GEOTECHNICAL CHARACTERISTICS OF FLY ASH-SOIL MIXTURES

S.R. Kaniraj[1] and V.G. Havanagi[2]

ABSTRACT

This paper presents the results of laboratory experimental studies carried out on fly ash-soil mixtures. Two fly ashes, one from Rajghat thermal power station, New Delhi, India, and the other from a chemical manufacturing industry Baumineral near Bochum, Germany, were collected and their physical and chemical characteristics were studied. The fly ashes were mixed with the soils available near their respective areas in different proportions and their geotechnical characteristics were investigated. The laboratory test program included compaction tests, unconfined compression tests, direct shear tests, unconsolidated undrained triaxial shear tests, consolidation tests, permeability tests and CBR tests. The results obtained were of similar magnitude and showed comparable characteristics as those reported in the literature on fly ashes from other parts of the world. It might be possible to make a reasonable estimate of the maximum dry unit weight and the optimum moisture content of fly ash-soil mixtures from their specific gravity.

INTRODUCTION

Fly ash is a by-product recovered from the flue gases of coal combustion plants. The quantity of ash produced depends upon the quality of coal burnt. The ash produced in Germany, U.K., U.S.A., and Canada is around 10% of the coal burnt whereas in India it is about 40% to 50%. The quality of the ash depends upon the quality of the coal and the method of burning. In India, less than 5% of the ash is used in the manufacture of brick, pozzolana cement and other products whereas in Germany the utilization rate is about 98%. Efforts are now being made in India, in a major way, to increase the utilization of fly ash in different applications. The Department of Science and Technology of the Government of India has launched a Mission Project to deal with the huge production of fly ash. The use of fly ash directly or in combination with soil, as fill material in embankments would facilitate mass utilization of fly ash.

In the present study, an Indian fly ash collected from a single electrostatic precipitator of the Rajghat thermal power station in New Delhi and a German fly ash from a chemical manufacturing industry Baumineral near Bochum have been used. The local soils used in the Rajghat fly ash-soil mixtures are silt and fine sand. The silt deposit is prevalent widely in and around Delhi. The fine sand is a deposit of the river Yamuna. In the case of Baumineral fly ash, the local soil used is a fine sand which is a deposit of the Rhine river. The fly ash and soils were mixed in different proportions, and their physical, chemical and geotechnical characteristics were investigated. The paper presents the results of the study on the Rajghat and Baumineral fly ash-soil mixtures and the appropriate conclusions from the study.

CHEMICAL COMPOSITION AND PHYSICAL PROPERTIES OF FLY ASHES

Chemical Composition

The chemical composition of the Rajghat and Baumineral fly ashes is shown in Table 1.

In both the Rajghat and Baumineral fly ashes the oxides of silicon, aluminium and iron together (95% and 86%, respectively) constitute the major portion of the fly ash. Both the fly ashes are classified as class *F* as per ASTM C 618 (1993) specifications. These types of fly ashes are normally produced from burning anthracite or bituminous coal. The ashes produced from these coals contain crystalline materials like quartz, mullite, magnetite, and hematite.

Physical Properties

Table 2 summarizes some of the physical properties of the Rajghat and the Baumineral fly ashes.

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Note: Discussion is open until 1 November 1999. This paper is part of the *Geotechnical Engineering Journal*, Vol. 30, No. 2, August 1999. Published by the Southeast Asian Geotechnical Society, ISSN 0046-5828.

Table 1 Chemical Composition of the Fly Ashes

Chemical composition	Rajghat fly ash* %	Baumineral fly ash** %
Silica (SiO_2)	61.21	52.26
Alumina (Al_2O_3)	30.07	25.74
Iron oxide (Fe_2O_3)	4.17	7.66
Lime (CaO)	0.10	0.21
Magnesia (MgO)	0.40	1.72
Titania (TiO_2)	2.60	Not available
Soda (Na_2O)	less than 0.01	5.00
Potash (K_2O)	0.02	4.13
Sulphates (SO_3)	less than 0.01	0.81

* SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, and SO_3 determined as per IS:1727 – 1967 specification
* Na_2O, and K_2O determined by flame photometry
** data as supplied by the chemical manufacturing industry Baumineral

Table 2 Physical Properties of the Fly Ashes

	Rajghat fly ash* %	Baumineral fly ash** %
Specific gravity	2.19	2.36
% finer than 75 micron size	80.00	86.00
Loss on ignition (%)	1.40	3.47
Specific surface area (cm^2/g)	4020.00	3375.00

The specific gravity of the Baumineral fly ash is more than that of the Rajghat fly ash, probably due to the presence of higher iron oxide content in the Baumineral fly ash (Table 1). The specific surface area or fineness influences the reactivity of the fly ash more than any other physical factor. The specific surface areas of both the fly ashes determined by Blaine's air permeability method are comparable with the values of similar Indian fly ashes reported by Rehsi and Garg (1988).

The fly ash, in general, is a pozzolanic material. The oxides of silicon, alumina, calcium, and the unburnt coal content affect the pozzolanic activity of the fly ash (Moller and Nilson, 1985). The silicious and aluminous materials of the fly ash, in the presence of moisture, react with calcium hydroxide at ordinary temperatures to form compounds possessing cementitious properties like calcium silicate hydrates and calcium aluminate hydrates. The low calcium fly ashes normally contains a higher proportion of non-reactive crystalline minerals and carbon, and relatively low glass content resulting in low pozzolanic activity. The amount of unburnt carbon, as indicated by loss on ignition (Table 2), is low in both the fly ashes. The maximum limit for loss on ignition specified by ASTM C 618 (1993) for class *F* fly ash pozzolan is generally 6% and can be up to 12% depending on laboratory test results.

The extent of gain in strength with time of moist compacted fly ash is indicative of its self- hardening behavior. The presence of free lime influences the age hardening characteristics of compacted fly ash (Indraratna, et al., 1995). The free lime content of class *F* fly ash is less than that of class *C* fly ash. Therefore the class *F* fly ash lacks self-hardening characteristics compared to the class *C* fly ash. Figure 1 shows the shape of the Rajghat fly ash particles obtained by scanning electron microscope. The individual particles are mostly spherical in shape and they have a porous structure.

GEOTECHNICAL CHARACTERISTICS OF FLY ASH-SOIL MIXTURES

If the transportation cost of fly ash is large, fly ash may be blended with the soil available near the construction site to make the utilization of fly ash cost effective. The Rajghat and the Baumineral fly ashes were mixed with soils available near their respective sources. The sand mixed with the Rajghat fly ash was collected from the deposits of river Yamuna and is therefore referred to as Yamuna sand. The sand used with the Baumineral fly ash was obtained from the deposits of a tributary of the Rhine river and referred to as Rhine sand. The silt used with the Rajghat fly ash is freely found in and around Delhi and is referred to as Delhi silt. The fly ashes were mixed with the soils in different proportions by dry weight as shown in Table 3. The experimental program for geotechnical characteristics included grain size analysis, Atterberg limit tests, compaction tests, direct shear tests, unconfined compression tests, drained triaxial shear tests, unconsolidated undrained triaxial shear tests, consolidation tests, permeability tests and CBR tests.

Grain Size Analysis

The grain size distribution curves of the two fly ashes, and the soils are shown in Fig. 2. More details of the particles type and the grain size characteristics are shown in Table 4 and Table 5, respectively. The grain size d_{10} influences the permeability and capillary moisture retention of non-plastic soils (Martin, et al., 1990). McLaren and DiGioia (1987) have reported the mean value of uniformity coefficient of 98 class *F* fly ashes collected from different parts of the U.S.A., as 5.49 ± 3.6. The uniformity coefficient of the Rajghat and Baumineral fly ashes is within this range.

Atterberg Limits Tests

The liquid limit of the Rajghat fly ash was determined by cone penetration method as per the Indian Standard specification IS: 11196 (1985) because cutting a groove using the Casagrande device was difficult. Similar observations were reported by Sivapullaiah, et al. (1996) while carrying out liquid limit tests on Indian fly ashes from Vijayawada and Neyveli. The liquid limit of the Rajghat fly ash ranges from 48% to 51%. The high liquid limit may be due to large absorption of water by the porous particles of the fly ash. The fly ash was non-plastic.

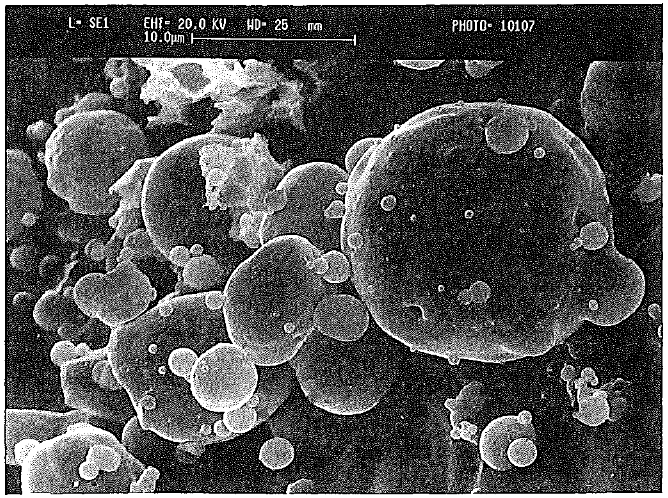
Preparation of Fly Ash-Soil Mixtures

The following procedure was adopted for the preparation of fly ash-soil mixtures in all tests. The materials were first dried under heating lamps (about 40° C) for minimum of 24 hours and brought to room temperature. Fly ash and soil were then mixed together in the required quantities and proportion (by dry weight) in dry form. The required amount of water was added to this mixture and mixed thoroughly to get even distribution of moisture content.

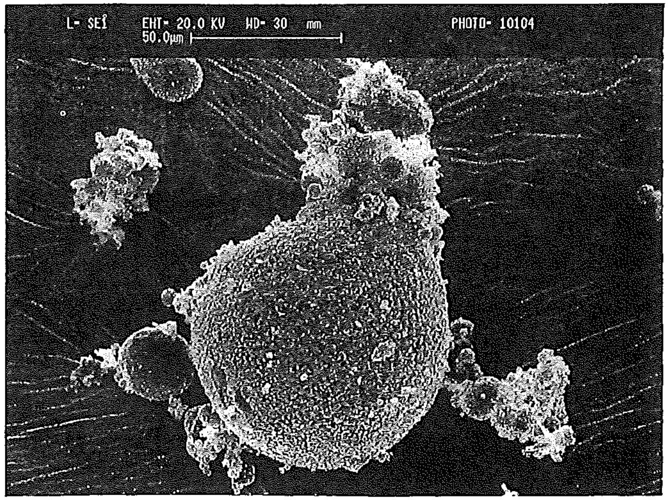
Compaction Characteristics

The maximum dry unit weight (*MDD*) and the optimum moisture content (*OMC*) were determined by light compaction (standard Proctor) tests. The *MDD* and *OMC* are respectively, 10.52 kN/m³ and 36.5% for the Rajghat fly ash and 14.18 kN/m³ and 18.4% for the Baumineral fly ash. The higher *MDD* of the Baumineral fly ash may be due to its higher specific gravity and higher iron oxide content than the Rajghat fly ash. The compaction curves of the different fly ash-soil mixtures and the corresponding zero air void curves are shown in Fig. 3. The compaction curves show that the degree of compaction is not sensitive to water content. Similar observations were made by Leonards and Bailey (1982), Martin, et al. (1990), and De Santayana and Mazo (1994) for Indianapolis, Delaware Valley and Lada fly ashes, respectively.

The *MDD* and *OMC* of all the fly ash-soil mixtures are summarized in Table 3. As the fly ash content increases, the *MDD* decreases and the *OMC* increases. Tsonis, et al. (1983) have reported similar changes in *MDD* and



(a)



(b)

Fig. 1 (a) Scanning Electron Micrograph of Rajghat Fly Ash Showing Spherical Shape of the Particles, (b) Scanning Electron Micrograph of Fly Ash Showing Porous Structure of Particles

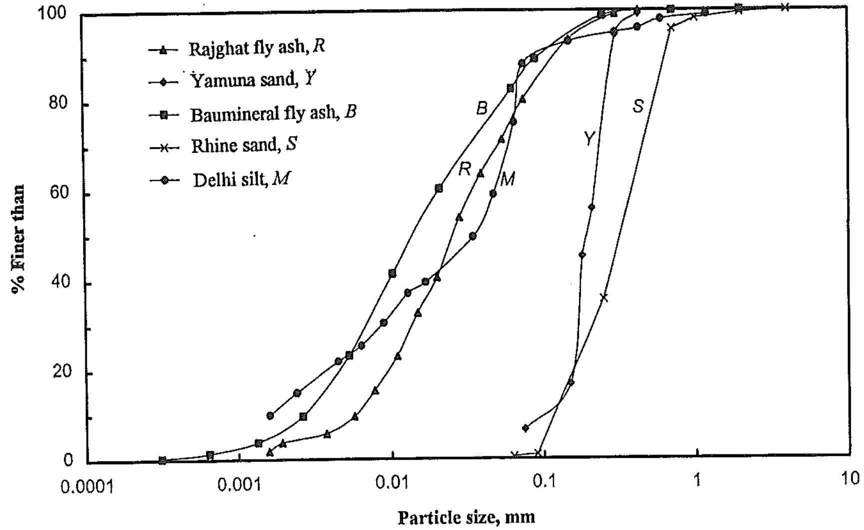


Fig. 2 Grain Size Distribution of Fly Ashes and Soils

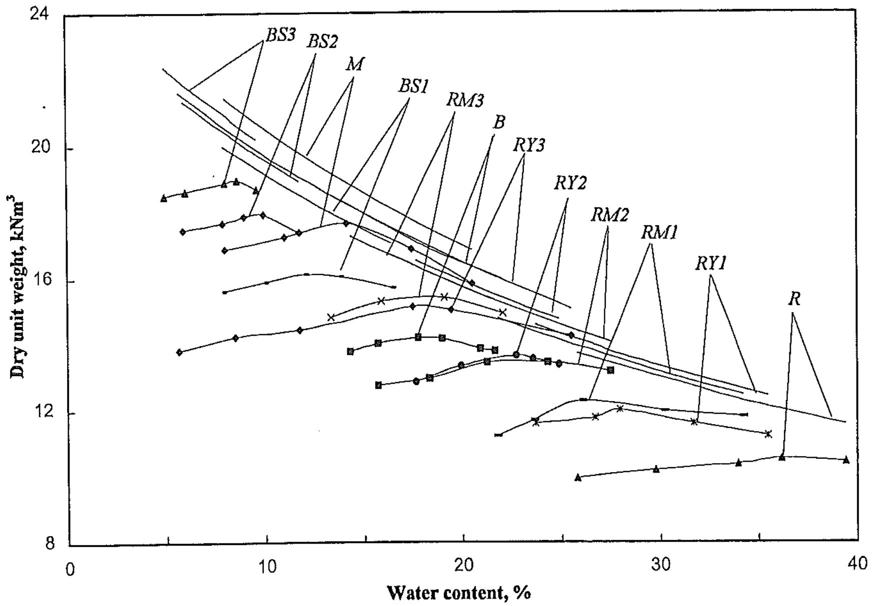


Fig. 3 Compaction Curves for Fly Ash-Soil Mixtures

Table 3 Results of Light Compaction (Standard Proctor) Tests

Mix designation	Fly ash-soil mixture	*MDD* kN/m^3	*OMC* %	*G*	Void ratio *e**	*S** %
R	Rajghat fly ash	10.52	36.5	2.19	1.04	76.7
RM1	75% *R* + 25% *M*	12.21	26.6	2.29	0.84	72.5
RM2	50% *R* + 50% *M*	13.54	22.6	2.39	0.73	73.8
RM3	25% *R* + 75% *M*	15.40	18.0	2.51	0.60	75.4
M	Delhi silt	17.66	14.0	2.64	0.47	79.2
RY1	75% *R* + 25% *Y*	11.92	28.6	2.29	0.88	74.0
RY2	50% *R* + 75% *Y*	13.64	22.6	2.40	0.73	74.7
RY3	25% *R* + 75% *Y*	15.11	17.5	2.52	0.64	69.3
Y	Yamuna sand	-	-	2.66	-	-
B	Baumineral fly ash	14.18	18.4	2.36	0.63	68.6
BS1	75% *B* + 25% *S*	16.09	13.0	2.43	0.48	65.6
BS2	50% *B* + 50% *S*	17.95	10.0	2.50	0.37	68.2
BS3	25% *B* + 75% *S*	18.98	8.2	2.57	0.33	64.2
S	Rhine sand	-	-	2.65	-	-

* void ratio and degree of saturation at *MDD-OMC*

Table 4 Particle Size Distribution of Fly Ashes and Soils

Particle type and size	Rajghat fly ash	Baumineral fly ash	Delhi silt	Yamuna sand	Rhine sand
Coarse sand size, 2-4.75 mm (%)	-	-	-	-	1
Medium sand size, 0.475-2mm (%)	-	-	-	-	16
Fine sand size, 0.075-0.475 mm (%)	20	14	14	94	82
Silt size, 0.002-0.075 mm (%)	77	79	73	6	1
Clay size, < 0.002 mm (%)	3	7	13	-	-

Table 5 Grain Size Characteristics of the Fly Ashes and Soils

Mix designation	d_{10} mm	d_{60} mm	d_{30} mm	C_u	C_c
R	0.0062	0.035	0.0140	5.65	0.90
B	0.0027	0.021	0.0065	7.78	0.75
Y	0.1100	0.205	0.1700	1.86	1.28
M	0.0016	0.048	0.0090	30.0	1.05
S	0.1350	0.320	0.2200	2.37	1.12

OMC from a study using coal ash-silty soil mixtures. The decrease in *MDD* may be attributed to the lower specific gravity of the ash particles, and the increase in moisture content due to the increase in the void ratio or porosity. The variation of *MDD* with fly ash content is nearly linear for all the fly ash-soil mixtures. The results of the linear regression analyses of the data are shown in Fig. 4. The Rajghat fly ash-silt and the Rajghat fly ash-sand mixtures have nearly identical trend of variation of *MDD* with fly ash content. Both the Rajghat and Baumineral fly ash-soil mixtures show almost the same rate of decrease of *MDD* with fly ash content as can be distinguished by the nearly parallel best fit trend lines and the small difference in their slopes (0.065 and 0.069). Further, the difference in the constants (3.67 kN/m^3) is almost the same as the difference in the *MDD* of Baumineral and Rajghat fly ashes (3.66 kN/m^3). The variation of *OMC* with fly ash content is non linear for all the fly ash-soil mixtures. The results of the regression analyses for best fit trend of the data are shown in Fig. 5.

Table 3 shows the void ratio and degree of saturation at the *MDD-OMC* state for the different fly ash-soil mixtures. The degree of saturation for all fly ash-soil mixtures at *MDD-OMC* state is low and is in the range of 69% to 77%. The trend of variation of void ratio at *MDD* (e_{MDD}) with fly ash content and the results of the regression analyses are shown in Fig. 6. The nature and trend of variation of e_{MDD} with fly ash content is in conformity with those of *OMC* with fly ash content in Fig. 5. Table 3 and Fig. 4 to Fig. 6 indicate that different fly ash-soil mixtures are likely to have distinctly different *OMC* and *MDD* which can be determined by separate compaction tests.

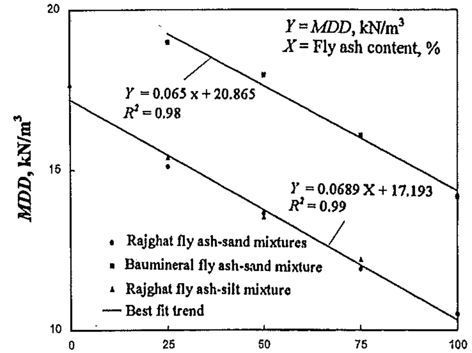


Fig. 4 Variation of *MDD* with Fly Ash Content for Fly Ash-Soil Mixtures

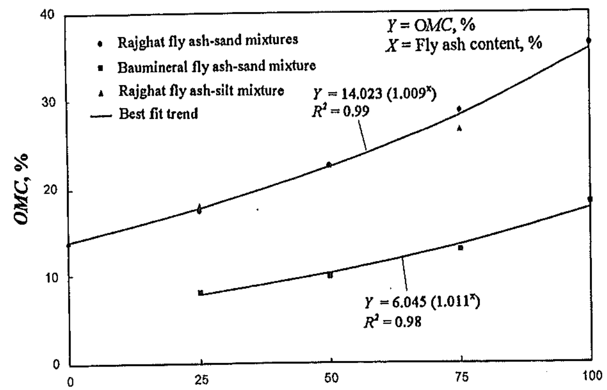


Fig. 5 Variation of *OMC* with Fly Ash Content for Fly Ash-Soil Mixtures

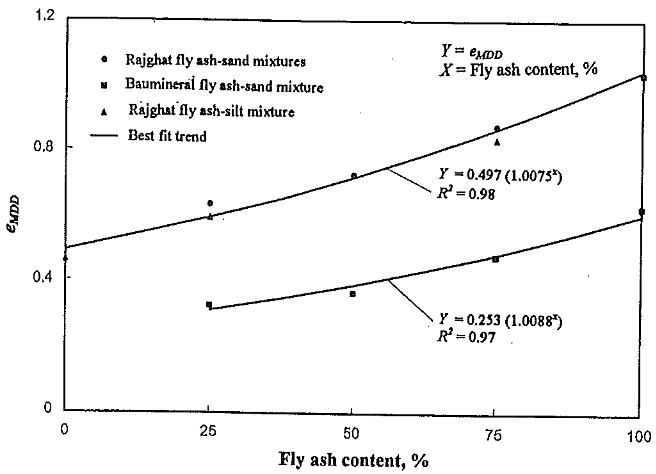


Fig. 6 Variation of e with Fly ash Content for Fly Ash-Soil Mixtures

The test for specific gravity of solids, G can be performed more easily, quickly, and inexpensively than the compaction tests. The authors have established empirical correlations (Kaniraj and Havanagi, 1999) by which the *MDD* and *OMC* of fly ashes can be determined approximately for a given value of G. The *MDD-OMC* thus determined can be used for preliminary estimates and to design the compaction test. In the case of the light compaction (standard Proctor) test the correlations are used as follows:

Step 1 : The average, upper and lower limits for *MDD* for a given G are calculated from Eq. (1), Eq. (2) and Eq. (3), respectively.

$$MDD = 27.156 - 22.544\,G + 7.162\,G^2 \;\; \text{kN/m}^3 \quad (1)$$

$$MDD = 18.085 - 12.561\,G + 4.223\,G^2 \;\; \text{kN/m}^3 \quad (2)$$

$$MDD = 18.296 - 4.536\,G - 4.151\,G^2 + 2.326\,G^3 \;\; \text{kN/m}^3 \quad (3)$$

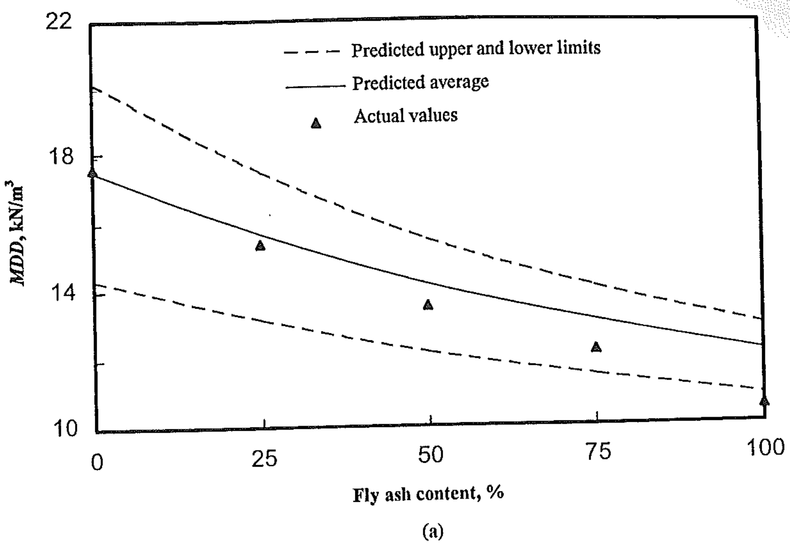
Step 2 : The *OMC* values corresponding to the *MDD* calculated in step 1 are determined from Eq. (4).

$$MDD = 27.49 - 1.197\,OMC + 0.0325\,OMC^2 - 0.00033\,OMC^3 \;\; \text{kN/m}^3 \quad (4)$$

Figures 7, 8 and 9 show the predicted variation of the average, lower and upper limits of the *MDD* and *OMC* with fly ash content and the actual experimental values for the Rajghat fly ash-silt, Rajghat fly ash-sand and Baumineral fly ash-sand mixtures, respectively. Generally, the actual values of *MDD* and *OMC* are within the predicted range. However, in the case of Baumineral fly ash-sand mixtures the actual *MDD* values are closer to the upper limit of the predicted range and the actual *OMC* values are closer to the lower limit of the predicted range. It should, however, be noted that all the actual *OMC* and *MDD* values were also part of the total fifty-seven samples used to establish the correlations. The data for forty five other samples, collected from literature, represent the characteristics of fly ashes from Australia, Canada, Germany, India, Japan, Spain, U.K., and the U.S.A.

Direct Shear Tests

Direct shear tests were carried out on 60 mm x 60 mm x 29 mm size samples in case of Rajghat fly ash-soil mixtures and on 60 mm x 60 mm x 20 mm size samples in case of Baumineral fly ash-soil mixtures. The samples were statically compacted at their respective *MDD* and *OMC*. Minimum four tests were carried out on each fly ash-soil



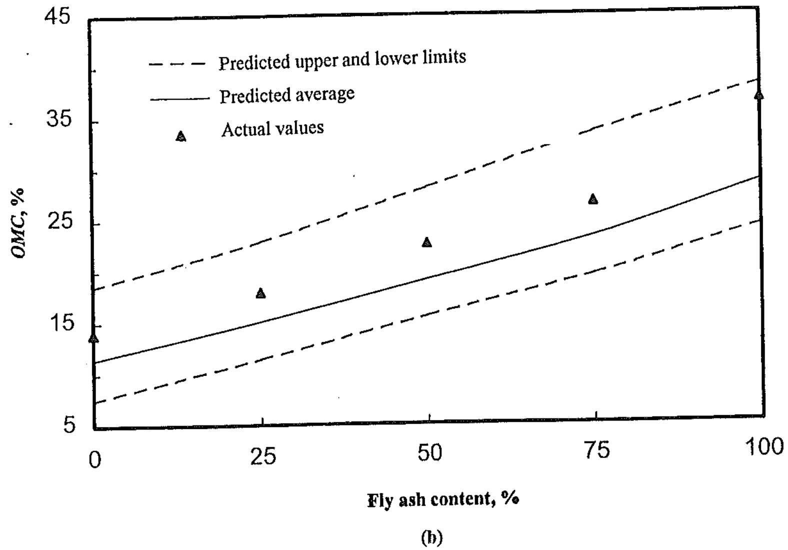


Fig. 7 (a) Predicted Variation of *MDD* with Fly Ash Content and the Actual Values for the Rajghat Fly Ash-Silt Mixtures, (b) Predicted Variation of *OMC* with Fly Ash Content and the Actual Values for the Rajghat Fly Ash-Silt Mixtures.

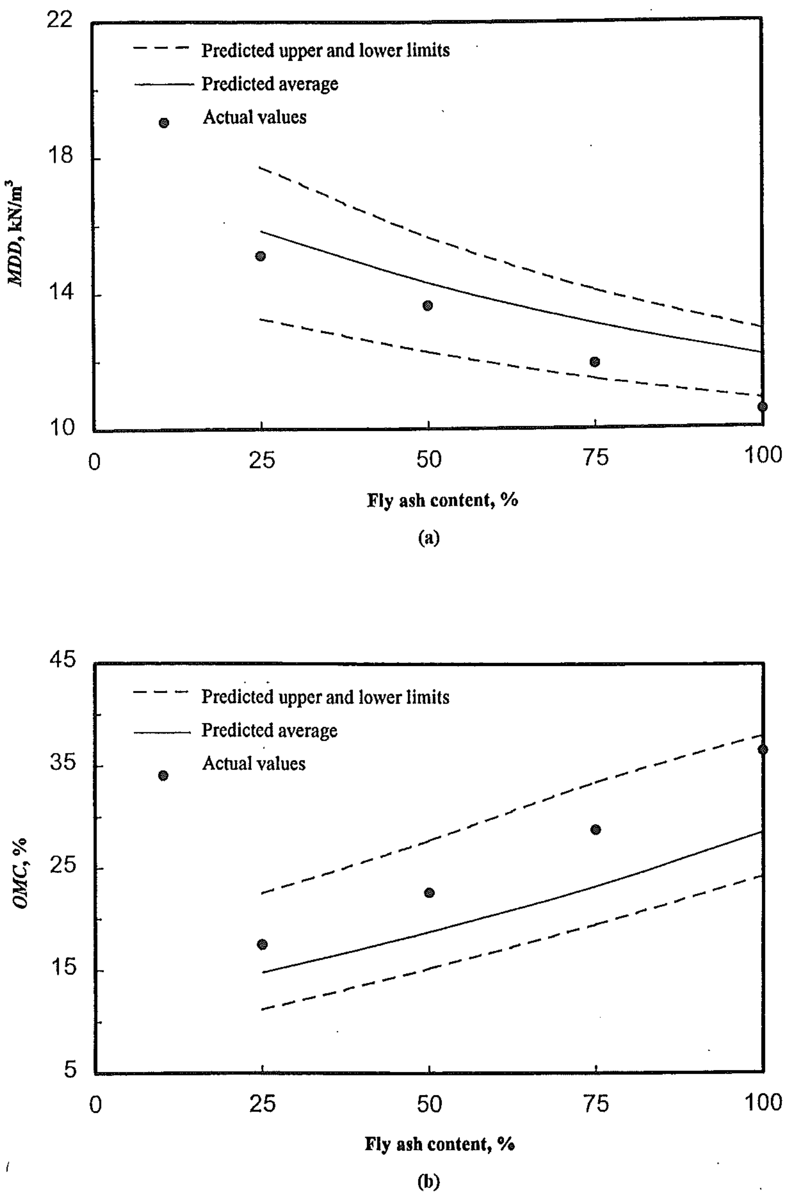


Fig. 8 **(a) Predicted Variation of *MDD* with Fly Ash Content and the Actual Values for the Rajghat Fly Ash-Sand Mixtures, (b) Predicted Variation of *OMC* with Fly Ash Content and the Actual Values for the Rajghat Fly Ash-Sand Mixtures.**

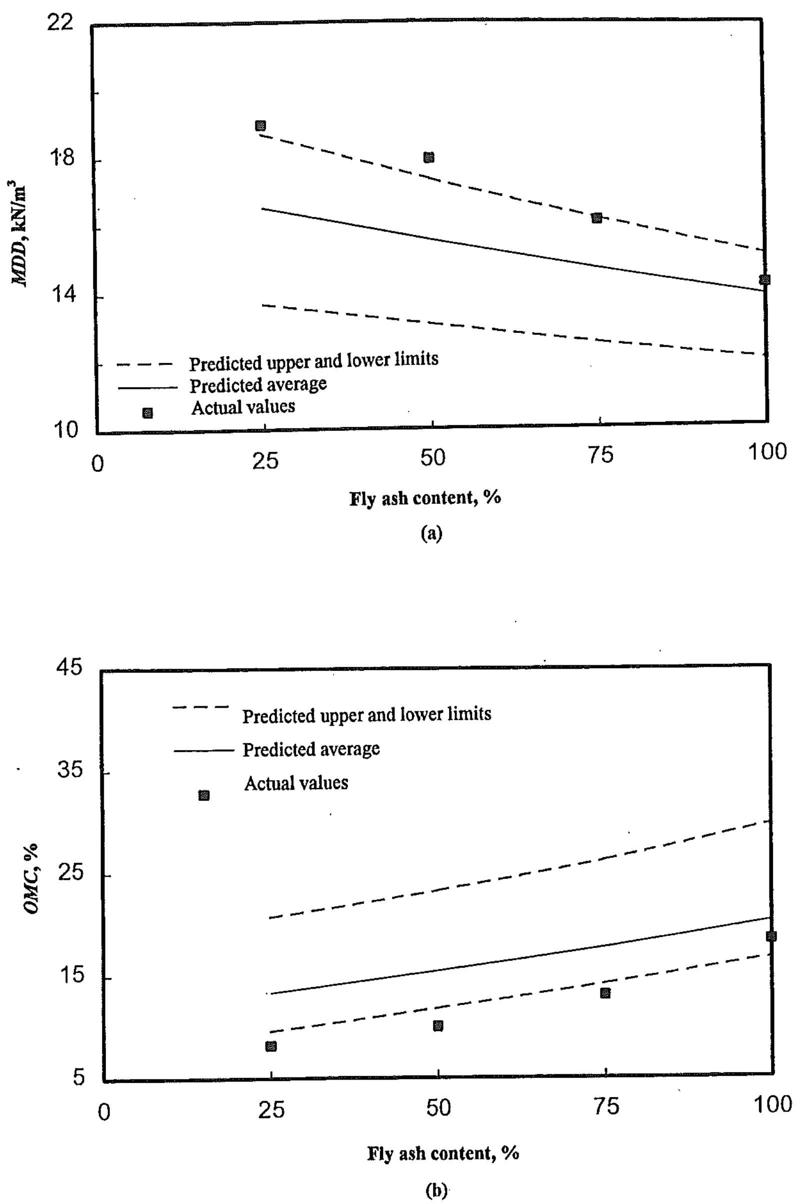


Fig. 9 **(a) Predicted Variation of *MDD* with Fly Ash Content and the Actual Values for the Baumineral Fly Ash-Sand Mixtures, (b) Predicted Variation of *OMC* with Fly Ash Content and the Actual Values for the Baumineral Fly Ash-Sand Mixtures.**

mixture with the normal stress varying from 24.5 kN/m² to 98.1 kN/m². The samples were sheared at the rate of 0.25 mm/min.The total stress shear strength parameters obtained from the direct shear tests for the different fly ash-soil mixtures are summarized in Table 6.

For the Hanasaari fly ash which is comparable to the Rajghat fly ash, Havukainen (1983) has reported *c* and ϕ similar to that for the Rajghat fly ash. The failure state was reached at shear displacements of 1 mm to 2 mm in the case of Rajghat fly ash-soil mixtures and less than 1 mm in the case of Baumineral fly ash-soil mixtures. All samples dilated during shear and the dilation during shear in all the fly ash-soil mixture was small and the volumetric strain was in the range of 0.1% to 1.1%. For the Rajghat fly ash-soil mixtures there is a consistent increase in the angle of shearing resistance as the fly ash content increases. But, the variation of cohesion intercept with fly ash content does not show a consistent trend.

The Baumineral fly ash-soil mixtures show a consistent trend in the variation of *c* with fly ash content but not of ϕ. The dilation of the sample during shear could have set up suction or negative pore water pressure in the unsaturated sample. This could have occurred randomly in the direct shear test and could be the reason for the inconsistent variation of the shear strength parameters. The Baumineral fly ash-soil mixtures distinctly show a higher strength than the Rajghat fly ash-soil mixtures. This could be expected because of their higher dry unit weight than the Rajghat fly ash-soil mixtures.

Unconfined Compression Tests

Unconfined compression tests were carried out on 37.7 mm diameter and 73.5 mm height samples in the case of the Rajghat fly ash-soil mixtures. The samples were statically compacted. The static compaction was carried out alternatively from both ends of a steel mold to ensure uniform compaction of the sample. For the Baumineral fly ash-soil mixtures, 100 mm diameter and 120 mm height samples were used. These samples were dynamically compacted in the Proctor mold. All samples were compacted at their respective *OMC* and *MDD*. Minimum three samples were tested for each fly ash-soil mixture. The average unconfined compressive strength (*UCS*) and strain at failure (ε_f) of the fly ash-soil samples are summarized in Table 7.

Table 6 Direct Shear Test Results of the Fly Ash-Soil Mixtures

Mix designation	*c* (kN/m²)	∅
R	19.6	37.5
RM1	13.7	37.0
RM2	14.7	36.0
RM3	22.6	30.5
M	15.7	29.5
RY1	18.6	34.0
RY2	9.8	33.0
RY3	21.6	31.5
B	28.4	30.0
BS1	26.5	38.0
BS2	23.54	37.0
BS3	11.8	34.0

Table 7 Results of Unconfined Compression Tests on Fly Ash-Soil Samples

Mix designation	*UCS* kN/m²	Strain at failure ε_f %
R	65.70	2.0 – 2.5
RM1	61.68	1.4 – 2.0
RM2	47.07	1.6 – 2.0
RM3	50.60	2.2 – 2.3
M	36.28	2.2 – 2.7
RY1	44.13	1.0 – 2.0
RY2	33.34	1.9 – 2.1
RY3	20.59	2.0 – 2.1
B	165.52	2.2 – 2.5
BS1	146.42	1.6 – 2.1
BS2	133.69	1.8 – 2.0
BS3	57.29	1.0 –1.5

The Baumineral fly ash-soil samples have a significantly higher *UCS* than the Rajghat fly ash-soil samples. This may be probably due to their higher *MDD* and lower *OMC*. Their *L/D* ratio of 1.2 was smaller as compared to nearly two of the Rajghat fly ash-soil mixtures. The dynamic compaction also could have had some influence. In all the fly ash-soil mixtures the *UCS* increases as the fly ash content increases. The increase is gradual in the case of Rajghat fly ash-soil mixtures. But, in the Baumineral fly ash-sand mixtures there is a strong increase in *UCS* until 50% fly ash content beyond which the increase is much reduced. The strain at failure is generally around 2% and is not appreciably or consistently affected by the fly ash content.

Unconsolidated Undrained Triaxial Shear Tests

Unconsolidated undrained triaxial shear tests were carried out on the Rajghat fly ash-soil samples prepared in the same manner as for unconfined compression tests. The confining stress in the case of Rajghat fly ash samples was varied from 49 kN/m² to 392.3 kN/m² (four tests per strength envelope) and in the Rajghat fly ash-soil samples from 49 kN/m² to 147.1 kN/m² (three tests per strength envelope). The samples were tested at a rate of deformation of 0.41 mm/min. The results of the tests are summarized in Table 8. Figures 10 and 11 show the deviator stress-strain curves for Rajghat fly ash and Rajghat fly ash-soil mixtures, respectively.

The addition of soil to the Rajghat fly ash decreased the maximum deviator stress. This is consistent with the decrease in the *UCS* upon addition of soil to fly ash (Table 7). During shear the fly ash-sand samples reached a peak deviator stress whereas in the fly ash-silt samples the strain increased continuously without the deviator stress reaching a peak value. In their experiments with Japanese fly ashes Kunio, et al. (1996) also did not observe a clear peak point in the stress-strain curve and the deviator stress gradually increased. The addition of sand to the fly ash has decreased the strain at failure. However, the addition of silt has had no significant effect on the failure strain. The secant modulus E_s was determined as the slope of the straight line joining the origin and the point on the stress-strain curve corresponding to one half of the maximum deviator stress. The secant modulus generally increases with the increase in the confining stress. There seems to be no significant difference in the secant moduli of the different fly ash-soil

Table 8 Results of Unconsolidated Undrained Triaxial Shear Tests

Quantities	Mix designation		
	R	*RM2*	*RM3*
σ_3, kN/m²	49.0 98.1 196.1	49.0 98.1 147.1	49.0 98.1 147.1
$(\sigma_1-\sigma_3)$ kN/m²	165.2 346.2 549.0	184.2 297.6 381.9	153.3 268.9 353.7
ε_f%	More than 10%	More than 15%	2.80 2.80 6.56
Es, MPa	8.75 20.06 18.61	13.2 18.60 30.86	10.59 18.56 28.55
C_{uu} (kN/m²)	20	30	15
$\varnothing_{uu}$	33°	29°	30.5°

C_{uu} = Undrained cohesion
$\varnothing_{uu}$ = Undrained shearing resistance

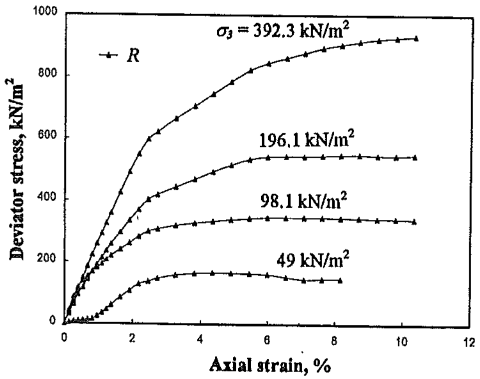


Fig. 10 Deviator Stress-Strain Curves for Rajghat Fly Ash in *UU* Test

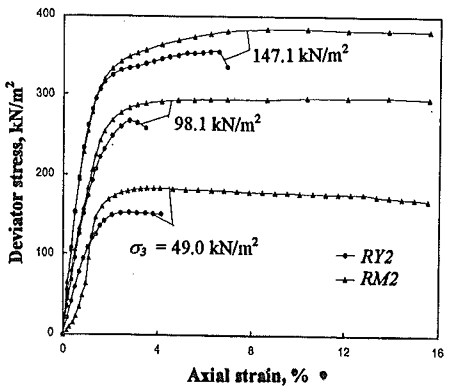


Fig. 11 Deviator Stress-Strain Curves for Rajghat Fly Ash-Soil Mixtures in *UU* Test

mixtures. For Los Barrios CCS fly ash which is similar to Rajghat fly ash, Carrillo (1992) has reported a relatively higher c_{uu} (103 kN/m²) and a lower ϕ_{uu} (30°). The addition of soil to fly ash tends to reduce the ϕ_{uu} and has no consistent effect on c_{uu} as already observed in the direct shear tests.

Drained Triaxial Shear Test

Drained triaxial shear tests were carried out on Rajghat fly ash samples. Attempts were made first to conduct the test with samples prepared as for the unconfined compression tests. But it was not possible to saturate these samples by applying back pressure or suction, because of their low initial degree of saturation. Next, the mixing water content was increased to saturation water content at the time of sample preparation. As the fly ash is non-cohesive, these samples collapsed due to self weight. Therefore, the test was conducted on samples prepared by depositing the fly ash through water and then compacting the slurry. The dry unit weight of these samples varied from 10.1 kN/m³ to 10.3 kN/m³. The samples were subjected to confining stresses in the range of 98.1 kN/m² to 294.2 kN/m². The consolidation under the confining stress took place rapidly and was nearly complete within 15 seconds. The consolidated samples were sheared at the rate of deformation of 0.3 mm/min. During shear, there was a decrease in the volume of the samples initially followed by an increase in their volume. The initial volumetric compression and the subsequent volumetric expansion ranged from 1.1% to 1.8% and 0.2% to 0.4%, respectively.

The effective stress parameters c' and ϕ' of the compacted Rajghat fly ash are 24.5 kN/m² and 38.7°, respectively. For compacted Indianapolis fly ash, Leonards and Bailey (1982) have reported $c' < 19$ kN/m² and $\phi' = 38°$. McLaren and DiGioia (1987) have reported that the ϕ' for 51 class *F* fly ashes was in the range of 34° ± 3.3°. For Los Barrios CCS fly ash, Carillo (1992) has reported $c' = 49$ kN/m² and $\phi' = 35.4°$. The values of the effective stress strength parameters for the Rajghat fly ash samples are similar to those reported by different investigators. The effective cohesion of fly ash which is a granular material appears to be high. It is possibly due to the incomplete dissipation of negative pore water pressure that might develop during dilation of the samples.

Consolidation Tests

The Rajghat fly ash-soil mixture was statically compacted in a consolidation ring to get a sample at *OMC* and *MDD*. The sample was then saturated by keeping it in the water bath in the consolidometer. Standard one-dimensional consolidation tests were carried out by increasing the vertical stress up to 1255.3 kN/m². The consolidation took place rapidly as has been observed by Web and Hughes (1987) and by Havukainen (1983) for the Helsinki fly ashes. The e-logσ' curves for the Rajghat fly ash and Rajghat fly ash-soil mixtures are shown in Fig. 12 and Fig. 13, respectively. The values of the compression index C_c, recompression index C_r and coefficient of consolidation c_v are summarized in Table 9.

The GAI consultants (1992) reported that C_c for virgin compression ranged from 0.05 to 0.37 and C_r from 0.006 to 0.04. McLaren and Digioia (1987) reported that the C_c for class *F* fly ashes, with void ratio in the range of 0.8 ± 0.2, was in the range of 0.13 ± 0.088. Web and Hughes (1987) have reported the c_v of compacted fly ashes to be in the range of 100 m²/year to 1000 m²/year. For the undisturbed samples from fly ash reclamation fill (having dry unit weight in the range of 7.36 kN/m³ to 12.75 kN/m³), Capco (1990) has reported the c_v to be in the range of 30 m²/year to 60 m²/year.

Permeability Tests

Permeability tests were carried out on cylindrical Baumineral fly ash samples of diameter 100 mm and height 120 mm compacted at *OMC* and *MDD*. The tests were carried out as per DIN: 18130 (1985). The relationship between the coefficient of permeability k (m/sec) and void ratio is shown in Fig. 14. Yudhbir and Honjo (1991) have reported that the coefficient of permeability of class *F* fly ashes was in the range of 6×10^{-7} m/s to 2×10^{-8} m/s. For Helsinki fly ashes Havukainen (1983) has reported the k value to be in the range of 1×10^{-7} m/s to 2.5×10^{-7} m/s. The average value of k for the Baumineral fly ash is 1.25×10^{-7} m/s.

California Bearing Ratio

The California Bearing Ratio (*CBR*) test for the Rajghat fly ash was carried out as per the Indian standard specification IS: 2720, Part 16 (1979). The sample was compacted in the *CBR* test mold at *OMC* and *MDD* and then tested after soaking it in water for 4 days. The *CBR* of the Rajghat fly ash is 2.07% which is low compared to the *CBR* of 6.8% to 13.5% in soaked condition of the class *F* Ontario fly ash (Toth, et al., 1988).

Table 9 Compressibility Parameters of Fly Ash-Soil Samples

Mix designation	C_c	C_r	C_v m²/year
R	0.072	0.017	238 - 299
RY2	0.123	0.021	254 – 290
RY2	0.093	0.016	291 - 315

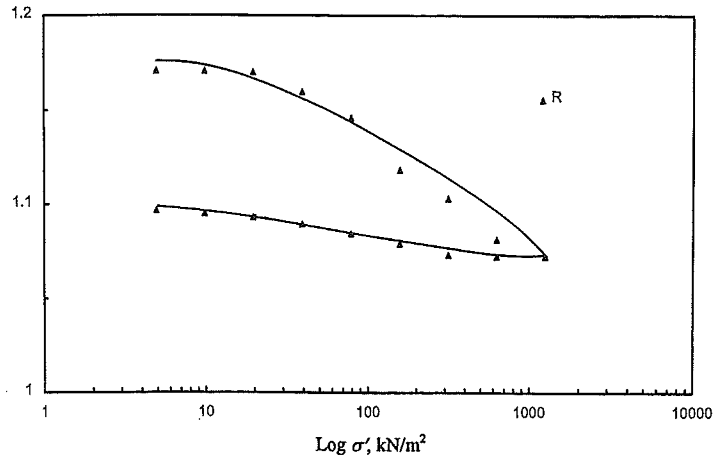


Fig. 12 *e*-log σ′ **Curve for Rajghat Fly Ash**

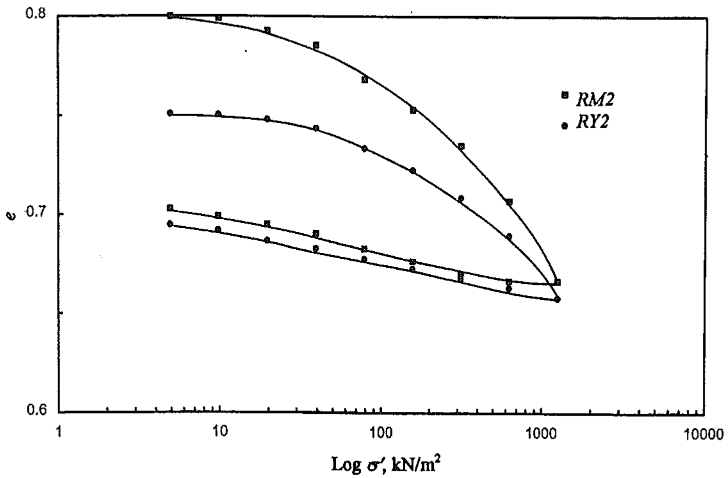


Fig. 13 *e*-log σ′ **Curve for Rajghat Fly Ash-Soil Mixtures**

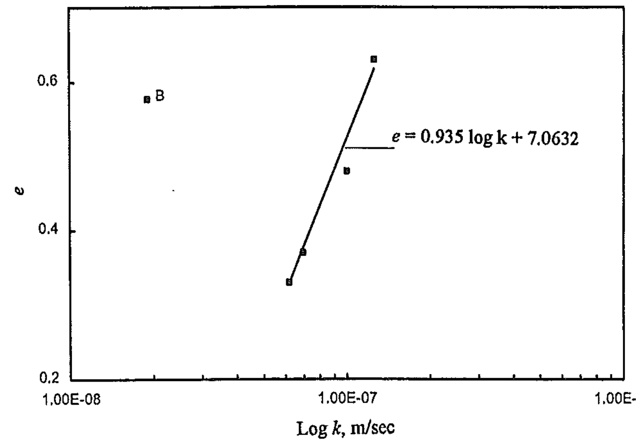


Fig. 14 Variation of Coefficient of Permeability with Void Ratio for Baumineral Fly Ash

CONCLUSIONS

An Indian fly ash from Rajghat thermal power station, New Delhi and a German fly ash from a chemical manufacturing unit Baumineral have been used in the laboratory experimental study. These fly ashes are predominantly silty material and are mainly composed of silica, alumina and iron oxide. They can be classified as class *F* fly ash. The fly ashes were mixed with sand and silt soils available near their respective sources in different proportions and their geotechnical characteristics were investigated. Based on these investigations it is concluded that:

1. The degree of compaction of the fly ash-soil mixtures is not sensitive to water content.
2. As the fly ash content increases, the *MDD* decreases and the *OMC* increases. The variation of *MDD* with fly ash content is more or less linear whereas that of *OMC* with fly ash content is slightly non linear.
3. The actual values of *MDD* and *OMC* mostly lie within the range predicted from specific gravity *G* and empirical correlations between *MDD*, *OMC* and *G*.
4. In direct shear tests on Rajghat fly ash-soil mixtures, the angle of shearing resistance increases with increase in fly ash content, but there was no consistent trend in the variation of the cohesion intercept. In the Baumineral fly ash-sand mixtures the trend was opposite to that of Rajghat fly ash-soil mixtures.
5. The unconfined compressive strength of the fly ash-soil mixtures increases with increase in the fly ash content.
6. In unconsolidated undrained triaxial shear tests, addition of soil to Rajghat fly ash decreases the maximum deviator stress. This tends to reduce ϕ_{uu} but the change in c_{uu} is not consistent.
7. The consolidation of the compacted fly ash occurs very rapidly both in the consolidation test and in the drained triaxial shear test. The compression and recompression indices of the Rajghat fly ash-soil mixtures are small. The compression of compacted fly ash fills will therefore be small and will occur quickly.
8. The coefficient of permeability of the Baumineral fly ash-soil mixtures is in the range of 1.25×10^{-7} m/s to 6.19×10^{-8} m/s. The void ratio varies linearly with log *k*.

ACKNOWLEDGMENT

The experiments on the Baumineral fly ash-sand mixtures were performed at the Institute of Strassenwesen und Eisenbahnbau, Ruhr University Bochum, Germany. The assistance provided by the German Academic Exchange Service (DAAD) and Prof. Klaus Krass for the work is acknowledged. The liberal support from and help provided by Mr. A.V.S.R. Murty, Deputy director, Central Road Research Institute, New Delhi to the second author for his research work, are gratefully acknowledged.

REFERENCES

ASTM C-618. (1993). Specification for fly ash and raw or calcined natural pozzolana for use as a mineral admixture in portland cement concrete. *Annual book of ASTM standards,* Section 4, Vol. 4.02, pp. 310-312.

CAPCO. (1990). Pulverized fuel ash as a reclamation fill. *Report of the China Light and Power Co. Ltd.*, Hong Kong, pp. 1-34.

CARRILLO, F.P.S. (1992). Comportomiento Geotecnico de Cenzias Volantes en Rellenos Compactados y su Evolucion a lo Largo del Tiempo. Doctoral Thesis, Laboratorio de Geotecnica, Madrid, 247 p.

DE SANTAYANA, F.P., and MAZO, C.O. (1994). Behaviour of fly ash in experimental embankments. *Proceedings of the Thirteenth International Conference on Soil Mechanics and Foundation Engineering*, New Delhi, India, Vol. 4, pp. 1603-1606.

DIN: 18130. (1985). Bestimmung des Wasserdurchlassigkeitsbeiwerts, Laborversuche, Teil 1, pp. 1-18.

GAI CONSULTANTS. (1992). *Fly Ash Design Manual for Road and Site Applications,* Vol. 1, 244 p. California: Electric Power Research Institute.

HAVUKAINEN, J. (1983). The utilisation of compacted coal ash in earth works. *Proceedings of the Eighth European Conference on Soil Mechanics and Foundation Engineering*, Helsinki, Finland, Vol. 2, pp. 773-776.

INDRARATNA, B.; BALASUBRAMANIAM, A.S.; and KHAN, M.J. (1995). Effect of fly ash with lime and cement on the behaviour of a soft clay. *Journal of Engineering Geology*, Vol. 28, pp. 131-142.

IS: 1727. (1967). Methods of test for pozzolanic materials. *Bureau of Indian Standards.* New Delhi, India. pp. 1-49.

IS: 11196. (1985). Specification for equipment for determination of liquid limit of soils by cone penetration method. *Bureau of Indian Standards.* New Delhi, India. pp. 1-16

IS: 2720, Part 16. (1979). Laboratory determination of CBR, Compendium of Indian standard on soil engineering. *Bureau of Indian Standards*, Part I. New Delhi, India. pp. 278-283.

KANIRAJ, S.R., and HAVANAGI, V.G. (1999). Correlation analysis of compaction of fly ashes. Personal communication.

KUNIO, T.; KOJI, S.; KAZUO, O.; TATSURO, O.; and MASANORI, S. (1996). Geotechnical properties of aged fly ash in reclaimed land of thermal power plant. *Proceedings of the Second International Congress on Environmental Geotechnics*, Osaka, Japan, Vol. 2., pp. 679-684.

LEONARDS, G.A., and BAILEY, B. (1982). Pulverised coal ash as structural fill. *Journal of Soil Mechanics and Foundation Engineering Division*, ASCE. Vol. 108, No. GT4, pp. 517-550.

MARTIN, J.P.; COLLINS, R.A.; BROWNING, J.S.; and BIEHL, F.J. (1990). Properties and use of fly ashes for embankments. *Journal of Energy Engineering*, ASCE. Vol. 116, No.2, pp. 71-86.

McLAREN, R.J., and DIGIOIA, A.M. (1987). The typical engineering properties of fly ash. *Proceedings of the Conference on Geotechnical Practice For Waste Disposal, Geotechnical Special Publication No. 13*, ASCE. pp. 683-697.

MOLLER, B., and NILSON, G. (1985). Technical properties of waste products from coal combustion - A laboratory study in accordance with soil analysis procedures. *Proceedings of the Eleventh International Conference on Soil Mechanics and Foundation Engineering,* San Francisco, California, U.S.A., Vol. 3, pp. 1271-1274.

REHSI, S.S., and GARG, S.K. (1988). Characteristics of Indian fly ashes. *Proceedings of National Workshop on Utilisation of Fly Ash.* Roorkee, India. pp. B131-B135.

SIVAPULLAIAH, P.V.; PRASHANT, J.P.; and SRIDHARAN, A. (1996). Effect of fly ash on the index properties of black cotton soils. *Soils and Foundations,* Vol. 36, No.1, pp. 97-103.

TSONIS, P.; CHRISTOULAS, S.; and KOLIAS, S. (1983). Soil improvement with coal ash in road construction. *Proceedings of the Eighth European Conference on Soil Mechanics and Foundation Engineering*, Helsinki, Finland, Vol. 2, pp. 961-964.

TOTH, P.S.; CHAN, H.T.; and CRAGG, C.B. (1988). Coal ash structural fill with special reference to Ontario experience. *Canadian Geotechnical Journal*, Vol. 25, pp. 694-704.

WEB. D.L., and HUGHES, T.S. (1987). The consolidation characteristics of fly ash. Ash - a valuable resource. *Proceedings of the CSIR Conference.* Pretoria, Republic of South Africa.

YUDHBIR and HONJO, Y. (1991). Applications of geotechnical engineering to environmental control. *Proceedings of the Ninth Asian Regional Conference on Soil Mechanics and Foundation Engineering*, Bangkok, Thailand, Vol. 2. pp. 431-469.