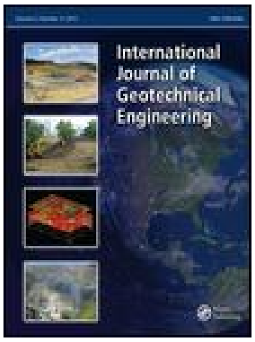

Taylor & Francis
Taylor & Francis Group

International Journal of Geotechnical Engineering

ISSN: 1938-6362 (Print) 1939-7879 (Online) Journal homepage: www.tandfonline.com/journals/yjge20

Permeability of Panki fly ash under stress

Ajanta Sachan & Krishna Rao

To cite this article: Ajanta Sachan & Krishna Rao (2010) Permeability of Panki fly ash under stress, International Journal of Geotechnical Engineering, 4:1, 63-70, DOI: 10.3328/IJGE.2010.04.01.63-70

To link to this article: https://doi.org/10.3328/IJGE.2010.04.01.63-70

Published online: 04 Sep 2013.

Ajanta Sachan[1] and Krishna Rao[2]*

Permeability of Panki fly ash under stress

ABSTRACT: The influence of stress state on permeability of fly ash has been investigated using a combined setup of odometer and falling head permeability devices. The specimens have been prepared using air pluviation method for obtaining loosest state, standard proctor test for compacted state, and soaking method under load for weathered state of Panki fly ash. A series of 1-D consolidation tests at different loading conditions have been performed on these specimens, and then the permeability of fly ash has been obtained for constant stresses of 27 kPa, 71 kPa, 143 kPa, 269 kPa, 528 kPa and 1046 kPa for three types of specimens. The correlations have been developed between permeability and stress values for all three cases considering the effect of initial state of the specimen. This research can be useful for designing and construction of civil engineering structures such as ash dyke, highway and railway embankments, small dams and other structures where continuous external forces act on them. Permeability of Panki fly ash was obtained to be significantly lower for soaked state as compared to loosest and compacted state of fly ash under given stress level possibly due to the formation of some substances between the particles during soaking of fly ash under water for 18 days indicating weathering reaction.

KEYWORDS: Fly ash, Permeability, Stress, Consolidation, Weathering

NOTATIONS

Abs ΔH = Absolute settlement of specimen ($\Delta H = H_{initial} - H_{after}$ consolidation)
C_c = coefficient of compression
C_s = coefficient of swelling
C_v = coefficient of consolidation
e = void ratio
e_o = initial void ratio
γ_d = dry density
k = coefficient of permeability
P = vertical stress applied
OMC = optimum moisture content
σ_v' = pre-consolidation pressure

INTRODUCTION

Fly ash is a waste product of coal based thermal power stations. It is a fine-grained material with most of the particles being of silt size. Due to the lack of space for dumping it, many researchers are now focused on its effective disposal techniques. For many years, fly ash is being used in many areas like cement and concrete industry, roads and embankments, fills, landfill liners, mining and stowing, agriculture, etc. The prompt action of utilization of Fly ash has made a remarkable progress in recent years. However, it is necessary to study its behavior in various conditions for its efficient use. In the current research, experiments and analysis have been performed on specimens of fly ash at its different initial states (loosest, compacted, and soaked) to evaluate its permeability properties under varying stress conditions. The results of this study can be further used to explore new efficient ways of using fly ash; such as filling material in embankments, dams, roads, etc. where continuous external forces act.

Permeability is the measurement of material's ability to transmit fluids through it. The fluid flow characteristics do not solely depend on availability of pores but their inter-connectivity too. The relative saturation of pores with fluid and nature of particle arrangement affects the coefficient of permeability. It also depends on fluid properties like viscosity and pressure gradient applied to porous media. Since fly ash comprises of fine particles, falling head method is more suitable to determine the coefficient of permeability under different stress conditions. The permeability of a material with high fines content is relatively negligible to sensitize accurate measurement of transmission or discharge of fluid using a constant head permeability test.

The consolidation process mainly depends up on the porosity and inter-connectivity of particles to allow fluids to pass through them. The consolidation process binds the

*Corresponding Author

[1]Ajanta Sachan, Senior Scientist, Dept. of Civil Engineering, Indian Institute of Technology, Kanpur, India. Phone: +91-512-2596114, E-mail: ajanta_sachan@yahoo.com (Corresponding author)

[2]Krishna Rao, Undergraduate Student, N.I.T. Warangal, India

DOI 10.3328/IJGE.2010.04.01.63-70

soil particles physically or chemically to form a matrix of decreased volume with reduced permeability. The volume of matrix decreases by squeezing out pore water from specimen on account of gradual dissipation of excess hydrostatic pressure induced by an imposed total stress. When stress is applied to a saturated specimen, the pore water seeped out from the material is indicative of the storage capacity of voids. On removal of stress, the particles partially regain their lost volume and thereby increase pore space. The reduction in volume is concomitant with stress transfer from water to soil grains, and therefore the effective stress plays a vital role rather the total stress. On understanding the nature of fly ash in the application of external stress conditions and bouncing back of particles on its removal elucidates the usage as a filling material in embankments, dams, roads, etc. where continuous external forces are applied to the structure.

PREVIOUS INVESTIGATION

Many researchers (Kaniraj and Havanagi 2001, Das and Yudhbir 2005) studied geotechnical engineering properties of fly ash such as; grain size, specific gravity, compaction characteristics and unconfined compression strength of both low and high calcium/lime fly ashes and suggested that geotechnical properties of fly ashes should be characterized by lime content, iron content, loss on ignition, morphology and mineralogy. Kaniraj and Gayathri (2004) studied the influence of the head loss across the specimen, the effective stress, and the void ratio on the permeability, and they reported that the permeability and consolidation behavior of compacted fly ash were comparable to those of non-plastic silts. They also suggested that the coefficient of permeability of fly ashes should be determined directly from permeability tests and not by back-calculation from consolidation tests, which is a general trend in practice.

Bolton (2000) reported that permeability is not simply a function of effective stress, but varies according to the consolidation state of the soil and whether effective stress variations arise through confining or pore fluid pressure changes. A typical elasto-plastic response was observed due to the change in confining stress, and more pronounced increase in permeability was observed due to the rise in fluid pressure. Di and Sato (2003) studied the liquefaction of saturated soils taking porosity and permeability with large deformation into account and presented a numerical method on Biot's two phase mixture theory and the updated Lagrangian method, and concluded that the coefficient of permeability changes with deformation in soil matrix. Zhang et al. (2007) experimentally proved that fluid flow and permeability varied greatly as a function of stress in fractured media. In the triaxial stress-permeability test, permeability decreased during the elastic deformation stage, but increased significantly in the inelastic deformation stage possibly due to the initiation of new cracks/paths for fluid flow.

Porbaha et al. (2000) investigated the effect of time on permeability and shear strength of two types of class-F Fly ash specimens from Japan under constant stress of 49 and 98 kPa for 12 days. They reported that the shear strength of both fly ash specimens increased with the increase in consolidation time; however, the rate of increase was different depending on the pozzolanic reactions taking place for the two ashes, each having a different Ca content. The permeability tests under a constant stress of 49 and 98 kPa for 12 days showed that the coefficient of permeability for the ashes was obtained to be in between 10-6 and 10-7 m/s. During this period, the coefficient of permeability remained constant for the fly ash with lower lime content, whereas it fell slightly for the fly ash with higher lime content. The examination of the microstructure using the SEM images revealed the formation of needlelike substances for the fly ash with higher lime content, which may contribute to the reduction of permeability with time. The permeability response of fly ash under different stress conditions (complete range from low to high stress) is still under-explored, which is important to know for the design of embankments, dams, roads, etc, where fly ash is used as a filling material and continuous external forces are applied to the structure.

MATERIAL PROPERTIES

In the present study fly ash was taken from Panki Thermal Power Plant, Kanpur; which was Class-F fly ash (ASTM C618-03) with low calcium content produced by bituminous coal. The grain size distribution analysis was performed for the Panki fly ash, which included both sieve analysis and hydrometer test. The Panki fly ash had 1.6% clay size particles, 66.1% silt sized particles, and 32.3% sand sized particles. The value of coefficient of uniformity (C_u) was obtained to be 5.3 and the coefficient of curvature (C_c) to be 1.7. On close observation, it was seen that the uniform distribution was predominantly in the silt zone which constituted nearly 60% of fly ash (Waseem, 2006). The specific gravity (G_s) of Panki fly ash was obtained to be 1.98, which was significantly lower than that of soils ($2.6 < G_s < 2.9$). It is important to note that the particle size of fly ash produced by bituminous coal is predominantly similar to that of silts, and the usual range of the specific gravity of F class fly ash is 1.7 to 2.2. Thus, the fly ash particles were much lighter than typical soil particles.

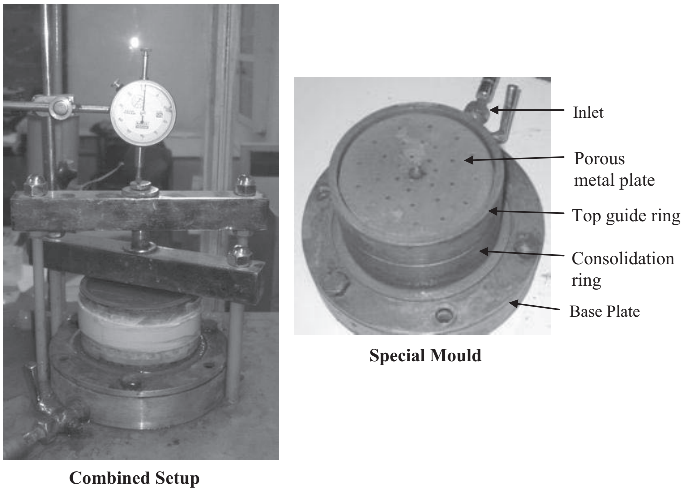

Figure 1. A picture of combined setup having Odometer and Falling head permeability testing devices to obtain permeability of fly ash under stress

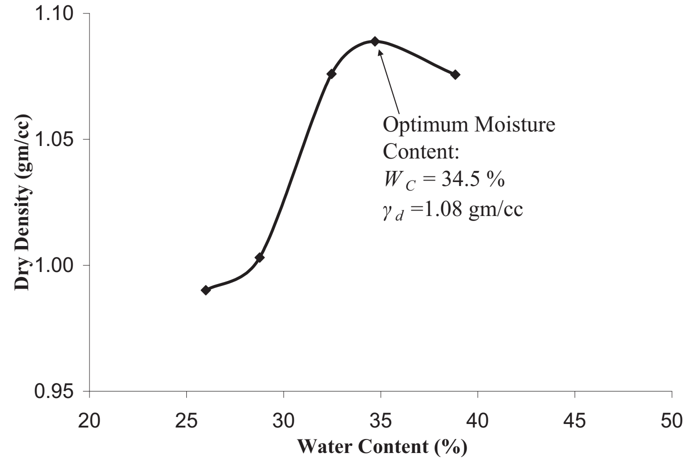

Figure 2. Standard proctor test of fly ash for optimum moisture content (OMC)

EQUIPMENT

All the experiments were performed on a test setup which was modified from the falling head test apparatus to facilitate axial loading of the sample as well. The modified apparatus consisted of a combination of fixed ring odometer device and falling head permeability device, as shown in Figure 1. This apparatus had a special mould, which was used for both odometer and permeability tests. This mould had a base plate with a porous stone placed at top and bottom of the specimen having two rings which could be fixed one onto the other. The inner diameter of both the rings was 99.2 mm, and the height of bottom consolidometer ring and top guide ring was 45 mm and 30 mm respectively. The diameter of consolidation ring was taken larger than its usual size in order to facilitate better permeability measurements. These rings controlled the lateral deformation of the specimen during axial loading. The porous stones at top and bottom of the specimen were provided for drainage of water from the soil. A perforated metal plate with a small metal ball placed on its central hole was provided at top of the special mould, which was used to transfer the load uniformly to the specimen in vertical direction from the odometer device. An inlet at the bottom of the base plate was connected to the falling head burette which allowed the water to pass through the specimen from bottom to top while the water level at the top was kept constant.

SPECIMEN PREPARATION

1. Loosest state specimen (LS)

The oven dried fly ash was taken to prepare the specimen in the special mould required for performing test in combined setup. The bottom consolidometer ring in special mould was fixed on the base plate with a porous stone and filter paper at the base. The specimen was then prepared through air pluviation method. In this process, the fly ash was sprinkled through a funnel keeping it at a constant height of about 25 mm from the top surface of fly ash in the ring. The ring was filled till the brim formed and it was then trimmed and leveled uniformly. The top guide ring was then grooved and fixed on the bottom consolidometer ring. A porous stone was placed inside the guide ring with a filter paper placed on the specimen. A porous metal plate was placed on the porous stone inside top guide ring, and then the special mould with specimen was placed on the platform of loading setup.

2. Compacted state specimen (CS)

The oven dried fly ash was taken for performing the standard proctor compaction test, and its optimum moisture content (OMC) was obtained. The observed compaction curve for the fly ash has been shown in Figure 2. The dry density (γ_d) of the specimen at OMC was found to be 1.08 gm/cc. The fly ash specimen was prepared in the "special mould" (required for combined setup) and the maximum dry density at OMC was achieved through trial and error method. In the final iteration, the specimen was obtained by compacting fly ash into the mould in two layers with 15 blows per layer using standard proctor hammer. Then the compacted specimen of fly ash was placed in combined setup.

3. Soaked state specimen (SS)

Specimen 3 was prepared by keeping it under soaked condition with a small load on top of it for some period. One kilogram of fly ash was placed in a large container using air pluviation method, and then de-ionized water was poured in the container to completely submerge the fly ash. A compressive load, applying 3.5 kPa of vertical stress, was placed on top of the submerged fly ash for a period of 18 days. A portion of soaked fly ash was then extruded very carefully without disturbing its particle arrangement for obtaining soaked state of fly ash specimen in the special mould; which was later fixed in the combined setup for determining the permeability of Panki fly ash under different stress conditions.

TESTING PROCEDURE

The specimen was placed in the odometer setup in such a way that the lever arm was rested at equilibrium under "no load" conditions. The dial gauge was used to record the settlement in fly ash specimen during its 1-D consolidation. The specimen was allowed to saturate for 24 hours under no load conditions (except the load of porous stone and perforated plate on top). Then, the incremental load was applied on the specimen to obtain stress levels of 27 kPa, 71 kPa, 143 kPa, 269 kPa, 528 kPa and 1046 kPa. The water inlet at the bottom was kept closed during settlement measurements throughout the consolidation test. The dial gauge readings were taken at time intervals; 0.25, 0.5, 1, 2, 4, 8, 15, 30, 60, 120 min, till the primary consolidation was achieved. A series of variable head permeability tests were conducted to obtain the permeability values of fly ash after the consolidation process at each stress level.

COMPRESSIBILITY OF VARIOUS FLY ASH SPECIMENS

Figure 3 shows the compressibility curve, void ratio vs. vertical effective stress (e – logσ_v'), for specimens of Panki fly ash. It could be observed that the fly ash specimen formed at loosest state (LS) exhibited considerable decrease in void ratio in response to the increase in stress level during loading in comparison to the specimens formed at compacted (CS) and soaked (SS) states. The effect of initial void ratio was quite evident from all the compression curves. The LS specimens had sufficient void space to allow for rearrangement of particles; whereas, the SS specimens had less void space and thus allowed less compression. Although, there was negligible pre-compression in the case of both LS and SS specimens, the compression curve due to its nonlinearity indicated pre-consolidation stress (σ_{vo}') in the range of 80 to 100 kPa. The CS specimen had the history of energy being introduced through compaction process and the test data showed the value of $\sigma_{vo}' \approx 300$ kPa. The non-linearity of compression curves was observed beyond these interpreted σ_{vo}' values and it continued up to the maximum loading that was applied to the specimens i.e. 1046 kPa. Similar non-linear compressibility curves were observed by Trivedi and Sud (2002). At the maximum applied vertical stress, the values of void ratio were close to each other in the range of 0.71 to 0.73. Probably for the same reason, the unloading curves for all the cases (LS, CS and SS) appeared close to each other with small variation in void ratio.

The compression curve of SS specimen approached to the LS specimen at large stress with the tendency of merging into it. Hence, soaking the fly ash for 18 days possibly did not change compressibility characteristics of the specimen. The variation in the compression curve was plausibly due to the change in initial void ratio. Another argument could be that the signature of possible effect of soaking in SS specimens was gradually lost at high stresses. This argument would be further discussed later in terms of the other form of signature i.e. the permeability. The CS specimen went beyond the compression line of LS specimen indicating much stiffer response. Such observation leads to the possibility of significant change in the grain size distribution (GSD) and packing of the particles during compaction process. The fly ash particles are generally hollow and their outer surface has frosted texture. They may undergo large deformation and become

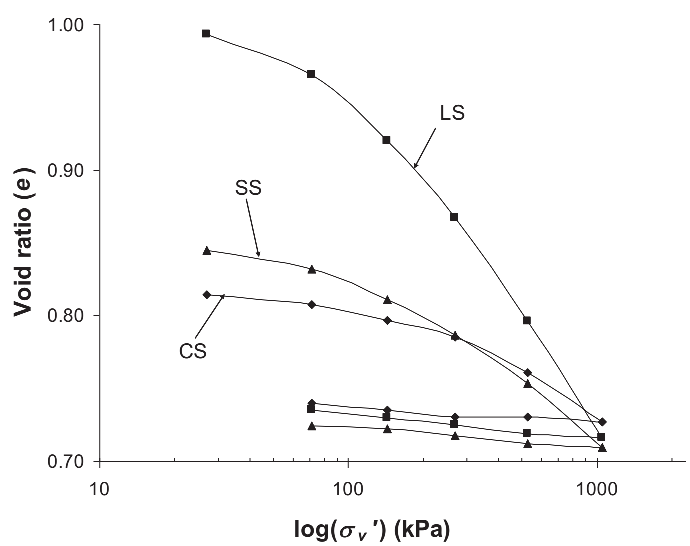

Figure 3. One-dimensional compression curves for Panki fly ash. (a) LS (loosest state), (b) CS (compacted state), (c) SS (soaked state)

Table 1. Consolidation properties of Panki fly ash

Fly ash specimen	Initial void ratio e_o	C_c	Void ratio at unloading e_p	C_s	$\frac{C_s}{1+e_p}$	$\frac{C_s - C_s}{1+e_o}$
LS: (Loosest state)	1.32	0.253	0.717	0.019	0.0111	0.1009
CS: (Compacted state)	0.837	0.092	0.727	0.016	0.0093	0.0414
SS: (Soaked state)	0.965	0.131	0.710	0.018	0.0105	0.0575

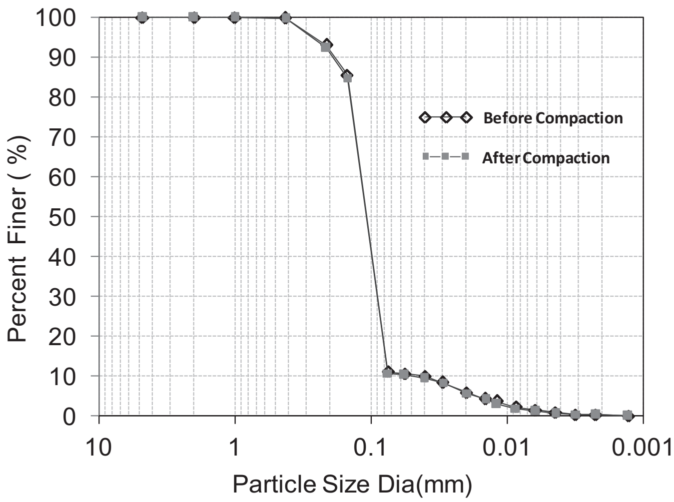

Figure 4. Grain-size distribution of fly ash before and after compaction

susceptible to crushing when subjected to large particle contact forces during compaction. To evaluate the possibility of crushing, the GSD analysis was performed on the specimens taken before and after compaction and they did not show any significant change in the particle sizes, as shown in Figure 4. Hence, crushing could not be the phenomenon causing such stiff response. The other possibility could be the interlocking of particles which could better in CS specimens in comparison to the other specimens due to frosted texture of particle surface. Such change could take the normal compression line of CS beyond the same of LS or SS specimens. The signature of good packing of CS specimen could be observed to some extent in unloading curve as well. The slope of unloading curve of CS specimen was relatively lower than the same of LS and SS specimens.

The value of compression index C_c was determined by approximating the later part of loading curve assuming it to be linear and the swelling index *Cs* was estimated by using the points at 1046 and 71 kPa along the unloading curve. Table 1 summarizes the compressibility parameters determined for the specimens LS, CS and SS. The parameters C_s and C_c are considered to be representing the elastic and elasto-plastic deformation of the material respectively. Hence, the logarithmic volume compressibility can be defined as $C_{ve} = C_s/(1 + e_p)$ for elastic component and $C_{vp} = C_c - C_s)/(1 + e_p)$ for plastic component. The values of the parameters have been also included in Table 1. It is evident that the reduction in void ratio after soaking/compaction reduced mainly the plastic compressibility. Figure 5 shows the relationship between C_{vp} and e_o. This data indicated an interesting observation that C_{vp} and e_o had perfectly linear relationship. Extrapolation of the linear relationship suggests that the plastic volume compressibility C_{vp} would go to zero at $e_o = 0.5$, which could be interpreted as the particle packing would reached its extreme at $e_o = 0.5$ and there would be no further plastic deformation in the matrix on axial loading.

PERMEABILITY OF FLY ASH AT VARIOUS STRESS LEVELS

The permeability of the specimens at various stress level can be obtained using consolidation data through compressibility information and time of consolidation. There are few approximate methods which can be used to determine the period of 50% or 90% consolidation. These methods were developed considering typical consolidation curves of soils. It has also been learnt from experience that use of these methods in most cases results into a range of permeability values at the same state of a soil. Figure 6 shows the

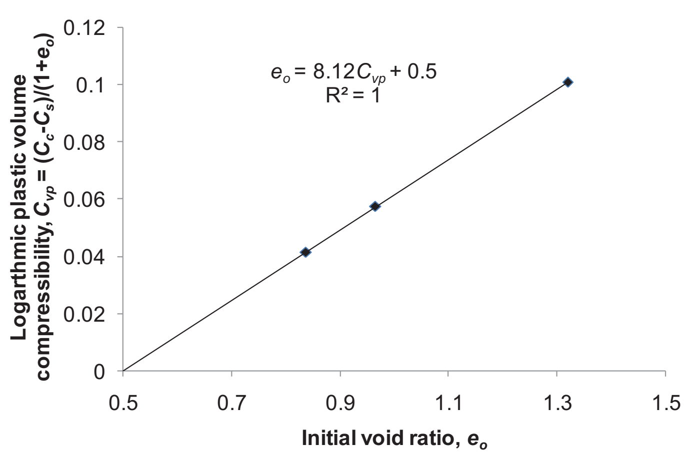

Figure 5. Plastic volume compressibility with initial void ratio of various specimens

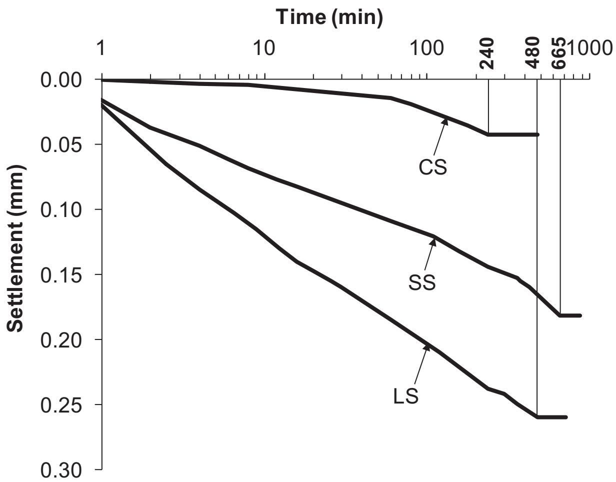

Figure 6. Settlement vs. time curve for vertical stress increase from 528 to 1046 kPa

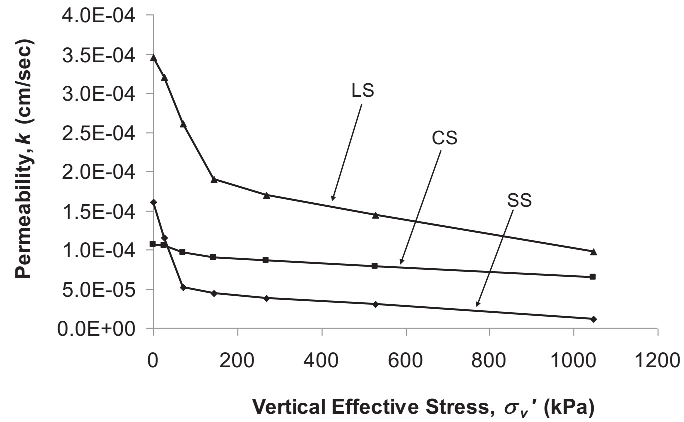

Figure 7. Permeability of Panki fly ash under stress conditions

consolidation curves (settlement with time at constant load) of three cases of fly ash specimens for vertical stress increase from 528 to 1046 kPa, which do not appear to be typical of soils. Considering the nonlinearity of e – $\log\sigma_v'$ relationship and uncertainty in determination of consolidation period through the conventional methods for soils, a series of variable head permeability tests were performed at each stress level after completing the consolidation process. Standard procedure of the test was carefully followed and the specimen size was taken such that it was suitable for both consolidation and permeability tests.

Figure 7 shows the relationship between permeability (k) and the applied vertical effective stress (s_v') on fly ash specimens. For all three cases (LS, CS and SS), the relationship between k and s_v' was observed to be bilinear. Although the CS specimen showed relatively less variation in the slope of the relationship, the bilinear form was quite evident. The point of intersection in bilinear relationships was observed at 150 kPa in the case of LS and CS specimens and at 75 kPa in the case of SS specimen. These points of intersection in fact correspond to the onset of approximately linear portion in the later part of e-log(s_v') curves. It is important to note that for all three specimens the permeability of fly ash was linearly dependent on effective vertical stress within the so called normal consolidation zone. This is atypical of soils which show more of nonlinear response and in most cases the permeability follows linear relationship with log(s_v'). Figure 7 shows that the permeability of CS specimen was the lowest at very low stresses due to given fact that the initial void ratio of CS specimen was the lowest. At larger stress the permeability of SS specimen was considerably lower than the CS specimen and the lowest among all the specimens (Table 2). This is important observation under the given fact that at any effective stress level the CS specimen still had the lowest void ratio among three specimens. Figure 8 shows the relationship of permeability and void ratio for these fly ash specimens, which indicates that at a given value of void ratio the SS specimen showed the lowest value of permeability as compared to LS and CS with considerable margin. For example at void ratio of 0.8 the permeability was observed to be 1.44E-04 cm/sec for LS, 9.17E-05 cm/sec for CS, and 4.17E-05 cm/sec for SS specimen.

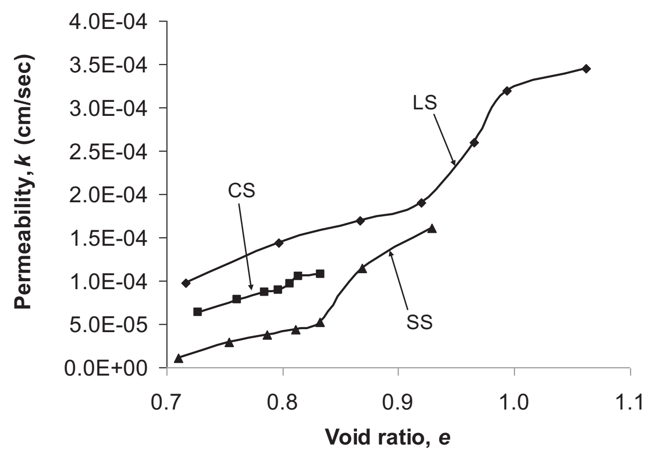

Figure 8. Void ratio and permeability relationship for weathering reaction

Despite having its void ratio larger than CS specimens the lowest permeability of SS specimens suggests some kind of weathering effect on the permeability of fly ash (Table 2). One of the possibilities is formation of some substances between the fly ash particles during soaking process under water for 18 days which could have allowed time dependent

Table 2. Permeability of fly ash under Stress

Stress P (kPa)	LS (loosest state)			CS (compacted state)			SS (soaked state)		
	Void ratio (*e*)	Abs *ΔH* (mm)	*k* (cm/sec)	Void ratio (*e*)	Abs *ΔH* (mm)	*k* (cm/sec)	Void ratio (e)	Abs *ΔH* (mm)	*k* (cm/sec)
1	1.062	5.00	3.45E-04	0.833	0.09	1.07E-04	0.929	0.82	1.61E-04
27	0.993	6.34	3.20E-04	0.814	0.56	1.05E-04	0.845	2.75	1.15E-04
71	0.965	6.88	2.60E-04	0.807	0.72	9.67E-05	0.832	3.05	5.21E-05
143	0.920	7.76	1.90E-04	0.797	0.99	8.95E-05	0.811	3.52	4.44E-05
269	0.867	8.78	1.70E-04	0.782	1.27	8.63E-05	0.787	4.08	3.81E-05
528	0.796	10.16	1.44E-04	0.761	1.87	7.81E-05	0.753	4.85	2.98E-05
1046	0.717	11.71	9.76E-05	0.727	2.69	6.40E-05	0.710	5.85	1.13E-05

chemical reactions to happen. Such formations might act as obstacles to free movement of water in the pores causing the increase in tortuosity of pore network and viscous forces per unit volume, which may eventually reduce the permeability of SS specimen significantly. Porbaha et al. (2000) examined the microstructure of Hekinan ash (soaked under water for 12 days) using SEM technique, which revealed the formation of needlelike substances between the fly ash particles; and this was considered to be the possible reason for the reduction in permeability of Hekinan ash with time.

The relationship of permeability with void ratio could be observed as bi-parabolic in all three cases by considering two separate continuous parabolic functions for before and after the point of intersection observed in bi-linear relationship of k-s_v'. The Kozeny–Carman equation of permeability variation with void ratio can also be approximated as parabolic relationship of *k* to *e*. However, the relationships in figure 8 suggest that the best fit parabolic functions for the fly ash specimens would be contradicting Kozeny–Carman equation i.e. the function would be quadratic in *k* and not in *e*.

CONCLUSIONS

The effect of stress level on permeability of Panki fly ash was explored in this paper for three types of specimens i.e. loose (LS), compacted (CS) and soaked (SS) under water for 18 days. The compressibility and permeability of the fly ash specimens was measured at various stress levels using a specially designed combined setup facilitating both one-dimensional compression and falling head permeability tests. The effect of initial void ratio was observed to be quite evident in compression curves of all three types of specimens; LS, CS and SS. The compression curve of SS specimen approached to the LS specimen at large stress levels with the tendency of merging into it, which indicated that soaking of fly ash for 18 days possibly did not change its compressibility characteristics. The CS specimen went beyond the normal compression line of LS specimen indicating much stiffer response possibly due to the unique packing achieved by the fly ash particles with frosted texture surface during compaction process. It was observed that the reduction in initial void ratio after soaking or compaction reduced mainly the plastic component of compressibility. The logarithmic form of plastic volume compressibility C_{vp} incidentally showed perfectly linear relationship with the initial void ratio of fly ash specimens.

For all three cases (LS, CS and SS), the relationship between permeability and effective vertical stress was observed to be bilinear, and the point of intersection was observed at 150 kPa in the case of LS and CS specimens and at 75 kPa in the case of SS specimen. It was inferred that the permeability of fly ash was linearly dependent on effective vertical stress within the “normal consolidation zone”. Despite the fact that SS specimen had its void ratio larger that CS specimen, the permeability values were lowest for the SS specimen. Such observation suggests significant influence of time dependent weathering effect on permeability characteristics. The relationship of permeability with void ratio was observed to be parabolic in two separate intervals of void ratio. In each segment, the increment of permeability was proportional to the square root of the increment of void ratio.

REFERENCES

ASTM C618-03 (2003). “Standard specifications for coal fly ash and raw or calcined natural pozzoaln for use as a mineral admixture in concrete.” *ASTM*, West Conshohocken, PA, USA

Bolton, A.J. (2000). “Some measurements of permeability and effective stress on a heterogeneous soil mixture: implications for recovery of inelastic strains.” *Engineering Geology*, 57, 95-104.

Das, S.K. and Yudhbir (2005). “Geotechnical characterization of some Indian fly ashes.” *Journal of Materials in Civil Engineering*, ASCE, 17(5), 544-552.

Di, Y. and Sato, T. (2003). "Liquefaction analysis of saturated soils taking into account variation in porosity and permeability with large deformation." *Computers and Geotechnics*, 30, 623-635.

Kaniraj, S.R. and Havanagi, V.G. (2001). "Correlation analysis of laboratory compaction of flyashes." *Practice Periodical of Hazardous, Toxic, and Radioactive Waste Management,* Vol. 5, No. 1, pp. 25-32.

Kaniraj, S.R. and Gayathri, V. (2004). "Permeability and consolidation characteristics of compacted fly ash." *Journal of Energy Engineering*, ASCE, 130(1), 18-43.

Porbaha, A., Pradhan, T.B.S., and Yamane, N. (2000). "Time effect on shear strength and permeability of fly ash." *Journal of Energy Engineering*, ASCE, 126(1), 15-31.

Trivedi, A. and Sud, V.K. (2002). "Grain characteristics and engineering properties of coal ash." *Granular Matter*, 4, 93-101.

Waseem, M. (2006). "Stress-strain behavior of Panki fly ash." Mtech. Thesis I.I.T. Kanpur.

Zang, J., Standifird, W.B., Roegiers, J.C., and Zhang, Y. (2007). "Stress dependent fluid flow and permeability in fractured media: from lab experiments to engineering applications." *Rock Mech. Rock Eng*, 40(1), 3-21.