
EFFECT OF MUNICIPAL SOLID WASTE LEACHATE ON PLASTICITY CHARACTERISTICS OF CLAY SOIL

**Adamu Umar Chinade^{1,*}, Musa Umar Chinade², Isa Zubairu^{1,3,4}, Muhammad Abdu
Nasara¹, Yakubu Hyelmura¹**

¹Department of Civil Engineering, Abubakar Tafawa Balewa University, Bauchi

²Department of Architecture, Abubakar Tafawa Balewa University, Bauchi

³Department of Water Resources and Environmental Engineering, Ahmadu Bello University Zaria
Nigeria

⁴Faculty of Civil Engineering, University Teknologi Malaysia

Email: umarchinade@atbu.edu.com*, muchinade@atbu.edu.ng, izubairu@atbu.edu.ng, manasara@atbu.edu.ng,
hyelmurayak@gmail.com

***Corresponding author:** Adamu Umar Chinade

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ABSTRACT

This study investigated the effect of municipal solid waste (MSW) leachate on the plasticity characteristics of a clay soil from Bauchi, Nigeria. Clay specimens were exposed to leachates collected from four municipal dumpsites and cured for 7, 14, 21, 28, and 35 days before determination of liquid limit, plastic limit, shrinkage limit, and plasticity index. The natural soil was classified as CL under the Unified Soil Classification System and A-6(11) under AASHTO, with a liquid limit of 32%, plastic limit of 14%, plasticity index of 18%, shrinkage limit of 12%, and free swell of 45%. Leachate exposure produced clear time-dependent changes in consistency. The liquid limit increased progressively to 37.5-39.5% after 35 days, while the plastic limit increased monotonically to 22-24% over the same period. Because the plastic limit increased more rapidly than the liquid limit, the plasticity index generally decreased to 15-16.5% by 35 days. The shrinkage limit decreased sharply during the first 7 days to 8.0-9.0% and then partially recovered to 10.5-11.0% by 35 days, remaining below the uncontaminated value. These trends show that MSW leachate alters the soil-water interaction and consistency range of the tested clay, with the magnitude of change depending on leachate chemistry and exposure period. The findings demonstrate the need to account for soil-leachate compatibility when this Bauchi clay or comparable fine-grained soils are considered beneath dumpsites or for waste-containment applications.

Keywords: municipal solid waste; leachate; clay soil; plasticity; curing period

1.0 INTRODUCTION

Municipal solid waste (MSW) leachate is the aqueous phase generated when infiltrating water and the moisture released during waste decomposition percolate through a waste mass and dissolve or mobilize soluble constituents. Its composition is highly variable, but commonly includes dissolved organic matter, inorganic macro-components, heavy metals, ammoniacal nitrogen, and a wide range of xenobiotic organic compounds (Kjeldsen et al., 2002; Christensen et al., 2001; Renou et al., 2008). Because leachate chemistry evolves with waste composition, landfill age, climatic conditions, and degree of stabilization, the pore fluid reaching the underlying soil can vary considerably in pH, ionic strength, organic loading, and cation composition.

The environmental significance of leachate is particularly important where waste is deposited in open or poorly engineered dumps without effective liner and leachate-collection systems. Studies in Nigeria have documented leachate migration and associated changes in groundwater and soil chemistry around municipal waste disposal sites, including locations in Bauchi and other urban areas (Aromolaran et al., 2023; Lagasi et al., 2023; Tijjani et al., 2023). A directly related study by Chinade et al. (2017), conducted on compacted tropical soil from the Bauchi environment, found that unconfined compressive strength generally decreased as MSW-leachate permeation time increased. In that study, the commonly cited minimum UCS criterion of 200 kN/m² for waste-containment materials was maintained only up to about 42 days under British Standard Heavy compaction and 21 days under West African Standard compaction. Those strength losses provide an important companion context for the present work:

changes in Atterberg limits and consistency should not be interpreted in isolation, because leachate-induced physicochemical alteration can occur together with deterioration in mechanical performance.

Fine-grained soils are especially sensitive to pore-fluid chemistry because their engineering behaviour is governed not only by particle size and stress state but also by mineral surface charge, cation exchange, diffuse-double-layer interactions, and soil fabric. Changes in electrolyte concentration, cation valence, pH, and pore-fluid permittivity can therefore alter particle association, water adsorption, volume change, strength, and compressibility (Mitchell & Soga, 2005; Di Maio, 1996; Di Maio et al., 2004; Jang et al., 2018). Recent work has also emphasized that the liquid and plastic limits of clays reflect physicochemical interactions at particle surfaces and are consequently sensitive to changes in pore-fluid composition (Hasan & Abuel-Naga, 2024).

The interaction between landfill leachate and natural or engineered clay barriers has been investigated in several geotechnical studies. Leachate exposure has been associated with changes in index properties, microstructure, compressibility, shear strength, hydraulic conductivity, and mineralogical composition, although the direction and magnitude of the response depend strongly on clay mineralogy and leachate chemistry (Frempong & Yanful, 2008; Oztoprak & Pisirici, 2011; Emami et al., 2019; Ouria & Farsijani, 2019; Bahaa et al., 2024; Priya & Thyagaraj, 2025). Observations from tropical soils also indicate that cation exchange, mineral transformations, and changes in soil fabric may occur during leachate permeation (Osinubi & Nwaiwu, 2010).

Atterberg limits provide a practical means of evaluating these changes because the liquid limit, plastic limit, and plasticity index are related to clay mineralogy, water adsorption, workability, swelling potential, compressibility, and the strength state of fine-grained soils. The mechanisms controlling liquid limit are influenced by both particle-level frictional resistance and physicochemical forces (Sridharan & Prakash, 2000), while experimental studies with saline pore fluids show that the response may increase or decrease depending on mineralogy, electrolyte concentration, and cation type (Spagnoli & Sridharan, 2012; Curtin et al., 1994). Chemical compatibility is therefore a critical consideration where clay is used as a natural foundation or as a landfill barrier, because long-term exposure to aggressive pore fluids may alter both index and transport properties (Jo et al., 2005; Katsumi et al., 2001; Bowders et al., 1985).

Accordingly, the present study evaluates the effect of municipal solid waste leachate from four dumpsites in Bauchi metropolis on the liquid limit, plastic limit, plasticity index, and shrinkage limit of a locally occurring clay soil over curing periods of up to 35 days.

2.0 MATERIALS AND METHODS

2.1 Materials

2.1.1 Soil:

The soil used in the study was a naturally occurring clayey soil obtained in Bauchi Local Government Area, Bauchi State, Nigeria (approximately 10°18'N, 9°49'E). The sample was collected as a disturbed specimen at a depth of 1 m below the natural ground level.

2.1.2 Municipal Solid Waste Leachate

The municipal solid waste leachate used for the study was collected from four (4) different dumpsites situated in Bauchi metropolis named (A, B, C, and D) respectively. The chemical characteristic of the leachate samples was determined at the Public Health Engineering Laboratory of Abubakar Tafawa Balewa University, Bauchi Nigeria.

2.1.3 Water

The water used is a potable drinking water which was sourced from the soil laboratory Tap.

2.2 Methods

The following laboratory test were conducted

Natural moisture content

Particle size distribution

Specific gravity

Free swell

Atterberg limits

a) Liquid limit

b) Plastic limit

c) Shrinkage limit

2.2.1 Natural Moisture Content

The natural moisture content test was conducted by the oven-drying method in accordance with BS 1377-2 (British Standards Institution, 1990). The moisture content of the soil specimen was calculated as a percentage of the dry mass of soil to the nearest 0.1%, using Equation (i).

$$w = [(M_2 - M_3)/(M_3 - M_1)] \times 100 \quad (i)$$

Where:

w = moisture content

M_1 = Mass of empty container (g)

M_2 = Mass of container + wet soil (g)

M_3 = Mass of container + dry soil (g)

2.2.2 Determination of Particle Size Distribution

Particle-size distribution of the natural soil was determined using mechanical sieve analysis and hydrometer sedimentation procedures in accordance with BS 1377-2 (British Standards Institution, 1990) and the laboratory procedures described by Head (1992).

2.2.3 Determination of Specific Gravity

The specific gravity of the soil solids was determined using the density-bottle method in accordance with BS 1377-2 (British Standards Institution, 1990). Specific gravity was calculated using Equation (ii).

$$G_s = (W_2 - W_1)/[(W_4 - W_1) - (W_3 - W_2)] \quad (ii)$$

Where:

G_s = Specific gravity

W_1 = Mass of density bottle + stopper (g)

W_2 = Mass of density bottle, soil and stopper (g)

W_3 = Mass of density bottle, stopper, water and soil (g)

W_4 = Mass of density bottle, stopper and water only (g)

2.2.4 Determination of Free Swell

The free swell index was determined on soil passing the 425- μ m sieve using distilled water and kerosene, following the free-swell-index procedure in IS 2720 (Part 40) (Bureau of Indian Standards, 1977). The free swell index was calculated using Equation (iii).

$$S.I = [(V_w - V_k)/V_k] \times 100 \quad (iii)$$

Where:

$S.I$ = Free swell index (%)

V_w = Volume of soil in water (mL)

V_k = Volume of soil in kerosene (mL)

2.2.5 Atterberg Limits Determination

The consistency characteristics of the soil - liquid limit (LL), plastic limit (PL), and shrinkage limit - were determined in accordance with BS 1377-2 (British Standards Institution, 1990). Tests were performed using distilled water for the uncontaminated soil and MSW leachate as the pore fluid for the contaminated specimens.

2.2.5.1 Determination of Liquid Limit and plastic limit

The soil specimen for liquid-limit determination was air-dried and gently broken down using a pestle and mortar. A 200 g portion passing the 425- μ m sieve was thoroughly mixed with water until a homogeneous paste was obtained. The paste was sealed in an airtight cellophane bag for 24 h to allow

moisture equilibration before testing. A penetration-versus-moisture-content relationship was established, and the liquid limit was taken as the moisture content corresponding to 20 mm cone penetration.

The same procedure was followed using municipal solid waste (MSW) leachate instead of distilled water. Five 200 g specimens were mixed with the respective leachate and cured for 7, 14, 21, 28, and 35 days before liquid-limit testing.

Plastic-limit tests were similarly conducted using distilled water for the uncontaminated soil and MSW leachate for the contaminated specimens.

The experimental records available for this study did not include replicate Atterberg-limit determinations or standard deviations for each leachate-curing combination. Consequently, the values reported in Figures 2-5 are treated as descriptive measurements of the observed trends, and no claim of statistical significance is made. This absence of replicate variability data is a limitation of the study and should be addressed in future work through duplicate or triplicate determinations with error estimates.

2.2.5.2 Determination of Plasticity Index

The plasticity index was calculated from the measured liquid and plastic limits using Equation (iv).

$$I_p = W_L - W_p \quad (iv)$$

Where:

I_p = Plasticity index (%)

W_L = Liquid limit (%)

W_p = Plastic limit (%)

2.2.5.3 Determination of Shrinkage Limit

The shrinkage response was determined in accordance with the adopted BS 1377-2 procedure, using distilled water and MSW leachate as the wetting fluids. Percentage shrinkage was calculated from specimen lengths before and after drying using Equation (v).

$$S = (1 - L_1/L_0) \times 100 \quad (v)$$

Where:

L_1 = Length after drying

L_0 = Length before drying

Distilled water and MSW leachate were used as the wetting fluids in the respective tests.

3.0 RESULTS AND DISCUSSION

3.1 Physical properties of the soil

The natural soil contained 89% material passing the No. 200 sieve, with a liquid limit of 32%, plastic limit of 14%, plasticity index of 18%, shrinkage limit of 12%, and free swell of 45%. On the basis of these properties, the soil was classified as CL (low-plasticity clay) under ASTM D2487-11 and A-6(11) under AASHTO M 145-2012. The high fines content confirms that the behaviour of the soil is strongly controlled by the clay-silt fraction rather than by coarse-grained particle contacts. Although the liquid limit places the soil in the low-plasticity range, the free swell value of 45% is comparatively high for a CL soil and indicates a measurable tendency for volume increase on wetting. Free-swell response is influenced by clay-mineral type, exchangeable cations, soil fabric, and the contrast between water and the non-polar reference fluid; therefore it does not necessarily vary in direct proportion to liquid limit alone. A small proportion of more expansive clay minerals or fabric-related effects could contribute to the measured value, but mineralogical analysis and cation-exchange-capacity testing were not performed in this study, so the specific cause cannot be confirmed. The PI of 18% and the measured free swell nevertheless indicate appreciable moisture sensitivity, making the soil a useful medium for examining the effect of changing pore-fluid chemistry (Mitchell & Soga, 2005; Jang et al., 2018; Hasan & Abuel-Naga, 2024).

Table 1: Physical properties of the natural soil

Soil properties	Value
Natural moisture content (%)	26.9
Specific gravity	2.58
% passing sieve No. 200	89
USCS	CL
AASHTO classification	A-6 (11)
Liquid limit (%)	32
Plastic limit (%)	14
Plasticity index (%)	18
Shrinkage limit (%)	12
Free swell (%)	45

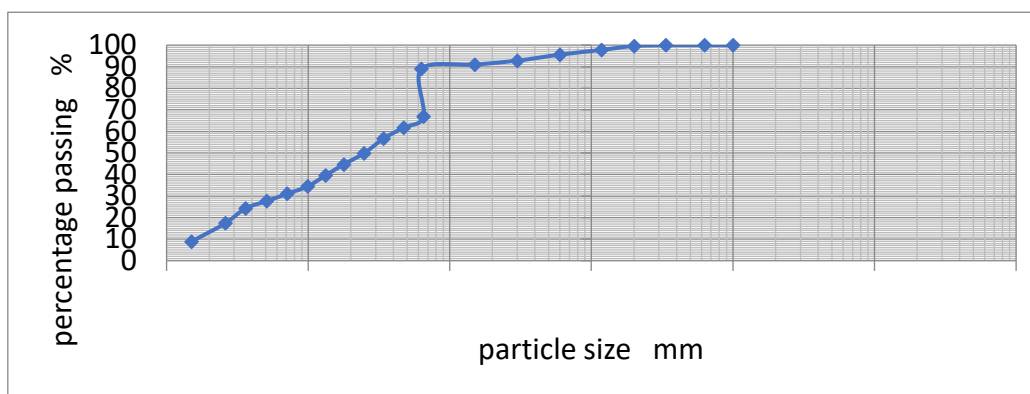


Table 2: Physical, chemical and biological properties of the leachate samples.

Property	Dumpsite Location			
	A	B	C	D
Temperature °C	25.5	26.2	25.9	25.8
pH	9.9	8.1	10.3	9.8
TDS	1270	1781	1407	1128
EC (µs/cm)	1730	2360	1910	1540
Turbidity (NTU)	5970	1640	1650	920
Colour	Black	Black	Black	Brown
Odour	Strong	Strong	Weak	Weak
BOD ₅	330	404	500	556
COD	1324	2334	2626	2837
Calcium (Ca)	55.9	438	168	54.4
Iron, (Fe)	5.60	0.64	0.30	0.08
Manganese, (Mn)	0.30	0.50	0.10	0.10
Sodium, (Na)	320	720	580	240
Potassium, (K)	400	500	500	600
Cadmium, (Cd)	0.003	0.014	0.0	0.005
Chromium, (Cr)	0.044	0.068	0.047	0.028
Zinc, (Zn)	0.56	0.04	0.54	0.24
Lead (Pb)	0.97	0.77	1.05	0.85

The leachates also contained substantial concentrations of major cations, particularly Na (240-720 mg/L), K (400-600 mg/L), and Ca (54.4-438 mg/L), together with measurable Fe, Mn, Cd, Cr, Zn, and Pb. These constituents are geotechnically relevant because cation type and ionic strength influence clay surface charge, cation exchange, diffuse-double-layer thickness, and particle aggregation. Monovalent sodium can favour dispersion under some chemical conditions, whereas divalent cations such as calcium may promote flocculation and reduce swelling; in mixed leachate systems, competing ions and organic matter can produce complex net effects (Curtin et al., 1994; Jo et al., 2005; Mitchell & Soga, 2005). The values measured in this study are also consistent with the broad chemical variability reported for landfill leachates and with evidence of dumpsite-related contamination in Nigeria (Christensen et al., 2001; Aromolaran et al., 2023; Lagasi et al., 2023; Tijjani et al., 2023).

3.3 Effect of leachate on liquid limit, plastic limit, shrinkage limit and plasticity index

Figures 2-5 show that the response of the clay to leachate was time-dependent and that the four leachates produced broadly similar trends, although with different magnitudes. The observed changes reflect the combined influence of dissolved salts, monovalent and divalent cations, organic constituents, and pH on clay-water interactions. Because these chemical effects may promote either dispersion or flocculation depending on mineralogy and pore-fluid composition, changes in consistency limits are

not expected to follow a single universal direction (Di Maio, 1996; Oztoprak & Pisirici, 2011; Jang et al., 2018).

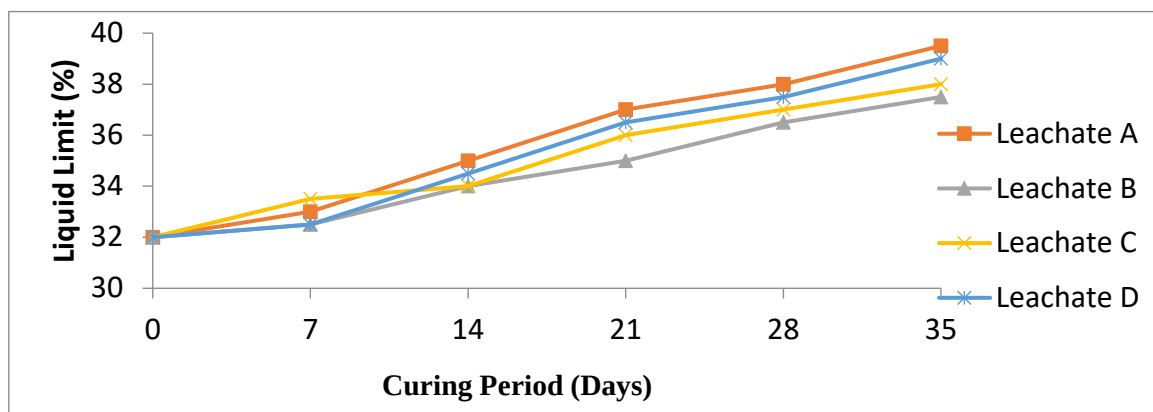


Figure 2: Variation of liquid limit with curing period

Liquid limit increased progressively with exposure time for all four leachates. From an uncontaminated value of 32%, the 35-day values reached 39.5%, 37.5%, 38.0%, and 39.0% for leachates A, B, C, and D, representing increases of approximately 17-23%. The increase indicates that a greater water content was required for the contaminated clay to reach the liquid state. This behaviour is consistent with a time-dependent alteration of the clay fabric and surface-water interaction rather than a simple dilution effect. Landfill leachate can induce cation exchange, dissolution/precipitation reactions, and mineral or fabric transformations in clay soils (Frempong & Yanful, 2008; Oztoprak & Pisirici, 2011). Although concentrated electrolytes often compress the diffuse double layer and can reduce the liquid limit of highly active clays, mixed leachates contain multiple ions and organic constituents, so the net response can be an increase, decrease, or limited change depending on clay mineralogy and exposure conditions (Di Maio et al., 2004; Spagnoli & Sridharan, 2012; Hasan & Abuel-Naga, 2024). The progressive increase observed here therefore suggests that, for this low-plasticity Bauchi clay, the leachate-induced changes increased the amount of pore fluid associated with the transition to liquid behavior.

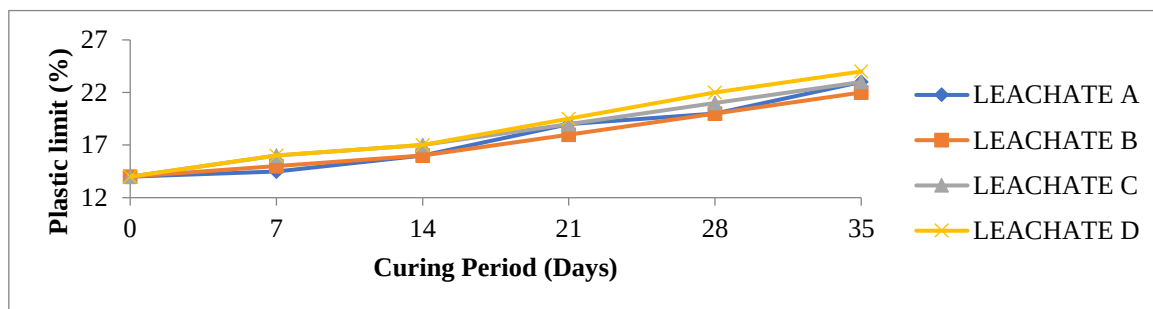


Figure 3: Variation of plastic limit with curing period

The plastic limit also increased with curing period, from 14% for the natural soil to 22-24% after 35 days. The increase was larger proportionally than the increase in liquid limit, amounting to approximately 57-71% across the four leachates. This indicates that leachate exposure shifted the lower boundary of the plastic state to substantially higher water contents. Plastic-limit changes can arise from modified particle associations, altered adsorbed-water conditions, and chemical reactions at clay surfaces. Pore-fluid chemistry has been shown to influence fine-grained soil fabric and macroscopic consistency through changes in electrical interparticle forces (Jang et al., 2018), while leachate-exposed clays have demonstrated time-dependent changes in index and microstructural properties (Oztoprak & Pisirici, 2011; Bahaa et al., 2024). The similarity of the trend for all four leachates suggests that exposure duration was an important controlling factor, although the slightly higher final plastic limit for leachate D indicates that differences in leachate composition also influenced the response.

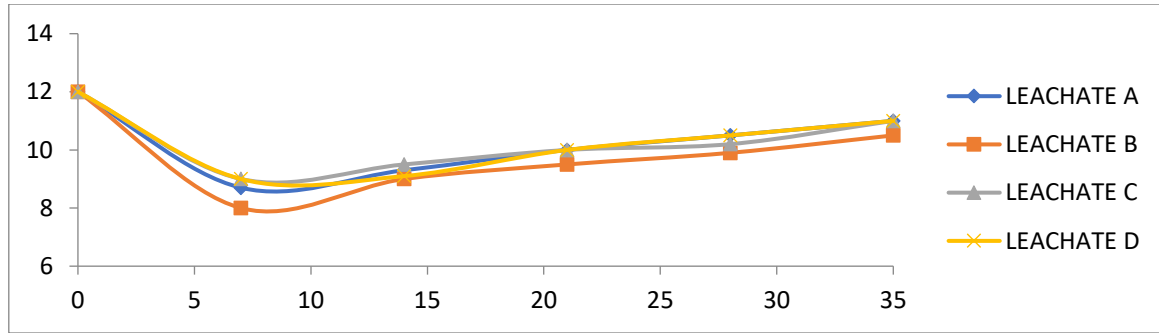


Figure 4: Variation of shrinkage limit with curing period

Shrinkage-limit behaviour differed from the liquid and plastic limits. The natural shrinkage limit of 12% fell sharply after 7 days of leachate exposure to approximately 8.0-9.0%, after which it gradually increased to 10.5-11.0% by 35 days. Thus, although partial recovery occurred with continued curing, the shrinkage limit remained below the uncontaminated value for all four leachates. A lower shrinkage limit means that volume reduction can continue to a lower water content before further drying ceases to cause shrinkage. The observed decrease-then-partial-recovery pattern is consistent with time-dependent physicochemical adjustment of the soil-leachate system, for example changes in ion exchange, diffuse-double-layer conditions, particle aggregation/dispersion, and fabric rearrangement reported for chemically exposed clays (Di Maio, 1996; Di Maio et al., 2004; Mitchell & Soga, 2005). However, these mechanisms are inferential in the present study rather than directly demonstrated, because the clay mineralogy, cation-exchange capacity, and post-exposure soil chemistry were not measured. The result should therefore be interpreted as an observed consistency change whose controlling mechanism remains to be verified by XRD, CEC, and related microstructural or chemical characterization. Similar studies of leachate-clay interaction have reported that index and volume-change characteristics evolve with exposure time rather than changing instantaneously (Ouria & Farsijani, 2019; Priya & Thyagaraj, 2025).

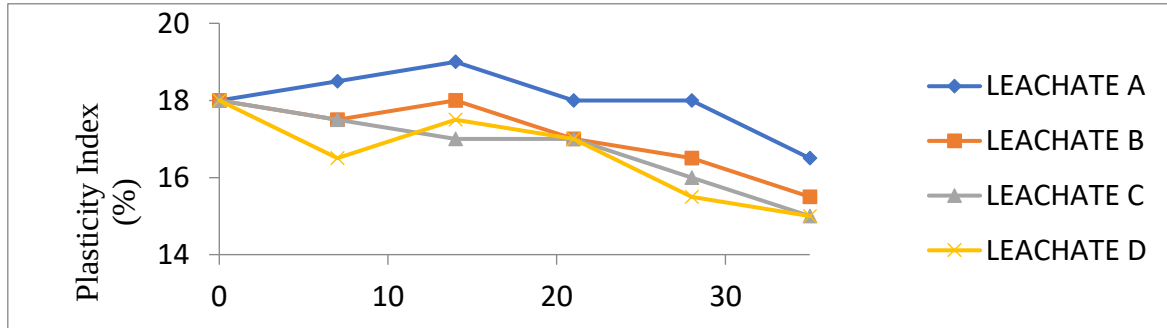


Figure 5: Variation of plasticity index with curing period

The plasticity index, calculated as $LL - PL$, showed a small early fluctuation but an overall decrease with prolonged exposure. From an initial value of 18%, the PI after 35 days decreased to 16.5%, 15.5%, 15.0%, and 15.0% for leachates A-D, respectively. This occurred because the plastic limit increased more rapidly than the liquid limit, thereby narrowing the range of water contents over which the soil remained plastic. The result is important because it differs from an interpretation based only on the increase in liquid limit: leachate exposure did not increase the overall plasticity range of this soil. Similar variability in the response of clay index properties to chemical pore fluids has been reported and depends strongly on mineralogy, electrolyte concentration, and cation valence (Sridharan & Prakash, 2000; Spagnoli & Sridharan, 2012; Curtin et al., 1994). Importantly, the reduction in PI should not be interpreted as improved engineering performance. In the companion Bauchti study of Chinade et al. (2017), unconfined compressive strength of compacted tropical soil generally decreased as MSW-leachate permeation time increased, despite the fact that strength behaviour cannot be inferred directly from PI alone. Taken together, the two studies suggest that leachate exposure can narrow the plasticity range while still degrading mechanical resistance. The practical implication is that a contaminated clay may become less plastic by the $LL - PL$ measure yet simultaneously experience changes in strength, compressibility, hydraulic conductivity, or fabric that are adverse for foundations

and landfill barriers (Frempong & Yanful, 2008; Emami et al., 2019; Bahaa et al., 2024). Direct strength and compressibility testing of the same specimens would be required to quantify those consequences.

From a waste-containment perspective, the combined changes in liquid limit, plastic limit, shrinkage limit, and plasticity index demonstrate that the tested Bauchi clay is sensitive to the chemistry of the four MSW leachates. Clay-barrier performance is controlled not only by initial classification but also by how the soil responds to the actual permeant; chemical-compatibility testing is therefore important before a clay is adopted as a landfill liner or relied upon as a natural attenuation layer (Bowders et al., 1985; Katsumi et al., 2001; Jo et al., 2005). Nevertheless, the present findings are specific to one clay soil and four leachates collected within Bauchi metropolis. They should not be generalized quantitatively to other soil mineralogies, landfill ages, or leachate chemistries without additional testing. Broader applicability would require replicate testing across multiple soil types, chemical/mineralogical characterization, and direct measurements of strength, compressibility, and hydraulic conductivity.

3.4 Study Limitations and Practical Implications

The principal limitation is the absence of replicate Atterberg-limit measurements and associated standard deviations, which prevents formal assessment of experimental scatter and statistical significance. In addition, XRD mineralogy, cation-exchange capacity, and post-exposure soil chemistry were not measured, so the mechanisms proposed for the observed consistency changes remain literature-supported hypotheses rather than directly verified processes. The study also considered only one Bauchi clay and four local leachates over a maximum curing period of 35 days. Future work should therefore include replicate testing, longer exposure periods, mineralogical and chemical characterization, and paired strength/compressibility/hydraulic-conductivity measurements. Such data would allow the observed plasticity changes to be linked quantitatively to engineering performance and would improve the basis for landfill-liner design or foundation assessment in contaminated ground.

CONCLUSION

From the results of the study, the following conclusions were drawn:

- i. The natural soil was classified as A-6(11) under AASHTO M 145-2012 and CL under ASTM D2487-11, with 89% passing the No. 200 sieve, liquid limit of 32%, plastic limit of 14%, plasticity index of 18%, shrinkage limit of 12%, and free swell of 45%.
- ii. The four MSW leachates were alkaline (pH 8.1-10.3) and contained high dissolved-solids and organic loads. BOD5/COD ratios of approximately 0.17-0.25 indicate low biodegradability and a relatively stabilized leachate character.
- iii. Leachate contamination caused systematic, time-dependent changes in the consistency characteristics of the clay soil.
- iv. Liquid limit increased from 32% to 37.5-39.5% and plastic limit increased from 14% to 22-24% after 35 days of exposure. In contrast, plasticity index generally decreased from 18% to 15-16.5% because the plastic limit increased more rapidly than the liquid limit.
- v. Shrinkage limit decreased sharply during the first 7 days of contamination and then partially recovered with curing, but remained below the natural-soil value after 35 days. This demonstrates that the effect of leachate on clay consistency is not monotonic and depends on the duration of soil-leachate interaction.
- vi. The observed changes are consistent with modification of clay-water interactions through effects such as ionic strength, cation exchange, pH, organic constituents, and time-dependent fabric rearrangement. Because mineralogy, cation-exchange capacity, and post-exposure soil chemistry were not measured, these mechanisms remain inferential and should be verified in future work.
- vii. For the tested Bauchi clay and the four local leachates, the results show that consistency properties are sensitive to leachate exposure and that chemical compatibility should be considered in waste-containment applications. The numerical trends should not be generalized to other clays or leachate chemistries without site-specific testing. Properly engineered landfill systems should incorporate effective liners, leachate collection and treatment, surface-water control, and routine monitoring of surrounding soil and groundwater.

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