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Hydraulic and compaction characteristics of leachate-contaminated lateritic soil

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Abstract

Large quantities of leachate-contaminated lateritic soil results from dump yards in the southwest coast of India. These dump yards receive large quantities of municipal solid waste which includes chemical, industrial and biomedical wastes. Large areas of land are currently being used for this purpose. An extensive laboratory testing program was carried out to determine the compaction characteristics and hydraulic conductivity of clean and contaminated lateritic soil. Batch tests were used to study the immediate effect of leachate contamination on the properties of lateritic soil. Contaminated specimens were prepared by mixing the lateritic soil with leachate in the amount of 5%, 10% and 20% by weight to vary the degree of contamination. The results indicated a small reduction in maximum dry density and an increase in hydraulic conductivity due to leachate-contamination. The change induced by chemical reaction in the microstructure of the soil was studied by scanning electron microscope before and after contamination of soil with leachate. The structure of the leachate contaminated soil sample appeared to be aggregated in scanning electron microscope analysis. The aggregated structure increases the effective pore space and thus increases the hydraulic conductivity. Fifty percent increase in hydraulic conductivity was observed for specimens prepared at standard Proctor density and mixed with 20% leachate. Compaction characteristics did not change much with the presence of leachate up to 10%. With 20% leachate the maximum dry density decreased slightly indicating excess leachate in the soil. However the changes are not significant.

Keywords: Lateritic soils; Leachate; Compaction characteristics; Hydraulic conductivity

1. Introduction

Lateritic soils constitute an important group of soils of one of the coastal districts of India. Inadequate disposal schemes of solid and liquid wastes have resulted in massive pollution of soil and groundwater in the coastal districts of the west coast of India. Substantial releases of leachate from dump yards (landfills without top and bottom impermeable layers) have occurred during the past few years and the lateritic soil at the dump yard revealed extensive contamination. These releases may have also covered extensive areas adjacent to the dumping area resulting in ground contamination. However the immediate program is not about the remediation of the heavily polluted soil as dumping of municipal solid wastes could continue for another few years. The study area is situated in southwest coast of India (Latitude 12°52′N, Longitude 74°49′E). Large areas of land are currently used for

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Table 1
Characteristics of solid waste (Khan et al., 1994)

Component	Percentage by weight
Metal	0.3
Rags and clothes	8.2
Plastics	1.53
Rubber	0.14
Glass	0.82
Wood	3.48
Garbage	58.52
Paper	25.82
Unclassified	1.47
Percentage moisture	68.0

open dumping purpose. At one of the dumping yard around 250 MT of municipal solid waste is being dumped without shredding and segregation (Ravishankar et al., 2004). The dump yard receives animal carcasses, chemical, industrial and bio-medical wastes. Lateritic soils constitute an important group of soils of this region. The high precipitation (3500 mm annually) coupled with open dumping without the top cover increases the chance of soil and ground water pollution.

In connection with any possible applications, knowledge of the geotechnical properties and behavior of contaminated soil is required. This work forms an initial part of a research program at National Institute of Technology Karnataka Surathkal. During the preliminary investigation the main focus of this study was to determine the effect of leachate contamination on hydraulic and compaction characteristics. Past work (Sridharan et al., 1981; Kumapley and Ishola, 1985; Foreman and Daniel, 1986; Kirov, 1989; Uppot and Stephenson, 1989; Al-Tabbaa and Walsh, 1994; Khan and Pise, 1994; Gnanapragasam et al., 1995; Kamon et al., 1996; Sivapullaiah and Savitha, 1997; Soule and Burns, 2001; Roque and Didier, 2006; Sunil et al., 2006) has shown that some types of contaminants change the properties of their host soils and this behavior has been shown to be dependent on the concentration of the contaminant solution. The majority of wastes generated

Table 2
Composition of leachates from domestic solid waste (Khan et al., 1994)

Substances extracted	Maximum concentration in mg/L
Chloride	1100
Calcium	875
Ammonia-N	1094
Total solids	18,252
COD	22,125
Volatile acids	110,028
pH	5.3–7.8

Table 3
Composition of leachate from dump yard (age 15 years) at Mangalore (Ravishankar et al., 2004)

Substances extracted	Maximum concentration in mg/L
Electrical conductance	15.16 to 18.45 (mS/cm)
Total solids	10,300 to 14,530
Total dissolved solids	6700 to 10,530
BOD	200 to 1200
COD	22,125
Ammonia-N	900
Sodium (Na)	1000
Potassium (K)	1000
Iron content	50
pH	8.1

BOD — Biochemical oxygen demand; COD — Chemical oxygen demand.

are disposed of at landfills (Bloor et al., 2006). Though the current landfill engineering emphasis on pollution reducing technology (by using suitable liner material to avoid the migration of leachate/hazardous waste chemicals generated in a landfill); there are however, a considerable number of closed landfill sites that were constructed in the past without engineering containment (Bloor et al., 2006). Open dumping is extensively practiced in India. The leachate generated from such landfill sites pose serious environmental risks to the surroundings by causing contamination of soil and groundwater systems.

This paper presents the results of a laboratory testing program carried out to determine the short term effect of leachate contamination on the hydraulic conductivity and compaction characteristics of lateritic soils. To select a representative leachate produced in landfills, a database was prepared from published literature (e.g. Khan et al., 1994; Ravishankar et al., 2004). The leachate used in the present study was simulated in the laboratory. The soils

Table 4
Characteristics of solid waste

Component	Percentage by weight
Vegetable matter	6.94
Tender coconut shell	16.33
Total compostible matter	41.39
Rags and clothes	8.95
Plastics	11.86
Leather	0.09
Wood	0.29
Rubber	1.11
Glass	0.18
Garbage	58.52
Paper	11.86
Unclassified	1.47
Percentage moisture	65.0

Table 5
Chemical composition of synthetic acid-leachate

Concentration (mg/l)						Other characteristics	
Cl^-	Mg^{2+}	Ca^{2+}	NH_4^+	TDS	COD	pH, 25 °C	EC 25 °C (μS/cm)
1400	2500	832	820	22740	20000	5.2	18600

TDS — Total dissolved solids; COD — Chemical oxygen demand; EC — Electrical conductance.

for hydraulic conductivity were prepared and studied at standard Proctor maximum dry density (γ_{dmax}) using optimum moisture content (w_{opt}). A Light compaction test was employed to study the compaction characteristics.

2. Scope of problem

An initial survey of the affected ground reveled extensive contamination. The total area affected due to inadequate disposal is about 15 to 30 acres of land. The maximum depth of leachate penetration is not known. With such dumping activity in process; the geotechnical engineers were also concerned with effect of leachate contamination on the geotechnical properties of the soil. They may face with situations in which they had to place new structures on sites with contaminated soils. The present testing program was carried out in an attempt to provide answers to these questions.

3. Methodology

This work forms an initial part of a research program at National Institute of Technology Karnataka Surathkal. During this investigation the main focus of this study was to determine the effect of leachate contamination on hydraulic and compaction characteristics. The study of hydraulic conductivity and compaction characteristics of lateritic soils of west coast of India has been done on the basis of the results obtained in an extensive experimental program. To attain the study objectives, the following steps were followed:

a) selecting lateritic soils from five sources as being representative of the lateritic soils in west coast of India and studying their geotechnical characteristics;
b) preparing a synthetic leachate with a chemical composition most representative as possible of that observed in real lactates.

Table 1a (Appendix A) summarizes the instrument used methodology and reference in determining chemical characteristics of soil and leachate.

Table 6
Index properties of five samples selected

Sample	Gs	Atterberg limits			Grain-size distribution			
		w_L (%)	w_P (%)	w_S (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)
1	2.64	41	28	22	21	58	16	5
2	2.61	43	28	22	2	70	22	6
3	2.63	49	28	18	21	49	22	8
4	2.65	50	29	–	8	62	19	11
5	2.70	45	25	–	14	64	14	8

Gs — Specific gravity of soil solids; w_L — Liquid limit; w_P — Plastic limit; w_S — Shrinkage limit.

3.1. Soil

Representative soil samples from the five sources were obtained from test pits of 1.2 m to 1.5 m depth. The soils were air dried and passed through 425 μm sieve before using the same for laboratory tests. Tables 6 and 7 show the main physical and chemical characteristics of these samples. To vary the degree of contamination the dry soil samples were mixed with 5%, 10% and 20% leachate by weight of dry soil. A light compaction and hydraulic conductivity tests were carried out on lateritic soil samples after 48 h. The maximum dry density and optimum moisture content values were established for uncontaminated soil. To study the hydraulic characteristics of lateritic soils after contamination with leachate the soil specimens were compacted to corresponding standard Proctor maximum dry density using standard Proctor optimum moisture content (w_{opt}).

3.2. Leachate

With the purpose of selecting representative municipal solid waste (MSW) leachate produced in landfills, a database was prepared from real leachates published in the literature (Khan et al., 1994). From the available literature, it was observed that the concentration of each

Table 7
Chemical characteristics of the five samples selected

Sample	pH of soil, 25 °C	EC of soil solution, 25 °C (μS/cm)	CEC (meq/100 g)	$CaCO_3$ (%)
1	5.21	30	6.23	3.10
2	5.26	40	7.32	2.23
3	4.31	25	8.15	2.26
4	5.28	34	9.14	3.08
5	5.13	64	8.18	2.66

EC — Electrical conductance; CEC — Cation exchange capacity; $CaCO_3$ — Calcium carbonate.

constituent in the real leachates can vary within a wide range. The composition of the leachate generated depends on many factors namely; type of waste, precipitation rates, temperature, food habits of general population etc. One study by Khan et al. (1994), reports the characteristics of solid waste (Table 1) and composition of leachate generated from domestic solid waste (Table 2) for one of the region of Indian subcontinent. The characteristics of the MSW leachate (as shown in Table 3) at a dump yard (this yard is being operated for 15 years) were reported by Ravishankar et al. (2004). These studies were taken as the basis to prepare leachate in the present study. Table 4 presents the characteristics of the solid wastes of west coast of India.

Table 5 shows concentration of each constituent of the leachate selected for this study. Chemicals were used in the preparation of leachate, and distilled water was used in its dissolution and dilution. The mass of each chemical product was obtained on a balance with a sensitivity of ±0.001 g. The electrical conductance of the distilled water used in the preparation of leachate was less than 1.8 μS/cm. The quality of the distilled water was periodically controlled during each preparation of the acid leachate.

3.3. Compaction characteristics

The compaction characteristics (B.I.S., 1987) of lateritic soils were studied in the laboratory using standard Proctor test. The equipment used in the test consists of cylindrical mould (with detachable base plate) having an internal diameter of 100 mm and 127.5 mm effective height, whose internal volume is 1000 ml. The rammer has a mass of 2.6 kg with a drop of 310 mm.

3.4. Hydraulic conductivity

Falling head permeability (B.I.S., 1987) tests were carried out on uncontaminated and contaminated soil samples to study the hydraulic conductivity compacted to standard Proctor maximum dry density in the permeability mould. After compaction of the soil, the collar was removed and the soil specimen was carefully trimmed.

Before the beginning of the seepage stage, a filter paper was placed on each face of the soil specimen so as to prevent the clogging of the perforated disks by the soil fines. After placing the bottom and top plate of the permeameter, the nuts were fastened and assembled properly. The permeameter is then connected to stand pipe (when testing uncontaminated soil the stand pipe was filled with distilled water and during testing of contaminated soil the stand pipe was filled with leachate); the soil is saturated by allowing distilled water/leachate to flow continuously through the sample from the stand pipe. Saturation of the soil sample was ensured under steady state flow conditions. The following method was followed:

a) the heights h_1, h_2 and $\sqrt{h_1 h_2}$ are marked on the stand pipe (the heights are measured above the centre of the outlet);
b) the stand pipe is then filled with distilled water/leachate and the time intervals is recorded for the level to fall from height h_1 to $\sqrt{h_1 h_2}$ and from $\sqrt{h_1 h_2}$ to h_2.

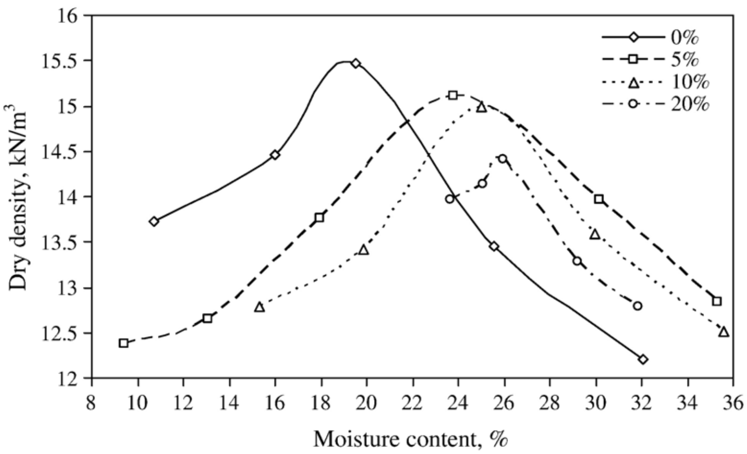

Fig. 1. Compaction curves for samples with different leachate content.

Table 8
Compaction characteristics of five samples selected

Sample	Compaction characteristics	
	w_{opt} (%)	γ_{dmax} (kN/m^3)
1	20.2	15.1
2	24.1	14.7
3	24.5	14.9
4	26.3	14.6
5	25.6	15.3

These two time intervals will be equal if a steady flow condition has been established. This was repeated at least twice changing the heights h_1 and h_2.

The termination criteria of the tests followed in this study were as follows:

a) flow rate of water proportional to hydraulic gradient;
b) volume of water proportional to time.

The hydraulic conductivity values reported in Table 9 were calculated using the following equation. Table 9 also presents the voids ratio values.

$$k = \frac{2.303aL}{At}\log_{10}\left(\frac{h_1}{h_2}\right) \qquad \text{where,}$$

k — coefficient of permeability in cm/s; a — cross-sectional area of the stand pipe in cm^2; A — cross-sectional area of the sample in cm^2; t — time taken for the drop from height h_1 to h_2 in s; h_1 — initial height of the fluid in stand pipe in cm; h_2 — final height of the fluid in stand pipe in cm after time t (Tables 6 and 7).

4. Results

4.1. Compaction characteristics

Standard Proctor compaction tests were carried on soils after 48 h after mixing with 5%, 10% and 20% leachate by weight. The results are plotted in Fig. 1, in the form of dry density versus water content curves. The maximum dry density for lateritic soil is 15.47 kN/m^3 at the optimum moisture content of 19.52%. With the presence of leachate up to 5% the compaction characteristics did not change much. With 10% leachate the maximum dry density and OMC were 14.98 kN/m^3 and 25.01%. However, with further increase of leachate content to 20% the compaction curve had an odd shape with inferior characteristics. This is shown in Fig. 1, which indicates that too much leachate is already present in soil. Table 8 presents the compaction characteristics of uncontaminated soil samples.

4.2. Compaction characteristics change due to leachate

The decrease in maximum dry density reflects the effect caused by chemical reaction (due to change in the nature of the pore fluid) between the leachate and the soil. Hence it is anticipated that in the present study the decrease in maximum dry density is due to chemical reaction between the acidic leachate and soil. At 20% leachate concentration, too much leachate is already present in soil which can cause chemical reaction between the acidic leachate and soil particles.

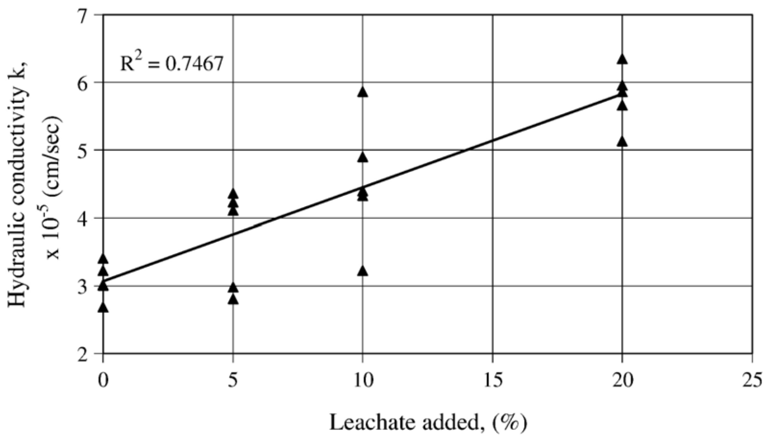

Fig. 2. Variation of hydraulic conductivity with concentration of leachate added.

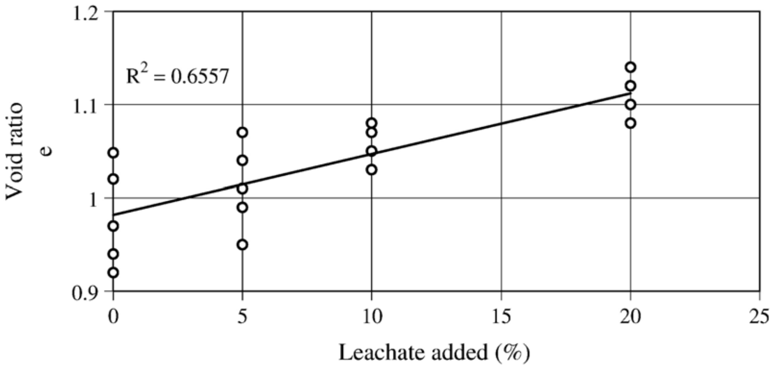

Fig. 3. Variation of void ratio with concentration of leachate added.

4.3. Hydraulic conductivity change due to leachate

The leachate used in the present study has acidic characteristic (pH = 5.2). Fig. 2 shows the hydraulic conductivity of the soil increased when compared to its base value. With increase in leachate concentration the hydraulic conductivity of the lateritic soil increases. Fig. 3 shows the variation of void ratio with percentage leachate added. With increase in leachate concentration, the voids ratio increases. This increase in hydraulic conductivity of the soil is attributed to chemical reaction between the acidic leachate and the clay minerals. It is reported in literature that strongly acidic and strongly basic liquids can dissolve clay minerals (Uppot and Stephenson, 1989). The dissolution of clay mineral particles by acid leachate increases the effective pore space and the hydraulic conductivity increases. Table 9 presents the hydraulic conductivity of uncontaminated soil samples. Table 10 shows the hydraulic conductivity and values of void ratios after contamination with leachate. Photomicrographs (Fig. 4) of soil samples were taken before and after contamination with acid leachate. The main elements of the microstructure are voids and aggregates of particles. The structure of the leachate contaminated soil sample appeared to be aggregated in scanning electron microscope analysis. The aggregated structure increases the effective pore space and thus increases the hydraulic conductivity. Hence the increase in hydraulic conductivity of lateritic soils after contamination with the acid leachate is attributed mainly to the following reasons:

a) chemical reaction between the leachate and the clay minerals;
b) the structural changes which occurred in a soil after contamination with leachate i.e. when pore water is replaced by leachate voids ratio increases than that with water as pore fluid.

Bibliographical information (Ola, 1978; Uppot and Stephenson, 1989; Sunil et al., 2006) indicates that the cementing agents in soils help to bind the finer particles together to form aggregates. However, strongly acidic

Table 9
Hydraulic conductivity of five samples selected

Sample	Void ratio, e	Hydraulic conductivity k, $\times 10^{-5}$ (cm/s)
1	1.02	2.7
2	1.05	3.0
3	0.97	3.4
4	0.94	3.2
5	0.92	3.0

Table 10
Hydraulic conductivity of soil after contamination with acid leachate

Sample	Soil mixed with leachate % by weight of soil	Hydraulic conductivity $k \times 10^{-5}$ (cm/s)	Void ratio, e	Percentage increase in hydraulic conductivity
1	0	2.69	1.02	
	5	2.81	1.07	4.3
	10	3.22	1.05	16.5
	20	5.66	1.10	52.5
2	0	3.02	1.05	
	5	2.98	1.04	–
	10	4.90	1.07	38.4
	20	5.13	1.12	41.1
3	0	3.41	0.97	–
	5	4.36	0.99	21.8
	10	4.40	1.03	22.5
	20	6.35	1.08	46.3
4	0	3.22	0.94	–
	5	4.23	1.01	23.9
	10	5.86	1.08	45.0
	20	5.96	1.14	45.6
5	0	3.01	0.92	–
	5	4.11	0.95	26.8
	10	4.33	1.05	30.5
	20	5.86	1.10	48.6

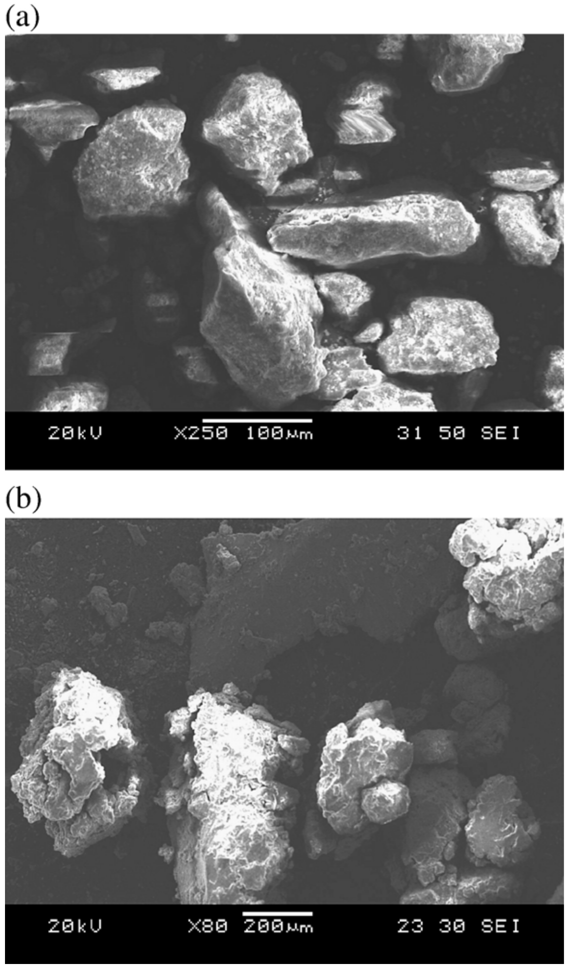

Fig. 4. Scanning Electron Micrographs of: (a) Uncontaminated soil; (b) Soil contaminated with leachate.

conditions lead to the destruction of soil structure. As the particles are transported by permeant, they clog pore space. But, as dissolution progress in the zones of clogging, particles will be removed and the hydraulic conductivity increases. Volume changes of in situ soil with regard to the effects of inflow and contamination by effluents has been reported by Sridharan et al. (1981).

5. Discussion

The preceding results present the short-term effect of leachate contamination on the hydraulic and compaction characteristics of lateritic soil. The results indicate 50% increase in hydraulic conductivity. However the effect is not significant on the compaction characteristics.

Open dumping is extensively practiced in this region and the present status of dump yards indicates that leachate infiltration is taking place without any hindrance. With heavy rain during monsoon the leachate mixed with water flows to other areas causing more contamination over a large surface area. The leachate flow will be very high during the monsoon and during summer and winter the flow reduces. As there is no system for the collection of the leachate at dump yard the leachate makes its way out of the dump yard through small trenches. During summer the generation is not sufficient and the leachate infiltrates within short distance out of the landfill.

Batch tests were used to study the short-term or immediate effect of leachate contamination on the properties of lateritic soil. It is anticipated that during summer the leachate generation is not sufficient and due to evaporation the residues would remain into the soil. Since the dump yard receives chemical, industrial and bio-medical wastes this could also lead to heavy metal contamination. The heavy metal contamination of the soil will have to be examined in a separate testing program. Because heavy metals are recognized as human health and environmental contaminants leaching of heavy metals to groundwater supplies is of particular concern.

6. Conclusions

An extensive laboratory testing program was carried out to determine the effect of leachate contamination on the properties of lateritic soils. To vary the degree of contamination the amount of leachate mixed with soil varied up to 20%. The following conclusions can be made based on test results.

The hydraulic conductivity and compaction characteristics of soil are likely to get altered due to the chemical reactions of the acidic leachate. The preceding results present the short-term effect of leachate contamination on the hydraulic and compaction characteristics of lateritic soil.

Leachate contamination leads to increased hydraulic conductivity. Fifty percent increase in hydraulic conductivity was observed for specimens prepared at standard Proctor density and mixed with 20% leachate.

Compaction characteristics did not change much with the presence of leachate up to 10%. With 20% leachate the maximum dry density decreased slightly indicating excess leachate in the soil. However the changes are not significant.

The use of contaminated soil for road construction is possible from an engineering point of view by using suitable stabilization technique. The stabilization and solidification technique uses additives or processes to chemically bind and immobilize contaminants to ensure no environmental pollution.

Appendix A

Table 1a
Methodology and Reference used in determining chemical characteristics of soil and leachate

Sl no.	Parameter	Instrument used	Methodology	Reference
1	pH	ELICO make Digital pH meter	–	–
2	Conductivity	ELICO make Microprocessor based Water analysis kit		–
3	Cation exchange capacity (CEC) (meq/100 g)	–		Compendium of Indian Standards on Soil Engineering (B.I.S., 1987) (Part 1) pp. 243–246
4	Calcium carbonate	–		Compendium of Indian Standards on Soil Engineering (B.I.S., 1987) (Part 1) pp. 252–252
5	Ammonia nitrogen as NH_4–N	LOVIBOND make spectrophotometer	Nesslerization	Standard methods (APHA et al., 1980) p. 356
6	Chloride as Cl^-	–	Argentometric method	Standard methods (APHA et al., 1998) pp. 4–67
7	Calcium as Ca^{2+}	SYSTRONICS make microprocessor based Flame photometer	Flame photometric method	–
8	Magnesium as Mg^{2+}		Calculation method	Standard methods (APHA et al., 1998) p. 3–83
9	Total dissolved solids	ELICO make Microprocessor based Water analysis kit	–	–
10	Chemical oxygen demand	LOVIBOND make spectrophotometer and digester	Closed reflux colorimetric method	Standard methods (APHA et al., 1998) pp. 5–17

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