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Geotechical characterization of Indian Coal Ash: A Review

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Abstract. Bottom ash and fly ash are the main residual products generated from the burning of coal in the thermal power plants. Fly ash and bottom ash mixed with large quantity of water and stored in the ash pond. Ash pond breaches is a major concern for engineers as well as localities residing near ash ponds. Bad characterization of coal ash material may be the primary reason for such failures. A proper geotechnical characterization of coal ash is required to assess an ash pond's short-term and long-term stability and its effective use in various geotechnical applications like filling of low-lying areas, construction of highway embankments, dykes etc. This paper reviews the applicability of the critical state soil mechanics approach to characterize coal ash. Furthermore, an extensive review has been done on coal ash's mineralogical, morphological, engineering characterization and Indian ash pond breach. The review suggests that the Indian coal ash possesses less specific gravity leading to lower unit weight. Coal ashes exhibit non plastic behavior, classified as sand to silt. XRD results show that coal ash consists of quartz and feldspar minerals and exhibits crystalline and amorphous phases. Coal ash's hydraulic conductivity is similarto fine sand/silt mixtures or silt. The charectersics of NCL (Normal compression line) and CSL (critical state line) in $- \ln '$ space is similar tothat of granular soils with few exceptions.

Keywords: coal ash, ash pond breach, CSSM

However it's behaviour is expected to be quite different from the soil.

1 Introduction

Coal ash consists of bottom ash (BA) and fly ash (FA) are produced from the burning of coal in thermal power plants. The unused BA and FA further mixed with large amount of water and pumped in to the ash pond. Indian coal based thermal power plants produce 226 million metric tonnes (MMT) of ash every year, which is expectedto rise to 600 MMT by the next decade.

The un utilized volume of ash occupied 40000 hectares of valuable land in India.It can be reduced by the utilization of pond ash for the construction of highway embankment, and filling of low lying area. A thorough understanding of pond ash's (PA) geotechnical characteristic is the need of the hour because of its wide applicationin geotechnical engineering. It is a common understanding that the coal ash engineering behaviour is similar to the granular soil. Several researchers have worked on the characterization of Indian coal ashes and its suitability as a construction material (Pandian 1998, Mohanty and Patra 2015, Das and Yudhbir 2005, Jakka et al. 2010, Kaniraj and Gayathri 2004, Reddy et al.2018, Prakash and Sridharan 2005). However, very few literature are available on synthesizing and modeling the behaviour of coal ash using the critical state soil mechanics approach.

Since 2010 to 2020, 76 coal ash pond breaches in India were reported leading to major damages to the paddy crops, human lives and aquatic ecosystem (https://www.indiaspend.com/uploads/2021/08/19/file_upload-535264.pdf).The failure of the dyke walls, bursting of pipe lines, over flow of ash slurry in to the near by agricultural land, residential area, and contamination of water bodies is one of the greatest concern for all the geotechnical engineers, local people and bureaucrats. The present paper provides an insight into the cause of the ash pond breaches and a few case studies of Indian ash pond failures. Furthermore, an extensive review ispresented on the morphological, chemical and geotechnical properties of Indian coal ashes collected from several sources. Recent development on the modelling ofgeomaterial are based on the Critical state soil mechanics parameters (CSSM).Unfortunately, there is no inform on CSSM of Indian coal ash. However in this paperthe applicability of Critical state soil mechanics has been reviewed.

2 Reasons of ash pond breaches and failure mechanisms

Due to the scarcity of land, the vertical rising dyke wall is constructed around the ash pond to dispose of the un utilized coal ash. The dyke is a ring embankment placed over the pond ash fill. Throughout the lifetime of an ash pond, the dyke rising is carried out multiple times. Up-stream, down-stream and center line method are usedto raise dyke of the ash ponds. The dyke raising height depends on the foundation soil's bearing capacity. The raising of the ash pond increases the load, and sometimes this can exceed the shear strength of pond ash and ultimately causes failure of thedyke wall. There are also some other mechanisms that cause the failure of ash ponds like piping, over topping, embankment instability, liquefaction and structural element failure.

2.1 Case studies on Indian ash pond breaches

The current research overviews ash pond breaches that occurred in India in the last three years. Table.1 shows the various ash pond breaches that occurred nationally over the last three years and their probable causes. Prasad (2020) reported that the failure of ash pond embankment was initiated by slippage, and further extent of damage is due to high hydro static pressure exerted on the upstream side of the embankment, which may be resulted from the newly constructed check dam on a stream in the year 2019. Various causes responsible for the ash pond dyke breach include substandard dyke construction, heavy rain falls, piping, and bad characterization of pond ash materials.

3 Physical, morphological characteristics of Indian coal ashes

Physical, morphological, geotechnical characteristics of different coal ashes (FA,BA, PA) were studied, and an extensive review is presented in this paper. Table.2 presents the various sources of pond ash, fly ash and bottom ash considered in this paper.

Table.1 Indian ash pond breaches and it’s causes

Name of thermal power plant	Date of incident	Cause of breach
Essar thermal power station (Madhya Pradesh)	07.08.2019	substandard construction of ash dyke , heavy rainfall
Vindhyachal Thermal Power Plant (Madhya Pradesh)	06.10.2019	heavy rainfall, more details under investigation
Reliance Sasan Ultra Mega Power project (Madhya Pradesh)	10.04.2020	collapse of wall of illegal ash dyke
Anpara Thermal Power Station (Uttar Pradesh)	constant discharge of ash slurry into the Rihand reservoir over a long period	Due to heavy rain ash pond filled with rain water leading to the overflow of ash into reservoir
Talcher thermal power station (Odisha)	06-Mar-20	pipe line carrying slurry from TTPS ash pond to South Balanda coal mine void burst
Bokaro thermal power station (Jharkhand)	12-09-2019	heavy rainfall causes hydraulic pressure build-up resulting in ash pond breach
North Chennai thermal power station (Tamil Nadu)	24-08-2020	bursting of pipeline carrying ash slurry from NCTPS to ash pond
Kahalgaon super thermal power station(Bihar)	07-11-2020, 21-01-2021	2020-problem in spillway or overflow of residual water,2021-bursting of main FA slurry pipeline

Table.2 Coal ash collected from different sources and it's naming

Sources of fly ash ,bottom ash and pond ash					
Fly ash	**Naming**	**Bottom ash**	**Naming**	**Pond ash**	**Naming**
Badarpur	F1	Baadrpur	B1	Panipat	P1
Dadri	F2	Ghaziabad	B2	Panki	P2
Ghaziabad	F3	Korba	B3	Baadrpur	P3
Korba	F4	Raebareli	B4	Korba	P4
Raebareli	F5	Vijayawada	B5	Raebareli	P5
Ramagundam	F6	Ramagundam	B6	Raichur	P6
Vijayawada	F7	KTPS	B7	Ramagundam	P7
KTPS	F8	GMR Dhenkanal	B8	Vijayawada	P8
Ropar	F9	Kahalgoan	B9	Badarpur inflow	P9
Parichha	F10	Rihand	B10	Badarpur outflow	P10
Neyveli	F11	Neyveli	B11	Indraprastha inflow	P11
GMR Dhenkanal	F12			Indraprastha outflow	P12
Rihand	F13			TTPS	P13
Panki	F14			Rihand	P14
Kahalgoan	F15			Neyveli	P15
				Kahalgoan	P16

3.1 Classification of coal ash (C, F)

Fly ash can be differentiated as Class C or Class F according to the chemical analysis. As per ASTM C618 fly ash contains more than 70% weight of Al_2O_3,SiO_2, and Fe_2O_3 are classified as Class F, where as Class C fly ash contains 50-70% weight of SiO_2, Al_2O_3 and Fe_2O_3. According to ASTM , Class C fly ash has higher calcium (CaO > 15%) content than Class F fly ash (CaO<5%). Class C FA is produced from the burning of younger lignite or sub bituminous coal, where as class F FA is the result ofburning of harder, older anthracite and bituminous coal. Silica present in the Class F fly ash reacts with calcium hydroxide to form compound that have cementitious properties. Class C fly ash has self-cementing properties and when it reacts with water, it hardens and became stronger with time. Both Class C and F fly ash have pozzolanic properties, but Class C possesses cementitious properties. Because of the pozzolanic properties engineering performance of fly ash enhanced over time. Consequently, it exerts low lateral pressure on retaining structures, less overburden pressures on foundation soils, decreased secondary settlements and permeability and increased shear strength. Low lime fly ash obtained from the Neyveli and Muddanur thermal plant was classified as Class F fly ash (Moghal 2013, Das et al. 2005, Jakka etal. 2010).

3.2 XRD

XRD test gives an idea of the mineral phases of a material. Coal ash mostly consists of quartz and less amount of feldspar, chlorites and carbonates (Pandian et al.2004, Mohanty and Patra 2015). Das and Yudhbir (2005) found that high calcium fly ash have tricalcium aluminate, tri calcium silicate, anhydrites and quartz mineral and low calcium fly ash possess mullite, hematite, magnetite and quartz minerals. FA from dadri power plant possess quartz, mullite, gehlenit, silimanite, melilite,magnetite, hematite (Kaniraj and Gayathri 2004, Trivedi and Sud 2007). Reddy et al.(2018) reported that KTPS fly ash exhibits quartz and mullite minerals, where as KTPS bottom ash have quartz ,mullite and calcium carbonate.

3.3 SEM, EDX

Morphological characteristics of coal ash can be studied by scanning electron microscope. Das and Yudhbir (2005) found that low calcium fly ashes possess smooth spherical spheres known as cenospheres and plerospheres of size ranging from 1 to 100 μm, where as high calcium fly ashes have spherical particle with irregular shape cluster and calcium coating over the surface. For low calcium FA, iron makes a cover over the cenospheres and for high calcium fly ash , iron spinel morphology was found for particles larger than 75μ. Pond ash particles have irregular and spherical shape with complex pore structure (Mohanty and Patra, 2015, Jakka et al. 2010). Dadri fly ash consists of spherical particles. (Kaniraj and Gaythri 2004, Reddy et al.2018, author's file). Reddy et al.(2018) found that because of the un burnt carbon bottomash consists of coarse-grained, asymmetrical, bigger size particles having rough surface texture.

Energy dispersive X-ray (EDX) test is used to find the elemental composition of different coal ash. From the EDX analysis, Reddy et al.(2018) found that FA contains higher amount of silicon (Si), a lesser amount of aluminum (Al), oxygen (O) and iron (Fe), whereas BA contains silicon (Si), aluminium (Al), carbon (C), calcium (Ca), potassium (K), oxygen (O) and iron (Fe). Author have conducted EDX test on bottom ash collected from GMR Kamalanga Energy Limited, Dhenkanal, Odisha, and found similar result as Panki and Panipat pond ash (Mohanty and Patra 2015).

3.4 Chemical Composition

Indian coal ash primarily consists of SiO_2 (23%-75%), Al_2O_3 (11%-54%) and Fe_2O_3 (3%-35%) with lesser amount of other minerals CaO, SO_3,K_2O, TiO_2, MgO, P_2O_5, Na_2O, SrO (Das and Yudhbir, 2005, Madhyannapu et al., 2008, Mohanty and Patra, 2015, Mishra and Das 2015, and Kaniraj and Gayathri, 2004, Prakash and Sridharan 2006).Nature of FA generally depend on burning condition and boiler temperature, boiler design, grain size of the coal and gas cleaning instrument (Bhatt et al. 2019).

3.5 Grain Size Distribution

Particle size distribution can influence the various geotechnial properties like permeability,shear strength, settlement etc. Table.3 shows the grain size of FA,PA and BA reported by various literature. For pond ash the gravel size, sand size and silt-clay size are in the range of 0 to 10%, 97 to 2% and 1 to 97% respectively. Fly ash does not contain the gravel size; its sand size and silt-clay size fraction are in the range of 7.5% to 82% and 13% to 80%. Similarly, bottom ash does not contain the silt-clay size; its gravel and sand sizes range from 0% to 91% and 5% to 92% respectively. The basic parameters commonly used to characterize the grain size distribution curve are the uniform and curvature coefficient.Table 3 suggests that Cu for FA, PA and BA falls in the range of 1.6 - 6, 2-9.4 and 4-8.8 respectively and Cc lies in the range of 1-2.5, 0.7-1.9 and 1-2.1. From Table 3 it can be conclude that FA consists of silt size - clay size fraction, PA particles lies in the range of silt size to sand and BA have coarse grained, consists of sand-silt size fraction.

Table.3 Grain size analysis of various coal ash

Source	**Sp. Gravity (G)**	**Gravel size (%)**	**Sand size (%)**	**Silt size (%)**	**Clay size (%)**	**Cu**	**Cc**	**Reference**
P1	2.21	0.0	95.2	4.8	0.0	2.3	0.8	Mohanty and Patra 2015
P2	2.30	0.7	87.2	12.0	0.0	2.0	0.7	
P4	1.91	-	86.0	12.5	1.0	3.6	1.8	Prakash and Sridharan 2005
P5	1.93	-	51.0	48.0	1.0	9.4	1.6	
P7	2.18	-	97.4	1.2	1.0	3.4	1.4	
P8	2.01	-	71.0	27.5	1.5	3.0	0.8	
P9	2.50	10.4	75.3	13.8	0.5	3.5	1.1	Jakka et al. 2012
P10	2.18	0.3	21.2	76.5	2.0	4.6	1.0	
P11	2.50	0.1	73.9	25.8	0.2	4.1	1.2	
P12	2.27	0.1	1.9	97.6	0.4	2.1	1.2	
P15	2.33	-	82.0	14.0	2.4	9.7	1.9	Pandian 2004
F1	1.97	-	-	-	-	5.5	2.5	
F2	2.20	5.0	82.0	13.0	-	4.8	1.0	Kaniraj and Gayathri (2004)
F3	2.31	-	10.0	85.0	5.0	-	-	Prakash and Sridharan (2005)

F4	1.98	NA	34.0	21.0	3.0	6.0	1.1	Pandian (2004)
F5	2.05	-	28.0	70.0	2.0	-	-	
F6	2.18	-	7.5	87.0	5.0	1.6	1.1	
F7	1.95	-	25.0	70.5	4.5	5.7	0.6	
F8	1.86	0.0	28.1	71.9	0.0	3.6	1.9	Reddy et al.(2018)
F11	2.62	NA	27.0	70.0	10.0	3.2	1.0	Pandian (2004)
B3	2.15	-	91.0	8.0	1.0	4.7	2.1	Prakash and Sridharan (2005)
B4	1.66	-	87.0	12.0	1.0	-	-	
B5	1.82	7.0	71.0	22.0		6.6	1.4	
B6	2.08	10.0	76.5	12.5	1.0	8.0	1.6	
B7	1.77	9.2	83.0	7.2	0.0	4.0	1.0	Reddy et al.(2018)
B9	2.17	18.3	65.9	14.8	1.0	8.8	1.3	Prakash and Sridharan (2005)
B11	2.08	91.5	5.5	3.0	2.1	5.2	2.1	

3.6 Specific gravity

Specific gravity depends on fineness of ash, loss of ignition, mineral constituent and iron content. Das and Yudhbir (2005) found that for iron content >10% , specific gravity is directly proportional to the iron content and for lime content >15%, G valueis higher regardless of the iron content and loss on ignition. The Sp. gravity of high calcium FA is greater than low calcium FA, which is attributed to the absence of cenospheres and the presence of a small amount of plerosphere. From Table 3, it was observed that the specific gravity of pond ash is in the range of 1.91-2.338, fly ash in the range of 1.86-2.62 and bottom ash is in the range of 1.66-2.19. The Sp. gravity of bottom ash is than fly ash due to the presence of cenospheres and poor gradation of bottom ash (Reddy et al.2018). Also, hollow fly ash particles or bottom ash particles having porous vesicular textures greatly influence the specific gravity. Coal ash exhibits less apparent G than natural soils having similar gradation, that may be attributed to entrapped micro air bubbles in the ash particle and the presence of un burned carbon.

3.7 Permeability

Permeability of coal ash is a function of the particle size, degree of compaction and pozzolanic reaction. It has a great role in the design of liner to prevent leachate migration, stability of slopes and usability as a sub-base material. The coefficient of hydraulic conductivity of PA is in the range of 5 x 10^{-5} cm/sec to 9.62 x 10^{-4} cm/sec. Fly ash possess least permeability which is in the range of 8 x 10^{-6} cm/sec to 1.87 x 10^{-4} cm/sec. The highest permeability possessed by bottom ash varies in the range of 9.9 x 10^{-5} cm/sec to 7 x 10^{-4} cm/sec (Pandian 2004). The falling head permeability test is suitable for coal ash as the particle size is smaller than sand size particles. Mohanty and Patra (2015) performed a falling head permeability test on two pond ash, namely Panki and Panipat and found that Panipat PA has less coefficient of permeability values than Panki PA due to the presence of silt size particles. Jakka et al.(2010) found that K value for fine pond ash samples falls in the range of silt, whereas coarse ash samples fall in the range of fine sand.The coefficient of permeability of FA fallsin the range of non plastic silts, resulting in better performance of embankments and retaining wall constructed over it with better drainage characteristics .Bottom ash has a coefficient of permeability in the range of clean sand/gravel mixture. Bottom ash possess larger voids than fly ash making it more permeable than fly ash and a suitable road embankment construction material (Reddy et al.2018, Prakash and Sridharan 2009).

3.8 Compaction

Compaction characteristics of coal ash mainly depends on component like gradation, iron and carbon content, residual carbon and fines. High calcium FA possesses high density and lesser water content than low calcium FA (Das and Yudhbir 2005). Due to higher specific gravity, Panki pond ash have high dry unit weight as compared to Panipat pond ash (Mohanty and Patra, 2015). Pond ash having coarser nature, has high density compared to finer samples because of its high specific gravity. It was observed that density initially reduces with increase of moisture content, which may be attributed to the bulking effect, subsequent addition of water will increase the density to a maximum value as the water content approaches to the saturation (Jakkaet al,.2010). Fly ash possesses low specific gravity resulting in low maximum dry density in standard proctor test. An empirical correlation between OMC, MDD andSp. gravity was suggested by Kaniraj and Havangi (2001) as follows:

$$\text{MDD} = 25.234 G^{0.488} \text{OMC}^{-0.336} \text{ kN/m}^3$$

MDD of BA is lower than FA and OMC is higher than FA. The asymmetrical surface texture and presence of un burnt carbon in BA results in higher moisture content and the presence of cenospheres and poor gradation causes lower density in BA (Reddy et al. 2018). Prakash and Sridharan (2009) suggested that for the standard compaction test, dry unit weight and moisture content of coal ash should be plotted after normalizing it with a standard Sp. gravity. Standard Sp. Gravity should be taken as 2.65, representing the G value for most soils. If w_m and Υ_{dm} are the moisture content and dry unit weight of coal ash having specific gravity Gm, then the normalized dry unit weight (Υ_{dn}) and normalized water content (w_n) can be obtained as follows:

$$\Upsilon_{dn} = \Upsilon_{dm}\left(\frac{sd}{m}\right), \quad w_n = w_m\left(\frac{m}{sd}\right)$$

Table 4. represents the MDD and OMC of Indian coal ash reported in various literature. Indian coal ashes exhibit compaction behavior similar to sand or sandy gravel. The change in moisture content for coal ash does not significantly affect the dry density, resulting in a flatter compaction curve compared to natural soils. (Sridharan et al.2001).

3.9 Strength characteristics of Indian coal ashes

Shear strength characteristics, cohesion and angle of internal friction of coal ashes can be determined from the direct shear test and triaxial test. Pond ash samples tested in the undrained condition showed that pore water pressure and amount of contraction increases with increase in the confining pressure (Mohanty and Patra 2015). The stress-strain behaviour suggests that the deviatoric stress and axial strain of FA and BA shows contractive behaviour during static shear loading for different confining pressure. The friction angle of fly ash is a function of the angularity of the particles that gives more resistance to rearrangement of particles .Apparent cohesion was noticed in fly ash in moist conditions. Coal ash possesses a high angle of shearing resistance at peak and residual stress levels, and strength loss due to saturation is negligible (Prakash and Sridharan, 2009). Irrespective of ash type, deviator stress increases with the increase in confining pressure (Pal and Ghosh 2009). For compacted samples stress-strain behavior is largely influenced by the mode andperiod of curing . Wet curing for high calcium FA results in larger strength gain than low calcium fly ash because of the presence of highly reactive material and glass phase.(Das and Yudhbir 2005). OMC, MDD,shear strength parameters of coal ash at different loading condition is presented in Table 4. From CU test on pond ash,the angle of internal friction is in a range from 22.3°-36.53° in the loosest state and 33.7°-38.6° at the densest state (Mohanty and Patra 2015, Jakka et al.2010)

It is a biggest challenge to make a sample that mimics the in situ conditions similar to the pond ash. Sample prepared by moist tamping using less water content to form a loose specimen and by compaction with high water content to form medium to dense specimen does not depict similar behavior as a representative of ash pond material. Further water pulviation method is not suitable for specimen preparation as it results in the segregation of material. Zhang et al.(2018) used the paste deposition techniques to make highly uniform samples, that is similar to the wet disposal process. Table 5 gives an idea of the sample preparation techniques for various shear test and their findings.

Table.4 Compaction and shear strength characteristics of coal ash

Sources	**OMC**	**MDD**	**C(kPa)**	**ϕ°**	**Test type & condition**	**Reference**
P2	34.6	11.21	0.00	36.53@50% RD, 37.68 @65% RD	CU test	Mohanty and Patra (2015)
P1	42.1	10.40	0.00	33.04 @50% RD, 34.28 @65% Rd		
P9	13.6	28.00	0.00	32.2@loose state, 33.7@dense state (CU test) 33.7 at loose state,40.1 at dense state (CD test),	CU test, CD test	Jakka et al.(2010)
P10	11.6	30.50	0.00	22.3 @loose state, 35.4 at dense state (CU test)32.9 at loose state,37 at dense state (CD test)		
P11	13.1	26.50	0.00	35.5 at loose state,38.6 at dense state (CU test)34.9 at loose state,41.7 at dense state (CD test)		
P12	12.3	30.00	0.00	24.2 at loose state,34.7 at dense state (CU test) 33.1 at loose state ,35.2 at dense state (CD test)		
P6	36.0	10.19	0.00	32	DS, loose state	Sridharan (1998)
P5	40.2	10.17	0.00	32		
P4	21.6	8.94	0.00	31		
P8	37.0	10.19	0.00	33		
P3	48.0	9.17	0.00	33		
P7	40.6	10.00	0.00	33		

F4	33.0	11.11	0.00	31	DS loose state	Sridharan (1998)
F7	23.6	12.74	0.00	33		
F1	37.4	10.17	0.00	32		
F3	24.4	13.01	0.00	29		
F6	27.6	12.15	0.00	32		
F2	21.0	13.80	12.60	31(UU),29.3°(CD)	UU, CD	Kaniraj and Gayathri (2004)
F8	19.8	12.64	47.13	33.63 at 97% RC	UU	Reddy et al.(2018)
F5	20.6	13.00	23.00	34	DS, Danse state	Sridharan (1998)
B4	63.4	7.57	17.00	32		
B3	54.2	9.02	0.00	33	DS loose state	Sridharan (1998)
B5	40.0	8.82	0.00	34		
B1	50.4	8.43	0.00	34		
B2	36.5	10.49	0.00	32		
B6	38.0	9.31	0.00	34		
B7	40.4	9.90	77.73	30.07 at 97% RC	UU	Reddy et al.(2018)

DS: Direct shear

Table.5 Sample preparation techniques and it's findings

Type of test	Methods of sample preparation	Findings	Reference
Consolidated drained (RD 50%, 65%)	Moist tamping	Under static shear loading condition pond ash specimen shows contractive behavior. Increase in confining pressure increase the pore water pressure and amount of contraction	Mohanty and Patra (2015)
Drained test (densification index (DI) 0.02-0.96)	Paste deposition	For DI>0.1, shows strong post peak strain softening and pre peak dilative response (SS-D) For DI<0.1 exhibit strain hardening with contractive volumetric response (SS-C)	Zhang et al.(2018)
Undrained test (DI 0.06-1)	Paste deposition	Observed non flow behavior	
Consolidated drained (RD 95%, 70%)	Static compaction technique	Dense specimen shows dilative behaviour under all confining pressure. Coarse ash material have high strength parameter than sand because of the interlocking between the irregular shaped coarse ash particles.	Jakka et al.(2010)
Consolidated undrained RD 95%, 70%)	Static compaction technique	Loose ash specimen develops +ve pore water pressure and dense specimen develops -ve pore water pressure in undrained test.	

Direct shear (loose dry condition)	Static compaction technique	In loose dry condition shear strength of fly ash is due to the frictional component and its cohesive component is zero.	Sridharan(1998), Prakash and Sridharan (2009)
Direct shear (loose saturated condition)	Static compaction technique	Fly ash under loose saturated conditions have reduced frictional value compared to dry conditions.	
Direct shear (Compacted)	Static compaction technique	Fly ash in the compacted condition is partially saturated with 78-88% degree of saturation. there is a increase in frictional angle due to the increase in density.	

3.10 Compressibility

Consolidation characteristics of coal ashes depend on the degree of saturation, compaction density, pozzolanic activity and self-hardening properties (Moghal and Sivapullaiah 2011).Mohanty and Patra (2015) conducted 1D consolidation test on Panki and Panipat pond ash, considering different parameters like relative density, degree of saturation, self-hardening properties and pozzolanic activity on the compressibility of pond ash and found Cc as 0.083,0.132 for Panki PA at a RD of50% and 65% respectively.With age, compressibility reduces significantly, which results in a reduction in the time rate of consolidation. Jakka et al.(2010) observedthat fine pond ash in a loose state exhibits very high rate of compressibility. Further it was found that 90% of the total settlement happened within 15 sec of the application of load for all types of ash, which indicates that the rate of consolidation is more. The high rate of compressibility and spherical nature of fine ash particles may lead to liquefaction when subjected to undrained shearing. Madyannapu et al.(2008) conducted a series of prototype and small scale consolidation and collapsibility tests on sedimented FA deposits and observed that ash deposits show a pseudo-over consolidation behavior, which may be attributed to the latent pozzolanic activity of flyash due to the presence of free lime or calcium oxide. With the increase in the average effective stress compression index of sedimented fly ash tends to increase. The increase is found to be sharp at low stress level and gradual at high stress. Amongthe coal ashes , pond ash and bottom ash possess a higher c_v value which is attributed to their coarser size (Prakash and Sridharan 2009). With the application of load, sedimented pond ash shows a decreasing trend of $c_{v,}$ indicating a reduction in compressibility (Mishra and Das 2015). The Cc for pond ash in the loosest state havea range from 0.057-0.132, and at densest state range rages from 0.051-0.169.(Jakka et al.2010, Mohanty and Patra 2015)

3.11 Critical state soil parameters

Soil mechanical behavior can be modeled using the critical state soil mechanics (CSSM) approach. Many researchers have found its applicability to sand and silty sand (Li Dafalias 2000). Limited information has been reported on the critical state parameters of coal ash material. Zhang et al.(2018) studied the applicability of the CSSM framework for pond ash's behavior in both drained and undrained conditions. Zhang et al.(2018) used a concept of densification index (DI) where

$$\mathrm{DI}=\frac{0,p-0}{0,p-0,o}$$

e_0 = void ratio at p_0',

$e_{0,up}$ and $e_{0,low}$ = void ratio on upper and lower bound isotropic consolidation line (ICL) at the same p_0'

In the q-p' plane CSL is a straight line passing through origin with a critical state stress ratio (M) of 1.357. In the e-log (p') space, CSL is approximated as a straight line with a slight curvature. Zhang et al.(2018) concluded that the critical state soil mechanics can be used in coal ash material. Like sand, the pond ash's state parameter Ψ_0 can be considered an important predictor for stress-strain and volume change behaviour. More study are needed to understand the critical state coal ash parameters.

4 Conclusion

In this paper, an extensive review on geotechnical aspect of Indian coal ash was presented. The review includes recent ash pond breaches in India and it's causes, an extensive review on the geotechnical characteristics of Indian coal ashes along with an insight in to the applicability of CSSM concept to simulate the pond ash behaviour, which is summarize as follows:

1. Ash pond breaches occur due to the heavy rainfall, substandard construction of ash dyke, bursting of pipe lines carrying ash slurry.
2. Indian coal ash mostly contain quartz, feldspar, mullite, hematite, magnetite etc.
3. Fly ash possess cenospheres and plerospheres , where as bottom ash posses coarser, irregular, large size particles.
4. Coal as mostly consists of major compound like SiO_2 (23% to 75%), Al_2O_3(11% to 54%), Fe_2O_3 (3% to 35%) and less amount of CaO, SO_3,K_2O, TiO_2, MgO, P_2O_5, Na_2O, SrO.
5. FA consists of silt size - clay size fraction, PA particles lies in the range of silt size to sand and BA have coarse grained, consists of sand-silt size fraction.
6. Sp. gravity of pond ash have values in the range of 1.91-2.338, fly ash in the range of 1.86-2.62 and bottom ash is in the range of 1.66-2.19.
7. Bottom ash has a coefficient of permeability in the range of clean sand/gravel mixture. (1.34×10^{-4} 5.42×10^{-4} cm/sec)
8. Indian coal ashes exhibit compaction behavior similar to sand or sandy gravel. OMC has a range of 11.6 %-62% and MDD has a range of 7.57-30.50 kN/m^3.
9. Pond ash and bottom ash have higher C_c value than fly ash.
10. Critical state soil mechanics can be used to simulate the behaviour of pond ash.

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