A DIMENSIONLESS APPROACH TO MODEL HYDRAULIC CONDUCTIVITY OF SOIL-FLY ASH MIXTURES

[1]ANURADHA PANDEY, [2]RAM PAL SINGH

[1, 2] Civil Engineering Department MNNIT Allahabad, Allahabad-21104, U.P., (INDIA)
Email: [1]anuparul24@gmail.com,[2]rps@mnnit.ac.in

Abstract - This paper is aimed to develop a data based mathematical model for the estimation of hydraulic conductivity of clayey soil-fly ash mixture using dimensionless approach. A locally available soil of class CL-ML from Lambhua, Sutanpur, India. and Fly ash (FA) from thermal power plant, Panki, Kanpur, India were collected and used in the experiments. Different proportions of FA varying from 0% to 100% by weight were added to the soil. The hydraulic conductivity of soil-fly ash mixtures was determined using falling head permeability test in the laboratory. Eight variables influencing the hydraulic conductivity of soil-fly ash mixture under permeability test viz. initial head, final head, cross sectional area of stand pipe, cross sectional area of soil specimen, void ratio, specific gravity of the soil, fly ash content and superficial velocity of flow were considered for the development of a dimensionless mathematical function for the estimation of hydraulic conductivity of soil-fly ash mixture. A multiplier function was developed using the various dimensionless groups. The multiplier function was fitted linearly with the experimental results with good R^2 value 0.9756. The results indicate that such mathematical function can be effectively used for estimation of hydraulic conductivity of soil-fly ash mixture. The error estimates between the experimental and predicted hydraulic conductivities show that the most of the predicted results are within ± 24% error band with few exceptions.

Keywords - Falling Head Permeability Test, Dimensionless Variables, Clayey Soil, Fly Ash, Hydraulic Conductivity, Multiplier Function.

I. INTRODUCTION

Now-a-days it has become a global concern and major challenges to dispose and reuse the fly ash safely, not only for safety of environment but also for geotechnical engineers, because i) disposal of enormous amount of fly ash involves consumption of huge land and ii) generate the problem of leaching and dusting in wet and dry conditions respectively. Therefore, the best way of disposing fly ash is to utilize it with some additives and converting it into a non-hazardous material and apply them in eco-friendly way. Fly ash is a pozzolana, a siliceous material which in the presence of water reacts with calcium hydroxide at ordinary temperatures to produce cementitious compounds. Fly ash possesses a wide range of chemical composition depending on the nature of coal and processes of coal burnt [1]. Because of its spherical shape and pozzolanic properties, fly ash is useful in cement and concrete applications. As emphasized by [2] that fly ash contains maximum hollow particles of lower apparent specific gravity than most of the solid particles. The modified characteristics of compacted soils resulting from soil- fly ash mixture may prove important to some geotechnical engineering applications such as pavement constructions, embankments construction and to combat expansibility and seepage problems. The utilization of fly ash may be a viable alternative for porous backfill material because fly ashes generally consist of silt-sized particles and consequently possess high permeability [3].

Permeability is vital to every project where the flow of water through soil is a concern (e.g. dam seepage, cutoff wall and diaphragm wall). In the context of soil, permeability generally relates to the porosity of a soil to allow fluid to move through its void spaces [3]. Tests must be performed to determine the permeability of soil-fly ash mixture since there is a lack of information on the horizontal permeability of the said mixes.

Various researchers have utilized the fly ash as stabilizing material in their studies ([1], [4], and [5]). Several researchers have studied the hydraulic conductivity of soils mixed with fly ash mostly for stabilization of the expansive soils and soil-ash mix as admixtures with subgrade soil for pavement constructions [5], [6] [7], and [8]. There are lack of studies on hydraulic conductivity tests conducted on local soils available nearby areas of KNIT Sultanpur and mixed with different proportions of fly ash.

Literature reveals that the hydraulic conductivity of soil or soil-fly ash mixture ‘k’ depends largely upon particle size, structure of soil mass, shape of particles, void ratio (e) or porosity (n), unit weight of water (γ_w) ,viscosity (μ), specific gravity (ρ_s) and percent ash content (p_a) [9]. In falling head permeability test, the hydraulic conductivity also depends upon area of stand pipe (a), area of soil sample (A), initial head (h_0) and final head (h_1). Void ratio (e) plays a major role and it has been established that the permeability of a soil varies as a function $\frac{e^3}{1+e}$, as per [9]. In the literature, little or no efforts are made to model the hydraulic conductivity of soil-fly ash mixture except its experimental determination in laboratory.

In the present work, a local clayey soil and Fly ash were used in the experiential determination of hydraulic conductivity using falling head permeability test. Geotechnical properties of soil and fly ash were determined in the soil engineering laboratory of KNIT Sultanpur, U.P. India as per standard methods and procedures. Various proportions of fly ash were added to the clayey soil to observe the changes in behaviour of hydraulic conductivity of the soil-fly ash mixtures. Using dimensionless approach, a multiplier function containing dimensionless variables has been developed and tested with experimental results of the present work.

II. MODEL DEVELOPMENT

In order to develop a mathematical model for hydraulic conductivity of soil fly ash mixture using dimensionless approach, Buckingham π-theorem has been applied. The hydraulic conductivity of soil fly ash mixture is dependent on various variables as mentioned earlier. Based on the available results from present experiments, the hydraulic conductivity is regarded as the function of the following eight variables as shown in Eq. (1) below:

$$K=f\,(h_0, h_1, a, A, e, \rho_s, p_a \text{ and } v) \quad (1)$$

Using Buckingham π-theorem, the various dimensionless groups formed are:

$$\left(\frac{v * p_a}{k}\right), \left(\frac{A}{a}\right), \left(\frac{h_0-h_1}{h_0}\right), \text{ and } \left(\frac{e^3}{(1+e)*\rho_s}\right) \quad (2)$$

The dimensionless function $\left(\frac{e^3}{(1+e)*\rho_s}\right)$ has been adopted directly from [9], where hydraulic conductivity of any soil is considered dependent on this function.
Therefore, the dimensionless function for hydraulic conductivity can be expressed as:

$$\frac{v * p_a}{k}=\varphi\left[\left(\frac{A}{a}\right), \left(\frac{h_0-h_1}{h_0}\right), \left(\frac{e^3}{(1+e)*\rho_s}\right)\right] \quad (3)$$

The L.H.S. function of Eq. (3) can be written as multiplication of remaining three dimensionless terms for estimation of hydraulic conductivity of soil fly ash mixture (L.H.S. of function) and can be expressed as follows:

$$\left(\frac{v * p_a}{k}\right) = \left[\left(\frac{A}{a}\right) * \left(\frac{h_0-h_1}{h_0}\right) * \left(\frac{e^3}{(1+e)*\rho_s}\right)\right. \quad (4)$$

This function can be used to test the linear dependency of hydraulic conductivity function with the observed variables. The linear dependency of the Eq. (4) has been tested using the acquired experimental results for the known variables and a suitable linear multiplier function is developed to estimate the hydraulic conductivity (k) of the soil-fly ash mixture.

III. MATERIALS AND METHODS

3.1. Materials

In the present investigations clayey soil added with different proportions of fly ash have been used in various experiments. Local soil was collected from the agricultural field near Lambhua Sultanpur, India. Soil sample was then oven dried and sieved through 4.75 micron IS sieve. Fly ash was obtained from Panki thermal power station, Kanpur, India. Fly ash was then oven dried before use in the experiments.

3.2. Methods

3.2.1. Measurement of Hydraulic Conductivity

The hydraulic conductivity of the soil with and without addition of fly ash was determined using falling head permeability test as per the procedure described by [9]. A detailed description of the test is available elsewhere [10].

3.2.2. Measurement of Specific Gravity and Porosity

Specific gravity of various proportions of soil fly ash mixture was determined using pycnometer. For determination of porosity of soil fly ash mixture, different proportions of fly ash was mixed to the clayey soil and the mixture was filled in a measuring cup and 200 ml water was poured into cup carefully until the water just reached the top of soil-fly ash mixture. Now exact volume of water used is recorded. The porosity of soil-fly ash mixture was determined using the following relationship:

$$\text{Porosity} = \frac{\text{Amount of water added to sample}}{\text{total sample volume}}*100. \quad (5)$$

3.2.3 Determination of Void Ratio

The void ratio of soil fly ash mixture was determined using the following relationship:

$$e = \frac{n}{1-n} \quad (6)$$

where n is the porosity of soil-fly ash mixture.

IV. RESULTS AND DISCUSSION

4.1 Geotechnical Properties of Soil and Fly ash

The experimentally determined geotechnical characteristics of soil and fly ash are shown in table 1.

Table 1: Geotechnical Characteristics of Soil and Fly ash

S. No.	Characteristics	Soil	Fly ash
1.	Specific gravity	2.79	2.30
2.	Particle size distribution		
	(a) gravel	1.06	1%
	(b) sand	10.192	13.8%
	(c) silt &clay	88.702	84.4%

3.	Liquid limit, %	24.1	*
4.	Plastic limit,%	21.10	*
5.	Plasticity index	3	Non plastic
6.	Classification of soil	CL-ML	ML
7.	Maximum dry density (gm/cc)	1.7294	*
8.	Optimum moisture content (%)	17.91	*
9.	Hydraulic conductivity (m/sec)	$1.877X10^{-7}$	$9.59X10^{-7}$

***- Not determined**

From the table 1, it is evident that soil belongs to CL-ML class and the fly ash corresponds to sandy silt category. The Proctor test results reveal that OMC and MDD for soil are 17.91% and 1.7294 gm/cc respectively. Fly ash has silt clay content of 84.4% and the hydraulic conductivity of Fly ash is slightly higher than that of clayey soil alone. The specific gravity results, the computed values of porosity of soil fly-ash mixture using Eq. (5) and the computed values of void ratio using Eq. (6) are shown in table 2 below.

Table 2. Determination of specific gravity, porosity & void ratio of soil-fly ash mixture

S. N.	% fly ash	Total mixture volume (ml)	Amount of water added (ml)	Specific gravity	Porosity (n)	Void ratio (e)
1.	0	200	76	2.79	0.380	0.613
2.	5	200	77.8	2.78	0.389	0.637
3.	10	200	79	2.77	0.395	0.653
4.	15	200	82	2.76	0.410	0.695
5.	20	200	85.6	2.755	0.428	0.748
6.	25	200	87.6	2.75	0.438	0.779
7.	30	200	89	2.74	0.445	0.802
8.	50	200	91	2.72	0.455	0.835
9.	75	200	93	2.62	0.465	0.869
10	100	200	95.2	2.55	0.476	0.908

4.2. Hydraulic Conductivity Test Results

In the experiment, the soil has been randomly mixed with fly ash in ten different proportions: 0, 5, 10, 15, 20, 25, 30, 50, 75and 100 % by weight. The hydraulic conductivity test was performed for each fly ash proportions using falling head permeability test and the test results are shown in table 3. Superficial velocity of flow was calculated using relationship [v = $(\frac{h0-h1}{t})$]. Table 3 shows the various variables viz. h_0, h_1, time(t), ash content (p_a), cross sectional area of stand pipe (a), cross sectional area of soil specimen (A), hydraulic conductivity (k) and superficial velocity (v).

Table 3: Experimental Results on Hydraulic Conductivity of Soil-Fly ash Mixture

h_o, cm	h_1, cm	time, sec	p_a	a, cm^2	A, cm^2	k, cm/sec	v, cm/s
99	96.8	300	0.00	0.342	31.65	1.88E-05	0.0073
99	96.43	300	0.05	0.342	31.65	1.88E-05	0.0086
99	95.17	300	0.10	0.342	31.65	2.82E-05	0.0128
99	94.96	300	0.15	0.342	31.65	2.98E-05	0.0135
99	93.03	300	0.20	0.342	31.65	4.44E-05	0.0199
99	91.97	300	0.25	0.342	31.65	5.27E-05	0.0234
99	91.26	300	0.30	0.342	31.65	5.82E-05	0.0258
99	90.5	300	0.50	0.342	31.65	6.42E-05	0.0283
99	89.3	300	0.75	0.342	31.65	7.48E-05	0.0323
99	86.56	300	1.00	0.342	31.65	9.59E-05	0.0415

The dimensionless parameters of Eq. (4) were computed and are shown in table 4.

Table 4: Calculated values of Dimensionless Parameters of Multiplier Function

h_1/h_0	h_o-h_1	a/A	$\frac{e3}{(1+e)\rho s}$	(k/v)	Multiplier Function value	P_a*v/k
0.977778	2.57	92.54386	0.051163849	4.445895888	0.10522	0.00E+00
0.97404	3.83	92.54386	0.056718089	4.620229033	0.13626	2.28E+01
0.961313	4.04	92.54386	0.060785608	4.612720103	0.217627	4.53E+01
0.959192	5.97	92.54386	0.071736216	4.610637323	0.270914	6.78E+01
0.939697	7.03	92.54386	0.086979648	4.601162023	0.485405	8.96E+01
0.92899	7.74	92.54386	0.096742433	4.592042129	0.635748	1.11E+02

0.921818	8.5	92.54386	0.104410339	4.58853639	0.755435	1.33E+02
0.914141	9.7	92.54386	0.116592947	4.583430609	0.926411	2.21E+02
0.90202	12.44	92.54386	0.134075678	4.559709982	1.215722	3.24E+02
0.874343		92.54386	0.154034536	4.560055512	1.791228	4.32E+02

The variations in hydraulic conductivity at various proportions of fly ash are shown graphically in **Fig. 1**. From this figure, it is evident that average hydraulic conductivity of the soil is observed increasing from 1.877 X 10^{-7} m/s without any addition of fly ash to 7.48 X 10^{-7} m/s at 75% fly ash content by weight. With increase in fly ash content, the rate of hydraulic conductivity is observed increasing. Increase in silt particles due to addition of fly ash makes the mixed sample comparatively coarser and hence there is an increase in the hydraulic conductivity values with increase in fly ash content. Fly ash with high percentage of ash content can be mixed with local soil wherever necessary to enhance the hydraulic conductivity of local clayey soil. Such materials may be used for land filling and embankments in the field of geotechnical constructions.

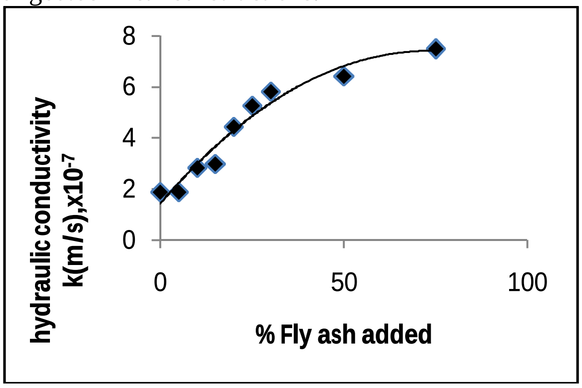

Fig. 1. Variations in hydraulic conductivity of soil replaced by fly ash in various proportions

4.3 Testing of Model Equation (4)

In order to test the linear dependency of hydraulic conductivity function (L.H.S. of Eq. (4) on the multiplier function (R.H.S. of Eq. 4), the experimental results of table. 3 and computed results of table 4 were used. The hydraulic conductivity function (L.H.S. of eq. (4)) was plotted against the multiplier function (R.H.S. of eq. (4)) and fitted linearly as shown in **Fig. 2.**

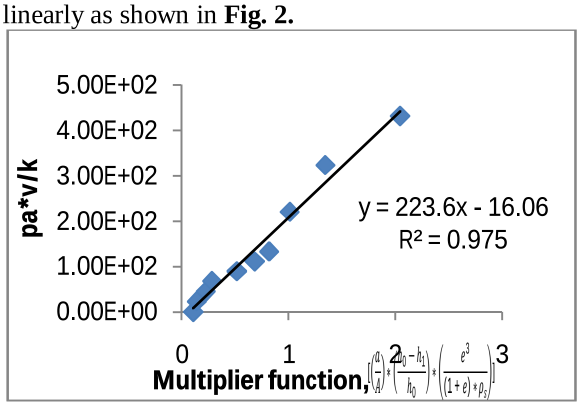

Fig. 2. Linear variation of hydraulic conductivity function with multiplier function

The experimental results are fitted reasonably well linearly with R^2 value of 0.9756, with few deviations as seen from **Fig.2**. The hydraulic conductivity of soil-fly ash mixture was computed using best fit linear equation shown within the curve in **Fig.2.** and the predicted hydraulic conductivity is compared with the experimental hydraulic conductivity values of table 3 and are compared in **Fig.3.**

From **Fig.3,** it is evident that maximum error in prediction lies within ±24% error band for most data points except two points where predicted hydraulic conductivity values are within ±37% error band. Thus, it's inferred that the proposed linear multiplier function for estimation of hydraulic conductivity can be satisfactorily used to compute the hydraulic conductivity of soil-fly ash mixture with reasonably good accuracy. However, it is absolutely necessary to validate the performance of this multiplier function for estimation of hydraulic conductivity in future investigations.

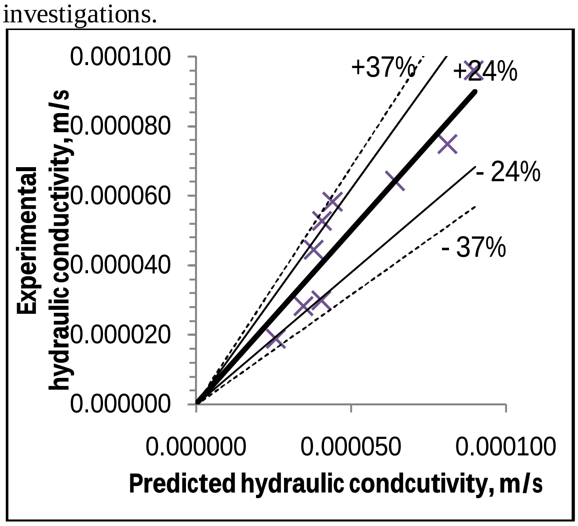

Fig3. Experimental versus predicted hydraulic conductivity

CONCLUSIONS

This paper was devoted to develop a mathematical function for estimation of hydraulic conductivity of soil-fly ash mixture using dimensionless approach. A multiplier function containing nine dimensionless variables affecting hydraulic conductivity of soil-fly ash mixture under falling head permeability test was developed and linear dependency of hydraulic conductivity of multiplier function is observed satisfactory with R^2 value of 0.9756 and most of the predicted results are found within ± 24% error band with few expectations. Therefore, it is inferred that the linear function developed in present work may prove useful in estimation of hydraulic conductivity of soil- fly ash mixture but requires validation in future investigations.

ACKNOWLEDGEMENTS

Authors are grateful to Director, KNIT, Sultanpur, and Director MNNIT Allahabad U.P., India for providing the required support in preparation of this manuscript.

REFERENCES

[1] T. Deb, and S.K Pal, "Effect of fly ash on geotechnical properties of local soil-fly ash mixed samples", International Journal of Research in Engineering and Technology (IJERT), vol.3, no.5, pp. 507-516, May 2014.

[2] Kim B., Prezzi M., Salgado R. "Geotechnical properties of fly and bottom ash mixture for use in highway embankments". Journal of geotechnical and geo-environmental engineering, vol. 131. no.7, pp. 914-924, 2005.

[3] Prashanth J. Sivapullaiah P. and Sridharan, "A..Pozzolanic fly ash as a hydraulic barrier in landfills.Engineering geology", vol. 60, pp. 245-252, 2001.

[4] M. R Brooks, "Soil stabilization with fly ash and rice husk ash", International Journal of Research and Reviews in Applied Sciences,vol. 1, no. 3, pp.209-217, December 2009.

[5] K. Anupam, P. Kumar, and R.N Ransinchung, "Permeability study on fly ash and rice husk ash admixes with subgrade soil for pavement construction", Proceedings of International Conference on Advances in Architecture and Civil Engineering, (AARCV-2012), vol. 1, pp. 489-493, June 2012.

[6] K. Sabat, Effect of Polypropylene fiber on engineering properties of rice husk-lime stabilized expansive soil, European Journal of Geotechnical Engineering, (EJGE), vol.17, pp 651-659, 2012.

[7] S. K. Pal, and A. Ghosh, Hydraulic conductivity of fly ash-Montmorillonite clay mixtures Indian Geotechnical Journal,vol.43, no.1, pp. 47-61, 2001.

[8] G. M. Ayininuola, and O. I. Olaosebikan, Influence of rice husk ash on soil permeability", Transnational Journal of Science and Technology (TJST). Vol.3, no. 10, pp. 29-32, 2013.

[9] K. R. Arora, "Soil Mechanics and Foundations Engineering", 7th Edition Standard publishers distributors, (2009).

[10] Pandey A., Maheshwari, U.K., "Influence of soil fly-ash and soil-bagasse ash mixture on hydraulic conductivity of soils". International journal of advanced technology in engineering and science (IJTES), vol.5, no.1, pp. 629-638, January 2017.

★★★