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Fly ash characterization with reference to geotechnical applications

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Abstract

Thermal power stations use pulverized coal as fuel. They produce enormous quantities of coal ash as a by-product of combustion. This calls for the development of strategies to encourage and establish technological concepts which will ensure consumption of fly ash in bulk. Among the various uses of fly ash, its bulk utilization is possible only in geotechnical engineering applications. This necessitates characterization of the fly ash with reference to geotechnical applications. This paper presents a review of such studies carried out. The results show that fly ash is a freely draining material with angle of internal friction of more than 30 degrees. The specific gravity is lower leading to lower unit weights resulting in lower earth pressures. It can be summarized that fly ash (with some modifications/additives, if required) can be effectively utilized in geotechnical applications.

Keywords: Nonplastic, consolidation, shear strength.

1. Introduction

Coal-based thermal power plants all over the world face serious problems of handling and disposal of the ash produced. The high ash content (30–50%) of the coal in India makes this problem complex. At present, about 80 thermal power stations produce nearly 100 million tonnes of coal ash per annum. Safe disposal of the ash without adversely affecting the environment and the large storage area required are major concerns. Hence attempts are being made to utilize the ash rather than dump it. The coal ash can be utilized in bulk only in geotechnical engineering applications such as construction of embankments, as a backfill material, as a sub-base material, etc. For this, an in-depth understanding of the physical and chemical properties, and engineering and leaching behavior are required. This paper reports the work carried out in this context elsewhere as well as at the Indian Institute of Science, Bangalore (IISc).

2. Physical properties

Physical properties help in classifying the coal ashes for engineering purposes and some are related to engineering properties. The properties discussed are specific gravity, grain size distribution, index properties, free swell index and specific surface as well as classification.

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2.1. *Specific gravity*

Specific gravity is one of the important physical properties needed for the use of coal ashes for geotechnical and other applications. In general, the specific gravity of coal ashes lies around 2.0 but can vary to a large extent (1.6 to 3.1) [1]. Because of the generally low value for the specific gravity of coal ash compared to soils, ash fills tend to result in low dry densities. The reduction in unit weight is of advantage in the case of its use as a backfill material for retaining walls since the pressure exerted on the retaining structure as well as the foundation structure will be less. The other application areas include embankments especially on weak foundation soils, reclamation of low-lying areas, etc. The variation of specific gravity of the coal ash is the result of a combination of many factors such as gradation, particle shape and chemical composition [2]. It is known that coal ash comprises mostly glassy cenospheres and some solid spheres [3]. The reason for a low specific gravity could either be due to the presence of large number of hollow cenospheres from which the entrapped air cannot be removed, or the variation in the chemical composition, in particular iron content, or both.

The investigations show that the specific gravity generally lies between 1.46 and 2.66 [4]. In most of the cases, fly ash will have higher specific gravity compared to pond and bottom ashes of the same locality. When the particles are crushed, they show a higher specific gravity compared to the uncrushed portion of the same material.

2.2. *Grain size distribution*

Grain size distribution indicates if a material is well graded, poorly graded, fine or coarse, etc. and also helps in classifying the coal ashes. Coal ashes are predominantly silt sized with some sand-size fraction. Leonards and Bailey [5] have reported the range of gradation for fly and bottom ashes which can be classified as silty sands or sandy silts.

The extensive investigation carried out on Indian coal ashes [4, 6, 7] demonstrates that the fly ashes consist predominantly of silt-size fraction with some clay-size fraction. The pond ashes consist of silt-size fraction with some sand-size fraction. The bottom ashes are coarser particles consisting predominantly of sand-size fraction with some silt-size fraction. Based on the grain-size distribution, the coal ashes can be classified as sandy silt to silty sand. They are poorly graded with coefficient of curvature ranging between 0.61 and 3.70. The coefficient of uniformity is in the range of 1.59–14.0.

2.3. *Index properties*

Index properties are extensively used in geotechnical engineering practice. Among them, liquid limit is an important physical property for use in classification and for correlations with engineering properties. While a number studies have been made on the liquid limit of fine-grained soils [8, 9] not much work has been done on coal ashes. Currently, two methods (Percussion cup and Fall cone methods) are popular for the determination of liquid limit of fine-grained soils. In the Percussion cup method it is very difficult to cut a groove in soils of low plasticity and the soils have tendency to slip rather than flow. Hence, this method is not suitable for fly ashes which are nonplastic in nature. Even in the Cone penetration method, there is a tendency for the fly ash in the cup to liquify at the surface. There is also a variation of water content in the cup with depth and it is very difficult to get a smooth level surface of the ash in the cup [9].

A new method of determining liquid limit called “Equilibrium water content under K_o stress method” [10] has been found to be effective for the determination of liquid limit of coal ashes. The proposed method is simple, reasonably error free, less time consuming and has good reproducibility. However, it is not suitable for class C fly ashes which gain strength with time.

The results obtained using the proposed method show that fly ashes have liquid limit water content ranging from 26 to 51%, 22 to 64% for pond ashes, and 45 to 104% for bottom ashes. The liquid limit values exhibited by coal ashes are not due to their plasticity characteristics but are due to their fabric and carbon content. All the coal ashes tested are nonplastic and hence plastic limit could not be determined. It was also not possible to carry out shrinkage limit tests since the ash pats crumbled upon drying. Since the amount of shrinkage is very less, the shrinkage limit will be quite high. Hence shrinkage will not be a constraint.

2.4. *Free swell index*

Free swell index in soil engineering serves as a tool to identify swelling soils. The free swell test method proposed by Holtz and Gibbs [11] to estimate the swell potential suffers from certain limitations. Sridharan *et al*. [12] modified the definition of free swell index itself to take care of the limitations. There is hardly any information on the free swell index of coal ashes in published literature. Hence, experiments were carried out to study the free swell index of coal ashes. The results indicate that 70% of the coal ashes show negative free swell index which is due to flocculation. Since the clay-size fraction in coal ashes is very less, the free swell index is negligible.

2.5. *Specific surface*

The study of specific surface of soils is widely recognized as a means to understand their physical and engineering behavior. Even though coal ashes are primarily silt/sand-sized particles and their specific surface is expected to be very low, results need be obtained for completeness and for use in certain cases. With this in mind, the surface area measurements were made using Desiccator method [13] and Blaines Air Permeability method.

The specific surface obtained using Dessiccator method ranges between 107 and 4560 m^2/kg and from 89 to 530 m^2/kg using Blaines Air Permeability method. These values are quite low compared to those for kaolinite (10000–20000 m^2/kg).

2.6. *Classification*

For an effective and efficient use of coal ashes in geotechnical engineering practice, their classification from geotechnical engineering point of view is important. While a number of studies have been made on the physical and engineering properties of coal ashes [4, 6, 7] and their utilization in geotechnical engineering practice [5, 14, 15], no information is

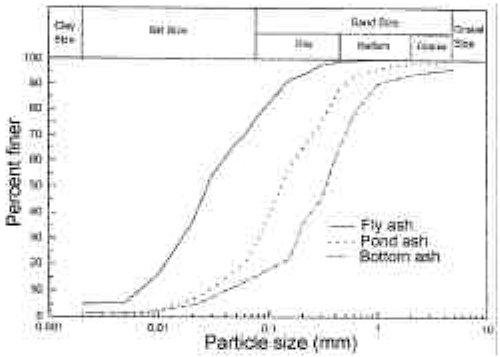

FIG. 1. Average particle size distribution.

available with respect to their classification. Based on the results obtained at IISc, the Indian coal ashes are classified using different classification systems keeping in mind their potential use in geotechnical applications.

Figure 1 presents the average grain size distribution curves for the fly pond ash and bottom ashes. Table I presents the physical, index and other properties for some Indian coal ashes. Table II presents the classification of some of the ashes using different classification

Table I
Physical, index and other properties of Indian coal ashes

Sl no.	Material	G	W_L (%)	W_L (%) (normalized)	% Passing through 75 *m* sieve	Group index	C_u	C_c
1.	Raichur							
	PA	1.93	50.5	36.8	16.8	0	9.00	1.25
2.	Korba							
	FA	1.98	37.8	28.2	72.2	7	6.00	1.14
	PA	1.91	60.0	43.2	15.0	0	3.60	1.80
	BA	2.15	77.0	62.5	8.6	0	4.70	2.10
3.	Vijayawada							
	FA	1.95	32.1	23.6	76.7	8	5.70	0.61
	PA	2.01	56.5	42.8	29.5	0	3.00	0.79
	BA	1.82	53.5	36.7	6.0	0	6.55	1.36
4.	Badarpur							
	FA	1.97	38.7	28.8	61.6	5	5.50	2.47
	PA	2.00	64.4	48.6	25.6	0	9.40	1.64
	BA	1.95	47.4	34.9	13.4	0	9.09	1.03
5.	Ramagundam							
	FA	2.18	39.2	32.3	92.5	8	1.59	1.09
	PA	2.15	29.9	48.6	2.2	0	3.37	1.41
	BA	2.08	65.1	51.1	14.0	0	8.02	1.60
6.	Neyveli							
	FA	2.55	60.4	49.3	73.4	9	3.16	1.04
	PA	2.50	49.9	47.1	16.4	0	9.67	1.93
	BA	2.08	104.1	81.7	8.5	0	5.20	2.05

FA: Fly ash; PA: Pond ash; BA: Bottom ash; G: Specific gravity; w_L: Liquid limit; C_c: Coefficient of curvature; and C_u: Coefficient of uniformity. All coal ashes are nonplastic.

Table II
Classification of coal ashes under different systems

Sl no.	Material	Clay	MIT classification							Classification as per			
			Silt size (%)			Sand size (%)			Gravel	Textural	PRA	Unified	IS
		Size (%)	F	M	C	F	M	C	Size (%)				
1.	Raichur												
	PA	1	0	5	8	32	36	13	5	Sand	A-2–4	SM	SM
2.	Rae Bareli												
	FA	1	5	28	32	26	7	1	0	Silty loam	A-4	ML	ML
	PA	1	1	9	25	58	7	0	0	Sandy loam	A-4	SM	SM
	BA	0	0	2	9	13	59	16	0	Sand	A-2–5	SM	SM
3.	Korba												
	FA	3	10	21	32	30	4	0	0	Silty loam	A-4	ML	ML
	PA	1	0	5	5	72	14	3	0	Sand	A-2–5	SM	SM
	BA	1	0	2	4	20	61	11	1	Sand	A-2–5	SP–SM	SP–SM
4.	Neyveli												
	FA	10	0	47	23	23	4	0	0	Silty loam	A-5	ML	ML
	PA	2	0	0	25	25	49	8	3	Sand	A-2–5	SM	SM
	BA	3	0	0	9	9	54	29	0	Sand	A-2–5	SP–SM	SP–SM

FA: Fly ash; PA: Pond ash; BA: Bottom ash; F: Fine; M, Medium and C: Coarse.

systems. Table III summarizes the classifications made. Based on the classification, it can be said that Indian coal ashes can be used beneficially in most of the geotechnical applications. In these tables, the normalized water content refers to the water content multiplied by the specific gravity of the coal ash divided by 2.65, the specific gravity of most of the soils. This normalization is done in order to make the values comparable with reference to soils since the specific gravity of coal ashes varies over a wide range.

3. Chemical properties

The chemical properties of the coal ashes greatly influence the environmental impacts that may arise out of their use/disposal as well as their engineering properties. The adverse impacts include contamination of surface and subsurface water with toxic heavy metals present in the coal ashes, loss of soil fertility around the plant sites, etc. Hence this calls for a detailed study of their chemical composition, morphological studies, pH, total soluble solids, etc.

Table III
Classification range of coal ashes

Sl no.	Ash type	Classification as per different systems				Group index	C_u	C_c
		Unified	IS	PRA	Textural			
1.	Fly ash	ML	MI–ML	A-4–A-5	Silty loam to sandy loam	5–9	1.59–6.00	0.61–2.47
2.	Pond ash	SM–SP	SM–SP	A-2–4–A-4	Sandy loam to sand	0–3	2.96–9.67	0.79–1.93
3.	Bottom ash	SW–SM	SW–SM	A-2–4–A-4	Sandy loam to sand	0	4.70–14.00	1.03–3.70

3.1. *Chemical composition*

Chemical composition suggests the possible applications for coal ash. Roode [16] reported that loss on ignition is generally equal to the carbon content. Throne and Watt [17] observed that the amount of SiO_2 or $SiO_2 + Al_2O_3$ in fly ash influences the pozzolonic activity. Minnick [18] has reported that a relatively high percentage of carbon decreases the pozzolonic activity.

The investigations carried out on Indian fly ashes show that all the fly ashes contain silica, alumina, iron oxide and calcium oxide [19]. The silica content in fly ashes is between 38 and 63%, 37 and 75% in pond ashes, and 27 and 73% in bottom ashes. The alumina content ranges between 27 and 44% for fly ashes, 11 and 53% for pond ashes and 13 and 27% for bottom ashes. The calcium oxide is in the range of 0 to 8% for fly ashes, 0.2 to 0.6% for pond ashes and 0 to 0.8% for bottom ashes. It is found that all the Indian coal ashes satisfy the chemical requirements for use as a pozzolona. According to ASTM classification, only Neyveli fly ash can be classified as Class C fly ash and all other coal ashes fall under Class F.

3.2. *X-ray diffraction*

X-ray diffraction studies are carried out primarily to identify the mineral phases. The studies carried out [20, 21] indicate that coal ashes predominantly consist of quartz and feldspar minerals. Sahu [22] reported that the nature and properties of the minerals mainly depend upon the source of coal. The process of ashification in turn controls the grain fusion, grain morphology as well as crystal growth.

The studies carried out at IISc reveal that the major mineral found in coal ashes is quartz with lesser proportions of feldspars, carbonates and chlorites. The coal ashes exhibit both crystalline and amorphous phases. The range of chemical composition of Indian coal ashes together with that for soil (for comparison purposes) is reported in Table IV.

3.3. *Scanning electron microscope studies*

SEM studies carried out to have a closer view of the individual particles of coal ashes show that fly ashes are finer particles compared to bottom ashes [20]. Pond ashes consist of both

Table IV
Range of chemical composition of Indian coal ashes and soils

Compounds	Fly ash	Pond ash	Bottom ash	Soils
SiO_2	38–63	37.7–75.1	23–73	43–61
Al_2O_3	27–44	11.7–53.3	13–26.7	12–39
TiO_2	0.4–1.8	0.2–1.4	0.2–1.8	0.2–2
Fe_2O_3	3.3–6.4	3.5–34.6	4–10.9	1–14
MnO	0–0.5	bd–0.6	bd–0.3	0–0.1
MgO	0.01–0.5	0.1–0.8	0.1–0.7	0.2–3.0
CaO	0.2–8	0.2–0.6	0.1–0.8	0–7
K_2O	0.04–0.9	0.1–0.7	bd–0.56	0.3–2
Na_2O	0.07–0.43	0.05–0.31	bd–0.3	0.2–3
LOI	0.2–3.4	0.01–20.9	0.61–51.6	5–16

bd: below detection; LOI: loss on ignition.

finer and coarser particles. Investigations at IISc show that the coal ash particles are generally cenospheres leading to low values for specific gravity [4]. They also confirm that fly ash particles are finer compared to bottom ash particles and the pond ash particles are sized in between fly and bottom ashes.

3.4. *pH*

In general, fly ash can be classified as an amorphous ferro-alumino silicate mineral. The amorphous iron aluminium oxides as well as manganese oxides present on the surface of fly ash particles act as a sink, adsorbing the trace elements [23]. It is this quantity of trace element which is available for leaching. The degree of solubility of these oxide sinks determines the release of the elements associated with them into the aqueous medium. The pH of the aqueous medium affects the solubility of these oxides and hence their physico-chemical characteristics [24]. Further, the mobilization of trace elements in aqueous medium is often regulated by the solubility of hydroxide and carbonate salts [25] which also depends on the pH of the aqueous media.

The investigations carried on Indian coal ashes at IISc show that fly ash has higher pH values compared to pond and bottom ashes. The fly ash with higher free lime and alkaline oxides exhibits higher pH values. Since all the coal ashes tested are nearly alkaline, they can be used in reinforced cement concrete which will be safe against corrosion.

3.5. *Total soluble solids*

The presence of soluble solids is an important aspect requiring examination since the water soluble solids greatly influence the engineering properties. Further, the solubility of nutrient elements such as calcium, magnesium, iron, sulphur, phosphorus, potassium and manganese affect the crop yield to a great extent [26].

The present investigations showed that the soluble solids range between 400 and 17600 ppm for fly ashes, 800 and 3600 ppm for pond ashes, and 1400 and 4100 ppm for bottom ashes.

3.6. *Lime reactivity*

The strength of fly ash generally improves with time due to pozzolanic reactions. Reactive silica and free lime contents are necessary for pozzolanic reactions to take place [17]. Lime reactivity is a property which depends on the proportion of reactive silica in coal ash. Prashanth [27] has reported the pozzolanic reactivity of some Indian fly ashes to range between 11.4 and 52.90 kg/cm^2.

Based on the work at IISc, the lime reactivity is found to be high for coal ashes with high silica content. It was also found to be high for fly ash compared to bottom and pond ashes. The results indicate that a high percentage of free lime in coal ash plays an important role in increasing its lime reactivity.

3.7. *Initial and final setting times*

Fly ash, a pozzolanic material, can be used in Portland pozzolana cement, as a partial replacement for cement in cement concrete. Its initial and final setting times are important in these applications. The initial/final setting times depend on the type and source of coal used, the method and degree of coal preparation, cleaning and pulverization, type and operation of the power plant, furnace temperatures, the efficiency of electrostatic precipitators and the collection and storage process adopted. Dhanabalan [28] reported that the initial setting time of Neyveli fly ash is between 8 and 15 minutes and the final setting time is between 13 and 24 minutes.

The investigations at IISc show that only Neyveli fly ash is class ‘C’ and all other coal ashes are class ‘F’. The initial and final setting times are applicable only to class ‘C’ fly ashes. Only the Neyveli fly ash is useful for partial replacement of cement in construction activities and manufacturing of bricks.

4. Compaction behavior

The density of coal ashes is an important parameter since it controls the strength, compressibility and permeability. Densification of ash improves the engineering properties. The compacted unit weight of the material depends on the amount and method of energy application, grain size distribution, plasticity characteristics and moisture content at compaction.

The variation of dry density with moisture content for fly ashes is less compared to that for a well-graded soil, both having the same median grain size [29]. The tendency for fly ash to be less sensitive to variation in moisture content than for soils could be explained by the higher air void content of fly ash. Soils normally have air void content ranging between 1 and 5% at maximum dry density, whereas fly ash contains 5 to 15%. The higher void content could tend to limit the build up of pore pressures during compaction, thus allowing the fly ash to be compacted over a larger range of water content [14]. Gray and Lin [2] have reported the engineering properties of compacted fly ash and have opined that properly compacted and stabilized fly ash has the requisite properties for use in load-bearing fills or highway sub-bases.

Compaction tests were carried out at IISc on coal ashes collected from 13 thermal power plants using standard Proctor effort. Figure 2 presents typical dry density versus water content relations obtained for fly ashes. It also contains the compaction curves presented by Joslin [30] for soils to serve as a comparison. These curves have four distinct points of dry density and water content. The first point corresponds to the density at air-dried condition. With the addition of water, the dry density decreases and reaches a minimum. The second point happens to be the minimum dry density. This phenomenon (bulking) is due to the capillary forces resisting the rearrangement of particles against the external compactive energy [31]. A further increase in the water content increases the density to its optimum value. This third point is the Proctor maximum dry density and optimum moisture content. The fourth point, which is the last one, corresponds to the density at almost saturation. The zero air void lines have been drawn for the extreme specific gravity values of 2.06 and 2.70.

To appreciate the real order of degree of compaction and corresponding water contents of different ashes with reference to soils, the compaction curves were plotted on a volume basis using void ratio (e) and volume water content (wG) [27]. Figure 3 presents typical plots of the same for fly ashes and soils. It can be seen that all the fly ashes (except Neyveli fly ash) fall between the curves for the soils and the zero air voids line is unique irrespective of

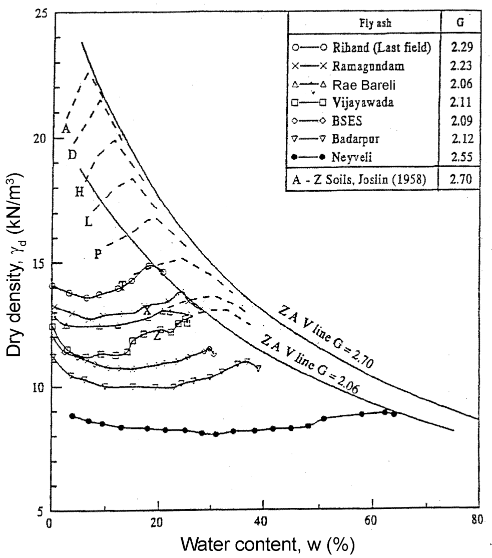

FIG. 2. Dry density vs water content relation for fly ashes and soils.

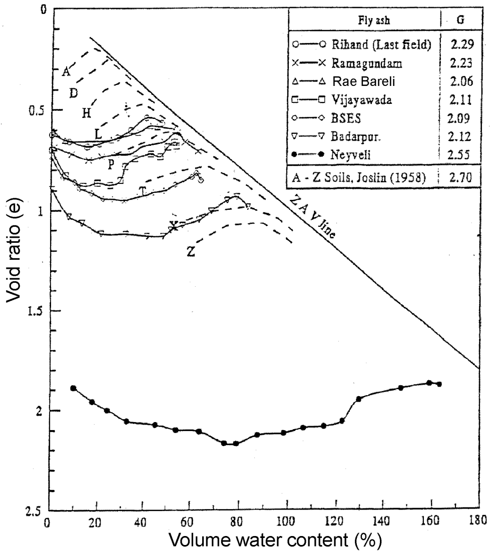

FIG. 3. Void ratio vs volume water content relation for fly ashes and soils.

specific gravity. This mode of presentation may not be preferred by the practicing engineers who are used to dry density–water content relations. Hence, the conventional dry density–water content relation is modified in terms of normalized dry density and normalized water content to account for the wide variation in the specific gravity of coal ashes.

Normalized dry density: $g_{\mathrm{dn}} = g_{\mathrm{dm}}\{G_{\mathrm{std}}/G_m\}$

Normalized water content: $w_n = w_m\{G_m/G_{\mathrm{std}}\}$

where g_{dm} is the dry density of given material (coal ash), w_m, the water content corresponding to g_{dm}, G_m, the specific gravity of the given material (coal ash), and G_{std}, the standard value of specific gravity with respect to which the plots are normalized (2.65). (The value of 2.65 is chosen since it represents the specific gravity of most of the soils).

Figure 4 presents the normalized dry density versus normalized water content relationships for fly ashes. Table V shows the actual dry densities and corresponding water content as well as their normalized values obtained for some of the coal ashes tested. Figure 5 gives the maximum dry density versus optimum water content relations for different coal ashes and soils. Figure 6 presents the same data as the normalized maximum dry density versus normalized optimum water content. It can be seen that the points are scattered in Fig. 5 compared to Fig. 6. This means that but for the variation in specific gravity the compaction behavior of soils and coal ashes is almost the same.

Since the dry densities in coal ashes are less sensitive to compaction water content, the field compaction can be carried out at dry side of the optimum taking care of the dust problem. With good shearing resistance available even at low densities, field compaction need not be constrained to achieve maximum dry density rather taking care of the construction difficulties.

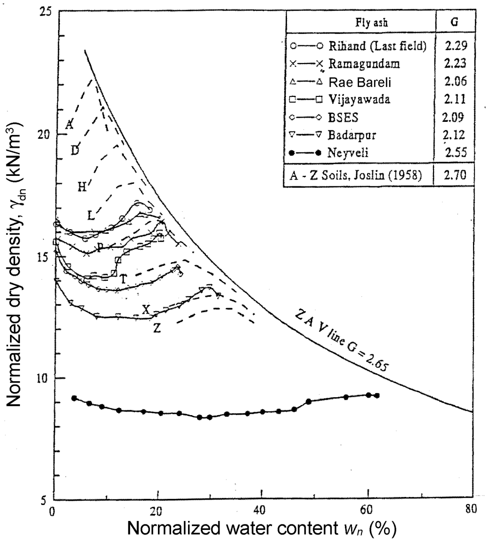

FIG. 4. Normalized dry density vs normalized water content for fly ashes and soils.

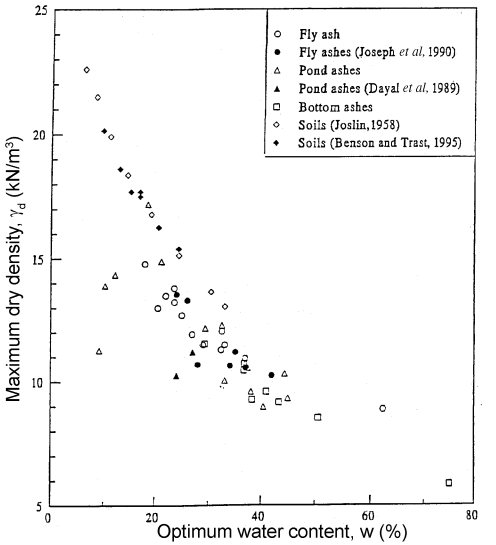

FIG. 5. Maximum dry density vs optimum water content for coal ashes and soils.

Table V
Compaction characteristics of Indian coal ashes

Sl no.	Material	G	Loose dry density	Compacted air-dried state		Lowest compacted state		Maximum density		Compacted saturated state	
			g_L (kN/m^3)	w(%)	g_d(kN/m^3)	w(%)	g_d(kN/m^3)	w (%)	g_d (kN/m^3)	w(%)	g_d(kN/m^3)
1.	Raichur										
	PA	2.01	9.7	1.0	10.8	24.0	09.7	33.0	10.1	36.0	10.0
				(0.7)	(14.2)	(18.2)	(12.8)	(25.0)	(13.3)	(27.3)	(13.2)
2.	Rae Bareli										
	FA	2.01	9.1	0.5	12.8	8.8	12.5	20.6	13.0	25.7	12.9
				(0.4)	(16.5)	(6.9)	(16.0)	(16.0)	(16.8)	(20.0)	(16.6)
	PA	2.10	9.4	1.8	10.2	24.4	09.6	39.9	10.2	42	10.1
				(1.4)	(12.9)	(19.3)	(12.1)	(31.7)	(12.9)	(33.3)	(12.7)
	BA	1.90	–	2.0	07.4	25.0	07.2	64.9	07.7	69.8	07.4
				(1.4)	(10.3)	(17.9)	(10.1)	(46.5)	(10.7)	(50.0)	(10.4)
3.	Neyveli										
	FA	2.55	7.7	3.9	08.8	30.9	08.0	62.3	08.9	63.9	08.9
				(3.8)	(9.2)	(29.8)	(8.4)	(59.9)	(9.2)	(61.5)	(9.2)
	PA	2.33	6.9	4.4	10.7	24.9	09.8	40.4	10.2	44.5	10.3
				(3.9)	(12.2)	(21.9)	(11.1)	(35.5)	(11.6)	(39.1)	(11.7)
	BA	2.05	5.9	1.0	06.8	47.9	05.6	75.1	05.8	80.8	06.1
				(0.8)	(8.9)	(37.0)	(7.3)	(58.1)	(7.6)	(62.5)	(7.9)
4.	Vijayawada										
	FA	2.11	9.6	0.1	12.4	06.4	11.2	25.0	12.7	25.4	12.5
				(0.1)	(15.6)	(5.1)	(14.1)	(19.9)	(16.0)	(20.2)	(15.8)
	PA	2.01	–	2.0	10.2	15.0	09.3	36.7	10.4	38.3	10.3
				(1.5)	(13.4)	(11.4)	(12.3)	(27.8)	(13.7)	(29.1)	(13.6)
	BA	2.04	8.3	0.1	09.5	18.4	08.5	38.3	09.3	42.3	09.1
				(0.1)	(12.4)	(14.2)	(11.1)	(29.5)	(12.0)	(32.6)	(11.9)

Figures in parenthesis present the normalized values. FA: fly ash; PA: pond ash; BA: bottom ash; G: Specific gravity.

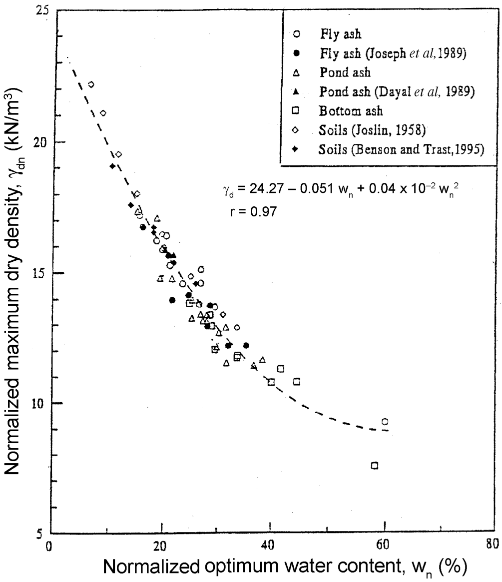

FIG. 6. Maximum dry density vs optimum water content based on normalized parameters for coal ashes and soils.

5. Strength behavior

An important engineering property that is necessary for using fly ash in many geotechnical applications is its strength. Leonards and Bailey [5] reported that the unconfined compressive strength values for fine ash are higher than those for the coarser ash specimens. Yudbir and Honjo [32] find that the free lime content of fly ash contributes to self-hardening. Sherwood and Ryley [9] reported that the fraction of lime, present as free lime in the form of calcium oxide or calcium hydroxide, controls self-hardening characteristics of fly ashes. Digioia and Nuzzo [33] indicated that age hardening can be best correlated with the amount of free lime present in the fly ash. Singh [34] studied the unconfined compressive strength of fly ashes as a function of free lime present in them.

Singh and Panda [35] performed shear strength tests on freshly compacted fly ash specimens at various water contents and concluded that most of the shear strength is due to internal friction. Indraratna *et al.* [36] compared cohesion intercept and angle of shearing resistance of saturated and unsaturated fresh fly ash specimens and reported complete loss of cohesion owing to full saturation and no change in the angle of shearing resistance. Martin *et al.* [37] state that fly ash in a moist but unsaturated condition displays an apparent cohesion due to tensile stress of retained capillary water but this cannot be relied upon for long-term stability and conclude that the strength property of major interest is the angle of shearing resistance. Many other research workers [38, 39] have conducted consolidated drained or undrained tests with pore water pressure measurements and reported the mean value of angle of shearing resistance as 34° (ranged from 29° to 40°).

Table VI(a)
Strength parameters from direct shear tests (Peak values)

Material	Condition	f_p (degrees)	c_p (kg/cm^2)
Fly ash	Loose dry	29–36	–
Pond ash	Loose dry	29–34	–
Bottom ash	Loose dry	32–34	–
Fly ash	Loose saturated	27–37	–
Pond ash	Loose saturated	25–40	–
Bottom ash	Loose saturated	30–37	–
Fly ash	Compacted	28–42	0.1–0.4
Pond ash	Compacted	29–38	0.5–0.16
Bottom ash	Compacted	31–37	0.1–0.2
Fly ash	Compacted and saturated	28–41	–
Pond ash	Compacted and saturated	29–36	–
Bottom ash	Compacted and saturated	30–37	–

Table VI(b)
Undrained strength parameters from triaxial tests (Standard Proctor optimum)

Material	Condition	f_{cu} (degrees)	c_{cu} (kPa)
Fly ash	Compacted and saturated	20–41	0
Pond ash		25–34	0–56
Bottom ash		24–35	0–27

Table VI(c)
Effective strength parameters from triaxial tests (Standard Proctor optimum)

Material	Condition	f' (degrees)	c' (kPa)
Fly ash	Compacted and saturated	26–39	16–96
Pond ash		28–36	28–101
Bottom ash		24–35	28–55

Table VI(d)
Drained strength parameters from triaxial tests

Material	Condition	f_{cd} (degrees)	C_{cd} (kPa)
Fly ash	Compacted	33–37	20–93
Fly ash	Compacted and saturated	33–43	0

Table VII
Recommended ratios for the angle of internal friction

Material	f_l/f_{ar}	f'(degrees)
Pond ash	0.9	32–35
Pond ash	0.85	35–40
Sand	1.1	32–40
Quarry dust	0.9	40–45

f_l: angle of internal friction at loose state, and f_{ar}: angle of repose.

A detailed experimental study of the strength properties of coal ashes under as compacted and saturated state has been made at IISc. Tables VI and VII summarize the strength parameters obtained under different test conditions

5.1. *Angle of repose*

A simple time-saving experimental procedure has been developed to determine the angle of repose which can be used in the field to determine the angle of internal friction under loose and dry conditions. The recommended ratio of angle of internal friction to angle of repose to estimate the angle of internal friction under loose and dry conditions is given in Table VII [40].

5.2. *Effect of additives*

The strength increases on the addition of 1 to 2% gypsum with the optimum lime content of 4%. The addition of gypsum alone even up to 6% has no effect on Badarpur, Ghaziabad, Ramagundam and Neyveli fly ashes. Actually, the addition of gypsum alone decreases the strength with curing. The Neyveli fly ash, with gypsum as an additive up to 4%, with 28 days of curing gives no appreciable increase in strength. The optimum lime content of 4%

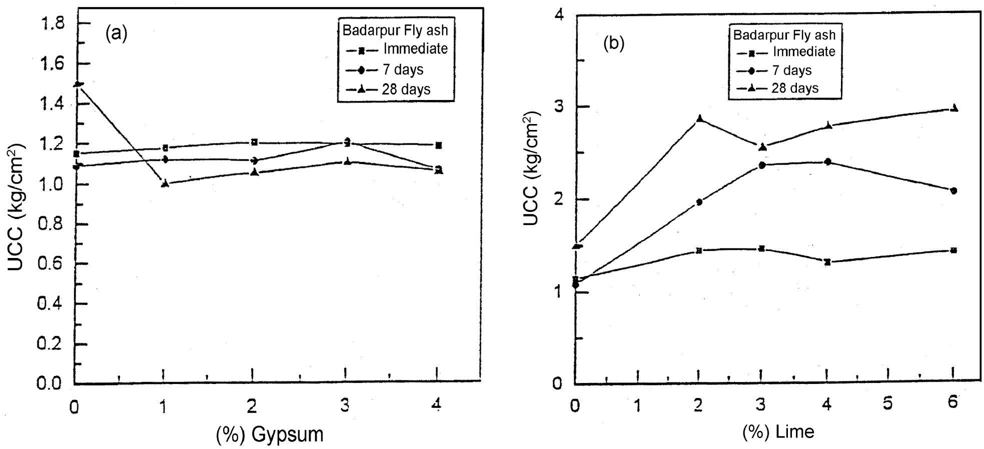

FIG. 7. Effect of (a) gypsum and curing, and (b) lime and curing on the unconfined compressive (UCC) strength of Badarpur fly ash.

with 4% optimum gypsum content gives maximum strength for fly ashes. The addition of gypsum alone has no effect, even if the ash contains both free lime and reactive silica. Figures 7 and 8 present the plots obtained for Badarpur fly ash for the strength gain as affected by the additives and curing.

6. California bearing ratio (CBR) behavior

A major application area for fly ash utilization is its use as a sub-base material in the construction of pavements. Among the various methods available for pavement design, the CBR method developed by Porter [41] and modified by the Corps of Engineers of the US Army continues to be used widely.

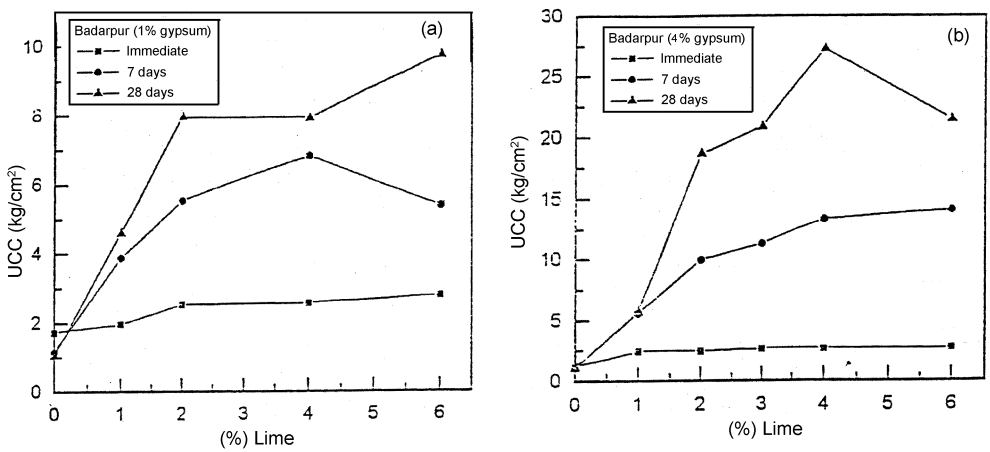

FIG. 8. Effect of lime and curing on the UCC of (a) Badarpur fly ash + 1% gypsum, and (b) Badarpur fly ash + 4% gypsum.

Toth *et al.* [14] reported the CBR values of coal ashes to vary between 6.8 and 13.5% for soaked condition, and 10.8 and 15.4% for unsoaked condition. Pond and bottom ashes show substantially higher CBR values. Poran and Ali [42] reported the CBR values of fly ashes mixed with lime and cement and consider the use of 5–10% of cement as an additive, to be better than lime. Indraratna *et al.* [36] conducted investigation on the engineering behavior of low carbon, pozzolanic fly ash and reported that CBR values at soaked condition are less than those at unsoaked condition and also concluded that properly compacted and cured fly ash samples give excellent CBR values. Sridharan *et al.* [7] reported the use of fly ash to improve the CBR of soils. The results clearly show that black cotton soil could be used as an additive to improve the CBR of fly ashes and fly ashes could be used to improve the CBR of black cotton soils. Pandian *et al.* [43] have also reported the beneficial use of fly ash to improve the CBR of soils. The usage of additives has an optimum level beyond which the value of CBR decreases. Jagapathi and Reddy [44] investigated the stabilized beach sand with lime and fly ash in the construction of low-cost pavements.

A simplified test for CBR was devised by Pandian *et al.* [45] to avoid large volume of material and effort involved in the conventional CBR test using a Proctor mould. The results show that it is possible to estimate the CBR (conventional) values using a Proctor mold and a plunger of 33.3 mm diameter and dividing the CBR (Proctor) values by a factor of 1.378 for fine-grained soils under unsoaked conditions. The CBR tests were conducted at IISc on a number of coal ashes using the method outlined [45]. Figure 9 shows typical stress vs penetration curves for Badarpur coal ashes tested under soaked and unsoaked conditions. The CBR values obtained at 2.5 mm penetration for some of the coal ashes are shown in Table VIII.

The results under unsoaked conditions show higher CBR values ranging between 8.4 and 20.6%. This is mainly because fly ash, a fine-grained material, when placed at 95% of Proctor maximum dry density and corresponding water content, exhibits capillary forces, in addition to friction resisting the penetration of the plunger and thus high values of CBR are obtained. On the contrary, when the same fly ash samples are soaked for 24 h maintaining the same placement conditions, they exhibited very low values of CBR. This can be attributed to the destruction of capillary forces under soaked conditions.

Murthy [46] and Sharma *et al.* [47] have reported the CBR values for fly ash with additives like lime, cement, sand and soils. It has to be remembered that the CBR values under soaked conditions would always give a highly conservative value for design. To overcome this problem, the samples could be placed at maximum Proctor's density and the water content could be maintained equal to saturation water content. A series of tests were conducted at IISc with fly ash–black cotton soil mixtures at maximum dry density and saturation water content.

Figure 10 shows the CBR values for various combinations of black cotton soil and Vindyanagar fly ash. It can be seen that the CBR values increase significantly with increase in percentage of black cotton soil up to 60% and a second peak is obtained with 80% of black cotton soil. It may be mentioned here that the Vindyanagar fly ash consists essentially of sandy silt-size fraction with a clay-size fraction of 12.9%. It is also a nonplastic material. With the addition of black cotton soil, the cohesion component increases giving higher CBR values.

Table VIII
CBR of Indian coal ashes

Sl no.	Material	CBR results (%)	
		Unsoaked condition	Soaked condition
1.	Raichur		
	PA	10.1	6.0
2.	Rae Bareli		
	FA	19.0	–
	PA	15.4	–
	BA	09.3	–
3.	Korba		
	FA	13.8	0.2
	PA	11.4	–
	BA	07.7	–
4.	Vijayawada		
	FA	20.6	0.2
	PA	10.1	–
	BA	06.8	–
5.	Badarpur		
	FA	11.3	–
	PA	11.1	4.4
	BA	11.3	8.5
6.	Neyveli		
	FA	15.0	–
	BA	8.4	3.5
7.	Ramagundam		
	FA	14.2	–
	PA	09.7	6.9
	BA	10.9	–
8.	BSES		
	FA	12.3	–

FA: fly ash; PA: pond ash; BA: bottom ash.

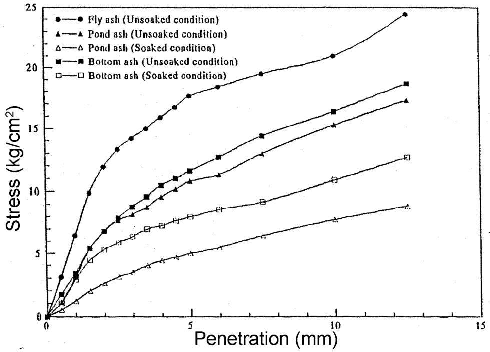

FIG. 9. Stress vs penetration of Badarpur coal ashes.

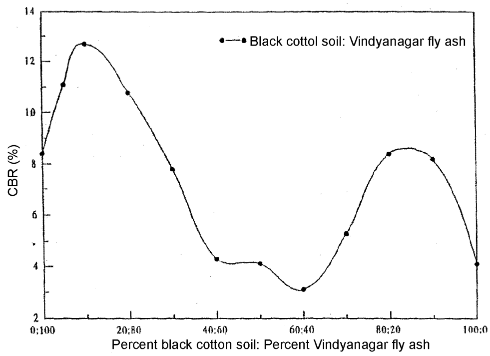

FIG. 10. CBR values of black cotton soil–Vindyanagar fly ash mixtures.

With further increase in the black cotton soil, the CBR value decreases because of the strength reduction due to reduction in fly ash decreasing the friction component. The second peak at 80% of black cotton soil can be attributed to the better packing of different fractions. It may be noted that while the water content was kept at saturation level, the density varies depending on the proportion of mixtures for a given compactive effort. The double peak in the CBR values is due to better packing of mixtures at constant compactive effort. Thus the results indicate that the CBR of Vindyanagar fly ash could be improved with a small percentage of BC soil. The CBR of BC soil could also be improved with small percentage of fly ash. It can be stated that the primary material (fly ash or BC soil) lacks certain fractions because of which it results in lower CBR values. The addition of such size fractions improves significantly the CBR values.

Figures 11 (a) and (b) show the variation of CBR values with D_{50} (mm) under unsoaked and soaked conditions, respectively. The CBR values for fly ashes are higher compared to

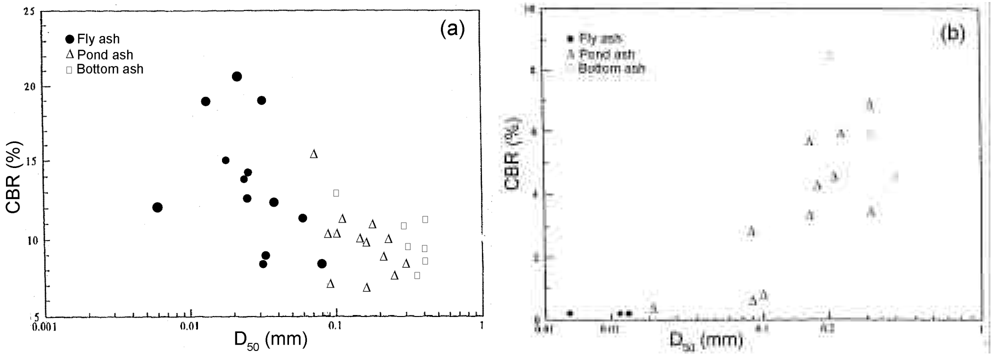

FIG. 11. CBR values vs D_{50} for (a) unsoaked, and (b) soaked conditions.

pond and bottom ashes under unsoaked conditions. Figure 11 clearly shows that as D_{50} increases the CBR value decreases. This can be attributed to the dominance of capillary forces in fly ashes against frictional resistance offered by the grains within. Pond and bottom ashes and the coarser materials exhibited less capillary forces and hence lower values for CBR.

In conclusion, it can be stated that fly ashes mixed with additives can be effectively used as sub-base materials even under soaked conditions. Pond and bottom ashes exhibit good CBR values both under soaked and unsoaked conditions without any additives.

7. Consolidation behavior

Compressibility characteristics of coal ash depends on its initial density, degree of saturation, self-hardening characteristics and pozzolanic activity. Partially saturated ashes are less compressible compared to fully saturated ones [32, 48]. To estimate the settlement of structures placed on fly ash embankments or fills, one-dimensional consolidation test results are required. Results of laboratory consolidation tests [49] on undisturbed samples from reclamation fills gave values of coefficient of consolidation, C_v, of the order of 0.57–1.14 cm^2/min (g_d in the range of 0.75–1.3 g/cm^3). Since primary consolidation for fly ash will be completed in about one minute, it is difficult to take the time-compression readings manually. Web and Hughes [50] used an automatic recording system for taking the consolidation readings at very small time intervals. They have reported C_v values of the order of 1.9–19 cm^2/min. This high rate of consolidation of fly ash is favorable particularly for its use in embankments and reclamation fills.

Figure 12(b) shows typical void ratio versus consolidation pressure curves for Rae Bareli coal ashes. The compressibility of fly ash is less than that of pond ash which is less than that of bottom ash. This can be confirmed from Table IX which presents the compression index of coal ashes. The compression index varies from 0.049 to 0.284 for fly ashes, 0.052 to 0.30 for pond ashes and 0.057 to 0.484 for bottom ashes. Compression index of fly ashes is lower than that for pond ash which is lower than that of bottom ash. Table X presents the coefficient of volume change of Indian coal ashes. The m_v value decreases with increase in stress level. The m_v varies from 0.004 to 0.039 for fly ashes, 0.005 to 0.052 for pond ashes and 0.003 to 0.069 for bottom ashes.

Table IX
Compression index of Indian coal ashes

Sl no.	Power plant	C_c Pressure (kg/cm^2) 0.5–1.0	1.0–2.0	2.0–4.0	4.0–8.0
1.	Farakka				
	FA	0.049	0.079	0.118	0.205
	PA	0.074	0.103	0.138	0.160
	BA	0.084	0.110	0.139	0.167
2.	Ramagundam				
	FA	0.064	0.080	0.154	0.284
	PA	0.097	0.108	0.153	0.187
	BA	0.123	0.156	0.171	0.193
3.	Vijayawada				
	FA	0.061	0.090	0.105	0.135
	PA	0.104	0.134	0.187	0.201
	BA	0.083	0.109	0.143	0.176
4.	Vindyanagar				
	FA	0.060	0.081	0.120	0.151
	BA	0.068	0.073	0.101	0.116
5.	Neyveli				
	FA	0.058	0.061	0.089	0.122
	PA	0.111	0.117	0.136	0.166
	BA	0.205	0.285	0.460	0.484
6.	Ghaziabad				
	FA	0.097	0.108	0.137	0.166
	BA	0.057	0.063	0.068	0.077
7.	Badarpur				
	FA	0.074	0.105	0.144	0.210
	PA	0.186	0.208	0.245	0.300
	BA	0.149	0.193	0.385	0.392
8.	Korba				
	FA	0.065	0.069	0.093	0.127
	PA	0.196	0.209	0.382	0.242
	BA	0.222	0.245	0.285	0.314
9.	Rae Bareli				
	FA	0.071	0.081	0.092	0.112
	PA	0.082	0.085	0.105	0.116
	BA	0.240	0.238	0.258	0.240
10.	Rihand				
	FA	0.129	0.162	0.173	0.222
	PA	0.085	0.100	0.112	0.137
	BA	0.178	0.093	0.122	0.236
11.	Kahalgaon				
	FA	0.062	0.083	0.111	0.139
	BA	0.069	0.137	0.241	0.332

Table X
Coefficient of volume change (m_v) of Indian coal ashes

Sl no.	Power plant	m_v(cm^2/kg) Pressure (kg/cm^2) 0.5–1.0	1.0–2.0	2.0–4.0	4.0–8.0
1.	Farakka				
	FA	0.015	0.012	0.009	0.008
	PA	0.026	0.018	0.012	0.007
	BA	0.020	0.013	0.009	0.005
2.	Ramagundam				
	FA	0.021	0.014	0.013	0.012
	PA	0.027	0.015	0.011	0.007
	BA	0.033	0.021	0.012	0.007
3.	Vijayawada				
	FA	0.022	0.016	0.010	0.006
	PA	0.032	0.021	0.015	0.008
	BA	0.024	0.016	0.011	0.007
4.	Vindyanagar				
	FA	0.022	0.015	0.011	0.007
	BA	0.023	0.012	0.009	0.005
5.	Neyveli				
	FA	0.016	0.008	0.006	0.004
	PA	0.030	0.016	0.009	0.006
	BA	0.041	0.028	0.023	0.013
6.	Ghaziabad				
	FA	0.036	0.021	0.013	0.008
	BA	0.018	0.010	0.005	0.003
7.	Badarpur				
	FA	0.024	0.017	0.012	0.009
	PA	0.052	0.030	0.018	0.010
	BA	0.042	0.028	0.028	0.015
8.	Korba				
	FA	0.022	0.012	0.008	0.005
	PA	0.050	0.027	0.026	0.008
	BA	0.059	0.033	0.020	0.012
9.	Rae Bareli				
	FA	0.032	0.019	0.011	0.007
	PA	0.026	0.014	0.009	0.005
	BA	0.069	0.036	0.020	0.010
10.	Rihand				
	FA	0.039	0.025	0.014	0.014
	PA	0.033	0.024	0.014	0.014
	BA	0.046	0.012	0.008	0.008
11.	Kahalgaon				
	FA	0.021	0.014	0.010	0.010
	BA	0.019	0.019	0.017	0.017

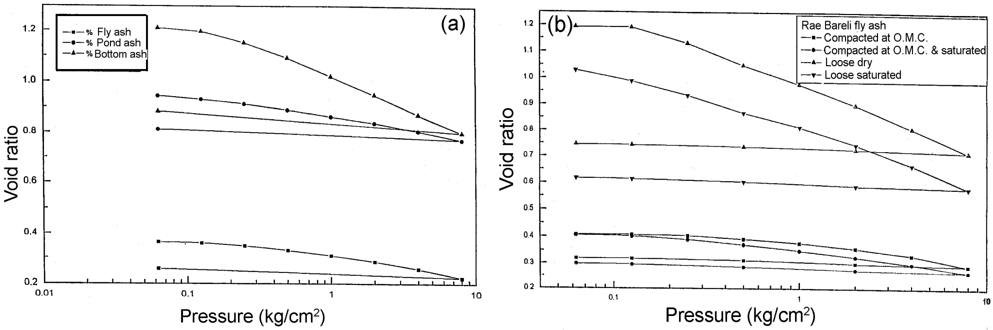

FIG. 12. Void ratio–pressure relationship for Rae Bareli (a) coal, and (b) fly ashes at different placement conditions.

Tables XI–XIII present the coefficient of consolidation (c_v) for fly, pond and bottom ashes, respectively, at different consolidation pressure ranges. The c_v varies from 0.694×10^3 to 7.641×10^{-3} cm^2/min for fly ashes, 1.76×10^{-5} to 4.90×10^{-4} cm^2/min for pond ashes and 0.46×10^{-4} to 2.01×10^{-3} cm^2/min for bottom ashes. For coal ashes the primary consolidation gets over within a very short interval of time. Figure 12(b) shows the void ratio consolidation plots obtained for Rae Bareli flyash at different placement conditions. Table XIV shows the compression index of fly ashes at different placement conditions. The C_c values vary from 0.146 to 0.676 at loose dry conditions, 0.110 to 0.691 at loose saturated condition, 0.068 to 0.301 for compacted at optimum moisture content (OMC) conditions, and 0.105 to 0.219 for compacted at OMC and inundated conditions. The compression index is less in the case of partially saturated ashes which is due to capillary forces. Upon inundation, the capillary forces vanish and hence the compressibility is more for saturated samples.

8. Permeability behavior

Permeability is an important parameter in the design of liners to contain leachate migration, dykes to predict the loss of water as well as the stability of slopes and as a sub-base material. The coefficient of permeability of ash depends upon the grain size, degree of compaction and

Table XI
Coefficient of consolidation (C_v) of fly ashes

Sl no.	Power plant	C_v(10^{-3}/kg) Pressure (kg/cm^2) 0.5–1.0	1.0–2.0	2.0–4.0	4.0–8.0
1.	Farakka	0.835	1.884	2.663	3.725
2.	Rama-gundam	2.304	1.839	1.793	2.951
3.	Vijayawada	2.136	2.170	3.254	4.117
4.	Vindyanagar	2.998	4.736	7.641	5.079
5.	Neyveli	0.987	2.158	2.398	2.711
6.	Ghaziabad	2.806	1.016	1.584	1.820
7.	Badarpur	–	4.505	5.771	4.086
8.	Korba	3.098	4.125	2.906	1.183
9.	Rae Bareli	0.694	1.636	1.709	2.465

Table XII
Coefficient of consolidation (C_v) of pond ashes

Sl no.	Power plant	C_v (10^{-5} cm^2/min) Pressure (kg/cm^2) 0.0–0.0625	0.0625–0.125	0.125–0.25	0.25–0.50	0.50–1.00	1.0–2.0	2.00–4.00
1.	Raichur	–	3.42	1.76	1.69	8.17	3.44	1.84
2.	Rama-gundam	23.2	8.30	9.60	40.30	49.00	8.90	4.20
3.	Vijayawada	3.65	2.46	4.12	2.93	4.30	8.35	3.05
4.	Badarpur	33.4	2.80	12.40	7.42	9.25	2.99	2.62
5.	Korba	2.32	13.65	7.27	8.26	1.80	5.60	4.18

Table XIII
Coefficient of consolidation (C_v) of bottom ashes

Sl. no.	Power plant	C_v(10^{-4} cm^2/min) Pressure (kg/cm^2)						
		0.0–0.0625	0.0625–0.125	0.125–0.25	0.25–0.50	0.50–1.00	1.0–2.0	2.00–4.00
1.	Rae Bareli	1.67	2.46	0.44	2.73	1.12	0.52	0.63
2.	Rama-gundam	5.56	0.69	2.09	0.51	0.46	0.61	0.57
3.	Badarpur	20.1	5.70	6.03	1.18	0.43	0.86	1.19
4.	Korba	5.40	0.58	1.97	0.78	0.49	1.44	0.50

Table XIV
Compression index (C_c) of fly ashes at different placement conditions

Sl no.	Power plant	Compression index (C_c) Loose Dry	Loose Saturated	Compacted at OMC	Compacted at OMC and saturated
1.	Farakka	0.239	0.216	0.155	0.163
2.	Ramagundam	0.323	0.277	0.093	0.219
3.	Vijayawada	0.359	0.214	0.076	0.121
4.	Vindyanagar	0.146	0.110	0.085	0.135
5.	Neyveli	0.515	0.626	0.086	0.105
6.	Ghaziabad	0.676	0.691	0.068	0.153
7.	Badarpur	0.409	0.266	0.301	0.178
8.	Korba	0.302	0.272	0.091	0.110
9.	Rae Bareli	0.306	0.276	0.115	0.103

pozzolanic activity [3, 51]. Table XV presents the permeability of some of the coal ashes studied. The permeability of fly ashes is in the range of 8×10^{-6} cm/s to 1.87×10^{-4} cm/s, 5×10^{-5} cm/s to 9.62×10^{-4} cm/s for pond ashes, and 9.9×10^{-5} cm/s to 7×10^{-4} cm/s for bottom ashes. It can be seen that the Ghaziabad fly ash has the lowest permeability due to its fine nature. It can be seen that Neyveli fly ash has lower permeability values since it contains more free calcium resulting in cementation leading to reduction in permeability. The bottom and pond ashes being coarse grained and devoid of fines compared to fly ash have a higher value for permeability coefficient. The consolidation pressure has negligible effect on the permeability.

9. Pinhole studies

A number of studies have been made on the dispersive behavior of soils [52, 53] but none with reference to coal ashes. A detailed study of the dispersive behavior of coal ashes was carried out at IISc using the existing methods. A new method has also been proposed keeping in mind the special requirements of coal ash.

9.1. *Double hydrometer test*

The dispersion ratio (double hydrometer) test is an indicator test developed [54] to evaluate the susceptibility of soils to erosion. In this, the grain size distribution curves are determined by hydrometer tests with and without chemical dispersant. The dispersion ratio is defined as the ratio of the per cent finer than 0.005 mm diameter measured without chemical dispersant to that measured with the chemical dispersant. The criteria for classification are:

Degree of dispersion (%)	Classification
Less than 35	Nondispersive
35 to 50	Moderately dispersive
50 to 75	High dispersive potential
Greater than 75	Extremely dispersive

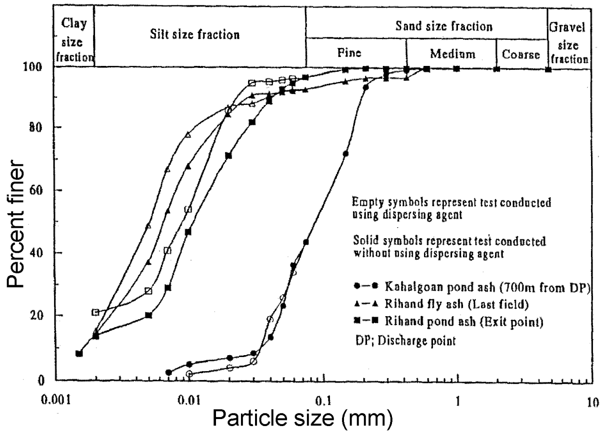

FIG. 13. Effect of dispersing agent on the particle size distribution of coal ashes.

This method is suitable for nonpozzolanic ashes (which do not produce cementitious compounds even upon the addition of lime), but not for self-pozzolanic ashes (which produce cementitious compounds and harden with time in the presence of water, without the addition of lime) and pozzolanic ashes (which produce cementitious compounds on the addition of lime).

Figure 13 shows the effect of dispersing agent on the particle size distribution curves of some coal ashes. From double hydrometer test, Rihand fly and pond ashes show high dispersive potential. Double hydrometer test is not suitable for Kahalgaon pond ash as it does not contain particle sizes finer than 0.005 mm.

10. Pinhole test

The pinhole test was developed for identification of dispersive soils by Sherard *et al.* [52] and modified by Schafer [55]. Here, distilled water is caused to flow through a 1/16th inch diameter pinhole made in a one-inch-long specimen compacted at maximum dry density and optimum water content. The classification of the ash is based on the appearance of the water, rate of flow and the final size of the specimen.

Table XVI presents the pinhole test results of coal ashes. Except for Neyveli fly ash, which is nondispersive due to self-pozzolanic property, all other fly ashes are highly dispersive in nature.

Despite being a nonplastic material, coal ash remains intact even after driving a hole inside the sample because of capillary forces. When water comes in contact with the sample during flow, the capillary forces vanish, the specimen collapses and the flow is not through the pinhole. Hence an alternative method has been proposed.

10.1. *New method to identify the dispersive behavior of ash (Turbidity test)*

This new method is proposed to identify the dispersiveness of ashes. The specimens were statically compacted to get a specimen of 7.62 cm height and 3.81 cm diameter. Proctor's maximum dry density and optimum water content was used to prepare the specimens. The

Table XV
Permeability of coal ashes

Sl. No.	Material	Permeability (10^{-4}) cm/s Pressure (kg/cm^2)							
		0	0.0625	0.125	0.25	0.50	1.00	2.00	4.00
1.	Rae Bareli								
	Fly ash	0.47	0.36	0.36	0.34	0.32	0.32	0.27	0.24
	Pond ash	1.21	1.06	1.00	0.86	0.81	0.70	0.55	0.50
	Bottom ash	4.46	4.31	4.01	3.87	3.49	2.95	2.45	2.40
2.	Korba								
	Fly ash	0.91	0.72	0.67	0.62	0.58	0.53	0.49	0.40
	Pond ash	2.96	2.86	2.86	2.83	2.80	2.72	2.35	1.59
	Bottom ash	3.20	2.87	2.78	2.56	2.51	2.28	1.84	1.58
3.	Vijayawada								
	Fly ash	0.34	0.32	0.32	0.32	0.30	0.30	0.30	0.28
	Pond ash	2.91	2.64	2.55	2.49	2.36	2.36	1.98	1.98
	Bottom ash	2.44	2.40	2.27	2.13	1.98	1.86	1.64	1.46
4.	Badarpur								
	Fly ash	1.87	1.87	1.83	1.83	1.80	1.77	1.54	1.25
	Pond ash	2.84	2.84	2.74	2.68	2.57	2.23	2.19	1.87
	Bottom ash	2.98	2.88	2.88	2.79	2.74	2.52	2.44	1.98
5	Ghaziabad								
	Fly ash	0.19	0.19	0.15	0.15	0.15	0.15	0.12	0.08
	Bottom ash	1.90	1.69	1.65	1.57	0.53	1.45	1.27	0.99
6.	Ramagundam								
	Fly ash	1.06	0.80	0.75	0.75	0.74	0.62	0.57	0.51
	Pond ash	7.08	6.73	6.42	6.42	6.01	6.01	5.63	5.07
	Bottom ash	4.40	4.29	3.94	3.63	3.51	3.51	2.98	2.86
7.	Neyveli								
	Fly ash	0.32	0.16	0.16	0.16	0.16	0.16	0.16	0.12
	Pond ash	3.53	3.31	2.90	2.71	2.54	2.21	2.14	1.92
	Bottom ash	6.18	6.18	6.18	6.18	5.66	5.42	5.20	5.00

specimens were cured in a dessiccator at 90–95% relative humidity and at a temperature of 27 ± 2°C. For lignite ashes, curing of one day is sufficient. For bituminous coal ashes, with additives of lime/cement, curing for 7 days is required for gaining strength. After curing, these samples were soaked in water for 6 h. If the sample collasped within 6 h after soaking, the ash is described as highly dispersive in nature. After 6 h, the water is stirred with a mechanical stirrer for a period of 2–3 h. If, during stirring, the sample either collapses or not with the water being turbid and distinctly dark, the ash is termed moderately dispersive in nature. If the sample does not collapse during stirring and the turbidity of the water is slightly dark or clear, the ash is considered as nondispersive. The test results obtained in this investigation are presented in Table XVII. The method can simulate different field conditions, and is simple and easy to perform. It is applicable to all types of ashes with and without additives.

Table XVI
Pinhole test results

Sl no.	Name	Fly ash	Pond ash	Bottom ash
1.	Vindyanagar	D1	D1	–
2.	Korba	D1	D1	–
3.	Vijayawada	D1	D1	D1
4.	BSES (Mumbai)	D1	D1	D1
5.	Ramagundam	D2	D1	D1
6.	Kahalgaon	D1	D1	D1
7.	Farakka	D1	D1	D1
8.	Rae Bareli	D2	D1	D1
9.	Badarpur	D1	D1	D1
10.	Ghaziabad	ND3	–	D1
11.	Neyveli	ND1	D1	D1
12.	Rihand	D1	D1	D1
13.	Raichur	–	D1	–

D1 and D2: Highly dispersive; ND3: Moderately dispersive: ND1: Nondispersive.

11. Leaching behavior

Depending on the sources of coals used in thermal power plants, fly ash may contain various toxic elements. Due to serious environmental problems involved, the leaching of these toxic elements from ash ponds is gaining considerable importance.

The review of literature reveals that the release of contaminants from fly ash and their subsequent influence on ground-water quality is governed by several factors including quality

Table XVII
Results based on the proposed method (Turbidity test)

Sl no.	Sample (fly ash)	Dispersive behavior after 1-day curing	Dispersive behavior after 7-day curing
1.	Badarpur + 2% lime	Highly dispersive	Nondispersive
2.	Badarpur + 4% lime	Highly dispersive	Nondispersive
3.	Badarpur + 6% lime	Highly dispersive	Highly dispersive
4.	Badarpur + 2% cement	Highly dispersive	Highly dispersive
5.	Badarpur + 4% cement	Highly dispersive	Highly dispersive
6.	Badarpur + 6% cement	Highly dispersive	Moderately dispersive
7.	Ghaziabad + 2% lime	Highly dispersive	Nondispersive
8.	Ghaziabad + 4% lime	Highly dispersive	Nondispersive
9.	Ghaziabad + 6% lime	Moderately dispersive	Moderately dispersive
10.	Ghaziabad + 2% cement	Moderately dispersive	Nondispersive
11.	Ghaziabad + 4% cement	Highly dispersive	Nondispersive
12.	Ghaziabad + 6% cement	Highly dispersive	Nondispersive
13.	Ramagundam + 2% lime	Highly dispersive	Nondispersive
14.	Ramagundam + 4% lime	Highly dispersive	Nondispersive
15.	Ramagundam + 2% cement	Nondispersive	Nondispersive
16.	Ramagundam + 4% cement	Nondispersive	Nondispersive
17.	Neyveli	Nondispersive	Nondispersive

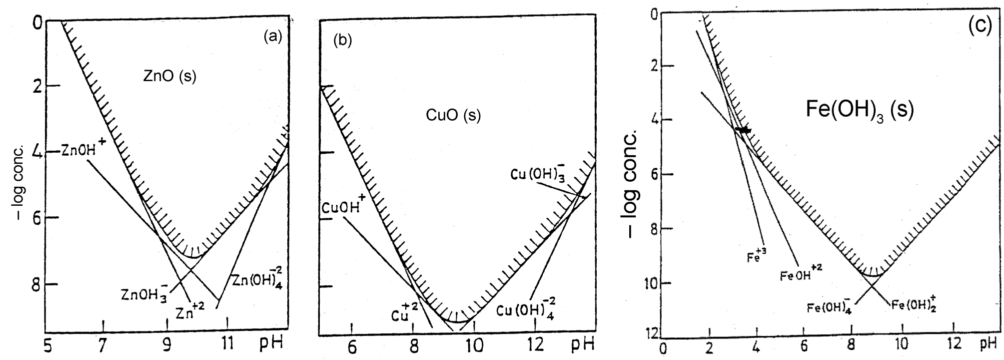

FIG. 14. Solubility of amorphous ZnO, CuO and $Fe(OH)_3$ with pH.

of coal, sources of water, pH, time, temperature, etc. The leachate characteristics are highly variable and even within a given landfill site, leachate quality varies over time and space [56]. Hydroxides and sulphides of metals often occur in amorphous and several crystalline modifications [57]. The solubility of amorphous Fe $(OH)_3$, ZnO and CuO with pH is shown in Fig. 14. It can be seen that there is a pH value at which the solubility is minimum. In highly alkaline or highly acidic regions, the solubility becomes larger. In natural water systems, the concentration of metal ions is controlled by the solubility of the metal carbonates. Theis and Wirth [23] have studied the sorptive behavior of trace metals on fly ash in aqueous systems. Dudas [58] has conducted a long-term leaching experiment to determine the release of ion and weathering characteristics of fly ash. Weng and Huang [59] have studied the treatment of industrial waste water containing heavy metals by fly ash and cement fixation. The fly ash has been demonstrated to be a potential heavy metal adsorption medium for industrial waste water [60]. Thus it can be seen that the release of metal ions from fly ash depends on its own characteristics (chemical composition, surface area, and cation exchange capacity), solution (permeant) characteristics (pH of the solution, valency and concentration of the ion), and other factors like duration of reaction of time, temperature, etc. The leaching characteristics of fly ash mainly depend on the amount of free lime present in it. The desorption of metal ions from fly ash also depends on the pH of the leachate.

The leaching characteristics of Neyveli and Badarpur fly ashes were studied using three methods, namely, (a) Accelerated process method [19], (b) Jar method [61] and (c) Oedometer method [62]. In the Accelerated process method, a known amount of fly ash was taken into conical flasks containing solutions of known pH and the samples were continuously agitated mechanically for the reactions to take place. Representative fractions of the supernatant solutions were taken out periodically and analyzed for different ions leached by fly ash. In the Jar method, a known weight of each fly ash was taken into a measuring jar and the measuring jar was filled with solutions of known pH. These samples were allowed to remain without any disturbance for the reactions to take place. Representative fractions of the solutions were taken out periodically and analyzed. In the Oedometer method, a known amount of fly ash was statically compacted and a solution of known pH was allowed to pass through the compacted sample in the upflow mode. The outflow was collected periodically and analyzed.

Neyveli and Badarpur fly ashes were chosen for the leaching study as they represent the extreme cases based on free lime content. The free lime content in the fly ash is the most likely dominant factor which changes the pH of the leaching solution. The Neyveli fly ash has 4.69% free lime and Badarpur 0.19%. It is known that each metal ion has its own pH range over which the metal hydroxide precipitation can occur and these ions have specific pH values for the completion of carbonate precipitation. The pH of the leaching solution against its initial pH value mainly depends on the free lime content present in the fly ash. Hydration and dissolution of calcium oxide present in the fly ash when it comes in contact with water will increase the pH value of the leaching solution. This increase in pH value is responsible for all possible mechanisms such as adsorption/desorption and precipitation/dissolution involved in the leaching of metals. Due to higher percentage of free lime in Neyveli fly ash, the equilibrium pH at the end of 72 h is high (more than 10.64). At this pH value (i.e. alkaline pH region), the concentration of most of the metal ions increases in the leaching solution due to the dissolution of these metal ions from their hydroxide and carbonate salts. This is the main reason for leaching of most of the trace elements from Neyveli fly ash. The metal ions of lead, zinc, cadmium, cobalt and manganese were leached out completely in the alkaline regions [62]. This is mainly due to the pH of the solution which is outside the pH range required for the formation of these metal hydroxides and for the completion of carbonate precipitation as well as the hydrated size of the metal ions. If the hydrated size of the metal ions is smaller and/or the pH value is higher, the complete leaching of metal ions from fly ash is possible.

Badarpur fly ash has less free lime which is not enough to increase the equilibrium pH values. Hence, the equilibrium pH at the end of 72 h is also almost the same as the initial pH. The pH values are responsible for the changes in the mechanisms involved in the leaching of metal ions from this fly ash. From Badarpur fly ash, leaching of most of the metals decreases with increase in the initial pH values.

Precipitation of the ions on to the surface of the fly ash particles occurs at pH values of 0.5 to 1.0 unit lower than that required for the precipitation of the same in the solution. This is because the pH value at the surface of the particle is 0.5 to 1.0 unit higher than the solution pH. Further, the particles also act as nucleii for precipitation. Due to this, precipitation

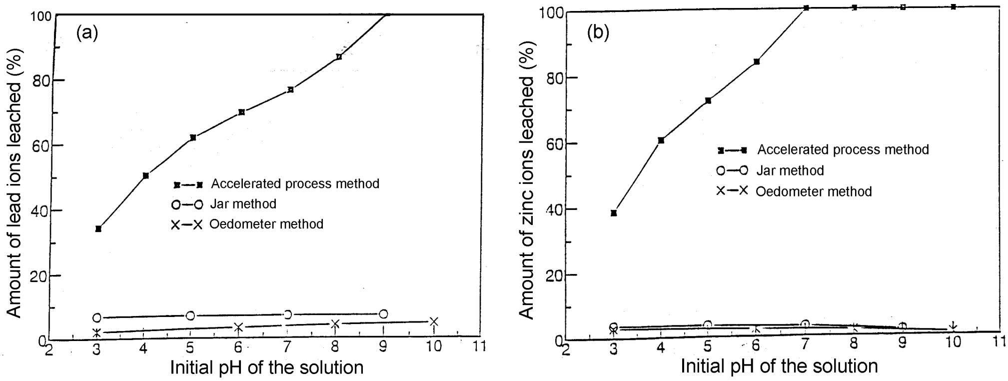

FIG. 15. Comparison of leaching of (a) lead, and (b) zinc ions by three methods for fly ash (N).

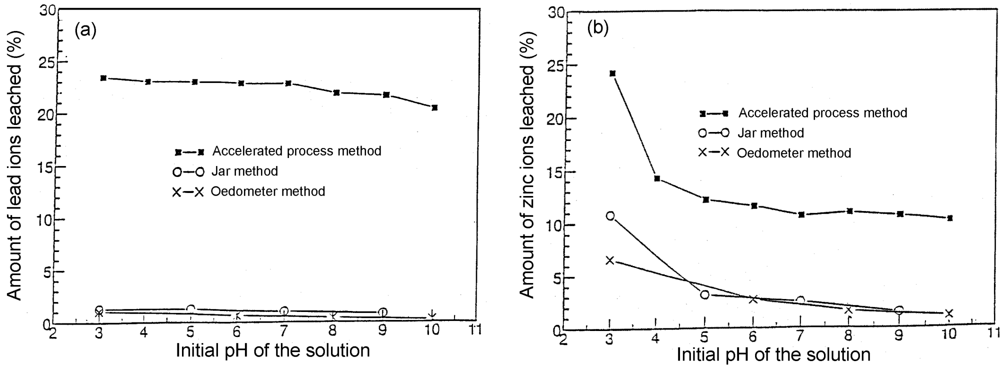

FIG. 16. Comparison of leaching of (a) lead, and (b) zinc ions by three methods for fly ash (B).

can still occur on to the surface of the materials up to pH values of 0.5 to 1.0 unit lower than that required for the metal precipitation in the solution. Due to the cation exchange capacity and/or adsorption on to the surface of the Badarpur fly ash particles, the concentration of metal ions decreases in the solution. Hence, when the pH is below that required for surface precipitation, Badarpur fly ash adsorbs the metal ions through ion exchange and/or adsorption on to the surface. Figures 15 and 16 show the leaching of lead and zinc metal ions (with respect to the total amount of the particular metal) with initial pH by all the three methods, for Neyveli and Badarpur fly ashes, respectively. It can be observed from these figures that the leaching of metal is high in the case of Accelerated process method compared to Jar and Oedometer methods. This is because more number of particles are exposed and are available for the reactions in the Accelerated process method due to continuous agitation. It indicates the worst possible condition. Compared to Accelerated process and Jar methods, the leaching of metal ions by Oedometer method is less. This is because less number of particles come in contact with the aqueous medium and are available for the reactions. The Oedometer method represents the field condition. In the case of Jar method, the percentage leaching of various metal ions is less than the Accelerated process method and marginally higher than the Oedometer method. This means that the particles available for the reactions in the Jar method are less than the Accelerated process method and more than the Oedometer method.

12. Conclusions

The detailed investigations carried out on fly ash elsewhere as well as at the Indian Institute of Science show that fly ash has good potential for use in geotechnical applications. Its low specific gravity, freely draining nature, ease of compaction, insensitiveness to changes in moisture content, good frictional properties, etc. can be gainfully exploited in the construction of embankments, roads, reclamation of low-lying areas, fill behind retaining structures, etc. It can be also used in reinforced concrete construction since the alkaline nature will not corrode steel. This not only solves the problems associated with the disposal of fly ash (like requirement of precious land, environmental pollution, etc.) but also helps in conserving the precious top soil required for growing food.

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