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Shear strength characteristics and chemical characteristics of leachate-contaminated lateritic soil

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ABSTRACT

Leachate is a hazardous liquid and is a major cause of concern in landfills. Numerous environmental problems such as soil and groundwater contamination occur in unlined landfills due to free flow of leachate. Large quantities of leachate-contaminated soils result from open dumping in the study area. These dump yards receive large quantities of municipal solid waste which includes chemical and industrial wastes. Large areas of land are currently being used for this purpose. An extensive laboratory testing program was carried out to determine the properties of clean and contaminated lateritic soils. Laboratory prepared municipal solid waste leachate was used in this study. Contaminated specimens were prepared by mixing the soils with MSW leachate in the increments of 0%, 5%, 10% and 20% by weight to vary the degree of contamination. The results showed that the MSW leachate affects the Atterberg limits, shear strength and chemical characteristics of the lateritic soils.

The liquid limit and the plasticity index of the lateritic soils increases with MSW leachate concentration. For specimens tested at the Proctor density, effective cohesion increases and effective friction angle decreases due to increase in leachate concentration. This is attributed due to the increase in clay content of lateritic soil after interaction with the leachate. This led to increase in cohesion parameter and the friction angle decreases. The pH measurements of lateritic soil contaminated with MSW leachate indicated an increase in pH values. This is also accompanied by slight increase in the cation exchange capacity of the soil. The change in chemical characteristics of lateritic soil contributed due to addition of leachate may be detrimental to foundation concrete in real field conditions. The present work deals with an attempt to study the effect of leachate on the Atterberg limits, shear strength properties and chemical characteristics of lateritic soil.

1. Introduction

The problems associated with solid waste management are many. Effective management is possible only when we appreciate the problems associated with waste disposal (solid or liquid). Any negligence in waste management will simply lead to numerous environmental problems including health affects.

Leachate is a hazardous liquid produced in landfills as a result of interaction of moisture with municipal solid waste (MSW). Inadequate disposal methods of municipal solid waste into the dumpyards results in pollution of soil and groundwater systems. Lateritic soils constitute an important group of soils in the coastal districts of Karnataka, India. The study area is situated in southwest coast of India (Latitude 12° 52'N, Longitude 74° 49'E) has extensive lateritic formations. These soils are considered to be a good foundation material. Due to very high permeability of lateritic soils open dumping of municipal solid waste may lead to environmental problems. Large areas of land are currently used for 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). Due to heavy rainfall (3500 mm annually) during monsoon leachate from such landfills flows out without any hindrance into the adjacent areas resulting in contamination of soil and groundwater. Substantial releases of leachate (due to open dumping) might have occurred during the past few years and the lateritic soil at the dump yard revealed extensive contamination. Leachate contamination may lead to significant effect on the behaviour of soils. Past work (Mesri and Olson, 1970; Sridharan and Venkatappa Rao, 1979; Sridharan et al., 1981; Kumapley and Ishola, 1985; Foreman and Daniel, 1986; Kirov, 1989; Uppot and Stephenson, 1989; 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 the index and engineering properties of soil contaminated with leachate tend to change due to chemical reactions between the soil mineral particles and the contaminant. In connection with any possible applications, knowledge of the behavior of contaminated soil is required and hence the present investigation.

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Table 1
Index and compaction characteristics of lateritic soils.

No.	G_s	Atterberg limits			Grain-size distribution				Compaction characteristics	
		w_L (%)	w_p (%)	w_s (%)	Gravel (%)	Sand (%)	Silt (%)	Clay (%)	$(w)_{opt}$ (%)	$(\gamma_d)_{max}$ (kN/m^3)
1	2.64	41	28	22	21	58	16	5	19.5	15.5
2	2.61	43	28	22	2	70	22	6	24.1	14.7
3	2.63	49	28	18	21	49	22	8	24.5	14.9
4	2.65	50	29	21	8	62	19	11	16	14.8
5	2.70	45	25	23	14	64	14	8	25.6	15.3

G_s – Specific gravity of soil solids; w_L – Liquid limit; w_P – Plastic limit; w_S – Shrinkage limit; $(w)_{opt}$ – Optimum moisture content; $(\gamma_d)_{max}$ – Maximum dry density.

In the study area, it is very difficult to obtain real leachate from the landfills. The leachate used in the present study was simulated in the laboratory. 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 shear strength characteristics of lateritic soils were prepared and studied at standard Proctor maximum dry density [$(\gamma_d)_{max}$] using optimum moisture content $(w)_{opt}$ for the soil passing through 425 micron sieve.

2. Scope of the problem

In the study area, lateritic soils are predominant and about 6–12 ha of land are currently used as dump yards from the past few years. Municipal solid waste is being dumped on such land without shredding and segregation. Lateritic soil at the disposal area revealed extensive contamination due to leachate. With such dumping activity in process, the geotechnical engineers were also concerned with the effect of leachate contamination on the properties of the soil. The present investigation was carried out keeping the above points in mind.

3. Experimental investigation

The study of lateritic soil samples contaminated with leachate has been done on the basis of the results obtained in an extensive experimental program. Representative lateritic soil samples from five sources were selected in the study area to study the effect of leachate contamination on shear strength, Atterberg limits and on the chemical characteristics of lateritic soils. It was very difficult to obtain real leachates from the existing landfills. Hence in the present investigation synthetic leachate with a chemical composition most representative of the real leachates was prepared in the laboratory.

4. Methodology

Representative soil samples from the five sources were obtained from test pits of 1.2 m to 1.5 m depth [Sample 1: Surathkal; Sample 2: Mangalore; Sample 3: Padubidri; Sample 4: Belman; Sample 5: B.C. Road]. The soils were air dried and passed through 425 µm sieve before using the same for laboratory tests. The soil specimens for shear strength parameters were prepared and studied at standard Proctor maximum dry density [$(\gamma_d)_{max}$] using optimum moisture content $(w)_{opt}$ as shown in Table 1.

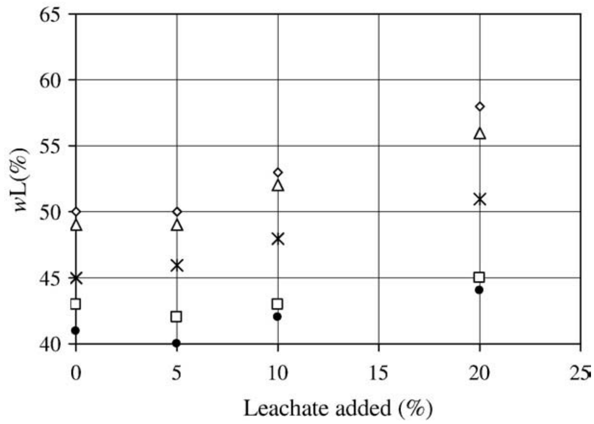

Fig. 1. Variation of liquid limit with leachate added (%).

4.1. Specimen preparation for triaxial test

In this study, specimens for the triaxial test were remolded to Proctor density (using optimum moisture content). The compaction characteristics i.e. the values of maximum dry density (γ_{dmax}) and optimum moisture content (w_{opt}) were first established (corresponding to the peak of the compaction curve) for soils passing 425 micron sieve in a standard Proctor mould. The soil samples were then mixed with leachate at increments of 5%, 10% and 20% by weight of soil. Each fraction of the dry soil was mixed thoroughly with the leachate in a tray. After mixing, the soil-leachate mix was kept for 48 h for moisture equilibrium. After 48 h the soil was compacted to the corresponding Proctor densities as shown in Table 1. Three specimens were then extruded from the sampling tube. The specimens were then trimmed to required length and diameter. The specimens used for the triaxial tests were 38 mm in diameter and 76 mm long.

Consolidated undrained (CU) triaxial compression test (with measurement of pore water pressure) were conducted on saturated soil samples as per Indian Standard procedures to determine shear strength parameters. Triaxial compression tests were conducted on saturated soil specimens remolded to Proctor maximum dry density [$(\gamma_d)_{max}$]. Back pressure was applied for saturating the sample. After 24 h the Skempton's pore pressure parameter 'B' is calculated and saturation of the specimen is ensured when B = 1. Pore water pressure was measured to establish total and effective shear strength parameters.

4.2. Atterberg limits

The Atterberg limits of soil, was determined using the standard liquid limit apparatus as per Indian Standard procedures.

4.3. Chemical characteristics

The chemical properties of the soils determined included pH of soil, electrical conductance of the soil solution, cation exchange capacity, organic matter, total soluble sulphates, iron content, silica

Table 2
Chemical characteristics of the five lateritic soil samples.

Sample	pH of soil 25 °C	EC of soil solution, (µS/cm)	CEC (meq/100 g)	$CaCO_3$ (%)	OM of soil (%)	$SO_4 \times 10^{-3}$ (%)	Fe_2O_3 (%)	SiO_2 (%)	Al_2O_3 (%)
1.	5.21	30	6.23	3.10	0.52	7	8	70	46.7
2.	5.26	40	7.32	2.23	0.45	5	6.9	73	38.6
3.	4.31	25	8.15	2.26	0.55	4	7.0	72	43.4
4.	5.28	34	9.14	3.08	0.41	6	5.1	70	37.0
5.	5.13	64	8.18	2.66	0.42	5	6.0	71	37.0

EC – Electrical conductance; CEC – Cation exchange capacity; $CaCO_3$ – Calcium carbonate; OM – Organic matter; SO_4 – Soluble sulphate; Fe_2O_3 – Iron content; SiO_2 – Silica; Al_2O_3 – Alumina content.

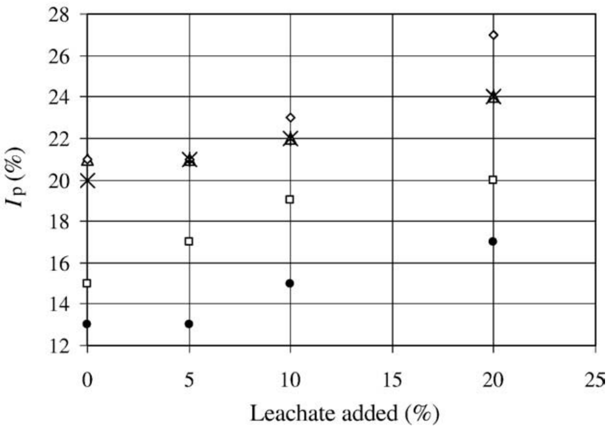

Fig. 2. Variation of plasticity index with leachate added (%).

etc. The results of chemical characteristics of uncontaminated lateritic soil are presented in Table 2.

5. Results and discussions

The effect of leachate on the hydraulic conductivity and compaction characteristics of lateritic soil is presented by Nayak et al. (2007). Effects of municipal solid waste (MSW) leachate on the shear strength and other properties of lateritic soils are discussed in subsequent sections.

5.1. Effect of leachate on Atterberg limits

Contaminants change the properties of their host soils. Fig. 1 illustrates the variation of liquid limit (w_L) of soil with percentage leachate added. It is observed from Fig. 2 that the leachate has significant effect on the liquid limit of the soil. The liquid limit of the soil increases with increase in percentage leachate added. This can be attributed to leachate characteristics (Table 3).

Mineralogical analyses of lateritic soil revealed the presence of kaolinite mineral in addition to montmorillonite, quartz, and calcite. The liquid limit behaviour of a montmorillonite soil is controlled essentially by diffuse double layer forces and that of kaolinitic soil by shearing resistance at particle level. In the case of lateritic soils, because of its low cation exchange capacity, the effects due to changes in diffuse double layer are negligible. However the increase in liquid limit (w_L) of the lateritic soil are mainly due to increase in clay content of the lateritic soil. As shown in Table 4 the liquid limit of the soil has increased from 50% to 58% (when leachate concentration increased from 0 to 20%) for sample no. 4.

Similar trend was observed with regard to plasticity index (I_p) of the soil. As illustrated in Fig. 2, the plasticity index (I_p) of the soil increases with the increase in the leachate concentration. Table 4 shows that the plasticity index of the soil has increased from 21% to 27% while the shrinkage limit of the soil has increased from 21% to 24% for sample no. 4.

5.2. Effect of leachate on shear strength characteristics

Isotropically consolidated undrained triaxial compression tests with pore pressure measurements were conducted on lateritic soil specimens mixed with 0%, 5%, 10% and 20% leachate. All specimens were prepared at standard Proctor maximum dry density [$(\gamma_d)_{max}$.] and were saturated prior to the test by application of back pressure.

Table 5 shows the shear strength parameters for clean and contaminated soil respectively. There is a slight increase in cohesion and the decrease in friction angle as a result of leachate contamination for specimens tested at the Proctor density. The increase in clay content of lateritic soil after interaction with the leachate has increased the cohesion and hence the friction angle decreases. The experimental results are plotted in Figs. 3 and 4.

5.3. Effect of leachate on soil pH

pH determination of soil is important as excessive acidity or alkalinity can be detrimental. It is reported in literature (Gidigasu, 1976) that under high rainfall conditions, cations especially Ca^{2+} leach, while under low rainfall conditions, Ca^{2+} and other cations are not easily leached.

The results of pH of five lateritic soil samples indicated that the soil is acidic. The experimental data indicated that the pH value of clean lateritic soil samples varied from 4.31 to 5.28. The acidic nature of soil is mainly due to two reasons. First, leaching of appreciable amounts of exchangeable bases from the soils due to high precipitation (3500 mm annually). Second, decomposition of organic matter, leads to the formation of organic and inorganic acid (eg. carbonic acid – H_2CO_3) which renders the soil acidic.

The experimental data of soil pH as a function of leachate added is presented in Fig. 5. It is observed from Fig. 5 that the pH of lateritic

Table 3
Chemical composition of synthetic 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	13,020	20,000	7.5–8.5	18,600

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

Table 4
Liquid limit and plasticity index of lateritic soil after contamination with leachate.

Sample		Soil mixed with leachate % by weight of soil			
		0	5	10	20
1	Clay (%)	5	5	5.5	6.5
	w_L (%)	41	40	42	44
	I_p (%)	13	13	15	17
	w_s (%)	22	22	23	24
2	Clay (%)	6	6.3	6.5	7.6
	w_L (%)	43	42	43	45
	I_p (%)	15	17	19	20
	w_s (%)	22	21	23	24
3	Clay (%)	8	8.2	9	9.5
	w_L (%)	49	49	52	56
	I_p (%)	21	21	22	24
	w_s (%)	18	19	20	22
4	Clay (%)	11	11.3	11.5	12.7
	w_L (%)	50	50	53	58
	I_p (%)	21	21	23	27
	w_s (%)	21	20	22	24
5	Clay (%)	8	8.2	8.4	9.6
	w_L (%)	45	46	48	51
	I_p (%)	20	21	22	24
	w_s (%)	23	23	24	25

Table 5
Shear strength parameters of lateritic soil after contamination with leachate.

Sample		Soil mixed with leachate % by weight of soil			
		0	5	10	20
1	c′ (kPa)	18.2	18.5	19	20
	φ′ (degrees)	31	30	28	26
2	c′ (kPa)	19.1	19.3	19.8	21
	φ′ (degrees)	30	31	28	25
3	c′ (kPa)	17.4	17.5	17.6	18.1
	φ′ (degrees)	31	31	29	27
4	c′ (kPa)	18.6	19	19.2	21
	φ′ (degrees)	30	29	28	26
5	c′ (kPa)	19	19.2	19.4	21
	φ′ (degrees)	30	29	29	25

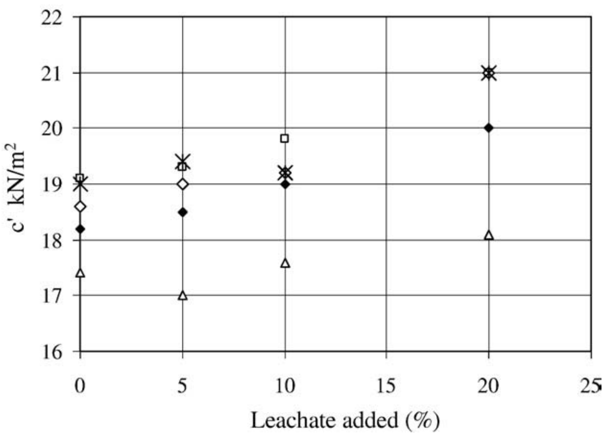

Fig. 3. Variation of effective cohesion with leachate added (%).

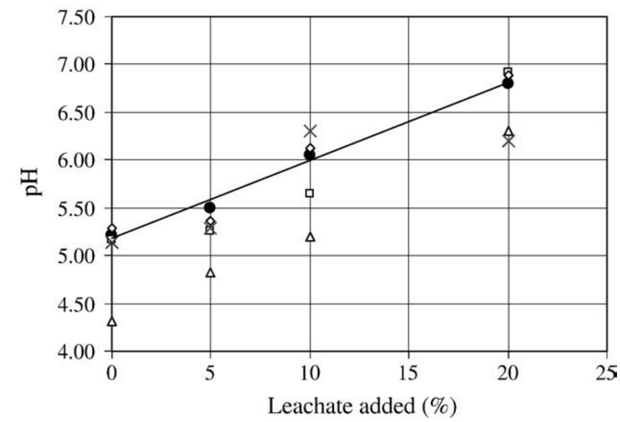

Fig. 5. Variation of soil pH with leachate added (%).

soil increases with increase in leachate concentration. The probable reason for this behaviour may be due to high concentration of monovalent and divalent cations contained in the leachate. The concentration of each constituent of leachate is presented in Table 3. The leachate also contained chloride and sulphate anions. As a result of negative charges developed by the clay particles, ions are adsorbed on the surface. When leachate is added to the soil the monovalent and divalent cations such as Ca^{2+}, Mg^{2+}, Na^{+} ions are adsorbed on the surface. Any process that encourages presence of high levels of exchangeable bases such as calcium, magnesium, potassium and sodium will reduce acidity and increase alkalinity. Hence the pH of the lateritic soil in Fig. 5 increases as the leachate concentration increased.

5.4. Effect of leachate on cation exchange capacity of soil

Ion exchange is the most important of all processes occurring in the soil. The capacity of soil to absorb and exchange ions varies greatly with the amount of clay. Exchange of ions takes place due to isomorphous substitution (i.e., substitution of one element for another). Results of CEC determinations are plotted in Fig. 6. From the results, it can be seen that CEC has increased from an initial value of 6.23 meq/100 g to 12.2 meq/100 g. While the increase in cation exchange capacity of soil is interesting and some researches attribute the following reason:

Mathew and Rao (1997) concludes that the increase in cation exchange capacity of soil is attributed due to rise in pH. The acquisition of extra negative charge with a rise in pH is mainly due to two reasons. First, the development of negative charge is due to the dissociation of hydrogen of SiOH groups present at the edges of the tetrahedral layers, and the surface of the clay is left with the negative charge of the oxygen ions according to the reaction.

$$\mathrm{SiOH} = \mathrm{SiO}^{-} + H^{+} \tag{1}$$

This type of negative charge is pH dependent charge. The amount of dissociation increases with increasing pH and results in an increase in the cation exchange capacity. Mathew and Rao (1997) also reported the changes in CEC to be pH dependent, and this arises from exposed –SOH and – AlOH sites. Second, the non-crystalline compounds formed contribute to CEC. At higher pH, silica and alumina present in the soil dissolve and form non-crystalline compounds of silicates and aluminates. These non-crystalline compounds acquire a negative charge and contribute to CEC. Although these changes are observed during experiments in the laboratory a different situation may arise in field. Toxic waste water/leachate from landfills may seep into the surrounding soil to increase the pH of the soil.

5.5. Effect of leachate on other chemical characteristics of soil

From Table 6 it is observed that electrical conductivity (EC), calcium, sulphate and iron content in the soil increases. This is mainly due to leachate characteristics rather than the chemical characteristics of soil. As the leachate is simulated in the laboratory and prepared using chemicals with a chemical composition most representative of the real leachates. Depending upon the composition of real leachates chemicals like acetic acid, ammonium chloride, calcium chloride, sodium chloride, magnesium chloride, ferric chloride, suphate were

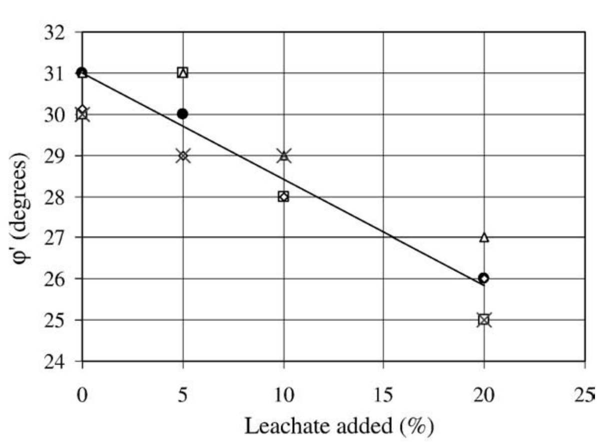

Fig. 4. Variation of effective friction angle with leachate added (%).

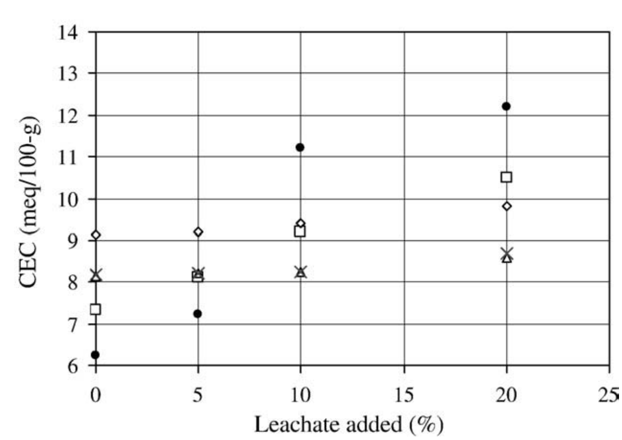

Fig. 6. Variation in cation exchange capacity with leachate added (%).

Table 6
Chemical characteristics of lateritic soil after contamination with leachate.

Sl. no.	Parameter	Soil mixed with leachate % by dry weight of soil			
		0%	5%	10%	20%
1.	pH of soil, 25 °C	5.21	5.5	6.05	6.8
		5.16	5.25	5.65	6.9
		4.31	4.83	5.2	6.3
		5.28	5.36	6.13	6.89
		5.13	5.28	6.3	6.2
2.	EC of soil Solution, 25 °C (µS/cm)	30	210	250	310
		40	180	220	290
		25	150	200	320
		34	170	240	300
		64	150	230	310
3.	CEC (meq/100 g)	6.23	7.23	11.2	12.2
		7.32	8.11	9.2	10.5
		8.15	8.2	8.25	8.6
		9.14	9.2	9.4	9.8
		8.18	8.2	8.23	8.7
4.	$CaCO_3$ (%)	3.10	3.14	4.11	4.43
		2.23	2.78	3.13	4.13
		2.26	2.55	2.86	3.86
		3.08	3.81	3.93	4.22
		2.66	4.28	3.78	4.78
5.	$SO_4 \times 10^{-3}$ (%)	7	3.3	4.6	6.4
		5	3.4	5.3	7
		4	5	13	54
		3	62	15	65
		5	4	13	45
6.	Fe_2O_3 (%)	8	8.12	8.9	9.2
		6.86	7.08	7.33	8.69
		7	7.3	8.5	9.2
		5.1	5.88	6.13	7.55
		6	6.3	7.2	7.8

used in the preparation of synthetic leachate. The adsorption of chemical constituents of leachate on the clay surface influences the chemical characteristics of soil and it is due to leachate characteristics.

6. Conclusions

An extensive laboratory testing program was carried out to study the effect of leachate contamination on the Atterberg limits, shear strength parameters and chemical characteristics of lateritic soils. The following conclusions are made based on the test results:

The leachate can alter the Atterberg limits of lateritic soils. All the leachate-contaminated lateritic soil samples showed an increase in liquid limit and plasticity index values. The increase in liquid limit (w_L) and plasticity index (I_p)of the lateritic soil is attributed due to change in nature of pore fluid which is shown by increase in clay content of the soil. The disintegration of clay particles from the aggregates due to acidic or alkaline leachate in the pore media tends to increase in specific surface area of soil which leads to high adsorption of water that changes the limit values.

Shear strength parameters of lateritic soils are affected by leachate contamination. For specimens tested at the Proctor density, effective cohesion increases and effective friction angle decreases due to increase in leachate concentration. The increase in clay content of lateritic soil after interaction with the leachate has increased the cohesion and hence the friction angle decreases.

Chemical characteristics of soil are altered depending upon the leachate constituents or the concentration of individual components. The pH of soils is marginally altered due to leachate. The increase in cation exchange capacity of soil may also be attributed due to marginal increase in pH value of soil with leachate. The increase in electrical conductivity, calcium, sulphate and iron content is due to leachate characteristics.

The change in chemical characteristics of lateritic soil may be detrimental to foundation concrete in real field conditions. For example, the increase in pH of soil may influence the corrosion of reinforcement. Also the sulphate content of the soil increases with increases in leachate concentration. This may have effect on the buried concrete leading to foundation problems. The preceding results present the short-term effect of leachate contamination on the Atterberg limits, shear strength parameters and chemical characteristics of lateritic soils.

Appendix A

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 [4] (Part 1) p. 243–246.
4	Calcium Carbonate	–		Compendium of Indian Standards on Soil Engineering [4] (Part 1) p. 252–252
5	Ammonia Nitrogen as NH_4–N	LOVIBOND make spectrophotometer	Nesslerization	Standard Methods [2] p.356
6	Chloride as Cl^-	–	Argentometric Method	Standard Methods [3] p. 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 [3] 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 [3] p.5–17

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