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ORIGINAL ARTICLE

Collapse Behaviour of Compacted Coal Ashes

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Abstract Coal ash is a by-product produced from the thermal power plants. It is characterized with low unit weight, high shear strength and low compressibility and finds a major application as an alternate material in the geotechnical engineering applications. However, some coal ash fills are susceptible to wetting-induced collapse due to the loss of capillary suction which stabilizes the inter-granular bonds. The present study examines the influence of placement conditions, vertical stress and pore fluid concentration on the collapse behaviour of compacted fly ash specimens. The experimental results showed that the maximum collapse potential for the coal ash specimens compacted to relative compaction of 80 % and water content of 15 % was in the range of 8.6–13 % at vertical stress of 100 kPa, which indicates that the apparent pre-consolidation stress for the coal ash specimens is equal to 100 kPa. Among the coal ashes, the compacted fly ash specimens are more susceptible to wetting-induced collapse in comparison to bottom ash and pond ash specimens which is attributed to the higher silt size fraction in the fly ash. This study also presents the collapse behaviour of lime stabilized compacted coal ash.

Keywords Coal ashes · Compacted granular fills · Collapse potential · Lime treatment

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Introduction

The greatest problem faced by thermal power plants is the safe and effective way of disposal of large quantities of coal ashes that are produced during the combustion of coal used for electricity generation. Depending on the method of collection, the coal ashes are classified as fly ash or pulverised fuel ash, bottom ash and pond ash. In the dry process, very fine particles of coal ash captured by electrostatic precipitators is called fly ash, whereas much coarser granular material collected from bottom of the boiler furnace is called as bottom ash. In the wet process of disposal of coal ash, the ash collected from the ash pond is known as pond ash. The present production rate of coal ash in India is about 185 million tons per year [1]. The staggering amount of coal ash and effective disposal is a major concern, which has pushed the boundaries for the novel use of coal ash. Bulk utilization of coal ash is possible in geotechnical engineering applications as an alternate material. Typically, coal ashes are characterized with low unit weight, high shear strength and experiences minimum compression on loading in comparison with natural soil, which makes them an ideal fill material [2–6]. Indraratana et al. [7] studied the behaviour of a class C fly ash from Thailand and reported that due to the accelerated pozzolanic reactions in class C fly ash, the fly ash gained strength within 2–3 weeks of curing and highlighted the potential use of fly ash as back fill material. Often the sedimented or compacted coal ash beds are used as foundation subgrades [8, 9]. Madhyanappu et al. [9] reported that the sedimented coal ash beds are characterised with an open structure arrangement of particles which are susceptible to wetting-induced collapse. Partially saturated deposits (compacted or sedimented) experience wetting-induced collapse under constant vertical stress. Dudley

[10], Barden et al. [11] and Mitchell and Soga [12] attributed the following reasons for collapse to occur:

- An open, partially saturated and unstable fabric.
- A high enough total stress that the structure is metastable.
- A bonding or cementing agent that stabilizes the inter-aggregate or inter-granular bonds in unsaturated state reduces on addition of water and causes the bonds to fail in shear.

Earlier researchers showed that the collapse phenomenon is restricted to sands and silts but the recent studies have shown that all types of compacted soils are susceptible to collapse under certain conditions [13–16]. Pusadkar and Ramasamy [17] and Madhyanappu et al. [9] observed phenomenon of collapse in compacted coal ash. Madhyanappu et al. [9] reported greater collapse potential in the sedimented beds in comparison with the compacted coal ash beds, which was attributed to the possible cementation before and after the collapse at higher stresses.

The collapse behaviour of compacted fills are influenced by factors such as initial dry unit weight, compaction water content, inundation pressure (vertical stress) and clay content [10, 14, 18–25]. Conclusions derived from these studies are that, in general, the collapse potential decreases with increasing water content and as-compacted dry unit weight. Pusadkar and Ramasamy [17] reported a decrease in collapse potential of fly ash with the increase in water content and relative compaction. Trivedi and Sud [26] have also observed a reduction in the settlement of pond ash from 1.45 to 1.05 mm when degree of compaction increased from 85.2 to 90.3 % on wet side of the critical. The collapse potential increases with increase in vertical stress and at some critical stress, the collapse potential is maximum, and beyond which it decreases [23, 27]. The reduction in the collapse potential is due to the densification and the increase in degree of saturation at higher stresses. The maximum wetting-induced collapse occurs at a vertical stress which corresponds approximately to the compactive prestress of the compacted soil specimen. Compactive prestress is the apparent preconsolidation induced in the soil specimen due to the application and removal of mechanical energy during compaction. Mishu [28], Booth [29] and Lawton et al. [22] reported that negligible collapse occurs at all ranges of relative compaction and overburden pressures above critical degree of saturation, which is defined as the initial or prewetting degree of saturation. The collapse behaviour of soils is also dependent on clay type and amount of clay present. Most of the naturally occurring collapsible soils comprise mainly of silt and fine sand sized particles where the bonds at the inter-granular level are either stabilized by capillary suctions and cementations or clay buttresses [10, 11, 14]. At low densities these natural soils exist in a metastable equilibrium due to the bonding by the clay buttresses.

Compacted fills and earth dams are susceptible to wetting-induced collapse [23]. Compared to natural soils the coal ashes are likely to experience greater collapse settlements as they are characterized with lower dry unit weights and higher void ratios. The severity of collapse was classified by Jennings and Knight [30] for soils and Luteneggar and Saber [31] modified this classification for soils. Trivedi and Sud [32] developed the classification of collapse for coal ashes. Table 1 compares the classification of severity of collapse for soils and coal ashes. In compacted coal ashes, the rainwater infiltration is sufficient to lower the matric suction which triggers failure. Sudden failure in fly ash disposal dumps and associated mudflows have been reported, and such failures are triggered due to poor compaction control of coal ashes in the field [7, 32, 33]. Fourie et al. [34] highlighted the importance of instability of an ash slope induced due to the infiltration. Even though many studies have focused to understand the behaviour of coal ashes as a potential back fill material and foundation subgrade [9, 17, 32], the present experimental study focuses on the potential use of locally available Ramagundam coal ashes as a back fill material, highlighting the significance of various factors which influence the wetting-induced collapse. Therefore, this paper discusses the influence of dry unit weight, water content, vertical stress and concentration of sodium chloride and lime solutions on the collapse behaviour of compacted coal ashes. These studies become important for fill design for mitigating the wetting-induced collapse in the critical zones of embankment, where the placement conditions are of prime concern as the vertical stresses are sufficiently high to cause collapse settlements [35].

Experimental Program

Coal ash produced from National Thermal Power Station, Ramagundam, India was used in the present study. Fly ash and bottom ash were collected respectively from the electrostatic precipitator and boiler furnace by dry process, whereas the pond ash was collected from an ash pond located few kilometers away from the plant. The coal ashes were oven dried, pulverized and sieved through 425 μm sieve prior to use for laboratory testing. Figure 1 presents the standard Proctor compaction curves of the Ramagundam coal ashes. Table 2 summarizes the properties of Ramagundam coal ashes used in the present study.

The present study examines the influence of placement conditions, vertical stress, and dissolved salts on the collapse behaviour of compacted coal ash specimens. Seventy

Table 1 Comparison of classification of severity of collapse for soils* and coal ashes**

Jennings and Knight* [30]		Luteneggar and Saber* [31]		Trivedi and Sud** [32]	
Collapse potential (%)	Likely severity of problem	Collapse potential (%)	Likely severity of problem	Collapse potential (%)	Likely severity of problem
Up to 1	No problem	2	Slight	<0.75	Non-collapsible
1–5	Moderate problem	6	Moderate	0.75–1.0	Low collapsible
5–10	Trouble	10	Severe	1.0–1.5	Medium collapsible
10–20	Severe trouble			>1.5	High collapsible
Above 20	Very severe trouble				

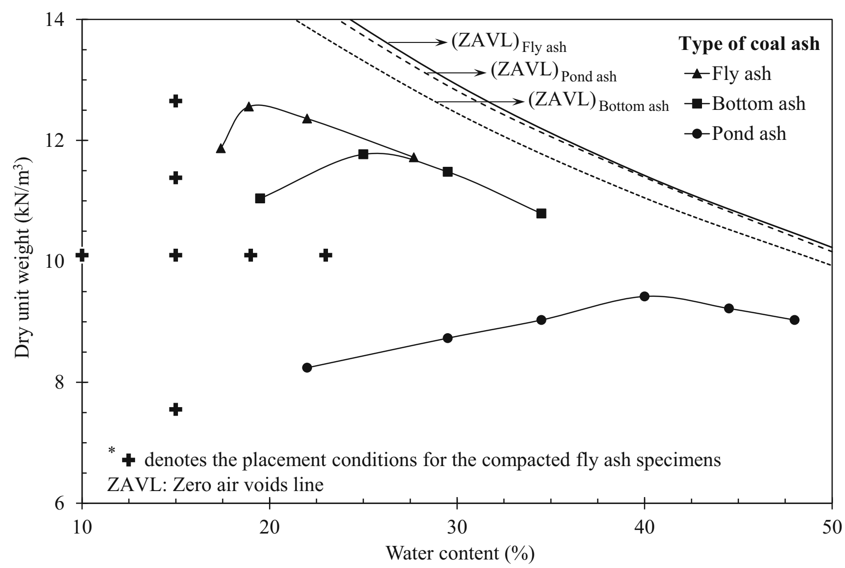


Fig. 1 Standard Proctor compaction curves of Ramagundam coal ashes

Table 2 Properties of Ramagundam coal ashes

Property	Value		
	Fly ash	Bottom ash	Pond ash
Specific gravity (G_s)	2.18	2.05	2.15
Atterberg limits			
Liquid limit (%)	35	69	28
Plastic limit (%)	Non plastic	Non plastic	Non plastic
Particle size distribution			
Sand size (%)	63.8	79.6	97.8
Silt size (%)	32.7	19.3	2.2
Clay size (%)	3.5	1.1	0.0
Standard compaction parameters			
Maximum dry unit weight (kN/m^3)	12.7	11.8	9.5
Optimum moisture content (%)	19.0	25.0	40.3

three single oedometer collapse tests were conducted in order to achieve the above stated objectives. The placement conditions adopted for the single oedometer collapse tests are also shown in Fig. 1.

Single Oedometer Collapse Tests

For the determination of collapse potential, the representative coal ash was remoulded with required volume of desired fluid (i.e., distilled water/sodium chloride or lime solution) to attain the desired water content and placed in a desiccator for moisture equilibration for 1 day. The required mass of moisture equilibrated coal ash, for a given dry unit weight, was taken and placed in oedometer ring of 60 mm diameter and 20 mm height and statically compacted. The compacted specimens were then set up in standard oedometer assemblies and incrementally loaded (with a load increment ratio of 1) in unsoaked condition to a desired vertical stress. The compacted specimens in unsoaked condition under each applied vertical stress attained equilibrium in <45 min. At the desired vertical stress, the compacted specimens were inundated with tap water. The time-collapse readings were continuously recorded during the test. The majority of the collapse occurred in <60 min after inundation. However, the final deformations at the end of 24 h were used for the calculation of collapse potential in order to account for residual and secondary compression [23, 36]. The magnitude of collapse potential of the compacted specimens is given as:

$$\text{Collapse potential, } i_e = \frac{\Delta e}{1 + e_i} \quad (1)$$

where Δe and e_i are change in void ratio upon saturation and void ratio at the beginning of saturation, respectively. Typical *e*-log p plot for single oedometer collapse test result of compacted fly ash specimen is presented in Fig. 2.

Results and Discussion

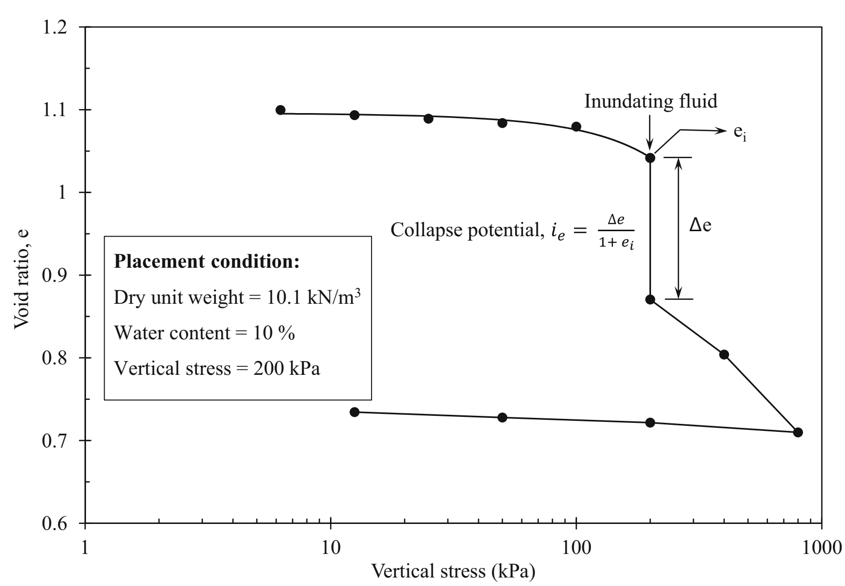
Influence of Type of Coal Ash

Figure 3 compares the variation of collapse potential with vertical stress for compacted specimens of coal ashes i.e., fly ash, bottom ash and pond ash. The coal ash specimens were compacted to a relative compaction of 80 % at water content of 15 %. It can be seen from Fig. 3 that the collapse potential of the compacted coal ash specimens increases with the increase in the vertical stress and is maximum at a vertical stress equal to 100 kPa, beyond which the collapse potential decreases with the vertical stress. The maximum collapse potential for the compacted coal ash specimens is in the range of 8.6–13 % corresponding to the vertical stress of 100 kPa, which indicates that the apparent preconsolidation stress for the compacted coal ash specimens is nearly equal to 100 kPa. It can also be seen that at any given vertical stress the collapse potentials of the compacted bottom ash and pond ash specimens are lower in comparison to the collapse potentials of the compacted fly ash specimens. This behaviour is attributed to the higher silt size fraction in the fly ash in comparison with the bottom ash and pond ash [23]. The silt size fractions of the fly ash, bottom ash and pond ash correspond to 32.7, 19.3 and 2.2 %, respectively. Therefore with the increase in the silt fraction the collapse potential increased. Lawton et al. [23] reported that at lower clay contents, the collapse potential of silt was greater than the sand, whereas at high clay contents silts collapsed less owing to the swelling. Since the collapse potentials are remarkably high for the compacted specimens of fly ash (e.g., 13 % at 100 kPa; Fig. 3) in comparison to the bottom ash and pond ash specimens (e.g., 8.6 and 9 % at 100 kPa; Fig. 3), therefore further parametric studies were conducted only on the compacted fly ash specimens.

Influence of Dry Unit Weight

Figure 4 presents the variation of collapse potential with relative compaction (dry unit weight) of compacted fly ash

Fig. 2 Typical e-log p plot for single oedometer collapse test of compacted fly ash specimen



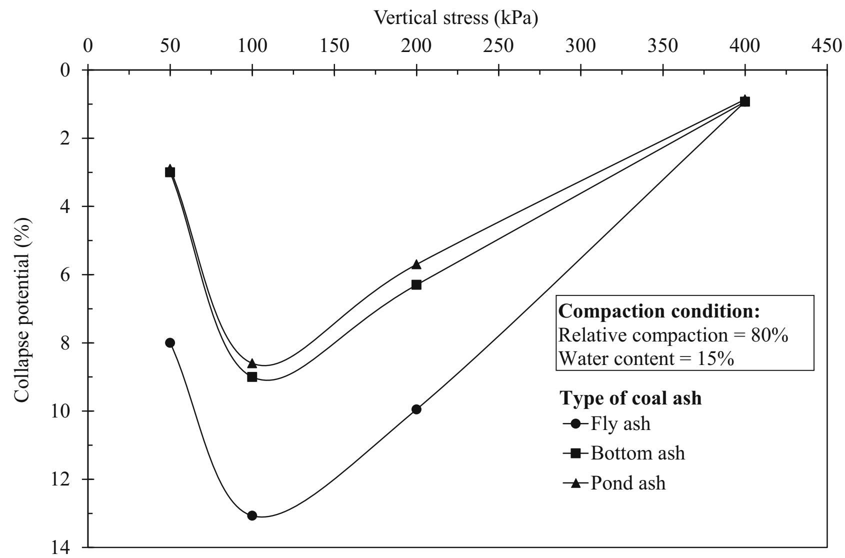


Fig. 3 Comparison of collapse potentials of Ramagundam coal ashes at different vertical stresses

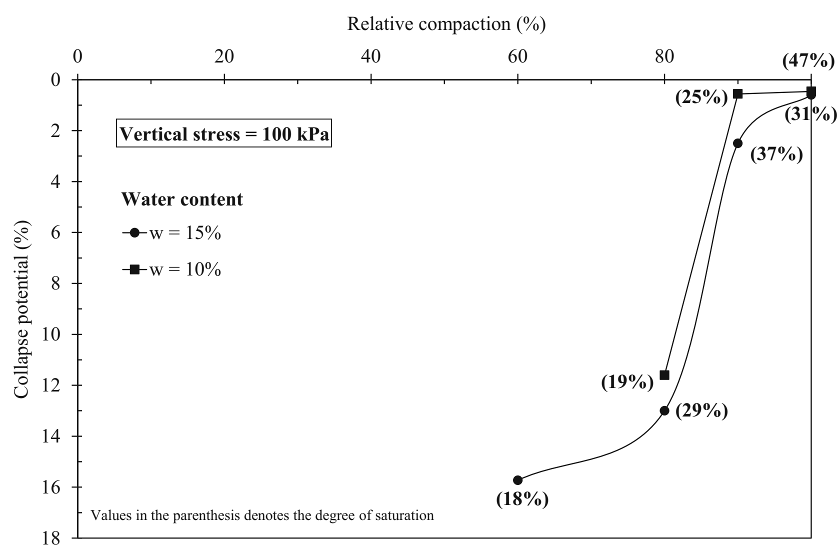


Fig. 4 Influence of relative compaction on the collapse potential of compacted fly ash specimens at different water contents (vertical stress = 100 kPa)

specimens at water contents of 10 and 15 % under a vertical stress of 100 kPa. It can be seen from Fig. 4 that the collapse potential decreases with the increase in the relative compaction at given water content and vertical stress, which is attributed to the closer arrangement of particles at the inter-granular level. Due to increase in the densification and reduction in void ratio, the inter-granular stresses are high and provide greater resistance against the compressibility and wetting-induced collapse. Similar results for the collapse behaviour of compacted soils were also reported by Dudley [10], Foss [18], Lawton et al. [23] and Tadepalli et al. [37]. Table 3 presents the single oedometer collapse test results obtained at vertical stresses of 50, 100 and 200 kPa for the fly ash specimens compacted to different dry unit weights at a water content of 15 %. The lower limiting values for the degree of severity for collapsible soils and coal ashes are considered as 2 and 0.75 %, respectively [31, 32]. The collapse potentials (vertical stress = 100 kPa) of the fly ash specimens compacted to a dry unit weight of 10.1 kN/m^3 at water contents of 10 and 15 % are in the range of 11.6–13 % which are categorized to have severe collapsibility [31, 32]. Figure 5 presents the variation of collapse potential with vertical stress for the fly ash specimens compacted to different dry unit weights at a water content of 15 %. It is evident from Fig. 5 that there is a sharp reduction in the collapse potential (determined at vertical stress of 100 kPa) from 13 to 2.5 %, with the increase in the dry unit weight from 10.1 to 11.4 kN/m^3. As the maximum collapse potentials for compacted fly ash specimens occurred at a dry unit weight of 10.1 kN/m^3 and also this dry unit weight represents the typical in situ condition of the ash ponds (6.25–9.95 kN/m^3) [38], a dry unit weight of 10.1 kN/m^3 is adopted for further parametric studies.

Table 3 Effect of dry unit weight and vertical stress on the collapse potential of compacted fly ash specimens at water content of 15 %

Vertical stress (kPa)	Collapse potential (%)		
	$\gamma_d = 10.1$ kN/m^3	$\gamma_d = 11.4$ kN/m^3	$\gamma_d = 12.7$ kN/m^3
50	5.35	2.30	0.53
100	13.07	2.50	0.60
200	9.95	1.90	0.50

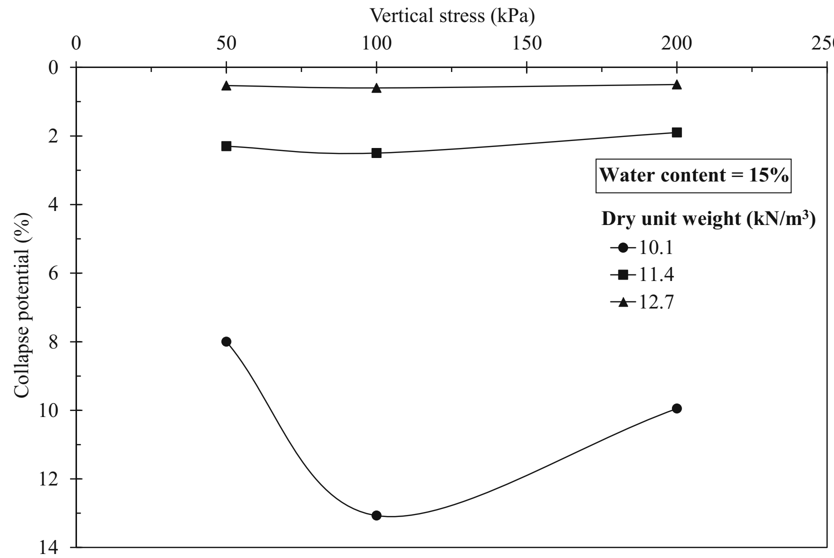


Fig. 5 Comparison of collapse potential variation of fly ash with vertical stress at different dry unit weights ($w = 15$ %)

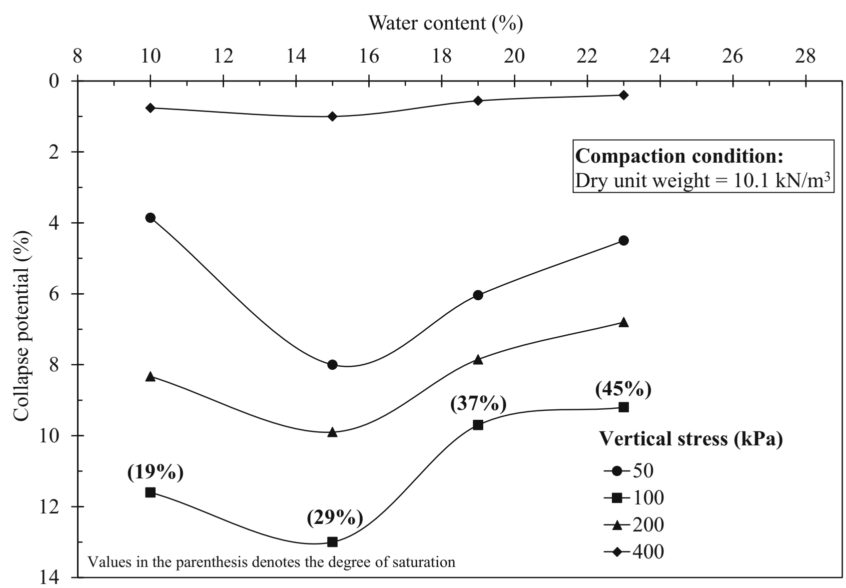


Fig. 6 Influence of water content on the collapse potential of compacted fly ash specimens ($\gamma_d = 10.1$ kN/m^3) at different vertical stresses

Influence of Water Content

Figure 6 presents the variation of collapse potential with water content for the fly ash specimens compacted to a dry unit weight (γ_d) of 10.1 kN/m^3 at different vertical stresses. It is evident from Fig. 6 that as the as-compacted water content increased the collapse potential increased up to a critical water content of 15 %, and beyond which it decreased. It can also be seen that the collapse potential at a given water content increases with the increase in the vertical stress up to a critical vertical stress of 100 kPa and beyond which it decreases. Trivedi and Sud [32] also

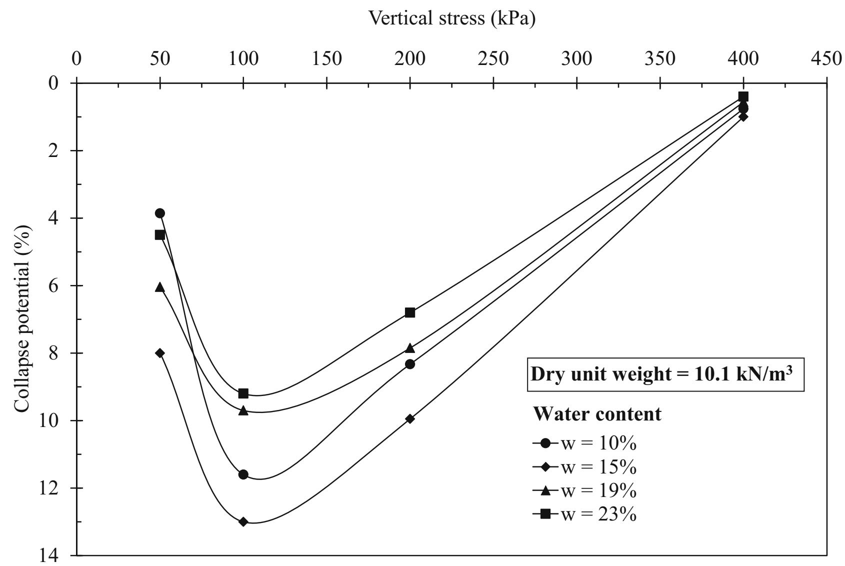


Fig. 7 Variation of collapse potential with vertical stress for fly ash specimens compacted to a dry unit weight of 10.1 kN/m^3 at different water contents

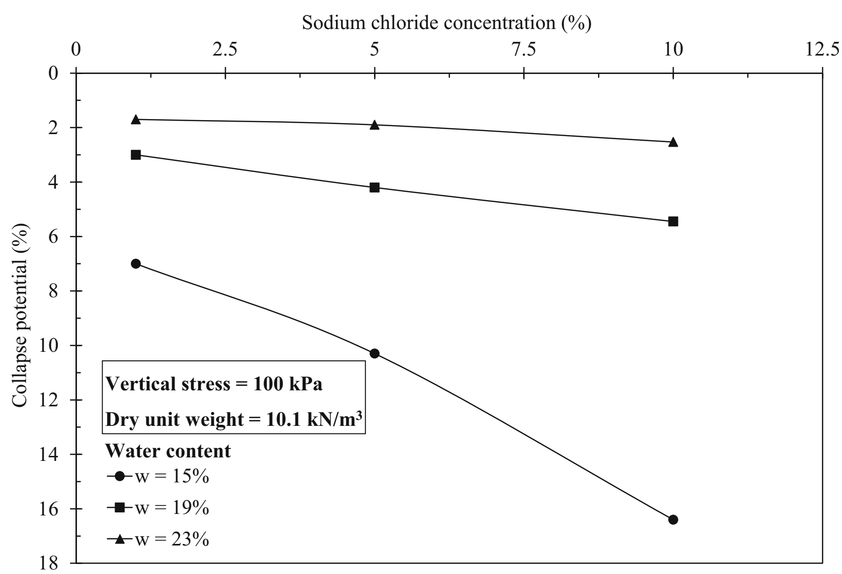


Fig. 8 Variation of collapse potential with sodium chloride concentration for fly ash specimens compacted at different water contents (γ_d = 10.1 kN/m^3)

reported similar results for the fine coal ash, where the critical vertical stress and water content were in the range of 50–100 kPa and 10–30 %, respectively. The capillary forces (i.e., suction) reduce to zero at completely dry or wet state; and in the partially wet state i.e., unsaturated condition the compacted specimens are stabilized by capillary forces, which bind the fly ash particles together [32]. In granular soils, the capillary forces are maximum at the critical water content as the menisci between the fly ash particles are fully developed at this water content. Thus the fly ash specimen sustains large vertical stresses in unsoaked condition as the water phase remains continuous. In unsoaked condition, the soil structure exists in the state of metastable equilibrium even upon the application of additional vertical loading. On inundation, the suction reduces and leads to the wetting-induced collapse. Therefore, the collapse potential increases with the increase in water content and attain a maximum value at the critical water content, and beyond which it decreases. This critical water content is lower than the optimum water content. Booth [29], Lawton et al. [22] and Mishu [28] have reported that the concept of critical moisture condition is valid if expressed in terms of degree of saturation, and not the water content.

Influence of Vertical Stress

Figure 7 compares the variation of collapse potential with vertical stress of fly ash specimens compacted to a dry unit weight of 10.1 kN/m^3 at different water contents (10–23 %). The collapse potential for all the compacted fly ash specimens initially increased with the increase in the

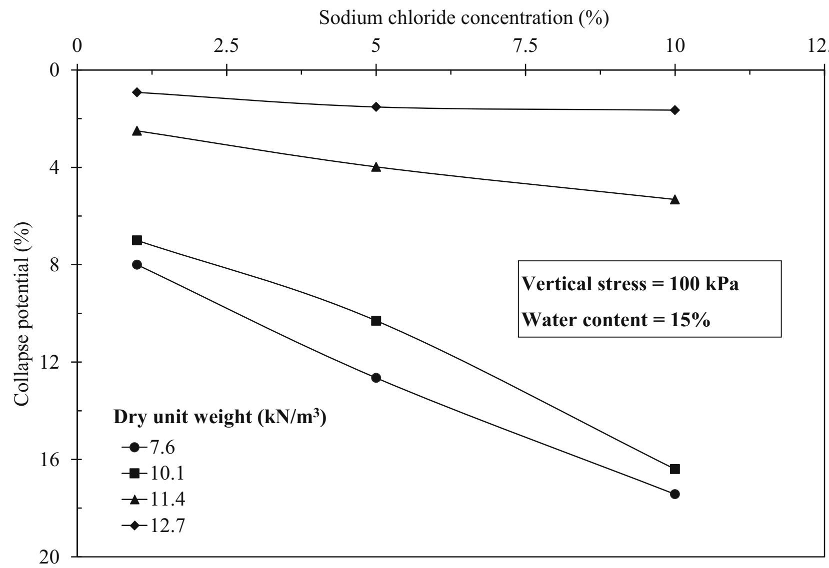


Fig. 9 Variation of collapse potential with sodium chloride concentration for fly ash specimens compacted to different dry unit weights ($w = 15$ %)

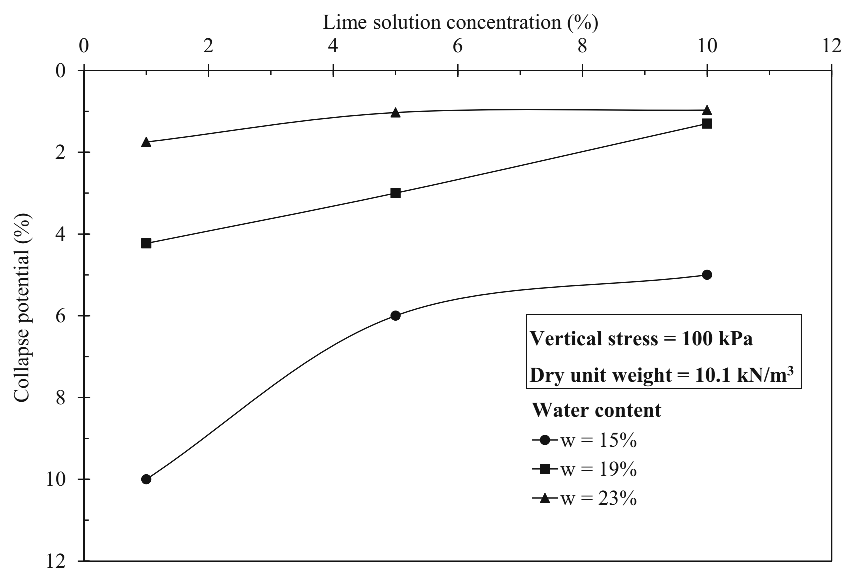


Fig. 10 Influence of lime solution concentration on the collapse potential of fly ash specimens compacted to a dry unit weight of 10.1 kN/m^3 at different water contents

vertical stress to a critical vertical stress value of 100 kPa, and beyond which it decreases with the further increase in the vertical stress. The maximum collapse potential for the fly ash specimens compacted to different water contents is in the range of 9.2–13 %. Kaushik [39] and Pusadkar and Ramasamy [17] also reported similar results, wherein the collapse potential increased with the increase in the vertical stress for the coal ash specimens compacted at different water contents. Indraratna et al. [7] reported maximum collapse potential of 4.6 % for a class C fly ash. Similar behaviour is also observed in compacted soil specimens, where the maximum collapse potential occurs at a critical vertical stress value, which corresponds to the apparent preconsolidation stress or compactive prestress for the compacted specimen, and beyond this critical vertical stress the collapse potentials decreases with further increase in the vertical stress [22, 23, 27]. The decrease in the collapse potential with the vertical stress is attributed to densification and the increase in the degree of saturation at higher vertical stresses.

Influence of Pore Fluid

Figures 8 and 9 present the variation of collapse potential with the sodium chloride concentration of the remoulding fluid for fly ash specimens compacted at different water contents and dry unit weights, respectively. It can be seen from Figs. 8 and 9 that for a given water content or dry unit weight, the collapse potential increased with the increase in the sodium chloride concentration. Coal ashes being inert

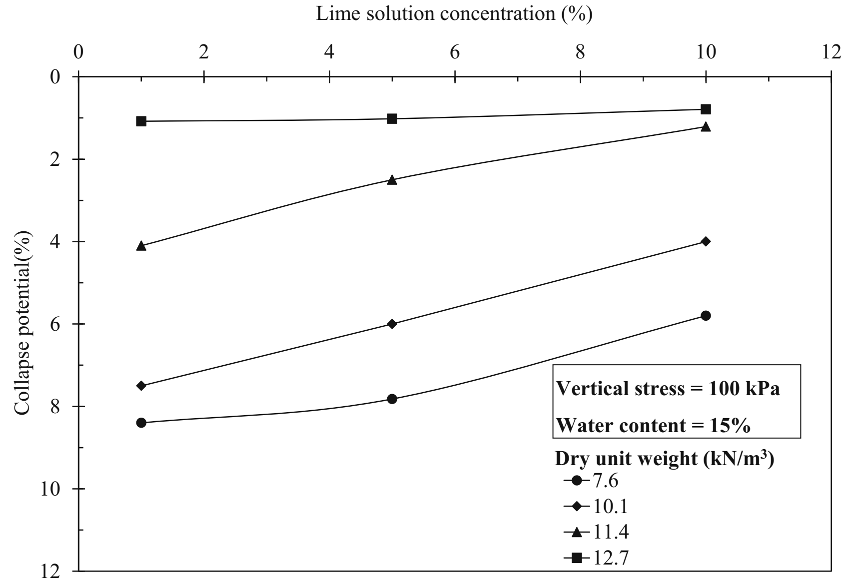


Fig. 11 Influence of lime solution concentration on the collapse potential of fly ash specimens compacted to different dry unit weights at water content of 15 %

material are coated with soluble substances when mixed with sodium chloride solution. On inundation with water, the coal ashes come in contact with water which results in the dissolution of particles. Thus the compacted coal ash specimens become unstable and the dissolution of particles increases with the increase in the sodium chloride concentration which in turn leads to higher wetting-induced collapse. Reginatto and Ferrero [40] reported that the pore fluid chemistry also contributes to the wetting-induced collapse.

Apart from the reasons cited above for the increase in collapse potential with the increase in sodium chloride concentration, it can also be attributed to the changes in the structure; wherein the volume of macro pores could have increased at the expense of mico pores and caused the additional collapse settlement. Recently, Thyagaraj and Salini [41] showed that remoulding the expansive soil with sodium chloride solution increased the volume of macro pores at the expense of micropores.

Figures 10 and 11 presents the influence of lime solution concentration on the collapse potential of compacted fly ash specimens at different water contents (dry unit weight = 10.1 kN/m^3) and dry unit weights (water content = 15 %), respectively. It is evident from Figs. 10 and 11 that the collapse potential decreases with the increase in the lime solution concentration which is mainly attributed to the cementation bonds that develop due to pozzolanic reactions between the fly ash and the lime, which induces the self-cementing property in the fly ash. Further, the strength of 5 and 10 % lime solution remoulded fly ash specimens increased with curing period and reduced the collapse potentials from 3 to 0.93 % and 1.3 to 0.78 % when cured for 7 days, respectively. These results indicate that the curing reduces the collapse potential of lime solution treated fly ash. Indraratana et al. [7] also reported that class C fly ash gained strength within 2–3 weeks of curing due to the accelerated pozzolanic reactions.

Summary and Conclusions

The present paper examines the influence of placement conditions, vertical stress and pore fluid on the collapse behaviour of compacted coal ashes. Series of single oedometer collapse tests were conducted in order to determine the above stated effects on the collapse. The experimental results showed that, among the coal ashes the compacted fly ash specimens are more susceptible to wetting-induced collapse in comparison to bottom ash and pond ash which is attributed to the higher silt size fraction in the fly ash. Therefore, further parametric studies were conducted only on the compacted fly ash specimens and the main outcomes are as follows:

- The collapse potential of the compacted fly ash specimens increases up to a critical water content of 15 %, and beyond which it decreases with the increase in the water content.
- The collapse potential decreases with the increase in the degree of compaction at given water content and vertical stress. The collapse potentials (vertical stress = 100 kPa) of the fly ash specimens compacted to a dry unit weight of 10.1 kN/m^3 at water contents of 10 and 15 % were in the range of 11.6–13 % and the degree of severity of collapse is classified as severe.
- The collapse potential of the compacted fly ash specimens initially increased with the increase in the vertical stress to a critical vertical stress value of

100 kPa, and beyond which it decreases with the further increase in the vertical stress. Thus the apparent preconsolidation stress for the compacted Ramagundam fly ash specimens is 100 kPa.

- The collapse potential increases with the increase in the sodium chloride concentration which is attributed to the dissolution of particles on inundation with water. With the increase in the lime solution concentration and curing period, the collapse decreases owing to the pozzolanic reactions.

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