undisturbed samples were collected from different radial distances as well as different depths (Figure 2a & 2b) after specified days of curing with the help of thin walled sampling tube having diameter same as the permeability mold and height equal to 15cm. The collected sample was transferred into the permeability mold. Tap water of pH 7.20 was allowed to flow though the sample and saturate it well. The effluents coming from the outlets of hydraulic conductivity molds were collected in measuring cylinders and the hydraulic conductivity of the samples was determined.

Unconfined Compressive Strength Test

To conduct unconfined compression test, a thin sampling tube of 36mm diameter and 78mm height was inserted in the permeability mould and sample were collected at the end of each curing period. The samples for unconfined compressive strength were obtained in the thin sampling tube are trimmed to make final size of 36mm diameter and 72mm height.

RESULT AND DISCUSSION

Water Content

Figure 3 and 4 represent the variation of water content with radial distance (RD) as well as depth for sedimented and compacted fly ash beds respectively. From the figures it is observed that with water content is less at the locations near to the lime column. With increase in radial distance, the same value increases. This is due to the higher concentration of lime at the location near to the lime column and migration of lime in downward direction which participate in pozzolanic reaction. On the other hand, water holding capacity of the pond ash deposits decreases with increase in depth. At greater depths, the overburden pressure becomes higher, causing more consolidation, thereby resulting in lower water content.

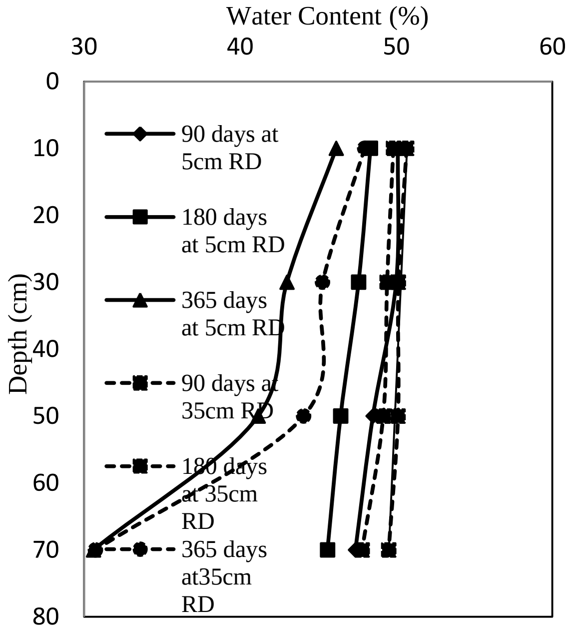


Fig. 3 Variation of water content with depth on different days of curing for sedimented fly ash bed

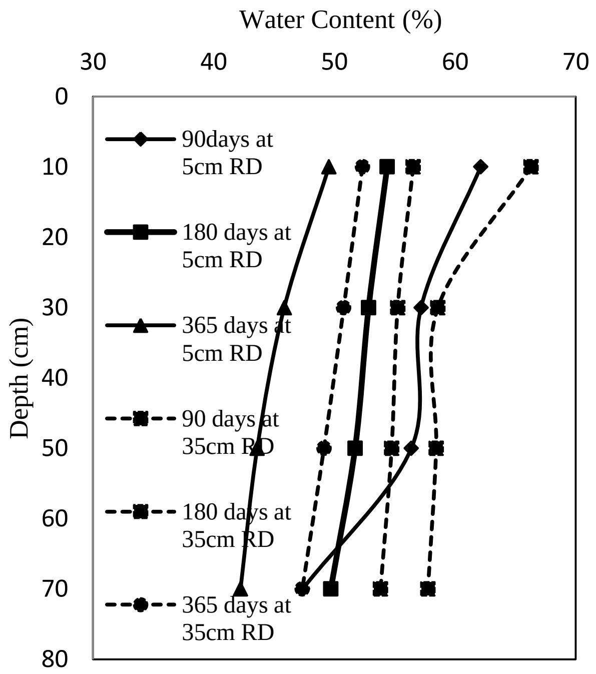


Fig. 4 Variation of water content with depth on different days of curing for compacted fly ash bed

A comprarative study (Fig. 5) shows that water holding capacity of sediment fly ash bed is less than the water holding capacity of compacted fly ash bed.

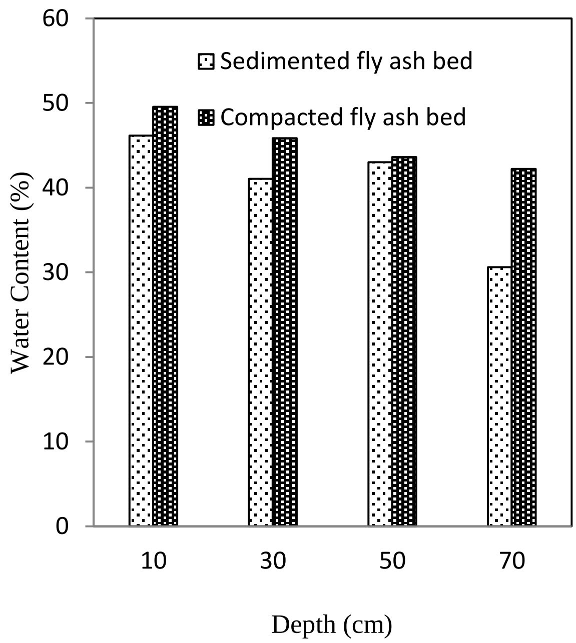


Fig. 5 Variation of water content with depth in the specimens collected from 5cm radial distance in the ash beds on 365 days curing

Density

The variation of dry density with radial distance and depth at different curing periods for sedimented and compacted fly ash bed is shown in (Fig. 6& 7) and (Fig. 8&9) respectively. It is observed that the dry density is more in the sample collected near to the lime column and with increase in radial distance the dry density decreases. On the other hand, with increase in depth, the dry density increases. This is due to the higher concentration of lime at the location near to the lime column and migration of lime in downward direction which participate in pozzolanic reaction. The dry density of fly ash slurry is lower at top portion due to reduction in the confinement pressure occurs with less surcharge and higher water content. In addition to this, with increase in curing period, the dry density increases .This confirms that with increase in curing period the pozzolanic reaction becomes even stronger.

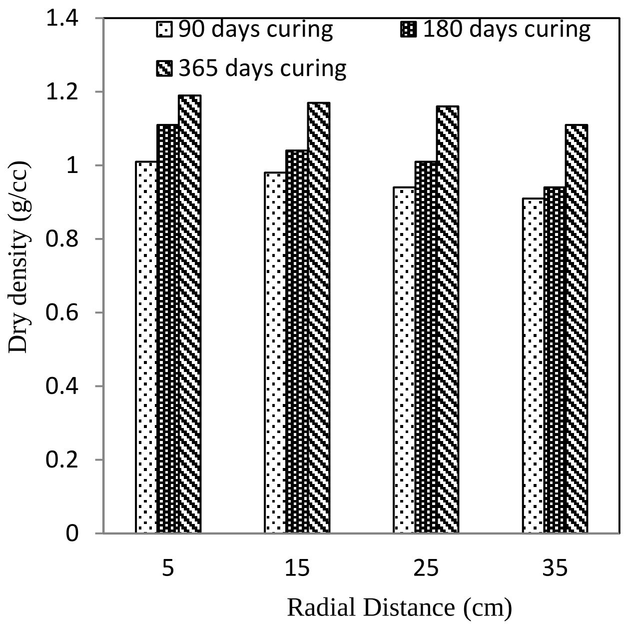


Fig. 6 Variation of dry density with radial distance at 50cm depth for sedimented fly ash bed

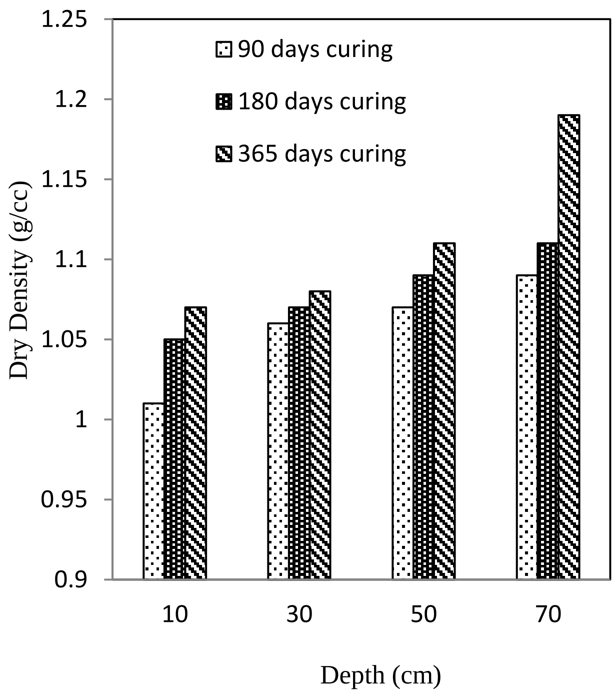


Fig. 7 Variation of dry density with depth at 5cm radial distance for sedimented fly ash bed

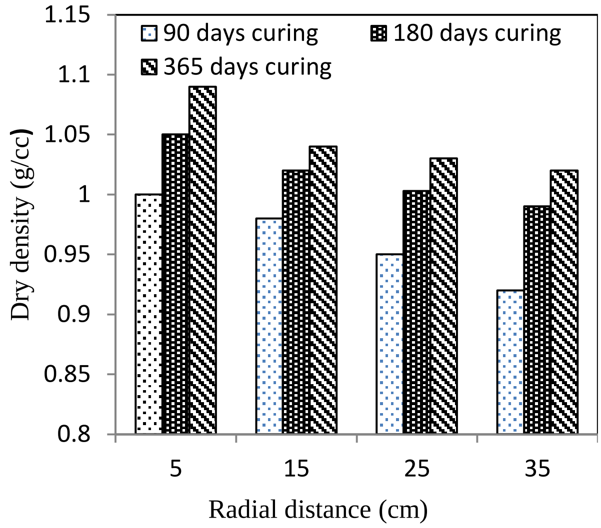


Fig. 8 Variation of dry density with radial distance at 50cm depth for compacted fly ash bed

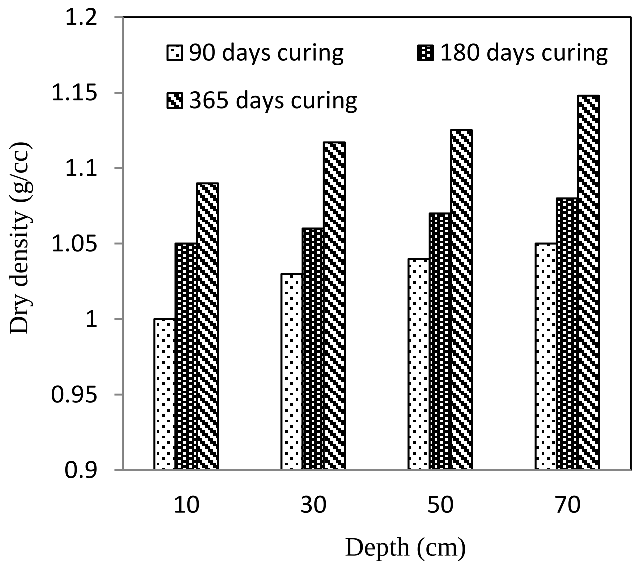


Fig. 9 Variation of dry density with depth at 5cm radial distance for compacted fly ash bed

A comparative study in the samples collected in the sedimented and compacted fly ash beds shows that the dry density ofsamples collected on 365 days curing is more in case of compacted fly ash bed . This may be due to the presence of dense layer in case of compacted fly ash bed and loose material in case of sedimented fly ash bed

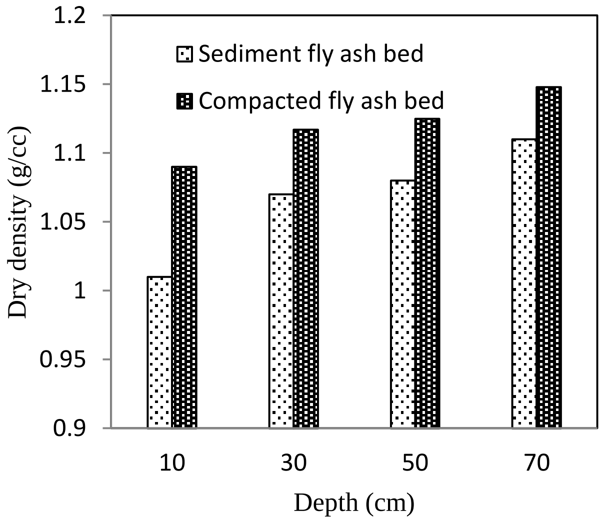


Fig. 10 Variation of dry density with depth in the specimens collected from 5cm radial distance in the ash beds on 365 days curing

Unconfined Compressive Strength

The variation of unconfined compressive strength with with depth at different curing periods for sedimented and compacted fly ash bed is shown in (Fig. 11 and 12). From the test results, it is found that the the UCS value is higher in the sample collected near to the lime column as compared to the specimen collected at a greater radial distance. The same follow an increasing trend with increase in depth from the top surface of the fly ash bed. This is due to the presence of higher concentration of lime at the location adjacent to the lime column which takes part in pozzolanic reaction and results in formation of more amount of C-S-H gel near the lime column. It is also observed from (Figure 8) that as the curing period increases, significant increase in UCS value occurs in all the depths of sediment pond ash deposit. This indicates that the hydration reaction continues with time for a considerable curing period, generating more amounts of hydration products and hence increases in strength.

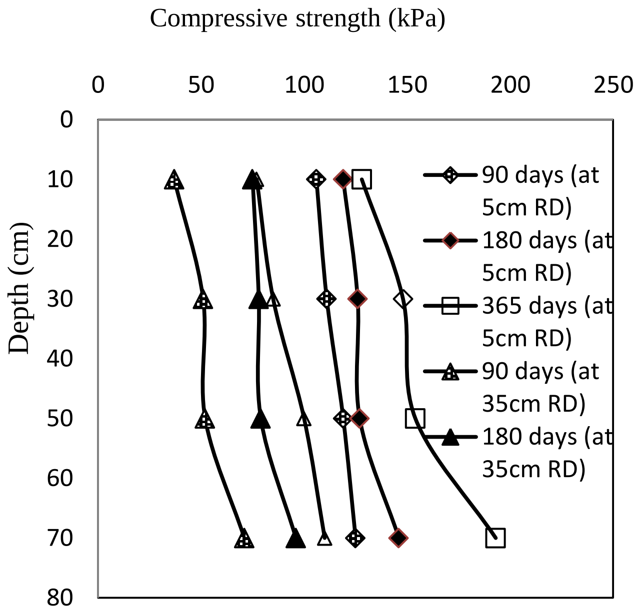


Fig. 11 Variation of UCS with depth at different curing periods for sedimented fly ash bed

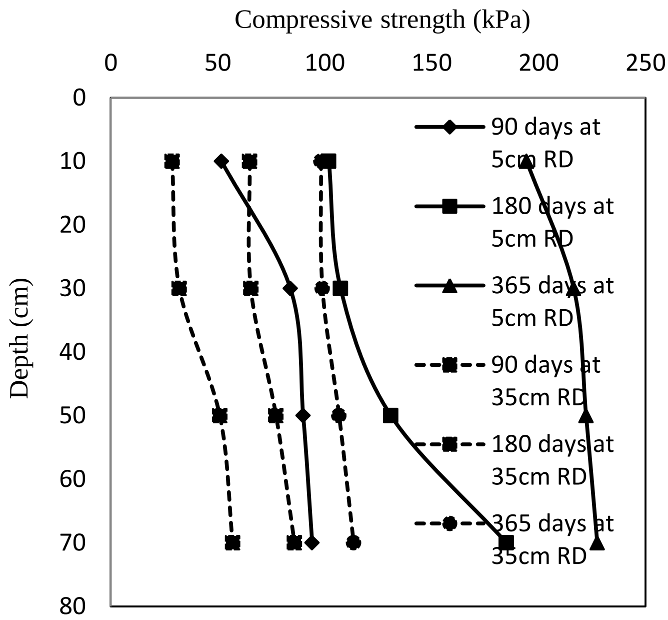


Fig. 12 Variation of UCS with depth at different curing periods for compacted fly ash bed

A comparactive study (Fig. 13) shows that the UCS value is more in the samples collected from compacted fly ash bed than that of sedimented fly ash bed. This is due to the presence of more dense layer in case of compacted fly ash bed than that of sedimented pond ash bed which leads to the increase in strength.

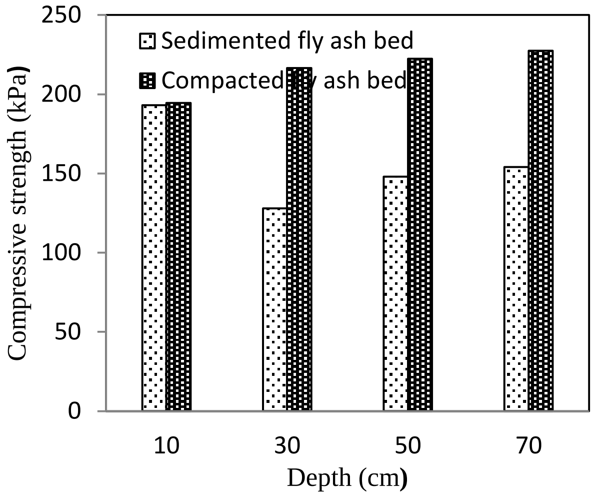


Fig. 13 Variation of UCS with depth in the specimens collected from 5cm radial distance in the ash beds on 365 days curing

Hydraulic Conductivity (k)

From the permeability test results, it is found that the hydraulic conductivity values of the specimens follow a decreasing trend with increase in depth from the top surface of the fly ash bed and also a reduced value is obtained in the samples collected adjacent to the lime column. This is due to the distribution of migrated lime over a wider area. As there is much concentration of lime near the at the location near to the lime column, so hydraulic conductivity is lesser for the samples collected adjacent to the column whereas the hydraulic conductivity is more for the samples collected at a remote area from the lime column. The reduced value of hydraulic conductivity is due to the participation of lime in pozzolanic reaction and formation of hydration products like C-S-H gel which causes reduction of void space and in the interconnectivity of pore channel. The test results show that hydraulic conductivity at depth of 10cm is less than that of 90. This indicates the presence of finer size particles on the top layer and coarser size at the bottom layer. Another possible reason for decrease in permeability on the top layer may be due to the evaporation of water from the surface of the ash deposit thus increase in concentration of lime in the pore water due to deposition of efflorescent lime. This higher concentration of lime in pore water results in formation of more hydration products thus reducing the hydraulic conductivity of the ash bed.

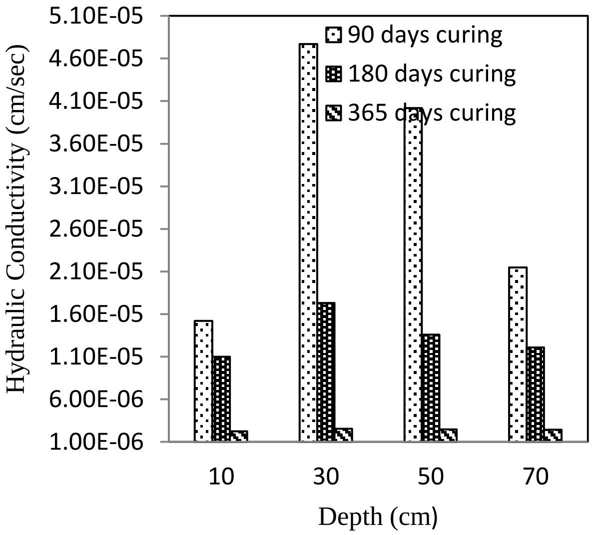


Fig. 14 Variation of k with depth at 5cm radial distance for sedimented fly assh bed

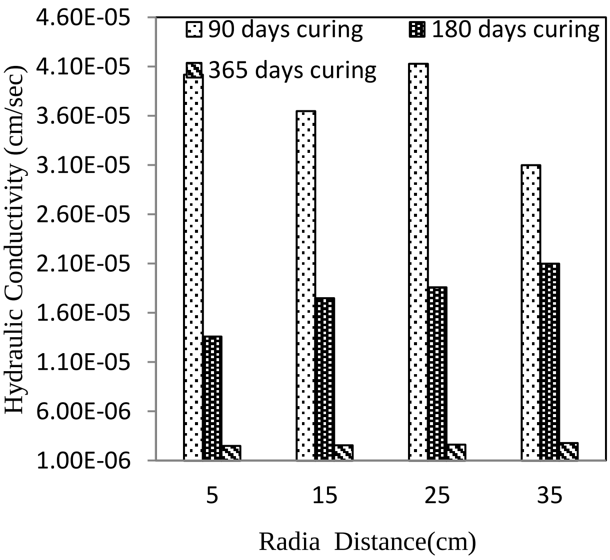


Fig. 15 Variation of k with radial distance at 50cm depth for sedimented fly ash bed

It is also observed that as the curing period increases, significant reduction in hydraulic conductivity occurs in all the depths of sediment pond ash deposit. This indicates that the hydration reaction continues with time for a considerable curing period, generating more amount of hydration products and hence reduction in hydraulic conductivity.

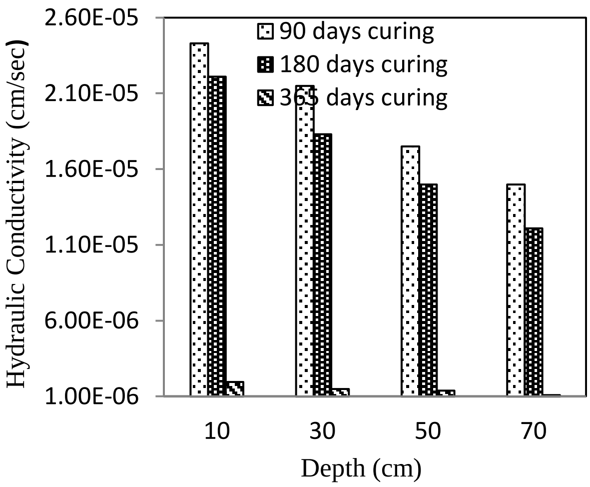


Fig. 16 Variation of hydraulic conductivity with depth at 5cm radial distance for compacted fly ash bed

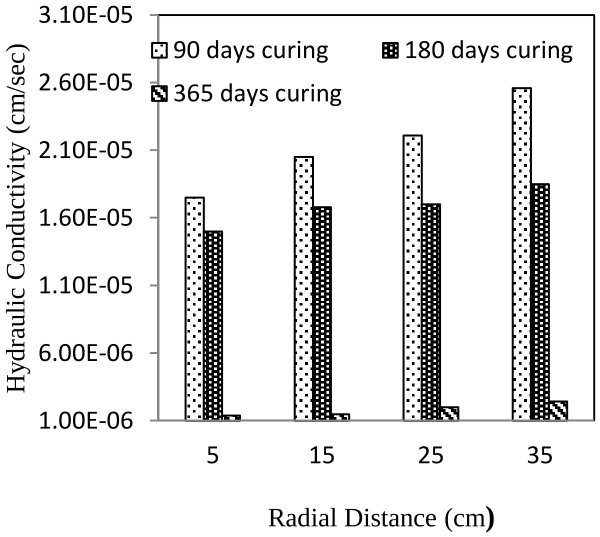


Fig. 17 Variation of hydraulic conductivity with radial distance at 50cm depth for compacted fly ash bed

A comparative study (Fig. 18) shows that the hydraulic conductivity in the samples collected from compacted fly ash bed is less than that of sedimented fly ash bed. This is due to the presence of more dense layer in case of compacted fly ash bed than that of sedimented pond ash bed which leads to the reduction of voids and hence, reduction in hydraulic conductivity

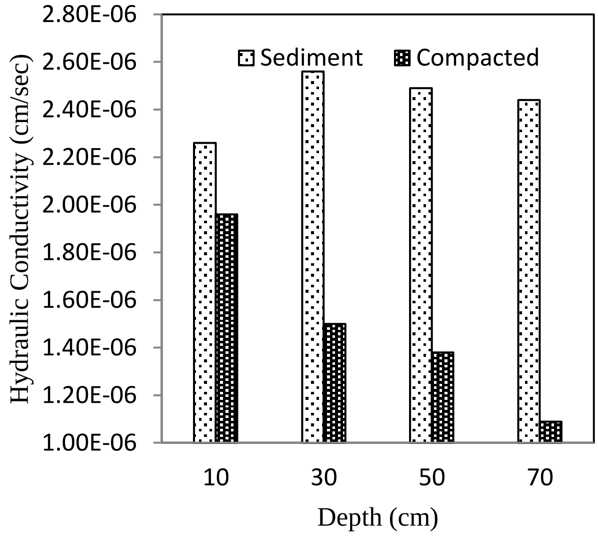


Fig. 18 Variation of hydraulic conductivity with depth in the specimens collected from 5cm radial distance in the ash beds on 365 days curing

CONCLUSIONS

Based on the experimental investigation the following conclusions can be drawn

- The dry density and UCS values were found to be increased with increase in depth and curing period. However, the same is found to be reduced with increase in radial distance from the lime column.
- The water content and hydraulic conductivity values were found to be decreased with increase in depth and curing period. However the same is found to be more with increase in radial distance from the lime column.

- A comparative study shows that the dry density and strength of compacted fly ash bed is much higher than the sedimented fly ash bed whereas the hydraulic conductivity value of the samples collected from compacted fly ash bed is less than that of sedimented fly ash bed.

Thus, the in-place stabilization by lime column technique has been found to be effective in increasing the unconfined compressive strength and reducing hydraulic conductivity of pond ash deposits in addition to modifying other geotechnical parameters including water content, density.

REFERENCES

1. Barnes, B.L., Ericson, W.A. and Madrid, L.D. (1993), In-place stabilization of waste phosphatic clay using lime columns, *Proceedings of third international conference on case histories in geotechnical engineering*, St. Louis, Missouri, 1301-1304
2. Chand, S K. and Subbarao, C. (2007), In-place stabilization of pond ash deposits by hydrated lime columns, *J. Geotech. and Geoenvironmental Eng*., 133(12), 1609–1616.
3. Ghosh, A. and Subbarao, C. (1998), Hydraulic conductivity and leachate characteristics of stabilized fly ash, *Journal of Environmental Engineering*, 124(9), 812-820.
4. Ghosh, A. and Subbarao, C. (2001), Microstructural development in fly ash modified with lime and gypsum, *J. Mater. Civ. Eng.*, 13, 65–70.
5. Ghosh, A. and Subbarao, C. (2007), Strength characteristics of class F fly ash modified with lime and gypsum, *Journal of Geotechnical and Geoenvironmental Engineering*, 133(7), 757-766.
6. Gupta, A K., Kumar, S. and Tolia, D S. (1998), Lime slurry injection, lime piles and stone columns for improvement of soft soils-field trials, *4th international conf. on case histories in Geotech. Eng.*, St.Louis, Missouri, Paper No. 7.10.
7. Hardianto, F S., and Ericson, W A. (1994), Stabilization of Phosphatic Clay Using Lime Columns. Florida Institute of Phosphate Research (FIPR), Bromwell & Carrier, Inc., Lakeland, Florida, 91-02-088.
8. Kishan, D., Dindorkar, N. and Shrivastava, R. (2012), Characteristics of low lime fly ash stabilized with lime and gypsum., *International Conference on Future Environment and Energy*, IPCBEE, Vol. 28 (2012), IACSIT press, Singapore.
9. Kokusho, T., Nakashima, S., Kubo, A. and Ikeda, K. (2011), Soil investigation of fly ash deposit improved by heavy compaction method, *Journal of Geotechnical and Geoenvironmental Engineering*, 138(6), 738-746.
10. Moghal, A A B. and Sivapullaiah, P V. (2011), Effect of pozzolanic reactivity on compressibility characteristics of stabilised low lime fly ashes, *J. Geotech and Geology Eng.*, 29, 665–673.
11. Muntohar, A S. (2010), A laboratory test on the strength and load-settlement characteristic of improved soft soil using lime-column. *Akreditasi BAN DIKTI No: 110/DIKTI/Kep/2009*, 10(3), 202-207.
12. Raju, V. R. (2011), Ground improvement using vibro techniques in flyash deposits, *National Conf. Recent Ad. Ground Improve. Techniques*, February 24-25, CBRI Roorkee, India, Indraratna, B & Chu., J. (eds.), 601-638.
13. Tonoz, M., Gokceoglu, C. and Ulusay, R. (2003), a laboratory-scale experimental investigation on the performance of lime columns in expansive Ankara (Turkey) clay. *Bulletin of Engineering Geology and the Environment*, 62(2), 91-106.
14. Wilkinson, A., Haque, A., Kodikara, J., Adamson, J. and Christie, D. (2010), Improvement of problematic soils by lime slurry pressure injection: case study, *Journal of Geotechnical and Geoenvironmental Engineering*, 136(10), 1459-1468.