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Settlement of compacted ash fills

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Abstract The coal ash is a by-product of coal-fired thermal power station. It is extensively used as a geo-material for landfill. The compacted ash is used as a structural fill if it is properly characterized for load-bearing capacity and settlement. The main objective of the present work is to characterize ash material and to evaluate its settlement characteristics. The ash is normally compacted by vibration at or near optimum moisture for its performance as structural fill. The overt characteristics of ashes are viewed similar to cohesionless soils. However, the mass behavior may have differences due to the subtle influence of chemical and physical processes involved in its formation. The empirical and analytical methods predicting settlement of footing under static loading require direct or indirect measurement of density and stress state in the deposit. In the present work, experimental investigations for settlement prediction were carried out on compacted coal ash produced at Ropar thermal power station in India, which was conveniently classified as ASTM class *F* ash. The settlement was experimentally obtained for the rigid plates having least dimension more than 0.3 m on ashes compacted at varying degree of compaction. The predicted settlement based on the observed data of coal ash using conventional techniques for soils was found to be conservative. A relationship between settlement and foundation size is proposed at varying compaction to obtain the settlement of compacted ash. At a higher degree of compaction, the settlement of a foundation may not exceed the allowable settlements in the working stress range.

Keywords Coal ash · Settlement behavior · Degree of compaction · Plate load test

List of Notations

γ_d^{max}	Maximum dry unit weight (kN m^{-3}) in Proctor compaction
γ_d	Dry unit weight (kN m^{-3})
B_f, B_p	Width of footing and plate, respectively in meter
D_c	Degree of compaction, a ratio of γ_d and γ_d^{max}, normally presented as percent.
D_{50}	Mean size (mm)
e_{min}	Minimum void ratio
e_{max}	Maximum void ratio
F1, F2, F4, F5	Ash sampled from various fields of electrostaticprecipitator
OMC	Optimum moisture content

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PA1, PA2	Ash sampled from different locations of ash ponds
S_f, S_p	Settlement of footing and plate, respectively in mm
S_σ	Settlement of plate in mm at a stress level (σ in kPa)
S_{100}	Settlement of footing in mm at 100 kPa

Introduction

The coal-based power is one of the heavily relied means of power generation in India. One of the continuing practices throughout the world has been to consider the disposal of ash by often dumping into an area previously considered a wasteland. The viability of land reclamation for structural foundation using coal ash is presently investigated with special reference to the settlement.

In the present study, coal ash was procured from Ropar thermal plant in Punjab, India. As per the common nomenclature, the ash collected from electrostatic precipitators of thermal power plant is classified as fly ash. The coal ash produced from furnace bottom, known as bottom ash, is around 20–25% of the total ash produced. There is a normal practice to dispose off fly ash into a pond by mixing it with the bottom ash and water to form slurry. The slurry usually contains 20% solids by weight. This method of ash disposal is called wet method. The landfill of ash may be used as a structural fill if the suitable ashes are properly compacted. The fine ashes may collapse upon wetting. To avoid excessive settlement upon wetting suitability of coal ash should be examined as per the criteria of collapse (Trivedi and Sud 2004).

The chemical and physical characteristics of the ash produced depend upon the quality of coal used, the performance of washeries, efficiency of the furnace and several other factors. As per the source of coal used by in different countries, the condition and type of thermal units and disposal techniques, the chemical composition of the ashes is found to be different (Table 1). The ASTM classifications of coal ash are related to the percentage of calcium oxide in ash. The ashes with high amount of calcium oxide show self-hardening pozzolanic properties in presence of water. Such ashes are designated as class *C* ash. A typical class *C* ash is obtained from the burning of lignite coal. The ashes from bituminous coal, that do not possess self-hardening properties, are called class *F* ash. The ash produced at Ropar may be classified as class *F*. The coal ash is used in the construction of ash dykes, reclamation of low-lying land, man-made earth structures such as embankments, road fills, etc where settlement analysis of fill is required.

Review of previous work

Some of the case studies are reported on investigation and assessment of load bearing behavior of ash fills. These techniques are namely standard penetration test (SPT), static cone penetration tests (CPT) and plate load test (PLT). A summary of SPT results on compacted ash at varied degree of compaction (D_c) is listed (Table 2). The degree of compaction is defined as the percent ratio of dry

Table 1 Chemical composition of coal ashes[a] Skarzynska et al. (1989), [b] Author

Chemical components% (1)	British ash[a] (2)	American ash[a] (3)	Swedish ash[a] (4)	Polish ash[a] (5)	Ropar ash[b] (6)
SiO_2	38–58	30–58	30–53	43–52	57.5
Al_2O_3	20–40	7–38	14–33	19–34	27.2
Fe_2O_3	6–16	10–42	10–14	0.7–10.7	5.4
CaO	2–10	0–13	0.9–6.1	1.7–9.4	3.1
MgO	1–3.5	0–3	4–6	1–2.9	0.4
Na_2O, K_2O	2–5.5	0.4–2	1.6–3.5	0.4–0.9	0.9
SO_3	0.5–2.5	0.2–1	0.4–1.5	0.3–0.8	–
Unburned Carbon	–	0–4.8	0.9–3.3	1.9–9.9	4.1

Table 2 Variation of SPT value for ash deposits

Ash type	D_c (%)	*N*-value	Reported by
Compacted Kanawaha ash	95–100	10–31	Cunnigham et al. 1977
Hydraulically deposited Illinois ash	Loose state	Zero	Cunnigham et al. 1977
Well compacted Ontario flyash	85–100	10–55	Toth et al. 1988
Compacted ash dyke	~95	4–27	Dayal et al. 1999
Hydraulically deposited Ropar ash	Loose state	Zero-1	Sood et al. 1993
Compacted Ropar ash	~95	2–34	Sood et al. 1993

density of the compacted fill to the maximum dry density obtained in the proctor compaction test.

The investigations carried out by Cousens and Stewart (2003) for the range of cone resistance and the friction ratio (200 kPa and 8%, respectively) indicated grain sizes in the range of silt (60–80%) and clay (5–10%). For a target relative density (50–85%) variation in standard cone resistance is among 2000–6000 kPa (Trivedi and Singh 2004). However, the evaluation of settlement of these ash fills based on Schmertmann (1970) method was found to be a non-conservative estimate.

Based on a case study on Indianapolis ash, Leonard's and Bailey (1982) suggest that load settlement relation for foundation on compacted ash cannot be inferred from standard penetration test or static cone penetration tests. They largely attributed the inadequacy of penetration tests to sense the effect of compaction related pre-stressing of coal ash. The predicted settlements for a selected footing (2.1-m wide) at a design pressure of 239 kPa on a well-compacted ash from the data of SPT, CPT and plate load test (PLT) are presented in Table 3.

The plate load test results on compacted ash compared with Terzaghi and Peck (1948) results for very dense sand ($N = 50$ blows/305 mm penetration) indicated that ash materials are significantly less compressible in the pressure range of interest. At 100 kPa, compacted ash may settle less (half) compared to the settlement of same plate on sand.

Table 3 Predicted settlement for well-compacted area (Leonard's and Bailey 1982)

Testing technique	CPT	SPT	PLT
Settlement (mm)	15	25.4	5.08

Toth et al. (1988) reported a case study on performance of Ontario ash (a typical ASTM class *F* ash). During the compaction of ash as a landfill, it was observed that the densities being achieved in the field were normally below 95% of maximum Proctor density. Based on good bearing capacity observed in plate load test, Crag and Chan (1985) suggested 90% of maximum Proctor density as the target density for the fly ash landfills. Toth et al. (1988) obtained short term and long-term test results for circular plates of 0.3-m and 0.6-m diameter. The settlements for long-term tests occurred within the first hour of load application. The settlement of rigid plates on compacted ash is summarized in Table 4. There is a significant variation in the fineness of the ash deposits along the beaches of ash ponds. The fineness results in to variation of settlement characteristics of dry and saturated ashes at a common degree of compaction (Trivedi and Sud 2004).

Ash as a structural fill

There is only scanty data available on the interpretation of load bearing behavior of ash fills. The penetration test results analyzed by Cousens and Stewart (2003) and Trivedi and Singh (2004) showed the scope for development of a new correlations for evaluation of foundation settlements on coal ash. Leonards and Bailey (1982) favored the use of plate load test results for interpretation of load bearing behavior of the ash fill. The present work characterizes the coal ash for its physical, chemical and engineering characteristics and examines the plate settlement to work out a strategy for evaluation of foundation settlement on the ash fills.

Table 4 Settlement of test plate on compacted ash fill

Plate size, least dimensions in mm and shape	Degree of compaction (%)	Moisture content	Settlement at 100 kPa (mm)	Interpolation from experimental data of
900, square	85.24	Wet of critical	5.10	Present investigation
600, square	85.24	Wet of critical	3.80	Present investigation
300, square	85.24	Wet of critical	1.45	Present investigation
300, square	90.29	Wet of critical	1.05	Present investigation
300, square	85.24	Dry of critical	3.10	Present investigation
300, square	81.55	Dry of critical	4.70	Present investigation
600, square	90.29	Wet of critical	2.40	Present investigation
900, square	90.29	Wet of Critical	3.10	Present investigation
600, circular	93.40	Wet of critical	2.60	Toth et al. 1988
			3.05	Toth et al. 1988
600, circular	98.20	Wet of critical	1.40	Toth et al. 1988
300, circular	98.20	Wet of critical	0.45	Toth et al. 1988
300, square, long-term	–	Wet of critical	0.45	Toth et al. 1988
600, square	< 95%	Wet of critical	1.34	Leonard's and Bailey 1982
300, square	< 95%	Wet of critical	0.7	Leonard's and Bailey 1982
300, square	Sand, SPT, $N = 50$	–	1.1	Leonard's and Bailey 1982

Characterization

The ashes selected for evaluation of its settlement response was characterized by various established techniques. X-ray diffraction study was carried out to identify the mineral phases present in the ash. X-ray diffraction showed that the ash contains traces of aluminum silicate, quartz and some heavy minerals like hematite and magnetite. The identification of specific crystalline mineral was based on Bragg's equation,

$$\lambda = 2d \sin 2\theta, \tag{1}$$

where λ is the wavelength of X-ray specific to the Cu target element (=1.542 Å) and d is the inter planner spacing. The test was conducted between 0° and – 70° (2θ), at a rate of 0.8°/s using the CuK$_\alpha$ characteristic radiation of Cu target element. The inter planner spacing of respective peaks on the X-ray pattern were calculated from the corresponding 2θ angle. These peaks were associated with the characteristic minerals. In crystalline form, the ash contains traces of aluminum silicate, quartz and some heavy minerals (Fig. 1).

The potential clay minerals were found to be absent in the Ropar ash (Table 1). The absence of any peak associated with hydrated calcium silicate group that is responsible for the development of cohesion due to pozzolanic reaction (marked by the formation of crystals of hydrated calcium aluminum silicate on curing in presence of water) indicates non-self hardening properties of ash. Therefore, coal ash was treated as cohesionless material while evaluating its behavior as engineering fills.

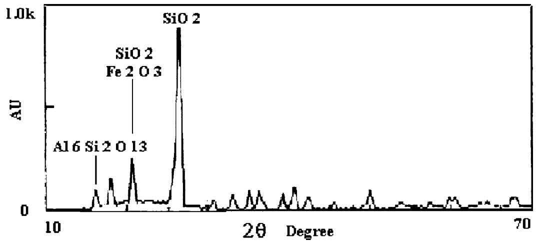


Fig. 1 X-ray diffraction pattern of a typical ash sample

Electron micrographs

The micrographic observation of a typical pond ash sample (PA1) indicated presence of predominantly coarse grain particles while the other one (PA2) indicated finer particles (Fig. 2). The coarse ash contained rounded spherules, subrounded, and opaque particles. The ash sample (PA2) contained superfine that formed agglomerates (a tendency to stick together and appear as larger particle upon pressing).

Grain size distribution

The ash contains particle sizes in the range of coarse sand to silt as shown in Fig. 3. However,

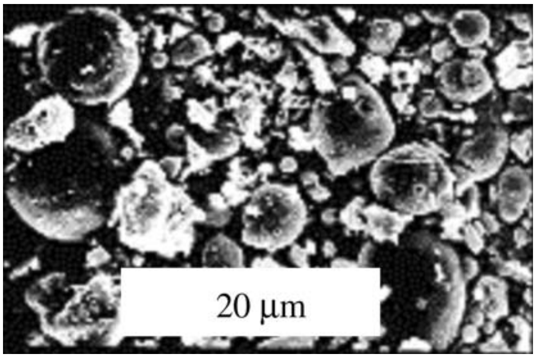


Fig. 2 Electron micrograph of a typical ash sample

the maximum frequency of the particles is in the range of fine sand to silt. The pond ash, which was examined for settlement behavior, contains 5–10% of particle in coarse and medium sand size, 35–50% in fine sand size and 40–60% of particles in the range of silt. The presence of superfine (size ~0.01 mm) increases inters particle friction, agglomeration and formation of pendular bonds in presence of moisture.

Apparent specific gravity

The coal ash has much lower apparent specific gravity than the natural soils of similar gradation, which is largely composed of silica among all the constituents. A low value of the specific gravity was attributed to the trapped micro bubble of air in the ash particle and the presence of unburned carbon. The air voids percentage of ash (5–15%) was found to be greater than the natural soils (1–5%) at maximum dry density. It was noticed that as fineness of the ash increases, the specific gravity also increases (Table 5a) partly due to the release of entrapped gases and breaking of bigger particles (Moulton 1978; Webb 1973; Leonards and Bailey 1982). The ashes with high iron content tend to have a higher specific gravity (Pandian et al. 1998). Seals et al. (1972) indicated that the bottom ash typically had a higher specific gravity. The pond ash (PA1 & PA2) had a higher specific gravity than the other samples obtained from the fields of electrostatic precipitator designated as F1, F2, F4 and F5 with decreasing mean size. It was partly due to the presence of bottom ash in the pond, which contains heavier components of the coal ash. Some of the ash solids contain pores, which are not interconnected, and hence they possess, on measurement, less specific gravity, although the specific gravity of constituent mineral remains in the usual range. In all cases, it is referred as apparent specific gravity, which is based on the weight in air of a given volume of ash solids, which includes the isolated voids.

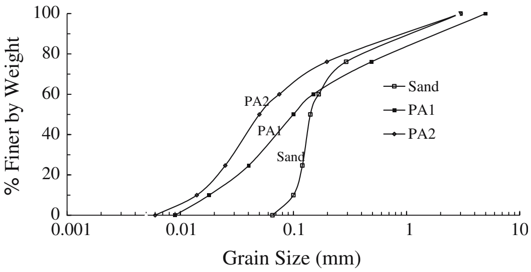


Fig. 3 Grain size distribution of coal ash

Compaction

In the design of ash dykes and ash fills, it is desirable to consider the compaction characteristics of the ashes. The hydraulically disposed ash in the ash ponds is normally in a low-density state. In order to improve its engineering properties the compaction is required. The coal ash may be compacted by vibration due to its non-plastic nature. However, owing to the significant percentage of fines it may also be compacted by impact.

The ash may be placed in varying states of density i.e. loosest state or in dense states as shown in Table 5b. The void ratio of ash sample in the loosest state was obtained by a slow pouring technique. The ash was poured in a fixed volume mold from a constant height of fall of 20 mm. In vibration test, ash was deposited at varying moisture contents in a standard thick-walled cylindrical mold with a volume of 2830 cm^3. The ash was vertically vibrated at double amplitude of 0.38 mm for 7 min in this mold mounted on a vibration table with a frequency of 60 Hz. Double amplitude of vertical vibration of 0.38 mm was found to be optimum for ash samples. Figure 4a shows the results of the vibratory, the Proctor compaction, and the

Table 5

Ash type	Specific gravity	D_{50} (mm)	Maximum dry unit weight (kN m^{-3})	Optimum moisture content (%)
(a) Specific gravity, mean size, Procter density and optimum moisture content				
F1	1.72	0.2	9.10	42
PA-1	1.98	0.1	9.50	40
F2	1.78	0.08	10.0	36
PA-2	2.00	0.05	10.3	37.5
F4	1.91	0.025	10.5	34
F5	1.93	0.016	11.7	32

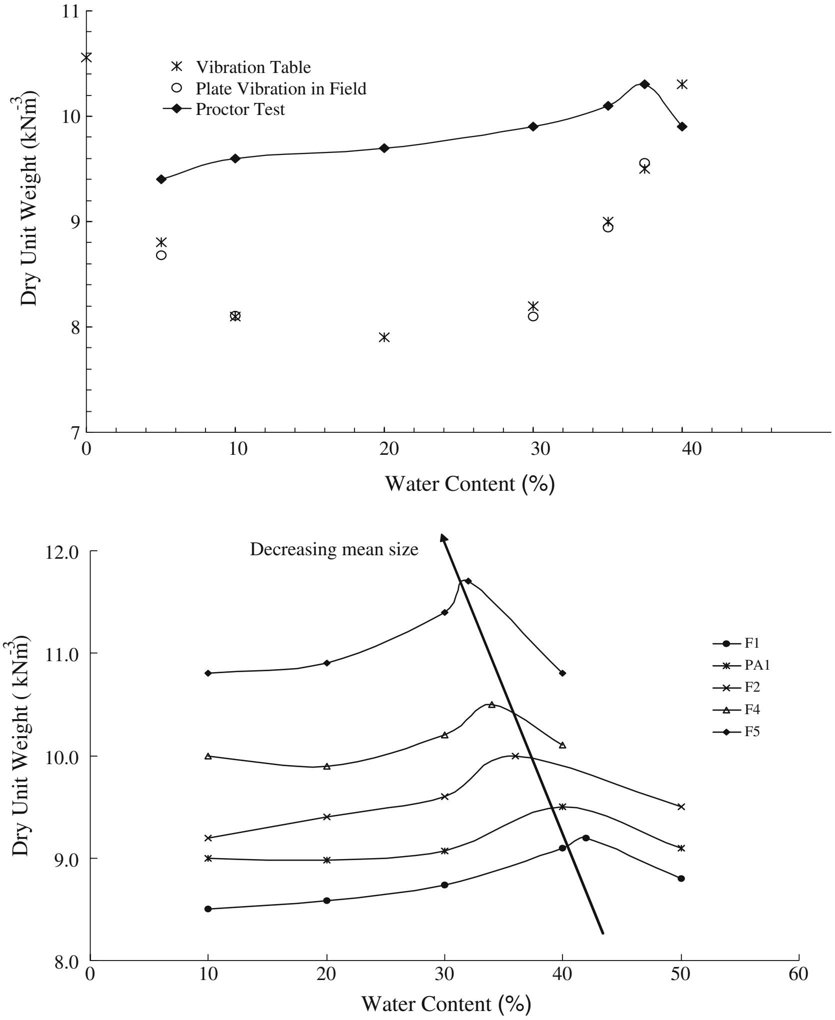
Ash type	$\gamma_{\mathrm{d}}^{\min}$	$e_{\max}$	$\gamma_{d}^{\max}$ (Dry)	$\gamma_{d}^{\max}$ (Wet)	$e_{\min}$ (Dry)	$e_{\min}$ (Wet)	$\gamma_{\mathrm{d}}^{\max}$ Proctor	Void Ratio at $\gamma_{\mathrm{d}}^{\max}$ Proctor
(b) Results of vibratory and Proctor compaction on PA1 and PA2								
PA-1	7.63	1.6	9.56	9.50	1.06	1.08	9.5	1.08
PA-2	7.85	1.54	10.56	10.3	0.89	0.94	10.3	0.94

plate mounted vibratory compaction of the ash sample (PA2). The result of Proctor compaction of the ashes with varying gradation indicates reduction in water requirement to achieve maximum density with fineness. The increasing fineness demonstrates a sharp increase in maximum dry density in the Proctor test (Fig.4b). The density in the vibration test was lower than that in the Proctor test in the dry side of optimum due to the rebound action of the spherical ash particles at a low degree of saturation. In the vibration test, a reduction in the density was observed with moisture content contrary to the Proctor test. It was due to the slacking of ash at a low saturation level. The minimum value of the dry unit weight is observed at critical moisture content (for PA2 at 20%). The dry unit weight increased beyond critical moisture due to the contravention of the surface tension force. The maximum dry unit weight was obtained at slightly higher moisture content in the vibration test. In addition, the maximum dry unit weight of coal ash was found to be less than that of the natural soils.

The maximum dry unit weight by Proctor test was obtained at significantly high moisture content (30–40%). The maximum dry unit weight by the vibration test was found to be slightly higher (~4%) than the Proctor test. A high optimum moisture content (OMC) is normally because of porous structure of the particles. The higher OMC of coal ashes compared to natural soils is due to a large percentage of the water inside the particles in initial stages. It is difficult to work the particles to higher density at lower moisture. The total air in porous structure is hardly expelled to saturate ash up to OMC. Hence, the vibratory densification technique resulted into a maximum dry unit weight in dry conditions only. However, the dry state compaction is not very useful in the field. By a slight vibration, ash becomes airborne and remains in air for hours. Sprinkling a little water helps to get rid of this problem but leads to the bulking of ash. In the standard equipment, there is no further improvement in unit weight beyond 6 min of vibration. Moreover, the finer sample, shows lesser variation in unit weight with time than coarse sample. It was due to greater inter-particle friction in fine ashes as found in the case of powders (Cooper and Eaton 1962). All ash samples initially show bulking there after they reach a stage of minimum dry unit weight at critical moisture content. The compaction beyond optimum moisture returns inconsistent densities. The presence of porous particle (unburned coal, pelerosphere and cenosphere) increases the optimum moisture content.

The ash is often compacted in field by vibratory rollers. In vibratory compaction, the maximum density in dry state is more than that in wet condition (Table 5b). A few of the air voids

Fig. 4 (**a**) Compaction plot for coal ash (PA2). (**b**) Proctor compaction of various ashes



remain entrapped among the hollow particles in wet condition. A resulting low density is attributed to surface tension in partly wet condition. The maximum dry density by vibration in wet condition nearly equals the maximum dry density as obtained in Proctor test. Modified Proctor test conducted on PA-2 suggests that there is no perceptible increase in the maximum dry density because of non-plastic nature.

Compaction trials

The desired density in the field was achieved by vibration. There is a usual practice to compact ash by vibration using 10–20 ton vibratory roller at moisture content close to the optimum. The tests indicate that vibratory roller compaction offer better results when soil moisture is slightly higher than optimum moisture content as obtained in Proctor test (Hall 1968). Depending upon the proximity of available moisture with optimum moisture content, degree of compaction may vary from 80 to 100%. In a narrow area vibratory roller, compaction may not be possible. On these locations, the vibrating base plate compactor may be used. It produces results similar to that of vibratory rollers (Hiff 1991).

In field compaction of ash, the use of hand operated base plate compactor had been reported near foundation walls (Leonards and Bailey 1982). The use of heavy weight vibrators with low frequency is suggested for gravelly material. A light to medium weight vibrator with high frequency are suggested for finer materials

(Hiff 1991). Any surcharge was found to reduce amount of densification in case of ash compacted at constant moisture content (Chae and Snyder 1977). The weight and frequency of compactor control the thickness of compacted lift. A light-weight, high frequency compactor offers satisfactory densities in thin lifts and heavy weight low frequency compactors give satisfactory density in thick lifts (Hiff 1991). One of the reasons for selection of a high frequency, low weight, and a base plate compactor in the present study was based on the criterion sited above.

A plate compactor of 220 N and a plate size of 152 × 390 mm were selected for vibratory compaction. Vibration was induced on loose left of 150–200 mm. The time of vibration required was settled after several trials. The scheme of vibration for 5 s and three passes at a frequency of 49.166 cps was found to be most appropriate. This produced satisfactory results of density at selected moisture contents. The moisture content density data obtained by core cutters at several locations and depth on the test area is plotted along with the data of laboratory vibration test in Fig. 4a. As ash becomes airborne by slight vibration in dry state and remains suspended in air for long. Therefore, compaction below 5% of moisture content was not recommended.

Test setup and testing technique

The load capacity of an ash fill was estimated by conducting load tests using different plates on ashes (PA1 and PA2) on varying degree of compaction. A summary of the experimental program is given in Table 6. An average of two tests was considered to reach a common load settlement plot if the settlement values were within the range of 10%.

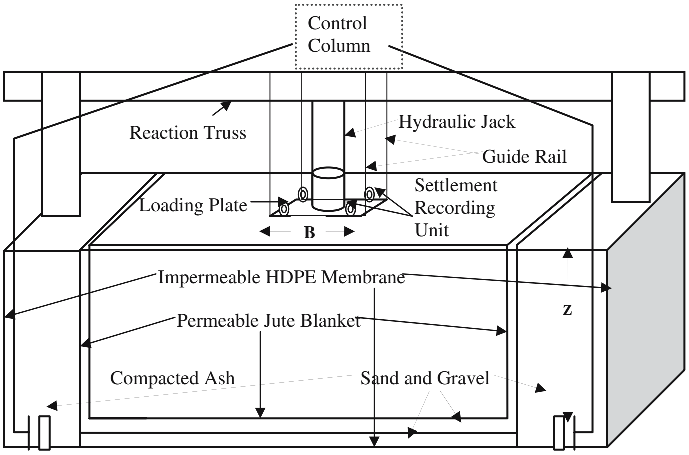
The ash was deposited in loose lift of 150 mm in a trench of plan dimension of 1.5 × 1.5 m (Fig. 5). It was compacted by a pre-calibrated plate vibrator mounted on a flat rectangular plate (152 × 390 mm). The rating of the plate vibrator was 2950 rpm. A constant magnitude of vibration was required to achieve the desired density. The trench was filled up in layers maintaining constant density throughout. The density checks were applied at regular intervals using thin core cutter sampling and penetration of 11 mm diameter needle penetrometer under a constant pressure. Few model load tests were carried out on surface footings (0.1 and 0.125 m wide strip and 0.3 m squares) in dry as well as submerged conditions for two different ashes and a sand to check the reproducibility of the results. The displacement of the plate was monitored using pre-calibrated settlement gauges of least count 0.01 mm. The total assembly including hydraulic jack, proving ring and the plate was aligned with the help of a plumb bob to attain verticality.

A plate of desired size was placed on the ash fill. A leveled 10-mm thick layer of dry ash was spread on compacted ash to ensure relatively complete and uniform contact between bearing plate and compacted ash. The plate was loaded with a hydraulic jack against a reaction truss. After application of the seating load, the load was increased in regular increments. The bearing plate settlement was measured with an accuracy of 0.01 mm. Each load increment was maintained on the bearing plate as long as no change

Table 6 Summary of experimental program

Ash type	Test conditions	Size (m)	Shape	D_c (%)	No. of tests	Max. Pressure
Sand	Dry	0.1	Strip	–	2	Failure
PA1	Dry of critical	0.1	Strip	–	2	Failure
	Wet of critical	0.1	Strip		2	Failure
PA2	Dry of critical	0.1	Strip	–	2	Failure
	Wet of critical	0.1	Strip		2	Failure
PA2	Dry of critical	0.3	Square	81.55,	4	Failure
		0.6		85.24	4	
	Wet of critical	0.3	Square	85.24,	4	200 kPa
		0.6		90.29	4	160 kPa
		0.9			4	90 kPa

Fig. 5 Line sketch of plate load test (free scale)



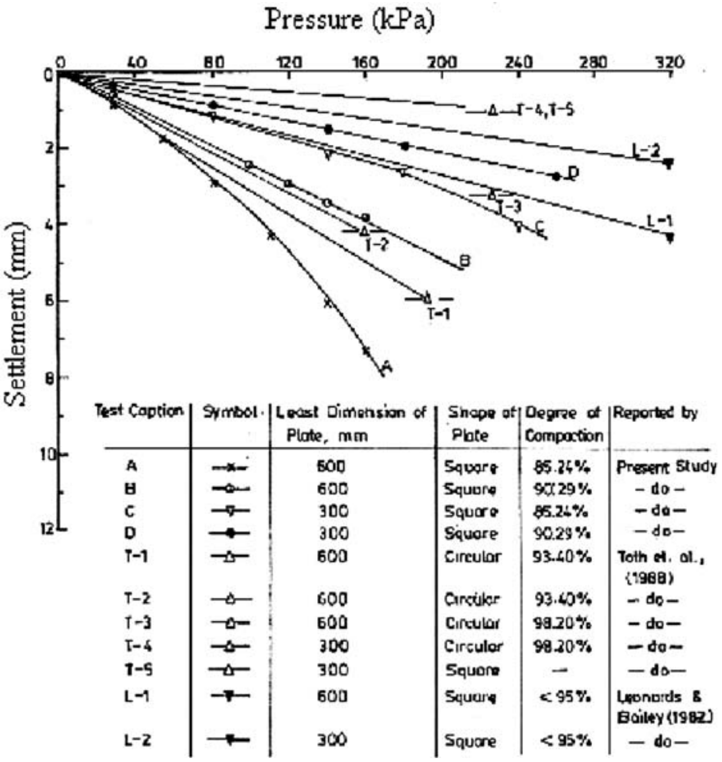
in the settlement was observed for two hours in succession. The typical pressure settlement plots are shown in Fig. 6.

The maximums loads required for failure of the deposit were estimated by the bearing capacity factors obtained from small-scale tests. A sharp increase of bearing plate settlement was considered as an indication of beginning of the ash failure phase. The settlement observation under final load was taken to the maximum of 24 h.

Settlement of compacted ash fill

In order to investigate settlement characteristics of compacted coal ash, load test results were analyzed for ash compacted to varying degree of compaction

Fig. 6 Pressure settlement plots for coal ash



Test Caption	Symbol	Least Dimension of Plate, mm	Shape of Plate	Degree of Compaction	Reported by
A	—×—	600	Square	85.24%	Present Study
B	—○—	600	Square	90.29%	– do –
C	—▽—	300	Square	85.24%	– do –
D	—●—	300	Square	90.29%	– do –
T-1	—△—	600	Circular	93.40%	Toth et. al., (1988)
T-2	—△—	600	Circular	93.40%	– do –
T-3	—△—	600	Circular	98.20%	– do –
T-4	—△—	300	Circular	98.20%	– do –
T-5	—△—	300	Square	–	– do –
L-1	—▼—	600	Square	< 95%	Leonards & Bailey (1982)
L-2	—▼—	300	Square	< 95%	– do –

and plate sizes. The ash was compacted to same degree of compaction at two different moisture contents one at the dry of the critical and other at the wet of the critical moisture content. The critical moisture is defined as the range of moisture content in which vibratory compactive effort becomes ineffective and ash bounces back to the loosest packing corresponding to which dry unit weight of ash is minimum in presence of moisture. In the dry side of the critical, ash packing is very sensitive to moisture. Within the limitation of workability in the field, the different degrees of compaction ware selected (i.e. 85.24 and 81.55%). The observations of density moisture relationship in field were found similar to that in laboratory vibration test (Fig. 4a). The increasing moisture content from 5 to 10% decreases the degree of compaction from 85.24 to 81.55%. The corresponding settlement at 100 kPa for a test plate (0.3 × 0.3 m) increases from 3.1 to 4.7 mm (Table 7a).

The coal ash (PA-2) was compacted at a degree of compaction of 85.24% on the wet side of critical moisture content. It was observed that settlement of 0.3 × 0.3 m plate is far less on the wet side of critical. The settlement of 0.3 × 0.3 m square plate at a constant degree of compaction (85.24%) on dry side of critical (3.1 mm) is almost double of the settlement at wet side of critical (1.45 mm) at constant stress intensity of 100 kPa (Table 7b).

By increasing the degree of compaction from 85.24 to 90.29% on the wet side of critical, settlement reduced from 1.45 to 1.05 mm and by improving the degree of compaction by 5% (from 85.24 to 90.29%), the settlement is reduced by one-third (Table 7c).

The investigations were carried out by conducting the tests on two plate sizes i.e. 0.3 × 0.3 m and 0.6 × 0.6 mm at varying degree of compaction (85.24 and 90.29%) on the wet side of critical. There was a significant increase in the settlement by increasing plate size at both compaction levels (Table 7d).

The case studies have shown that standard penetration test results might over estimate settlements of ash fill as high as five times that of the predicted value by the plate load test. While the cone penetration test over estimated settlements as high as three times (Leonards and Bailey 1982). The plate load tests tend to give more precise indication of actual settlements of larger sizes. The observed data of several investigators (Toth et al. 1988; Leonards and Bailey 1982) is given along with the

Table 7 (a) Settlement (0.3 × 0.3 m test plate) on ash compacted dry of critical

Degree of compaction, %	Settlement at 100 kPa (in mm)
81.55	4.7
85.24	3.1

(b) Settlement of 0.3 × 0.3 m test plate at a constant degree of compaction (85.24%)

Compaction moisture in	Settlement at 100 kPa in mm
Dry side of critical	3.10
Wet side of critical	1.45

(c) Effect of degree of compaction on settlement (0.3 × 0.3 m test plate)

Degree of compaction (wet of critical),%	Settlement at pressure of 100 kPa in mm
85.24	1.45
90.29	1.05

(d) Effect of plate size on settlement at varying degree of compaction

Plate Size (mm)	Settlement (wet of critical) at 100 kPa in mm	
	D_c = 90.29%	D_c = 85.24%
300 × 300	1.05	1.45
600 × 600	2.4	3.8
900 × 900	3.1	5.1

results of present investigation in Table 4. From the analysis of data of the present investigation and that published by Leonards and Bailey (1982), it is understood that well compacted ash for the footing size and stress level of interest, has settlement directly proportional to pressure up to 200 kPa. Hence the settlements at 100 kPa are interpolated from the data published by Leonards and Bailey (1982), Toth et al. (1988) and present investigation (Table 4).

The critical moisture content defined as moisture content at which ash attains minimum density when compacted by vibration, provides a symmetrical moisture–density relation about this moisture content. Therefore, the ash compacted at different moisture contents one at the dry of critical and other at the wet of critical was considered for testing. By adding the moisture beyond the critical moisture content, surface tension develops which tend to impede the deformation of the ash. It is destroyed gradually by the addition of water beyond the optimum moisture. The percentage increase in settlement by compacting ash at dry side of critical, instead of wet side of critical at 100 kPa (0.3 × 0.3 m square plate at D_c of 85.24%) is 113.79%.

There is a significant impact of degree of compaction on dry side of the critical. For a drop in the degree of compaction from 85.24 to 81.55% (% decrease in degree of compaction 4.32) there is increase of settlement at 100 kPa from 3.1 to 4.7 mm (percentage increase in settlement is 51.61%). Similarly on the wet side of critical, for a decrease in the degree of compaction from 90.29 to 85.24% (percentage decrease in degree of compaction 5.59%) there is increase in settlement from 1.05 to 1.45 mm (percentage increase in settlement is 38.09%).

The scale effects are clearly visible in the settlement of ash deposits. The plots are drawn (Fig. 7) from experimentally observed data set of a plate (0.3 × 0.3 m) and predicted settlement for 0.6 × 0.6 m and 0.9 × 0.9 m square size plates by the (Terzaghi and Peck 1948) expression (Eq. 2).

$$\begin{aligned} S_{\mathrm{f}} &= S_{\mathrm{p}}\left[\frac{B_{\mathrm{f}}(B_{\mathrm{p}}+0.3)}{B_{\mathrm{p}}(B_{\mathrm{f}}+0.3)}\right]^{2} \\ B_{\mathrm{f}}, B_{\mathrm{p}} &= \text{Width of footing and plate, respectively in meter.} \\ S_{\mathrm{f}}, S_{\mathrm{p}} &= \text{Settlement of footing and plate, respectively in mm.} \end{aligned} \tag{2}$$

The predicted settlements

The predicted settlements at 100 kPa according to Terzaghi and Peck extrapolation does not agree of settlement of footings larger than 0.6 m (least dimension) on compacted ash fill (Fig. 7). The predicted settlements based on actual settlement of 0.3 m (least dimension) seriously under estimates the observed settlements (D'Appolonia et al. 1968). The predicted settlements (Table 8) underestimated the actual settlement at all the degree of compaction. The settlement of 0.6 m (least dimension) plate has been under estimated by 44.36% and 7.44%, respectively by the estimates of Toth et al. (1988) and Leonards and Bailey (1982). The predicted settlement under estimated the

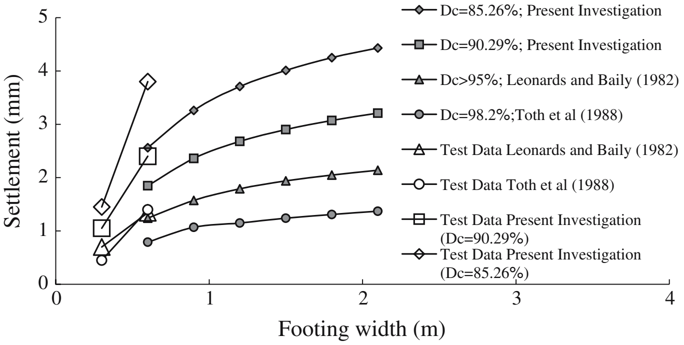


Fig. 7 Predicted settlements as per Terzaghi and Peck criteria and observed settlement at varying degree of compaction versus footing width at 100 kPa

Table 8 Predicted settlements (mm) as per Terzaghi and Peck formula

B_f (m)	D_c = 85.26%, Present investigation	D_c = 90.29%, Present investigation	D_c < 95%, Leonards and Bailey (1982)	D_c = 98.2%, Toth et al. (1988)
0.60	2.56	1.85	1.24	0.79
0.90	3.26	2.36	1.575	1.07
1.2	3.71	2.68	1.79	1.15
1.5	4.01	2.90	1.94	1.24
1.8	4.25	3.07	2.05	1.31
2.1	4.43	3.21	2.14	1.37

observed settlement of 0.6 m plate (90.29 and 85.24% degree of compaction) by 56.25 and 61.84%, respectively (Table 8).

The mean value of ratio of predicted settlement according to Terzaghi and Peck extrapolation and experimentally observed settlements was found to be 0.3. Table (9) presents percentage underestimation of (0.6 × 0.6 m) footing settlement by Terzaghi and Peck formula at varying degree of compaction at 100 kPa.

Table 9 Percentage underestimation of footing settlement by Terzaghi and Peck formula

D_c(%)	% Under estimation of settlement	Interpreted from the data of
98.2	44.36	Toth et al. (1988)
< 95	7.46	Leonard's and Bailey (1982)
90.29	56.25	Present investigation
85.24	61.84	Present investigation

The predicted settlements according to the modified criterion using linear relationship among the settlement (mm) at 100 kPa and the footing width (m) on logarithmic scale, is estimated (Fig. 8). The experimental data for varying size of footing at probable degree of compaction is also plotted in Fig. 8. The expected settlement curve, at a pressure of 100 kPa, for various foundation sizes, indicates least possibility of exceeding the allowable limit of settlements in the probable degree of compaction (Fig. 9).

Further tests are recommended to verify predicted settlements of large size footings at a lower degree of compaction. Based on loads obtained from the shear failure considerations (Trivedi and Sud 2005) and the safe settlements, the allowable bearing pressure may be worked out for a compacted ash fill. The settlement at pressure other than 100 kPa with in the elastic limits of compression of ash is calculated as

$$S_\sigma = S_{100}(\sigma/100)_\sigma \qquad (3)$$

Conclusions

The analysis of settlements is conducted to ascertain whether foundations on compacted ash fills can fulfill their intended function from structural and utilization point of view.

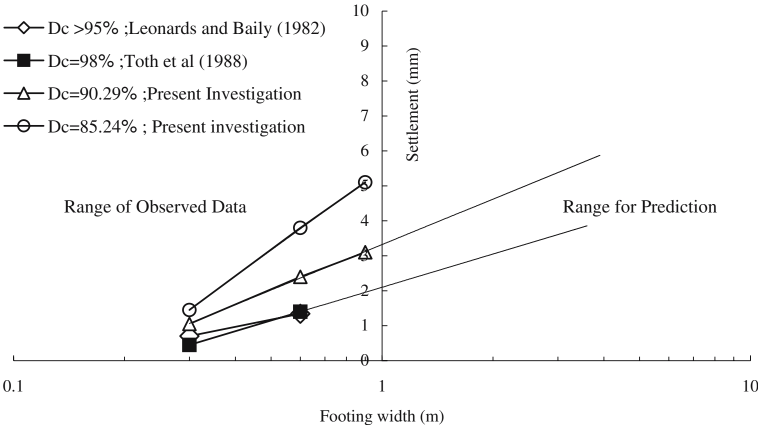


Fig. 8 Predicted and observed settlement at varying degree of compaction versus footing width

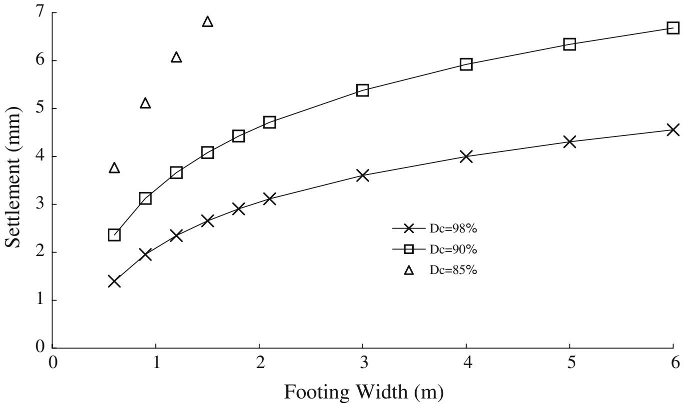


Fig. 9 Predicted settlement (at 100 kPa) of footings at varying degrees of compaction

The settlement of footing on ash compacted on dry side of critical is higher compared to that degree of compaction at wet side of critical. A shear failure (Trivedi and Sud 2005) or a collapse (Trivedi and Sud 2004) may precede allowable settlements at a lower degree of compaction than 90%. In the dry side of critical, a very high degree of compaction must be additionally ensured which is normally difficult in practice.

The settlement of footings may be worked one as per the desired degree of compaction (Fig. 9) and intended footing size and desired stress level (Eq. 3) for the ash compacted on the wet side of the critical. The pressure corresponding to safe settlement may also be ascertained from the available data.

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