Collapse Behavior of Coal Ash

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Abstract: The paper describes an investigation carried out to examine the factors influencing collapse settlement of the compacted coal ash due to wetting. The ashes produced by the coal fired thermal power plants are stored as a high mound in the disposal dump. Some of the ash dumps and ash fill structures wetted under certain conditions of loading may exhibit collapse. Attempts have been made to correlate the ash characteristics and the specific placement parameters such as ash type, soluble content, degree of compaction, overconsolidation ratio, moisture content, and stress level at wetting with collapse. This was based largely on the oedometer and partly on the model and the field test results. 378 single oedometer tests were conducted to obtain the collapse potential. The collapse potential was correlated with the mean size of the ash. The favorable pressure, moisture, fines, compaction, soluble substance, and prestressing decrease the collapse potential of an ash fill. The collapsible and the noncollapsible ashes were identified by the results of oedometer test and laboratory model test. Normally, if the collapse potential in the oedometer is more than 0.01, the collapse of soils may occur in the field. However, the model test demonstrated this to be an unconservative criterion. A value of 0.0075 at 80% degree of compaction was found appropriate for the ashes examined. The paper explains the technique of field test performed at the controlled densities. The field test confirmed incidence of collapse on a rising water table for a collapsible ash.

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CE Database subject headings: Fly ash; Collapse; Oedometers; Field tests.

Introduction

Coal ash is a waste product of the coal based thermal power plant. The power generation based on coal produces a huge amount of coal ash. There is a serious problem of its storage and disposal. Turgon (1988) reported use of blended ash in land reclamation. In recent years the coal ash was studied as a structural fill material without additives (Indraratana et al. 1991; Sood et al. 1993; Walia et al. 1995; Trivedi et al. 1996; Trivedi 1999; and Trivedi and Sud 2002). It was recognized that a loose ash fill structure may be prone to collapse on wetting. Therefore an investigation was carried out to examine the factors influencing the collapse of compacted ash fill on inundation.

Morland and Hastings (1973) evaluated collapse of the dry porous volcanic tuff which is similar to the coal ash in its characteristics. The general characteristics of collapsing soils are a sudden and a large volume decrease at a constant stress when inundated with water. According to Lutenegger and Saber (1988) the collapse is associated with the meta-stable structure of a large open and porous fabric of the material. Holtz (1948) suggested that earthen structures such as embankments, road fills and structural fills may collapse when the placement moisture content is dry of optimum. Fourie et al. (1999) found that infiltration of the rainfall may be sufficient to reduce the matric suction within the ash to a low value enough to trigger a shallow failure. Indraratna et al. (1991) studied the engineering behavior of pozzolanic (ASTM class C) Thailand ash and indicated its collapsible nature. However, little information is available on the collapsibility a typical nonpozzolanic (ASTM class F) coal ash. It has been observed that in a wide range of placement parameters the ash remains vulnerable to the collapse on submergence in working stress range. Fourie et al. (1999) reported the susceptibility of an ash slope to instability induced from a prolonged infiltration. A slip failure was described by Dhillon (1995) at the ash dump of Vijyawada thermal power plant resulting in the destruction of several houses and the swamping of land with fly ash. Indraratana et al. (1991) reported the sudden failure of a large fly ash disposal dump after rainfall and associated mudflow at Panki, Kanpur. Such failures are not quite representative of conventional failures. Several studies have indicated that compaction control of coal ash in the field by usual methods is often poor. It adds to the vulnerability of ash fill to a wetting induced collapse.

The soils that exhibit collapse have an open type of structure with a high void ratio as expected in the case of ashes. According to Barden et al. (1969) the collapse mechanism is controlled by three factors; (1) a potentially unstable structure, such as flocculent type associated with soils compacted dry of optimum or with loess soils; (2) a high applied pressure which further increases the instability; and (3) a high suction which provides the structure with only temporary strength which dissipates on wetting. As per an empirical study by Meckechnie (1989), the dry unit weight and water content are generally considered as important parameters that control the collapse of metastable structure of soils, if the dry unit weight is less than 16 $\mathrm{kN\,m^{-3}}$. The tentative dry unit weight of the coal ashes in Ropar ash pond was often found to be less than 10 $\mathrm{kN\,m^{-3}}$ suggesting possibility of collapse. Jennings and Knight (1975) indicated that collapse behavior is also dependent

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on the clay fraction. Foss (1973) and Reznik (1993) defined the magnitude of collapse by

$$C_p = dh/h_0 \tag{1}$$

where C_p=collapse potential; dh=decrease in the height of specimen subsequent to inundation; and h_0=height of specimen before saturation. Tadepalli and Fredlund (1990) and Foss (1973) observed that the percentage of collapse decreases with dry unit weight for Indian Head silt and residual clays of Kenya. As per Booth (1975) the collapse settlement exceeding 1% is likely to occur when the initial dry unit weight is less than both 15.7 $\mathrm{kN\,m^{-3}}$ and 85% of that obtained in the modified compaction test. The collapse potential is quantifiable in terms of the volume change that occurs when a soil is submerged with water. It is usually obtained by conducting oedometer tests on soil specimen. The collapse potential is expressed as a change in void ratio on wetting compared to the pre wetting volume of the soil at any stress level.

$$C_p = \Delta e/(1+e_i) \tag{2}$$

where Δe=change in void ratio upon wetting; and e_i=void ratio at the beginning of saturation. Knight (1963) defined the collapse potential at a stress level of 200 kPa selecting e_i as void ratio at the beginning of compression. If the C_p is less than 0.01, generally there is no risk of a collapse in the field. Lutenegger and Saber (1988) suggested the use of e_i as void ratio before saturation at an applied stress of 300 kPa. They recommended that a soil is slightly collapsible if the value of C_p is below a limit of 0.02. Their investigations reveal that the soils which have placement void ratio between 0.9 and 1.05 are slightly or moderately collapsible. The insitu void ratio of coal ash used in this study was found to be in a range between 0.8 and 1.6 suggesting a risk of collapse.

In this study several oedometer tests were performed and the results were verified by specially fabricated model test. A work program was devised to study the influence of ash characteristics, density, solubility, moisture content, stress level, and overconsolidation on the collapse of ashes. A field work was planned to examine the influence of density and rising water table on the incidence of collapse. It was observed that the ash having a marked morphological difference with the natural soils require a distinct criterion for the classification of its collapsibility. Based upon the oedometer and the model tests a new limit of collapse potential was assigned for the ashes. The collapsibility of ash was found to be highly correlated with its grain size characteristics.

Characterization

The ash was characterized to evaluate the feature and the quality that made it recognizable in physical, chemical, and engineering sense. The characteristics of ash depend upon the quality of coal used, the performance of washeries, the efficiency of furnace and several other factors. The physical and chemical properties of ash are dependent on type (e.g., anthracite, bituminous, subbituminous, and lignite) and source of coal, method and degree of coal preparation, cleaning and pulverization, type and operation of power generation unit, ash collection, handling and storage methods, etc.

The mineral groups present in coal, such as clay minerals (e.g., illite, kaolinite, and montmorillonite) carbonate (calcite and siderite), sulphate (gypsum), silicate (quartz and feldspar), phosphate (apatite), sulphide (pyrite and marcasite) group etc. and their varying proportions, play a major role in determining the chemical composition of the ash. During combustion, the above minerals are transformed into mullite, magnetite, tridymite, glass, etc., forming a composite ash. In the present study, coal ash was taken from Ropar thermal plant, Punjab, India. It was sampled from seven electrostatic precipitator (ESP) fields (referred as F1–F7), mixed ash of ESP mixed hopper (MH) and pond ash (PA1 and PA2). The ash collected from the ESP fields and the furnace bottom is classified as fly ash and bottom ash, respectively. The ash disposed by mixing the bottom ash with ESP ashes and water is known as pond ash. There are a large variety of particles found in the ashes. It comprises floating scum to heavy ceramic composites in varying amount. Together this assortment of particles is known as coal ash.

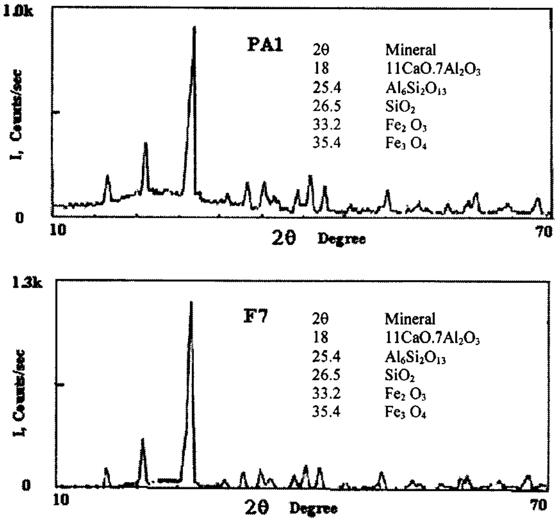


Fig. 1. X-ray diffraction pattern of coal ash (PA1 and F7)

Physical Characteristics and Chemical Composition

An x-ray diffraction was carried out to identify the mineral phases present in the ash (model: Rigaton D/max III C). X-ray diffraction showed that the ash contains traces of aluminum silicate, quartz and some heavy minerals like haematite and magnetite. Identification of definite crystalline mineral was based on Bragg's equation

$$\lambda = 2d\sin 2\theta \tag{3}$$

where λ=wavelength of x-ray specific to the Cu target element (=1.542 Å); and d=inter planner spacing. The test was conducted between 0° and 70° (2θ), at a rate of 0.8°/s using the CuK_α 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. The potential clay minerals (e.g., illite, kaolinite, and montmorillonite) were absent in the Ropar ash. This pointed towards lack of the structural cohesion in the ash. Ash samples contain distinguishable amount of amorphous phase minerals due to the presence of the unburned coal. Various ash samples reveal a constant overall chemistry but variation in the proportion of crystalline and amorphous phases distinguishable by sharp peaks and gradual humps in the x-ray diffraction pattern. The amorphous phase was at large in the coarse grain ashes. The fine ash was predominantly crystalline as manifested by the sharp peaks obtained in the x-ray diffraction pattern (Fig. 1).

Table 1. Chemical Composition of Coal Ashes

Chemical components (%)	British ash[a]	American ash[a]	Swedish ash[a]	Polish ash[a]	Indian ash[b]	Ropar ash[c]
SiO_2	38–58	30–58	30–53	43–52	55–71	57.5
Al_2O_3	20–40	7–38	14–33	19–34	20–27	27.2
Fe_2O_3	6–16	10–42	10–14	0.7–10.7	1.7–4.8	5.4
CaO	2–10	0–13	0.9–6.1	1.7–9.4	0.5–5.6	3.1
MgO	1–3.5	0–3	4–6	1–2.9	0.2–0.9	0.4
Na_2O, K_2O	2–5.5	0.4–2	1.6–3.5	0.4–0.9	0.7–0.81	0.9
SO_3	0.5–2.5	0.2–1	0.4–1.5	0.3–0.8	0.1–0.5	—
Unburned carbon	—	0–4.8	0.9–3.3	1.9–9.9	0.2–0.6	4.1

[a] Skarzynska et al. (1989).

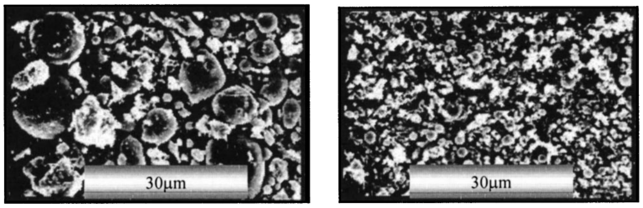
[b] Dayal (1996).

The chemical composition of the ashes was obtained from the noncombustible components produced by burning of the coal. The main chemical components of the coal ash are identified as silica, alumina, iron oxide, and alkalis. The comparison of a typical range of chemical composition of ashes from different parts of the world along with the Ropar ash is given in Table 1. The ASTM classification of the coal ash is related to the percentage of calcium oxide in the ash. The ashes with high amount of calcium oxide show self-hardening properties when in contact of water. Such ashes are designated as class C ash. They are obtained by the burning of the lignite coal. The ashes from the bituminous coal, which do not possess self-hardening properties, are called class F ash. Due to low percentage of CaO in the Ropar ash, it may be classified as class F ash.

The biggest constituent of the Ropar ash was silica followed by alumina, oxides of iron, and calcium (Table 1). The presence of sodium and potassium salts was known by the qualitative chemical analysis. The submergence of ashes was critical compared to the other granular soils due to the presence of these soluble matters. The solubility of each sample was determined separately at the boiling water and the room temperature. Each sample was thoroughly mixed with the boiling water by a stirrer. The entire experiment was repeated with the cold water mix at the room temperature. This mixture was filtered through the whatman-42 filter paper. The retained ash was dried in an electric oven at 105°C for 24 h and the percentage soluble in the ash was obtained. The solubility was significantly affected by the temperature of water as shown in Table 2.

Table 2. Results of Specific Gravity, Proctor Compaction, and Solubility Tests

Ash type	G_s	γ_{proctor} (kN m^{-3})	OMC (%)	Soluble by weight (%) 100°C	28°C
F1	1.72	9.10	42	0.8	0.6
F2	1.78	10.0	36	0.8	0.6
F3	1.88	10.2	35	0.4	0.3
F4	1.91	10.5	34	0.4	0.3
F5	1.93	11.7	32	1.1	0.9
F6	2.02	12.8	26	0.4	0.3
F7	2.03	13.1	24	0.4	0.3
MH	1.90	11.7	33	0.5	0.4
PA1	1.98	9.50	40	0.2	0.0
PA2	2.00	10.3	37.5	0.2	0.0



PA1 F7

Fig. 2. Electron micrograph of ash samples (PA1 and F7)

Various ash samples were scanned by an electron microscope. Electron micrographs of PA1 and F7 samples revealed the presence of predominantly open type of structures, similar to the collapsible soils (Fig. 2). The coarse ash contained rounded, subrounded, and opaque particles. F7 was mostly composed of the superfine spherules (size ~0.01 mm). The ash samples containing superfine had a tendency to form lumps on pressing called agglomerates. Fig. 3 shows grain size distribution of various samples. The grain size analysis plot was transferred as seven equivalent sizes corresponding to 0, 10, 50, 60, 80, and 100% finer by weight for each of the ashes. The maximum frequency of particle was in the range of fine sand to silt. F4, F5, F6, and F7 were uniformly graded with decreasing coefficient of uniformity. F6 and F7 contained significant fraction of particles finer than the silt size. The cohesionless soils of similar gradation as that of ash in general are characterized as coarse sand to silt as per ASTM (D2487) soil classification system.

The selected coal ashes typically have lower apparent specific gravity than the natural soils of similar gradation. A low value of the specific gravity can be attributed to the trapped micro bubble of air in the ash particle and the presence of unburned carbon (Raymond 1961). It was noticed that as fineness of the ash increases (F1–F7), the specific gravity also increases (Table 2) due to the release of entrapped gases. Webb (1973) and Leonards and Bailey (1982) reported a similar phenomenon in ash grounded by mortar and pestle, thought to indicate the release of gas by breaking of the bigger particles. The mineralogical composition is one of the other reasons for variation in the specific gravity of the ash relative to soils. The ashes with high iron content tend to have a higher specific gravity. Pandian et al. (1998) found that the presence of heavier minerals such as hematite and magnetite result into a higher specific gravity. Seals et al. (1972) indicated that the bottom ash typically had a higher specific gravity. The pond ash

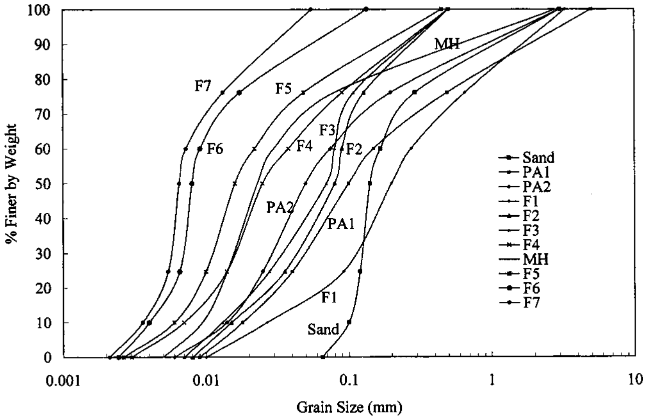


Fig. 3. Grain size distribution of ashes

(PA1 and PA2) had a higher specific gravity than the other samples. It was partly due to the presence of bottom ash in the pond which contained heavier components of the coal ash. Some of the ash solids possess less specific gravity on measurement, while the specific gravity of constituent mineral remains in the usual range. In such cases it is referred to as apparent specific gravity which is based on the weight in air of a given volume of ash solids and includes all the particles.

Compaction

In design of the ash dykes and the ash fills, it is desirable to take into account the compaction characteristics of the ashes. The hydraulically disposed ash in the ash ponds is normally in a low-density state. The void ratio of various ashes was obtained in the loosest state 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 2,830 cm^3. The ash was vertically vibrated at double amplitude of 0.38 mm for seven minutes in this mold mounted on a vibration table with a frequency of 60 Hz. Difficulties of flow of the fines were encountered in using this technique. The capping plate was modified to fit the top of the mold so that it pressed the ash with a minimum clearance between the capping and mold. Double amplitude of vertical vibration of 0.38 mm was found to be optimum for all the ash samples.

Being nonplastic in nature and containing a significant percentage of fines, the coal ash may be compacted both by the vibration and the proctor methods. In the proctor test ash could not be compacted in dry state ($w = 0$) as the impact of the compaction hammer resulted into the displacement of ash almost equal in volume.

Fig. 4(a) shows the results of the vibratory and the proctor compaction tests on a typical ash sample (PA2). Generally, the density in the vibration test was lower than that in the proctor test in the dry side of optimum. A reduction in the density was observed with moisture content, in the vibration test but not in the proctor test. This is commonly due to the bulking of ash at a low saturation level ($w < 10\%$). Similar phenomenon is observed as result of vibratory compaction of a cohesionless soil (Foster 1962). The minimum value of the dry unit weight of PA2 was observed at a critical moisture content of 20%. The dry unit weight increased far and wide away from critical moisture due to the reduction in the surface tension force. The second maxima in dry unit weight was obtained at a higher moisture content ($w = 40\%$) in the vibration test than the proctor test. The attempt to compact ash by vibration beyond this moisture content ($w > 40\%$) provided variable dry densities.

The maximum dry unit weight of coal ash was found to be less than that of the natural soils. This is likely due to a low specific gravity and a high air void content. Raymond (1961) and Moulton (1978) found that the air voids percentage in ash (10–15%) is greater than the natural soils (1–5%) at maximum dry density in proctor test.

Fig. 4(b) compares the proctor compaction of the various ash samples. As the fineness of the ash increases, its optimum moisture content reduces and the maximum dry unit weight increases. The coarse ashes show a higher air void content compared to the fine ashes. The presence of the porous particles tends to increase the optimum moisture content owing to absorption.

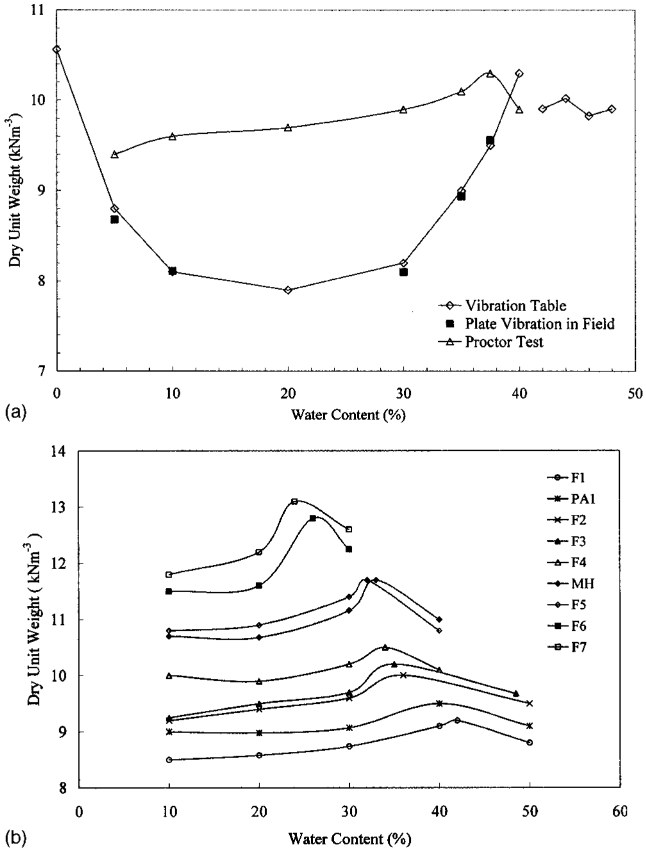


Fig. 4. (a) Compaction plot for coal ash (PA2) and (b) effect of proctor compaction on various ashes

Compressibility

The compressibility of coal ash was estimated by a 20 mm height and 60 mm diameter conventional oedometer test on the dry and the submerged ash samples of PA2 at varying degree of compaction. The degree of compaction (D_c) is defined as a ratio of a target dry unit weight (γ_t) to the maximum dry unit weight (γ_{proctor}) obtained in the proctor compaction.

$$D_c(\%) = (\gamma_t / \gamma_{\text{proctor}}) \times 100 \tag{4}$$

The target unit weight was achieved by compacting a calculated weight of dry ash to fill the sampler. A seating load of 5 kPa was applied on the sample and was withdrawn. An identical dry sample was submerged in the water at 5 kPa for the submerged test. The displacement on the dial gauge was reset at zero. Any compression that occurred under 5 kPa was assumed to arise primarily from the softening due to the sample disturbance and was not included in the compression measurements.

The dry and the submerged samples were compressed by an axial load increment until the consolidation ceased. The compression of the ash sample was recorded before the application of the next load increment. This process was repeated for the dry and the submerged ash samples made to the varying degree of compaction. Ash being a free draining material, a nearly saturated condition was observed at the end of the tests.

Fig. 5 shows the compressibility of the dry and the submerged ash at varying degree of compaction. The submergence and the decrease in the density decreased the stiffness. The difference of void ratio as per the best fit in the dry and the submerged conditions increased with vertical pressure and decreased with the den-

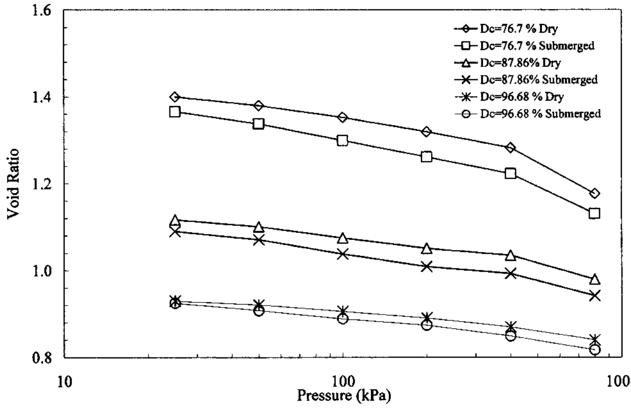


Fig. 5. One-dimensional compression of ash in oedometer (PA2)

sity. It varied among 0.04–0.01 for loose and dense placement conditions at 200 kPa. The ashes which show difference in the void ratio in the dry and the submerged states have a tendency to collapse upon wetting.

Shear Strength

The shear strength of ash (PA1 and PA2) was determined by direct shear test on the dry and the submerged samples (Fig. 6). The dry samples were prepared by compacting calculated weight of the dry ash to fill the shear box at varying degree of compaction. In this way the target density was achieved. A seating load of 5 kPa was applied on the sample and was withdrawn. An identical dry sample was submerged in the water at 5 kPa for the test on the submerged ash. The samples were sheared at normal stresses of 100 and 200 kPa. The angle of internal friction was generally proportional to the degree of compaction above 90%. The cohesion was equal to zero in the dry and the submerged states. Ash being a free draining material, a nearly saturated condition was observed at the end of the tests. The ashes which show a difference in the angle of internal friction in the dry and the submerged state may collapse upon wetting.

Collapse Behavior

Under certain placement condition, in the specific type of ashes the collapse settlement occurs on wetting. In this study the insitu void ratio of coal ash in ash pond was found to be in a range between 0.8 and 1.6. The water content of ashes in the ash pond typically ranged between 10 and 35% on the beach and 30 and 50% in the decantation zone. The ash collected from the ESP and the upstream surface of the ash pond contained moisture from zero to 6%. The SPT *N* value of a loose ash deposit was often found to be less than 4 (Cunningham et al. 1977; Sood et al. 1993; Dayal 1996). All these conditions favored the collapse of an ash fill on inundation in the working stress range.

The collapse of soils on wetting is generally measured by the oedometer test (Knight 1963). The collapse of coal ash was observed in the single and double oedometer, the model, and the field collapse test. A laboratory investigation was carried out to examine the relative importance of factors influencing the collapse settlement. The study was planned in terms of the variables that can be rapidly controlled in the practice, including degree of compaction, stress level, overconsolidation, and moisture content.

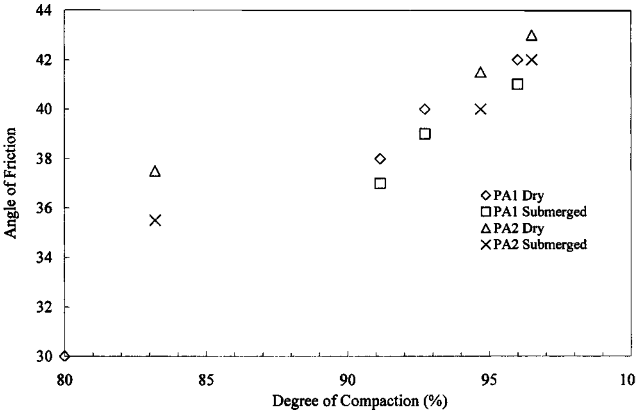


Fig. 6. Effect of degree of compaction on angle of friction

Single Oedometer Test

For the oedometer test, the ash was oven dried at 105°C for 24 h. The dry or moist specimens were compacted into a standard 60 mm diameter and 20 mm thick oedometer ring under a static load using a specially designed mold. The static method was selected to keep the uniformity in the sample though it was recognized that change in the method of compaction also influences the collapse. By calculating the exact amount of ash required for filling the mold, any predetermined dry density was obtained. In this way virtually identical specimens were prepared. A sample of known initial dry density was mounted in the oedometer ring. The vertical load was successively increased to a desired stress level. The specimen was permitted to attain an equilibrium deformation at each stress level so that the rate of deformation was less than 0.05 mm/h. The sample was inundated by the water from bottom at a desired stress level through an air dried porous stone to allow for the escape of air bubbles. The equilibrium deformation of sample was recorded on inundation. At least three tests were conducted to obtain the mean value of the collapse potential, consequently a total of 378 single oedometer tests were carried out to determine the effect of various parameters. These tests were performed on the different ashes under variable dry unit weight, water content and pressure on wetting. The collapse potential in the single oedometer was calculated using Eq. (2) selecting e_i as the initial void ratio at the beginning of saturation. In order to examine the reproducibility of the results, 15 samples of PA2 were tested each at 80 and 90% degree of compaction (D_c). The standard deviation in the collapse potential was observed to be 0.0004 and 0.00029, respectively, at 80 and 90% degree of compaction.

Double Oedometer Test

In the double oedometer test, the collapse potential was estimated by indirect measurement. The deformation of two identical samples one in the dry or moist and other in the submerged state was obtained as described in the section of compressibility.

The collapse potential in the double oedometer was calculated using Eq. (2) selecting e_i as void ratio of the dry and Δe as difference of the dry and submerged sample at a specified stress level. At least three set of the tests were conducted to obtain the mean value of the collapse potential. Consequently a total of 27 double oedometer tests were carried out to compare the collapse potential obtained from the single oedometer test. A difference was recorded in the magnitude of collapse potential obtained from the single and the double oedometer tests on a collapsible ash.

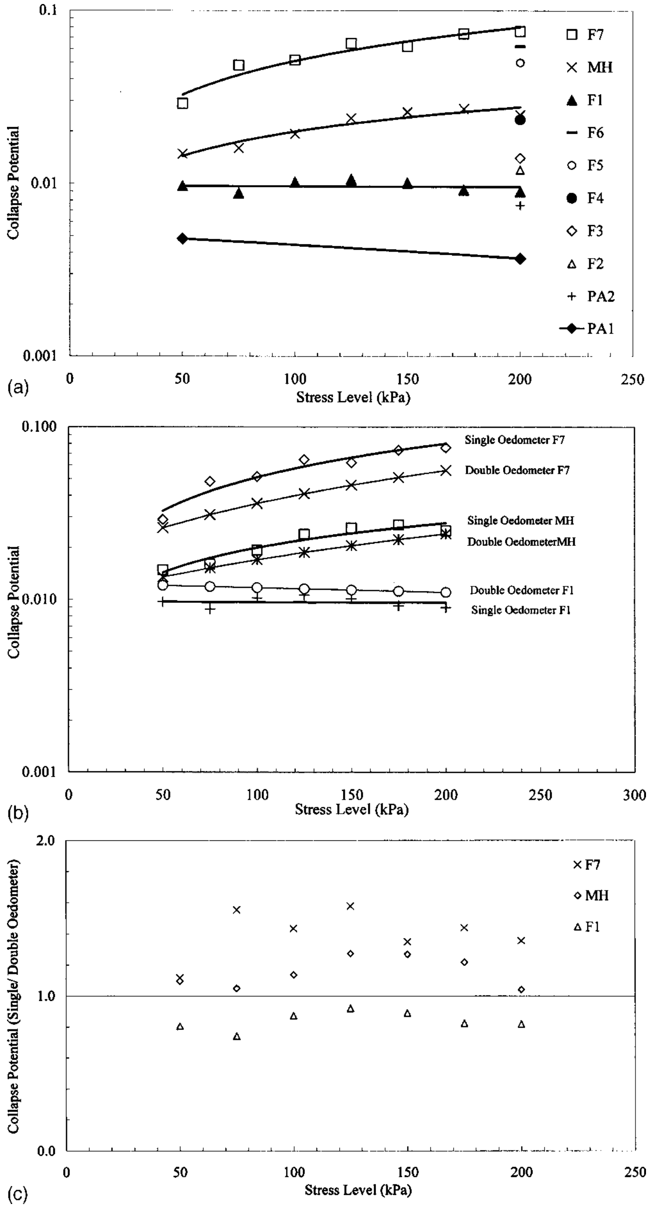


Fig. 7. (a) Effect of stress level on collapse potential in single oedometer; (b) collapse potential in single and double oedometer; and (c) classification of ash collapsibility on basis of oedometer test

Result of Oedometer Tests

Effect of Stress Level

Fig. 7(a) compares the collapse potential of ashes prepared dry at 80% degree of compaction. Virtually identical samples were inundated at varying stresses between 50 and 200 kPa at an interval of 25 kPa in separate tests. For F7 and MH increase in stress level tend to increase collapse potential while F1 and PA1 show a somewhat opposite trend. The fine ash exhibited the collapse potential well above the limiting value (0.01 for the soils) while coarse ash (F1) had collapse potential close to the limiting value. It was found that the collapse potential increases with the increase in the stress level for fine ashes up to 200 kPa. The predictors of collapse potential for fine ashes showed a satisfactory coefficient of determination (Table 3). The collapse potential slightly decreased with the increase in the stress level for the coarse ashes. The coarse ashes indicated scatter in the observed collapse potential. At 200 kPa, the collapse potential decreased with increasing coarseness of the grains. The collapse potential is represented as a function of stress level by the equation

$$C_p = a\sigma^b, \tag{5}$$

where a and b=fitting constants for an ash type; and σ=effective normal stress in kPa in the oedometer test. A negative value of b suggests a decrease in the collapse potential with an increase in the stress level.

Table 3. Variation of Collapse Potential in Single Oedometer with Stress Level

Ash type	Predictor	R^2
F7	$0.0026\sigma^{0.6488}$	0.93
MH	$0.0022\sigma^{0.4747}$	0.91
F1	$0.01\sigma^{-0.008}$	—
PA1	$0.01\sigma^{-0.18}$	—

Effect of Testing Technique

Fig. 7(b) compares the collapse potential of dry ashes in the single and the double oedometer at 80% degree of compaction. Fig. 7(c) attempts to classify the ash collapsibility on the basis of ratio of collapse potential obtained in the single and double oedometer test. A significant scatter in the data was observed at low stress levels. However, at 200 kPa the collapse potential ratio tends to stabilize. If this ratio is greater than one, ashes selected in the present data set have a tendency to collapse. The results of the single and double oedometer tests differed on the account of sample preparation (dry and wet conditions), measurement of collapse potential, wetting under actual condition of stress and dissolution of soluble. The double oedometer test only measured the difference in deformation characteristics of the dry or moist and the fully saturated specimen; while the collapse is characterized by the suddenness of settlement on inundation. This situation was closely simulated in the single oedometer tests. Ash being a free draining material, a nearly saturated condition was observed at the end of the tests. The difference in the final degree of saturation in the single and the double oedometer tests was insignificant in case of the ashes (Trivedi 1999) as compared to the plastic silt and the loess (Reznik 1993).

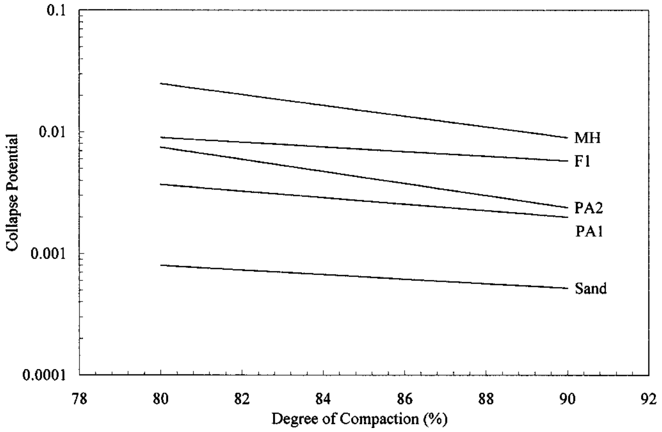


Fig. 8. Effect of degree of compaction on collapse potential at 200 kPa

Table 4. Collapse Potential, Dry Compression, and Recompression Index of Ashes

Ash type	Dry compression index at D_c of 80%	Dry compression index at D_c of 90%	Collapse potential at D_c of 80%	Collapse potential at D_c of 90%	Swelling; recompression index at D_c of 80%	Swelling; recompression index at D_c of 90%
PA1	0.096	0.076	0.0037	0.0020	0.0120	0.0110
PA2	0.070	0.049	0.0075	0.0021	0.0140	0.0130
MH	0.053	0.046	0.0250	0.0088	0.0166	0.0157
Sand	0.019	0.016	0.0008	0.0005	0.0014	0.0014

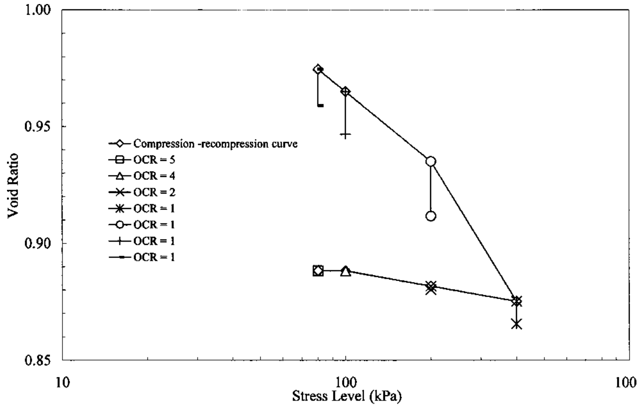


Fig. 9. Effect of overconsolidation on collapse potential of ash (MH)

Effect of Degree of Compaction

Fig. 8 shows the effect of the degree of compaction on the collapse potential of selected ashes and a sand sample in single oedometer at 200 kPa. The samples were prepared dry and compressed in increments up to 200 kPa. At 200 kPa, the samples were inundated and the changes in voids were allowed to stabilize. The submerged samples were allowed to swell against the withdrawal of stresses. The samples were recompressed and the recompression index was evaluated. With the increase in the degree of compaction, the collapse potential, the dry compression index, the swelling and recompression index decreased (Table 4). The swelling index of coal ash was equal to the re-compression index (0.012–0.016). The small value of the swelling index indicated stability of the densified ash fill by preloading and that of the recompression index showed stability of the compacted ash fill to moderate and heavy loads after the collapse. The collapse potential of 0.01 is normally considered to be a limiting value for the evaluation of soil collapse in the single oedometer. Lutenegger and Saber (1988) indicated that the soil is slightly susceptible to the collapse if the collapse potential [Eq. (2)] was below 0.02. At 80% degree of compaction, PA1, PA2, and sand samples were noncollapsible while MH was collapsible. There was a sharp decline in the collapse potential of fine ashes MH and PA2 as compared to the coarse ashes PA1 and F1 with an increase in the degree of compaction from 80 to 90%. At 90% degree of compaction even the fine ash (MH) showed noncollapsible nature.

Effect of Overconsolidation

Fig. 9 shows the effect of overconsolidation in the single oedometer tests of a dry fine ash (MH) pressed at overconsolidation ratio of 5, 4, 2, and 1 from a constant initial degree of compaction (80%). The overconsolidation ratio is defined as a ratio of the maximum stress the sample had experienced in the past to the present state of stress. The samples were compressed in increments to a desired stress level. The stresses were withdrawn to a target stress level to get an overconsolidated sample. The sample was inundated to find the collapse. The degree of compaction at inundation in these tests was not significantly different. At an overconsolidation ratio of 5 and 4, the collapse potential reduced to a minimum value.

The reduction in the collapse potential at a high overconsolidation ratio was attributed to the agglomeration of particles on compression. Stability of the sample was not significantly affected in the oedometer even in a steady state of saturation. At an overconsolidation ratio of two, the collapse potential was (0.0017), which is much below the limit of collapse for soils (0.01). At an over consolidation ratio of one at 200 kPa collapse potential was as high as 0.025 (Table 5). This pointed to a moderate collapsibility of the ash. At 400 kPa and an overconsolidation ratio of one, the collapse potential was just at the limiting value (0.01, criterion for soils). In the oedometer tests the collapse potential of ash is significantly reduced on overconsolidation.

Effect of Soluble Substances

There is a significant effect of the soluble substances (sodium and potassium salts) present in the ash on its collapsibility. Reginatto and Ferrero (1973) proposed that the quantity of dissolved salts and the chemical constituents in pore fluid are more fundamental than the initial unit weight in contributing to the collapse. The effect of soluble substances can be evaluated indirectly by estimating their magnitude in the specific ashes (Table 2). It is recognized that the ash is largely an inert material. It has coating of soluble substances on the surface of the grains. These are washed away on the application of water causing instability at the contact points. The weight and volume changes associated with the dissolution of the soluble substances is estimated by knowing the difference in weights of the dry and the water washed samples and weight volume relationship of the ash. The volume change

Table 5. Collapse Potential of Mixed Hopper Ash (MH) at Different Overconsolidation Ratio (OCR)

Preconsolidation pressure (kPa)	Inundation pressure (kPa)	OCR	D_c at inundation (%)	Collapse potential	Comment on collapse
400	80	5	86.00	0	Noncollapsible
400	100	4	86.00	0	Noncollapsible
400	200	2	86.30	0.0017	Noncollapsible
400	400	1	86.60	0.0110	Slight
200	200	1	83.92	0.0250	Moderate
100	100	1	82.64	0.0190	Moderate
80	80	1	82.24	0.0160	Moderate

Table 6. Correction for Collapse Potential due to Soluble in Ash Samples

Ash type	F1	F2	F3	F4	F5	F6	F7	MH	PA1	PA2
Correction ($\times 10^{-3}$)	6	6	3	3	9	3	3	4	0	0

due to the dissolution of soluble substances alone is defined as a correction required for the collapse potential of dry collected ashes. There were no soluble substances in PA1 and PA2 being wet disposed ashes; the collapse correction was not required (Table 6). A correction equivalent to the release of the soluble substances on inundation was applied to the ashes collected in the dry state (Table 7). At a high overconsolidation the effect of soluble was negligible in the oedometer.

Effect of Moisture Content

The coal ash is deposited at varying densities in the ash pond, at moisture contents between 0 and 50%. In order to examine the effect of moisture content on the collapsibility of ash, the samples were prepared by mixing a known weight of the ash with a predetermined quantity of water. The compaction water content was varied between 0 and 30%. Wet filter papers were placed between the sample and the porous stone provided to induce wetting through an outer water jacket. Identical samples were compressed to varying stress levels between 50 and 200 kPa in the increments of 25 kPa. The wetting was induced at a target stress level to find the collapse potential. Increasing the moisture content from zero to a critical value (identified in vibratory compaction) the surface tension increased hence the compressibility decreased. In the dry and the completely wet conditions this stiffness was lost. Figs. 10(a and b) show the collapse potential of a fine and a coarse ash respectively. The collapse potential increased significantly if estimated in a partly wet compared to a dry condition. In a partly wet condition, even the ash classified noncollapsible in dry condition (PA1) became collapsible [Fig. 10(a)].

The ashes showed a maximum collapse in a range of the critical stresses (i.e., 50–100 kPa) and the critical moisture (i.e., 10–30% for MH and 20–30% for PA1). At the critical stresses, the ashes had a greater tendency to collapse. The collapse potential decreased at a high moisture contents due to the dissolution of soluble and a decrease in the surface tension forces. The summary of increases in the collapse potential at the critical moisture compared to the dry state at various stresses indicate three- to sixfold increase in both types of ashes (Table 8).

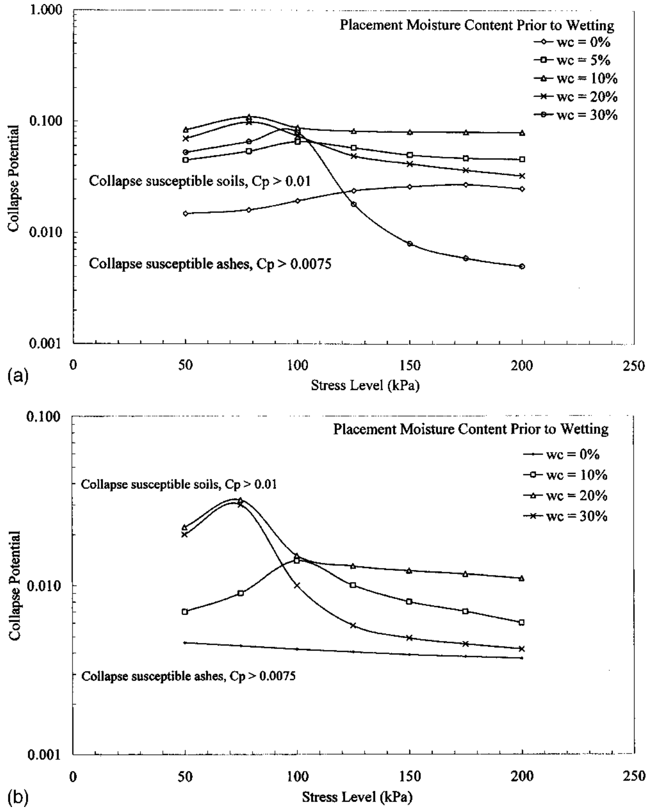


Fig. 10. (a) Collapse potential at varying stresses and prewetting moisture (MH) and (b) collapse potential at varying stresses and prewetting moisture (PA1)

Model Plate Load Collapse Test

The collapse potential obtained by the oedometer is qualitative in nature. The oedometer test takes in to account the one dimensional volume change of the sample strictly confined within a ring and two rigid plates. In the field there is a possibility of a vertical deformation of the ash accompanied with a volume change, side expulsion, slip, and migration of the fines under a slow rising head of water. The collapse of the ash structure below foundations may also depend upon the proximity of the applied loads to the ultimate loads required for a shear failure of the ash. While one dimensional volume change is quantified by the oedometer, the actual field conditions of side expulsion, the slip of fines and the proximity of loads to the shear failure remain far from incorporated. The model plate test simulates the condition of field collapse closely. Reznik (1993) suggested verifying the oedometer results by the plate load test, where an actual wetting is employed. Keeping this point in view, the model plate load collapse tests were conducted in a specially fabricated tank under a plane strain condition. Three tests were performed in each density states for the ashes PA1, PA2, and MH, identified by the oedometer test as noncollapsible and collapsible according to the existing criteria for soils.

Model Test Setup

A tank of inner plan dimension of 155 by 600 mm and a height of 500 mm was made up of a 10 mm thick mild steel sheet (Fig. 11). The horizontal and the vertical stiffeners were provided to restrict the lateral movement of the vertical plates on the load application. On the front vertical face, a cut slot 100 mm wide was left for the placement of a plate with fine perforations. The perforated plates were provided to allow the seepage of water into the deposit from the downward to the upward direction. The perforations were plugged with the filter to disallow migration of fines outside the

Table 7. Corrected Collapse Potential at 200 kPa and $D_c = 80\%$

Ash type	F1	PA1	PA2	Limit of collapse for soils	F2	F3	F4	MH	F5	F6	F7
Observed C_p	0.009	0.0037	0.0075	—	0.012	0.014	0.023	0.025	0.050	0.060	0.076
Corrected C_p	0.003	0.0037	0.0075	0.01	0.006	0.011	0.020	0.021	0.041	0.057	0.073

Table 8. Collapse Potential of Dry and Moist Ash

Ash type	Condition at collapse	Collapse potential at stress level (kPa)				
		50	75	100	125	200
PA1	Critical moisture content	0.032	0.02	0.015	0.013	0.0115
	Dry condition	0.0046	0.0044	0.0041	0.00405	0.0037
	C_p critical/C_p dry	6.95	4.54	3.65	3.20	3.10
MH	Critical moisture content	0.084	0.099	0.088	0.082	0.08
	Dry condition	0.014	0.018	0.021	0.022	0.025
	C_p critical/C_p dry	6.00	5.50	4.19	3.72	3.20

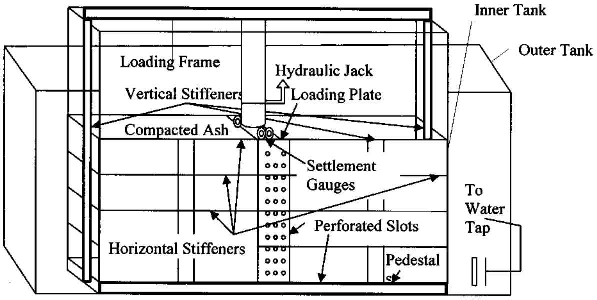


Fig. 11. Line sketch of model plate load collapse test

inner tank containing saturated ash. The displacement of longitudinal stiffeners was monitored by mounting the dial gages on both sides of the tank.

Model Testing Technique

The coal ash is a predominantly silt sized cohesionless material. The rainfall or vibratory densification technique is generally used for the deposition of cohesionless material on a uniform density. It was found to be unsuitable for the deposition of the dry ash, as with a little blow of air, ash became air borne. A special technique was adopted for the densification in tank by first pouring ash in a loose state up to a specified depth by a slow pouring technique. A 55.8 mm thick layer of ash was uniformly pressed by a stiff plate to achieve a desired dry density in the tank. A density gradient was observed to exist along thickness if the thickness of loose layer was kept above 55.8 mm. Several such pressed layers were required to fill the tank. After filling the ash to a desired density, load test was conducted using a plate 155 mm long, 100 mm wide. The clearance was filled with a tight packing of the smooth strips of polythene to ensure least friction between the plate and the tank wall. To check the plane strain condition, the deflection of the tank walls was monitored with the dial gauges placed on both sides of the tank during the loading of the test plate.

The collapse tests were conducted by keeping the model ash filled tank in a submergence tank (700 by 500 mm plan and 600 mm deep). After the deposition of the ash at a desired unit weight, the load was applied through a hydraulic jack, corresponding to a specified stress level and the plate settlement was recorded. The water was allowed into the external tank for the saturation of the ash. The water level in the external tank was finally maintained exactly at the level of the ash fill in the internal tank to ensure saturation. The settlement of the loading plate was continuously monitored and the load level was constantly maintained. The actual wetting was induced at a stress level of 80 kPa. The dry settlement up to the collapse load, the collapse settlement on inundation, and the postcollapse wet settlement of ash pressed at various overconsolidation ratio were noted for all the tests. The post collapse degree of saturation was recorded on the completion of each of the test.

Result of Model Tests

Table 9 summarizes the results of the model tests on various ashes. PA1 showed insignificant settlement (~17%) on wetting for the tests conducted on pressed ash at all the densities [Fig. 12(a)]. The tests conducted on PA2 at a high overconsolidation ratio (OCR=5; D_c=96%) indicated an arrested increase in the settlement of dry ash upon wetting [Fig. 12(b)]. Normally, the volume change of ash at 96% D_c should not trigger any significant settlement. This settlement was visibly accompanied with the side expulsion of ash particles. In the oedometer at 80% D_c the ash was loosely bound that allowed for the rearrangement of particles on saturation. At 90% D_c there was insignificant collapse (C_p=0.0021) which neither explains significant volume change nor the rearrangement and relocation of particles.

It was seen that PA2 with a collapse potential of 0.0075 at 80% D_c collapsed in the model tests at 87 and 94% D_c. Further increase in the density of this ash arrested the collapse in the model test. Coal ash PA1 with a lower collapse potential (0.0037 at 80% D_c) did not collapse at all. Mixed hopper ash with a higher collapse potential (0.021 at 80% D_c) showed collapse at all the densities examined in the model test. Mixed hopper ash showed continuous settlement [Fig. 12(c)] of plate upon wetting in spite of the high overconsolidation ratio. Therefore, the limiting value of the collapse potential for classification of the collapsibility of coal ashes was recommended as 0.0075 at 80% degree of compaction in the oedometer.

Table 9. Model Plate Load Collapse Test Results

Ash type	Dry unit weight (kN/m^3)	Overconsolidation		D_c (%)	Settlement at 80 kPa			
		Pressure (kPa)	Ratio		Dry state (mm)	On inundation (mm)	Increase (%) on wetting	Collapsibility
PA1	8.66	100	1.25	91.15	4.17	4.88	17.00	Noncollapsible
	8.81	200	2.50	92.73	2.50	2.91	16.40	
	9.12	400	5.00	96.00	1.75	2.04	16.57	
PA2	9.00	100	1.25	87.37	4.50	Controlled	—	
	9.75	200	2.50	94.66	2.25	Controlled	—	Low collapsible
	9.94	400	5.00	96.50	1.80	3.90	116.66	
MH	9.12	100	1.25	77.94	3.80	Controlled	—	
	9.37	200	2.50	80.08	2.10	Controlled	—	High collapsible
	9.62	400	5.00	82.22	1.80	Controlled	—	

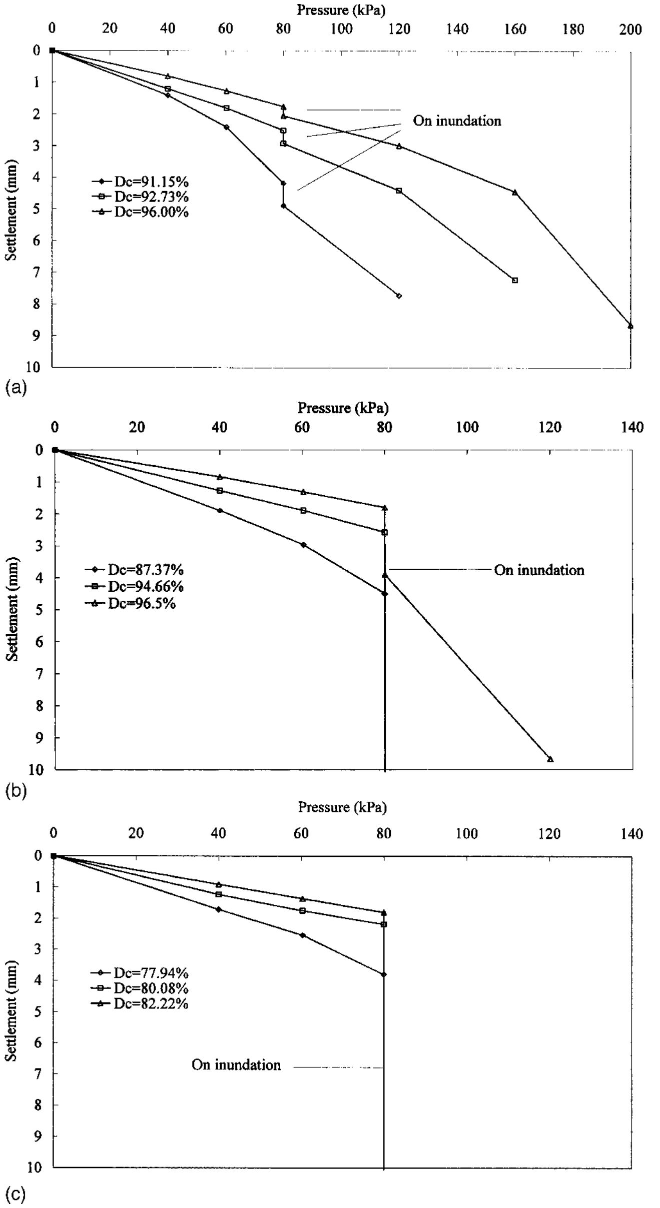


Fig. 12. (a) Collapse settlement in model test (PA1); (b) collapse settlement in model test (PA2); and (c) collapse settlement in model test (MH)

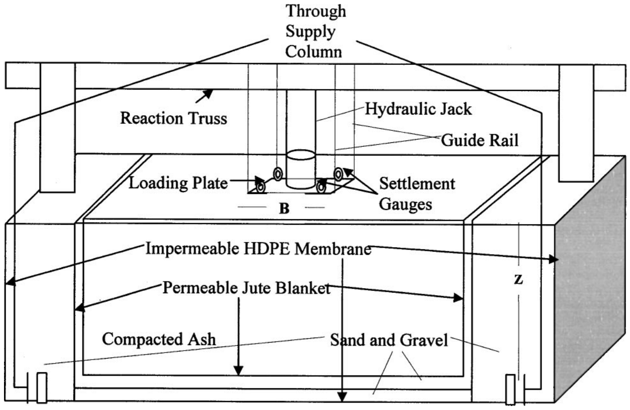


Fig. 13. Line sketch of field collapse test

Field Collapse Test

Reznik (1993) and Houston et al. (1995) have described a method for field collapse tests with a difference in the technique and the scale of trial. In the present study the field collapse test was conducted on a square plate (300 by 300 mm) on the surface of ash (PA2) compacted on wet side of critical moisture content ($D_c = 85.4$ and 90.3%). The ash was deposited in a test pit (1.5 by 1.5 m plan and 2 m deep) in the field with sides covered by impermeable high density poly ethylene membrane. The soil profile below the test pit was silty sand with an average observed value of standard penetration test, N_{60} of 16. A 200 mm thick layer of well-compacted sand and fine gravel was provided all around the walls and bottom of the pit to serve as a free draining layer for upward flow of water (Fig. 13). Inundation was induced through a constant head supply column provided in the vicinity of fill to maintain a constant depth of wetting front from ground level. Above the sand and gravel layer, a 10 mm thick Jute (coarse woven fabric from a plant of Linden family; family: Tiliaceae, Species: Corchorus Capsularis) membrane was placed to separate it from the ash. The ash was deposited in a moist state in loose lifts of 150 mm each and compacted by a plate vibrator mounted on a rectangular plate (152 by 390 mm). The plate vibrator had a dead weight of 0.2323 kN and 2950 rpm, and was operated by a three-phase motor. Three passes were sufficient to get a desired degree of compaction. The pressure on the loading plate was increased in increments with the hydraulic jack against a reaction truss. The bearing plate settlement was measured with an accuracy of 0.01 mm. A separate test was conducted to asses load deformation response of the ash fill. The magnitude of pressure up to which the deformations were directly proportional to the load applications is known as proportionality limit. The pressure at proportionality limit was estimated to be 670 kPa for the dense ash. For the collapse test the load increments were applied up to a stress level of 205 kPa [Fig. 14(a)]. After the initial settlement, the flooding was induced from bottom through a sand and gravel layer by a connected supply column. A controlled amount of water was allowed into the water column for saturation. The water was allowed to wet ash up to a fixed level called wetting front. A wetting front (W_r) was defined as a ratio of the depth of water level in supply column from plate base (Z) to the width of plate (B)

$$W_r = Z/B \tag{6}$$

Along with the plate settlement, moisture content at the surface was also recorded. With the upward movement of wetting front, an increase in settlement was observed. The increase in settlement (S_r) is defined as a ratio of percent settlement on saturation (S_c) at collapse stress to the settlement before saturation (S_b)

$$S_r = (S_c/S_b) \times 100 \tag{7}$$

The collapse settlement was rapid when the wetting front ratio decreased below one [Fig. 14(b)]. The attempt to maintain collapse pressure actuated large deformations in ash and tilting of plate. To allow only vertical movement of base plate the guide rails consisting of an L section were vertically installed in the compacted ash through a reaction truss. The collapse settlement was taken as an average of readings of all the settlement gauges. There was a sudden increase in the settlement when the degree of saturation at surface of ash fill increased beyond 88%. The field test demonstrated that magnitude of collapse depend upon the depth of wetting front. If the wetting front ratio (W_r) is more than 1.8, there shall be no risk of collapse.

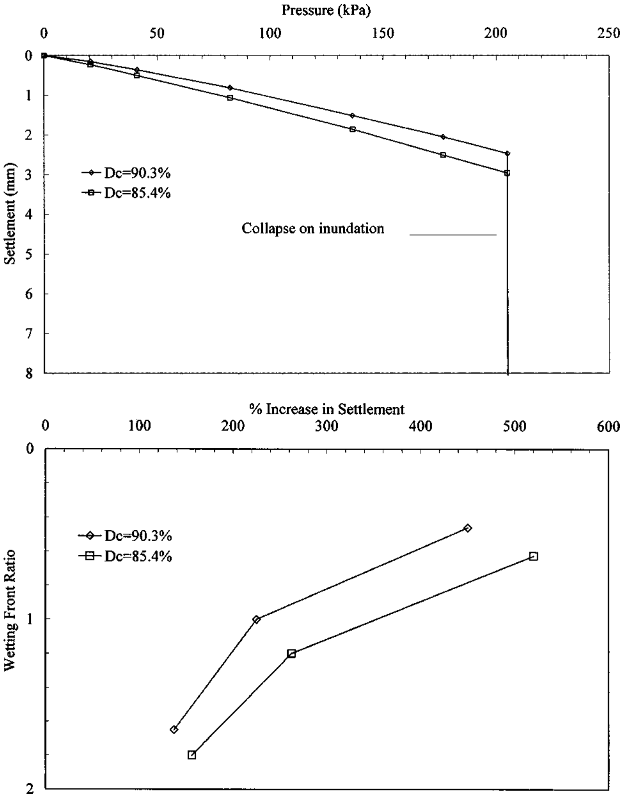


Fig. 14. (a) Pressure settlement plot in field collapse test (PA2) and (b) effect of wetting front ratio on settlement (PA2)

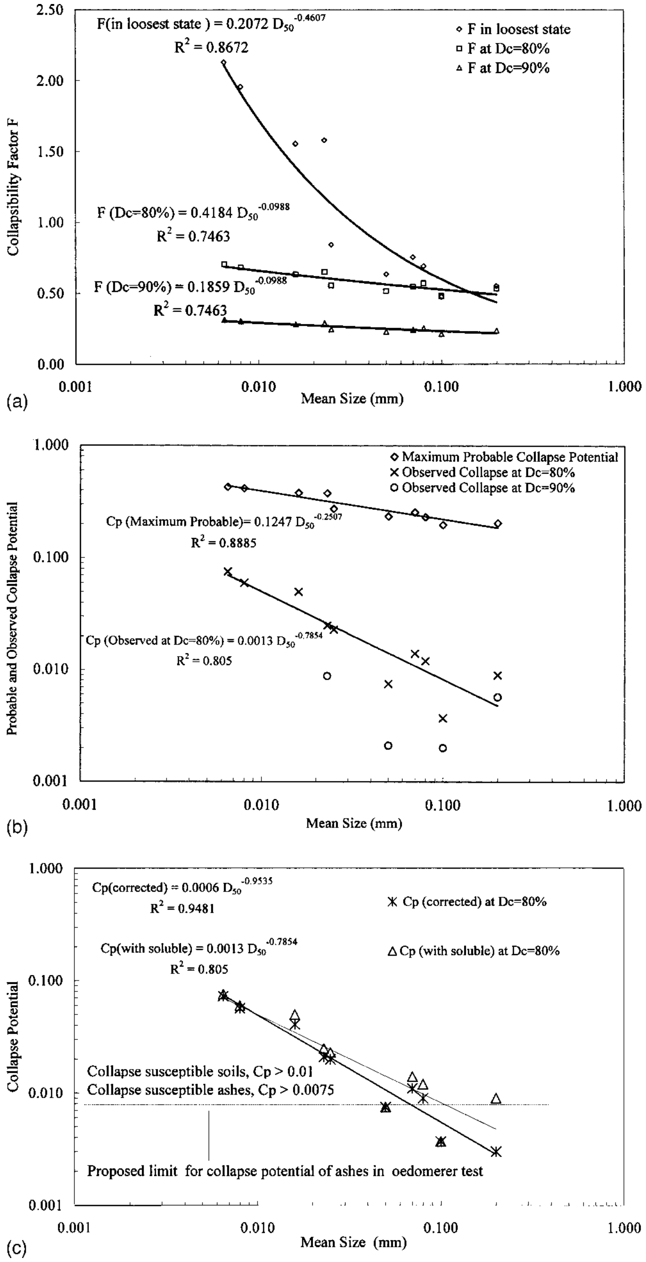


Fig. 15. (a) Variation of collapsibility factor with mean size; (b) variation of probable and observed collapse potential with mean size; and (c) effect of mean size on observed and corrected collapse potential

Criteria for Collapsibility of Coal Ash

The physical and the chemical characteristic of coal ash calls for the treatment of this geomaterial like a cohesionless soil. It is recognized that a granular material follows a closer packing under a favorable condition of pressure and moisture. This tendency may be quantified in terms of the distance of placement void ratio to the minimum void ratio. It is supposed that minimum void ratio occurs in proctor compaction. Therefore a collapsibility factor (F) is defined as

$$F=(e_i-e_{\min})/e_{\min} \tag{8}$$

where e_i=placement void ratio of ash; and $e_{\min}$=void ratio corresponding to maximum dry density in proctor compaction. Larger the value of F, ash is more predisposed to collapse. Fig. 15(a) shows a reduction in collapsibility factor F, with mean size in the loosest and the compacted states. Compared to the loosest state, all the ashes reach almost a common collapsibility level in a compacted state. At 90% degree of compaction a low collapsibility level is reached, which is associated with a small volume change on collapse that does not reflect collapse. Moreover, it has practical problem of precise measurement of the volume change. Thus, the variations in the measured collapse at 90% degree of compaction may forbid interpretation of any trend. The collapsibility factor allows for assessment of the probable collapse. The probable collapse is assumed to occur if the sample attains a minimum void ratio on inundation. The maximum probable collapse potential is computed by

$$C_{\mathrm{pr}}=(e_i-e_{\min})/(1+e_i) \tag{9}$$

where C_{pr}=maximum probable collapse potential; e_i=void ratio in a loose state; and $e_{\min}$=void ratio corresponding to a maximum dry density in proctor compaction. The probable and the observed collapse potential are plotted in Fig. 15(b). It shows that the decreasing mean size tend to reduce the difference between the maximum probable and the observed collapse at 80% degree of compaction. While at 90% degree of compaction a significant scatter of data is observed.

As a result of the above observations the classification of coal ashes at 80% degree of compaction was found to be appropriate for the evaluation of collapse. The mean particle size was seen to control the collapse of ashes. If the mean size was greater than 0.1 mm the ashes were noncollapsible and others were collapsible under specific conditions. The value of collapse potential for PA1 in the critical range of stress and moisture was 3–6 times that of the corresponding dry condition. It suggests susceptibility of a

Table 10. Classification of Ashes

Classification	Collapse potential	Ashes
Noncollapsible	Less than 0.0075	PA1
Collapsible		
Low	0.0075–0.01	F1, PA2
Medium	0.01–0.015	F2, F3
High	greater than 0.015	MH, F4–F7

noncollapsible dry ash to the collapse in partly saturated condition. In order to obtain the value of collapse potential of partly wet ash from Fig. 15(c), a multiplier may be applied on the pattern shown in Table 8.

The collapsible ashes were further divided into the ashes of low, medium and high collapsibility on the basis of their collapse potential (Table 10). The collapsible and the noncollapsible ashes were identified using the model plate load collapse test on selected samples. Normally, the weight of a particle of a natural soil of similar grain size distribution is 1.5–1.3 times that of an ash. These soils remain stable at or less than 1% volume change ($C_p = 0.01$). Being light in weight, the ash has a propensity to be unstable in the presence of buoyancy which plays a role in the model and the field tests. Therefore, among the light weight ash particles 0.75% volume change ($C_p = 0.0075$) triggered collapse failure in the field. Coincidentally, 1% volume change of soils is 1.3 times that of the limit recognized for the collapsible ashes.

At a common mean size of 0.08–0.1 mm, the ashes conditioned and collected dry from the ESP are more collapsible due to the presence of the soluble substances. The ashes are disposed in a dry condition by the hopper. If dispensed loose in the ash ponds, normally a rain may wash away the soluble substances. For the ashes obtained from the dry disposal mode, a correction equivalent to the dissolution of the soluble substances was applied on the collapse potential [Fig. 15(c)]. It was observed that the sand and the F1 had very close value of the median size, F1 being an ash collected dry and having around 25% particles in silt range, had a higher collapse potential than the sand. It was recognized that all the collapsible ashes had more than 50% fines. Among coarse grained ashes a scatter in collapse potential was observed. A relationship between corrected collapse potential at 200 kPa ($D_c = 80\%$) and mean particle size is obtained with a satisfactory coefficient of determination ($R^2 = 0.94$). The corrected collapse potential is expressed by

$$C_p^{\mathrm{cr}} = n \cdot D_{50}^m \tag{10}$$

where C_p^{cr}=corrected collapse potential of an ash; D_{50}=mean particle size in mm; $m = -0.9535$; and $n = 0.0006$ are fitting constants for the coal ashes.

The coefficient of determination for the fitting curve of observed collapse potential with the mean size improves upon application of correction for soluble substances. Eq. (10) can predict the value of corrected collapse potential of coal ash. It overestimates collapse potential of pond ashes and underestimates that from ESP in the coarse range of particle sizes. It furnishes a guide by which one may compare the potential severity of the collapse situation according to the grain size. It can be utilized to tell when to expect a problem. The meticulous use of Fig. 15(c) in judging just how much collapse will take place is a matter of further investigation.

Conclusions

The collapsibility of coal ash is one of the most important parameters for using ash as a fill material. The present work provides a framework for the assessment of collapsibility of the ashes. Several single and double oedometer collapse tests have been performed to test the collapsibility of coal ashes and the results were verified using the model and the field collapse test. Based upon the test results various outcomes of this study are summarized as:

1. The collapse potential obtained by the oedometer test is a dependent parameter of several factors such as grain size characteristics, stress level, testing technique, degree of compaction, a finite consolidation ratio, moisture content, soluble substance, etc.
2. At a prewetting critical moisture content and in the critical stress range (50–125 kPa), the ashes tend to collapse more than those in the dry condition. The observed collapse potential was proportional to the collapsibility factor identified from the maximum and minimum void state of the ashes. The ashes with more than 50% of the particles in silt size range were found to be collapsible.
3. The dry disposed ashes were more collapsible due to the presence of soluble substances as compared to that obtained by the wet disposal. Therefore a correction was applied in the observed collapse potential of the dry disposed ashes to obtain a common correlation with the mean size as of the wet disposed ashes [Fig. 15(c)].
4. The generally recognized lower limit of collapse potential for the collapsible soils in the oedometer is 0.01. It was observed that the coal ash with a collapse potential of 0.0075 at 80% degree of compaction (D_c) collapsed in model tests at 87 and 94% D_c. Increasing the density of this ash arrested the collapse in the model test. The coal ash with a lower collapse potential (0.0037 at 80% D_c) did not collapse at all, while an ash with a higher collapse potential (0.021 at 80% D_c) collapsed at all the densities examined in the model test. Therefore, the lower limit of collapse potential of the collapsible ashes was recommended as 0.0075 at 80% degree of compaction in the oedometer.
5. In field, the collapse may occur due to the accidental wetting or a rise of water table. In such cases the magnitude of measured collapse is a function of the depth of wetting front from the ground level. If the wetting front ratio is more than 1.8, a threat of collapse is bare minimum. The field collapse test is recommended under an actual condition of wetting, if ashes are to be used as a structural fill.

Acknowledgments

The study presented here is based on the doctoral thesis work on coal ash at Thapar Institute of Engineering and Technology, Patiala, India. However, any opinion, findings and conclusions expressed herein are that of the writers and pertain only to the observed data set and do not necessarily reflect the behavior of all types of coal ashes. The savant input from the reviewers and the editorial board members in improving the quality of this paper are greatly appreciated. The cooperation of colleagues, namely, Professor Sundar Singh, Professor Rajesh Pathak, and numerous fellow workers in carrying out the study, is gratefully acknowledged.

Notation

The following symbols are used in this paper:

a,b,m,n = fitting constant for ashes;
B = width of plate in field collapse test;

$C_p, C_p^{\mathrm{cr}}, C_{\mathrm{pr}}$ = observed, corrected and maximum probable collapse potential;
D_c = degree of compaction;
D_{50} = mean size;
dh = decrease in height of sample on inundation;
$e_{\max}, e_i, e_{\min}$ = void ratio in loosest, placement, and proctor compaction;
F = collapsibility factor;
F1–F7 = ash obtained in dry state from field -1 to 7 of hopper;
h_0 = height of sample before wetting;
I = intensity of characteristics radiation in x-ray diffraction;
OMC = optimum moisture content;
R^2 = coefficient of determination;
S_b, S_c = settlement before and after wetting at collapse stress in field test;
S_r = percent increase in settlement in field collapse test;
W_r = wetting font ratio;
w_c = prewetting placement moisture content;
Z = depth of water level below plate base;
Δe = change in void ratio upon wetting due to collapse;
σ = normal effective stress in oedometer; and
ϕ = angle of internal friction.

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