EFFECT OF MUNICIPAL SOLID WASTE LEACHATE ON THE STRENGTH OF COMPACTED TROPICAL SOIL FOR LANDFILL LINER

Adamu Umar Chinade[1], Umar Saeed Yusuf[1], Kolawole Juwonlo Osinubi[2]

[1]Lecturer, Department of Civil Engineering, Abubakar Tafawa Balewa University, PMB 0248, Bauchi, Nigeria.
[2]Professor, Department of Civil Engineering, Ahmadu Bello University, Zaria, Nigeria.

***

Abstract - *The paper discusses the effect of municipal solid waste (MSW) leachate on the strength of compacted tropical soil for landfill liner. The leachate was obtained from an open dump site in Bauchi, Bauchi state Nigeria. The Mineralogy and chemical compositions of the soil were determined by means of X-ray Diffraction (XRD) and X-ray fluorescence (XRF) respectively. Tests specimens for unconfined compressive strength (UCS) was compacted at water contents of -2, 0, and +2% relative to the optimum moisture contents derived from three compactive efforts, namely; British Standard Light (BSL), West African Standard (WAS) and British Standard Heavy (BSH). UCS tests were carried out on specimens permeated with MSW leachate for period of 7, 21, 42, 84, and 120 days respectively. Results of the study showed that UCS of the compacted specimens generally decreased with increase in permeating periods for BSH, WAS and BSL compactive efforts respectively. The reduction in strength was due to the increase in clay size particles which lowered the frictional resistance between the solid particles at their contact points. UCS values greater than 200 kN/m^2 (minimum required for a material to be used in waste containment applications) where recorded for permeating periods up to 42 days for BSH and 21 days for WAS compactive efforts.*

***Key Words*: municipal solid waste (MSW) leachate, landfill liner, compacted tropical soil, unconfined compressive strength (UCS), permeating period, clay size particle, frictional resistance.**

1. Introduction

A landfill is an engineered facility used for disposing solid wastes on land without creating nuisances or hazards to public health or safety (contamination of soil and water sources), and are provided to accommodate the solid waste generated at specific site and at minimal cost. Alternative way for managing waste apart from landfills is incineration, even though the residue of incineration will still be disposed off in landfills. Reducing the amount of waste generated, reusing and recycling of the waste also minimize the amount of trash that must be disposed in landfills.

Landfill leachate is generated by excess rainwater percolating through the waste body. The pollutants from the waste material are transferred to the percolating water by the combination of physical, chemical and microbial processes [1]. Leachate may be characterized as water based solution of four groups of pollutants; dissolved organic matter, heavy metals, inorganic macro components, and xenobiotic organic compounds [2]. The composition of landfill leachate varies with different sites and environmental conditions, depending on the nature of the deposited waste, soil characteristics, rainfall patterns and on the age of landfill [3, 4].

To ensure the minimization of pollutant migration over long term, compacted soil liners have been used for many decades as engineered landfill materials. Compacted soil liners constitute of clayey materials that are placed and compacted in lifts called layers. Naturally occurring soils that contain substantial amount of clay are commonly used materials for hydraulic barriers in landfills [5, 6]. Compacted clay liners are constructed with the aim of achieving the minimum regulatory standards for hydraulic conductivity, unconfined compressive strength (UCS) and volumetric shrinkage strain. The standard requires that for a soil to be used as a hydraulic barrier, the hydraulic conductivity should be less than or equal to 1×10^{-9} m/s, UCS greater than or equal to 200 kN/m^2 and the volumetric shrinkage strain should not be greater than 4 % [7].

Clay liners have been used widely as hydraulic barriers to intercept the flow of hazardous liquid into surface and groundwater or as a component of composite liners. The properties and structure of a compacted liner can change with time due to changes in moisture content, capillary forces, and physico-chemical interactions with the liquid waste resulting in a reduction of the effectiveness of the liner as a barrier to contain solid and liquid waste. The changes in chemical characteristics of soils due to leachate contamination may be detrimental to the compacted soils.

To protect the groundwater from landfill contaminants, clay liners are widely used to impede the flow of leachate from the landfill. The suitability of a material for constructing a liner or cover depends primarily on low hydraulic conductivity, durability, resistance to weathering and compatibility with the leachate [8].
According to Osinubi and Nwaiwu [6], for a compacted soil liner to have adequate shear strength (a minimum unconfined compressive strength of 200 kN/m^2) and withstand the destructive forces of alternating wet and dry cycles, it is imperative to investigate the long term effect of MSW leachate on the strength of compacted material.

This study investigate the effect of municipal solid waste leachate on the strength of compacted tropical soil for waste containment applications. The test specimens were compacted using three different compaction energies, namely; British Standard Light BSL, West African Standard (WAS) and British Standard Heavy (BSH) and permeated using municipal solid waste leachate as the permeant fluid for periods of 7 days, 21 days, 42 days, 84 days and 120 days before testing for UCS. The UCS results are used to discuss the effect of MSW leachate on the strength of the compacted soil.

2. Characterization of materials

2.1 Tropical soil:

Preliminary tests were carried out for the identification and determination of the soil properties. The properties of the soil sample listed in Table 1 show that the soil is light brown in color having a liquid limit of 31.7 % and plasticity index 14.1 %, while the sand and clay contents of the soil were 15.6 % and 57.4 % respectively, and the percentage that passed the number 200 sieve is 84.4 %. In view of the foregoing, the soil is clayey sand and is ideal for use as a liner material for containment of municipal solid waste. Naturally occurring soils that contain substantial amount of clay are commonly used materials for hydraulic barriers in landfills [5, 6]

From the results of the Atterberg limit and sieve analysis, the soil is classified as A-6 (11) and CL in accordance with the American Association of State Highway and Transportation Officials (AASHTO M 145-2012)[9] soil classification system and Unified Soil Classification system (ASTM D 2487-2011)[10] respectively. These classification confirmed the soil to be clayey soil of low plasticity.

The chemical compositions of the soil determined using the XRF spectroscopy at the National steel Raw Material Exploration Agency (NSRMEA), Kaduna, is summarized in Table 2. The major oxides present in the soil are silicon oxide (SiO_2), 61.04 %; iron oxide (Fe_2O_3), 27.02 %; potassium oxide (K_2O) 6.44 %; and titanium trioxide (Ti_2O_3) 2.28 %.

The silica sesquioxide molar ratio of iron and aluminium obtained by dividing the percentage of silicon oxide (SiO_2) by the summation of the percentages of iron oxide (Fe_2O_3) and aluminium oxide (Al_2O_3) is 2.16 which indicates that the soil is neither classified as laterite or lateritic soil, therefore classified as other types of tropical soil. Lateritic soils can be distinguished from other soil types based on the ratios of silica (SiO_2) to sesquioxides (Fe_2O_3, Al_2O_3). In laterite the ratio is less than 1.33. Those between 1.33 and 2.0 are termed lateritic soils, and if the ratio is greater than 2.0 indicates other types of tropical soils [11].

Table -1: Physical properties of the tropical soil

Soil properties	Value
Natural moisture content w, (%)	5.8
Specific gravity	2.41
Percent passing sieve no. 200	84.4
Sand (0.075mm – 4.75 mm) %	15.6
Clay (<0.002 mm)	57.4
USCS	CL
AASHTO Classification	A-6 (11)
Group Index	11
Liquid limit (%)	31.7
Plastic limit (%)	17.6
Plasticity index (%)	14.1
Linear shrinkage (%)	15
Color	Light - brown
Silica Sesquioxide molar ratio of iron and aluminium	2.16

Table -2: Oxide compositions of the tropical soil

Oxide	Concentration (%)
SiO_2	61.04
Fe_2O_3	27.02
K_2O	6.44
Ti_2O_3	2.28
Al_2O_3	1.21
P_2O_5	0.54
SO_3	0.08
ZrO_2	0.43
CaO	0.50
Eu_2O_3	0.22
PbO	0.09
Na_2O	0.01
Cr_2O_3	0.01
MgO	0.01
V_2O_5	0.01
MnO	0.02
CuO	0.02
ZnO	0.01

2.1 Municipal Solid Waste (MSW) Leachate: The MSW leachate was collected from an active dump site in Bauchi.

The chemical compositions of the leachate were determined by means of the atomic absorption spectrophotometer (AAS) at the Public Health Engineering Laboratory in Abubakar

Tafawa Balewa University, Bauchi. The chemical and biological characteristics of the municipal solid waste leachate are presented in Table 3. The leachate sample has a pH value of 7.7 and a BOD_5 to COD ratio of 0.29. According to Christensen *et al*. [12], leachate is generally found to have pH between 4.5 and 9, the pH of young leachate is less than 6.5 while old landfill leachate has pH higher than 7.5. Therefore, a pH of 7.7 indicates that the leachate investigated in this study is in the methanogenic phase. Bhalla *et al* [13], reported that the degree of biodegradation of leachate is described by the BOD_5 to COD ratio which also gives information on the age of the landfill. BOD_5 to COD ratio in the range of 0.1 to 0.3 indicates the presence of high concentration of non-biodegradable organic compounds in the leachate. The low concentration of metals in the leachate, where calcium appears to have the highest concentration of 365 mg/l while lead has the lowest concentration of 0.002 mg/l is attributed to the domestic nature of the waste from which the leachate is formed.

Table -3: Characteristics of the municipal solid waste leachate

Parameter	Concentration (mg/l)
pH (mol^{-1})	7.7
Chemical Oxygen Demand, COD	135
Biological Oxygen Demand, BOD_5	38.9
BOD_5/COD	0.288
Copper, Cu	0.18
Calcium, Ca	365.0
Manganese, Mn	28.0
Lead, Pb	0.02
Chromium, Cr	0.06
Zinc, Zn	5.0
Magnesium, Mg	111.0
Sodium, Na	34.0
Cadmium, Cd	0.03
Potassium, K	115.0
Iron, Fe	75.0

3. Methodology

3.1 Determination of Optimum Moisture Content and Maximum Dry Density: Compaction test was conducted in accordance with BS 1377: part 2: (1990)[14]. The soil specimens were air dried in the laboratory. Prior to compaction, the soil particles were crushed to pass 4.76 mm sieve opening (BS No. 4 sieve) in accordance with [15]. Test specimens were compacted using three compaction energies namely: British standard heavy (BSH), West African standard (WAS) and British standard light (BSL) compaction, with a range of molding water contents from 10 to 25 % by weight of dry soil.

Approximately 3 kg of the air dried soil sample was thoroughly mixed with 10 - 25 % of water and compacted into three equal layers for the BSL compactive effort. Each layer was then given 27 blows of the 2.5 kg rammer falling freely through a height of 300 mm. For the WAS compactive effort, the soil was compacted into five layers, each layer receiving 10 blows of the 5.0 kg rammer falling through a height of 450 mm. Similarly for the BSH compaction, 5.0 kg rammer was used falling through a height of 450 mm onto 5 layers of soils each receiving 27 blows.

The dry density – moisture contents relationships was constructed and the optimum moisture contents (OMCs) and maximum dry densities (MDD) for the three compactive efforts were determined. Equations (1) and (2) were used to compute the bulk densities and the dry densities from the compaction results;

$$\rho = \frac{M_2 - M_1}{V} \qquad \ldots (1)$$

$$\rho_d = \frac{100\rho}{100 + w} \qquad \ldots (2)$$

Where;

ρ= Bulk density (Mg/m^3), M_1 = Mass of empty compaction mould (g), M_2 = Mass of mould + wet soil (g), w = Moisture content (%), ρ_d = Dry density (Mg/m^3)

3.2 Determination of Unconfined Compressive Strength (UCS): The unconfined compressive strength tests were conducted in accordance with BS 1377-7: (1990)[16]. The test were performed on the specimens permeated with municipal solid waste leachate. A weight of 3 kg of the soil was measured and compacted at molding water contents of -2 %, 0 % and +2 % relative to OMCs derived from the BSL, WAS and BSH compactive efforts. Test specimens of diameter 38 mm and 76 mm length were extruded from the moulds after the compacted samples have been permeated with leachate for periods of 7 days, 21 days, 42 days, 84 days, and 120 days respectively to simulate the actual field scenario. At the end of the permeation periods, three specimens each were taken for determination of UCS. The average of these three UCS measurements were computed and reported as the UCS of the specimens. The UCS was computed using the relation in Equation (3);

$$\sigma = \frac{RC_R(100 - \varepsilon\%)X1000}{100A_0} \qquad \ldots (3)$$

Where:

$\varepsilon = \frac{\Delta l}{l_0}$, ε = Strain (%), σ = Compressive stress at strain ε (kN/m^2), Δl = Amount of compression at any stage (m), R = Loading ring reading (kN), C_r = Mean calibration of load ring, L_o = Initial length of specimen (m), A_o = Initial cross-sectional area of specimen (m^2)

4. Results and Discussion

4.1. Compaction Characteristics

The relationship between moulding water contents and compactive efforts of the soil specimen is shown in Figure 1. The plots show that the compacted density is a function of moulding water content and compactive effort.

The soil compacted at the energy level of BSH yielded the highest MDD value of 1.68 Mg/m^3 with corresponding OMC value of 14.0 %. When the soil was compacted at the energy levels of WAS and BSL, the MDD values are 1.62 Mg/m^3 and 1.58 Mg/m^3 with the corresponding OMCs of 14.7 % and 14.8 % respectively. The trends observed are those of increasing MDD with increase in compactive effort and corresponding decrease in OMC with increase in compactive effort. The reason being that the MDDs of compacted soils generally increase with increase in compactive effort [17]. The results are consistent with the findings of Umar *et al* [17, 18] who reported an increase in MDD with corresponding decrease in OMC of laterite soil compacted at RBSL, BSL, WAS and BSH compactive efforts. Similar trends were also reported in a number of literatures such as [19, 20, 6, 21].

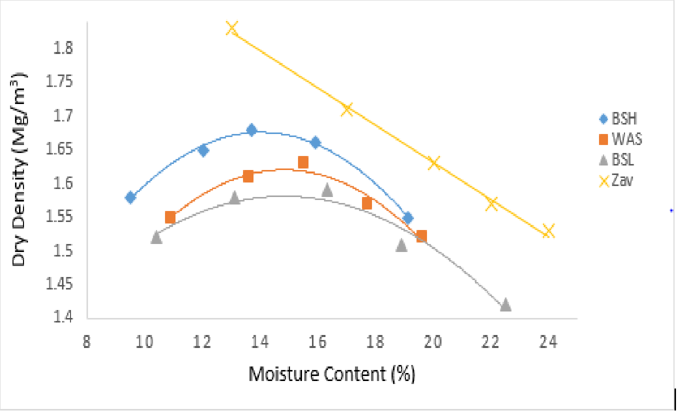
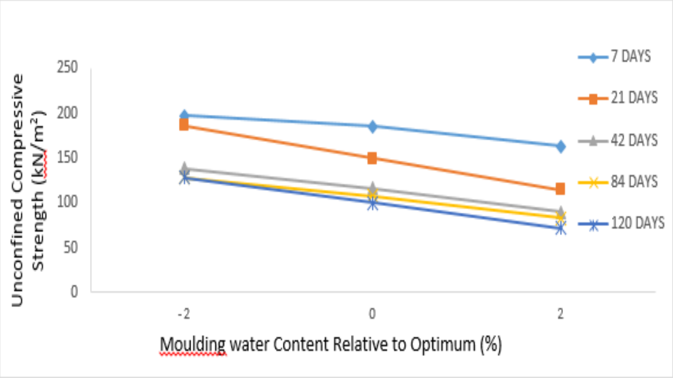


Figure 1: Moisture – Density Relationships of the Tropical Soil

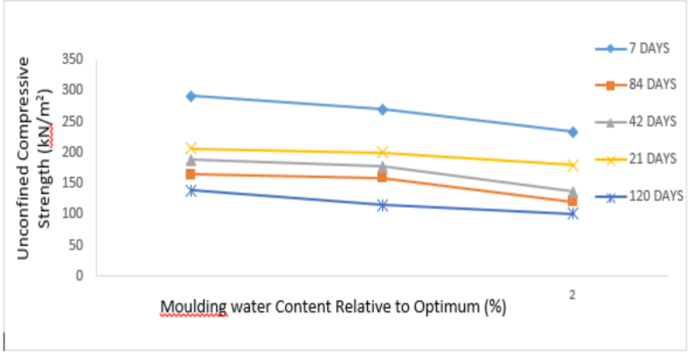
4.2. Effect of moulding water content relative to optimum on unconfined compressive strength

The variation of unconfined compressive strength of the compacted tropical soil with moulding water content relative to optimum for permeating ages of 7 days, 21 days, 42 days, 84 days and 120 days in MSW leachate are shown in Figures 2 (a, b, and c), for BSL, WAS and BSH compactive efforts respectively. The trends observed for the three compactive efforts used in the study are those of decreasing UCS with increase in moulding water content relative to optimum. The specimens compacted at -2 % of the OMCs gave UCS values that are greater than those compacted wet site of the optimum. This may be due to the fact that soil compacted at water content greater than the OMC would have lower MDD.

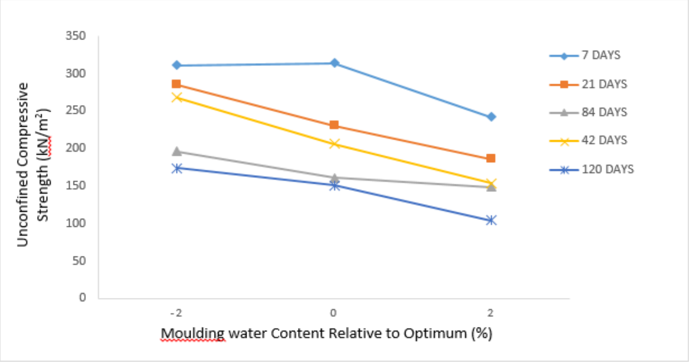
The results are consistent with those reported by Krishna *et al* [22], where it was observed that the moisture content of soil contaminated with MSW leachate increases with the degree of contamination thereby reducing the quality of soils underlying the MSW dumpsites.



(a) BSL Compactive Effort



(b) WAS Compactive Effort



(c) BSH Compactive Effort

Fig 2. Variation of Unconfined Compressive Strength with Moulding Water Content Relative to Optimum

4.3. Effect of permeating period on unconfined compressive strength.

The variation of UCS of soil specimens with permeating periods using MSW leachate as the permeant fluid at various compactive efforts and moulding water contents is shown in Figure 3. From the plots, there was a general decrease in UCS of the compacted specimens with increase in permeation period for all the compactive efforts used. The UCS of the compacted specimens decreased from 311 kN/m^2 to 104 kN/m^2, 292 kN/m^2 to 101 kN/m^2 and 197 kN/m^2 to 72 kN/m^2 for BSH, WAS and BSL compactive efforts respectively. The reduction in strength can be partly attributed to the increase in clay size particles which lowered the frictional resistance between the solid particles at their contact points. UCS values greater than 200 kN/m^2 (minimum required for a material to be used in waste containment applications) where recorded for permeating periods up to 42 days for BSH and 21 days for WAS compactive efforts. While for the BSL compactive effort, all the values recorded did not meet the UCS requirement for hydraulic barrier systems.

MSW leachate has been reported to have possessed degrading effect on compacted clay liner. [23], reported that leachate possesses the potential to disintegrate the coarser fraction of soil into clay size particles by physico-chemical reaction thereby increasing the expansive type clay fraction in the soil by altering the original particle size distribution. The gradual decrease in UCS could be due to this increased amount of clay mineral in the soil due to physico-chemical degradation of coarser grains.

The reduction in strength of the soil can also be explained from the diffuse double layer (DDL) theory [24]. Clay particles are negatively charged, therefore electrostatic forces exist between the negative surface and exchangeable cations. When clay particle comes in contact with a solution, cations from the solution are attracted to the clay surfaces to maintain electrical neutrality, as a consequence cation concentration gradient is formed. Because of this gradient, the cations will tend to diffuse away from the clay surface to the solution thereby producing an electrostatic surface property known as DDL of the clay particle. The nature and properties of these layers are highly dependent on the type of mineral and composition of the pore fluid. The thickness of the DL increases with decreasing concentration of cations contained in the fluid. The consequence of this double layer thickness is a reduction of the frictional properties of the clay through the separation of minerals and particles contacts by double layers or through swelling [25]. All processes that change the electric properties of DDL can change the physical properties and the macroscopic structure of clays. Therefore, the strength of the compacted soil may be affected by changes in attractive and repulsive pressures between the soil particles due to interaction of these DDLs.

The results are consistent with those reported by Alhassan [26]. The author showed a trend of decreasing MDD associated with higher OMC. An increase in the fine particles content of soil contaminated with MSW leachate was also reported by the author. On the contrary, Jayasekera and Mohajerani [23] reported a slight increase in UCS with maturing period for basaltic clay soil.

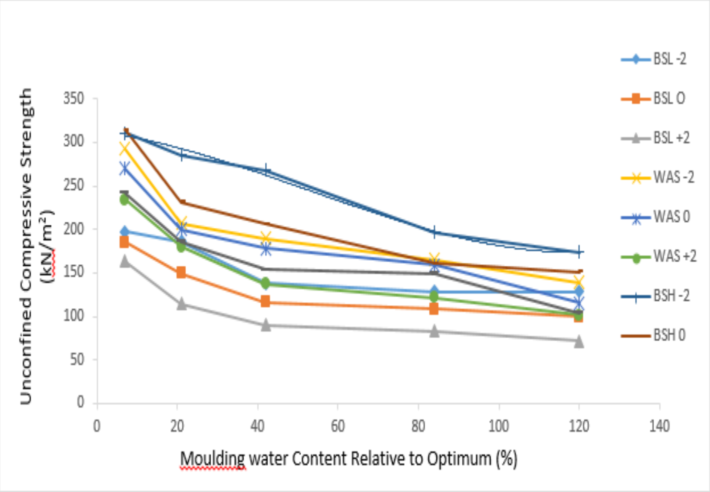


Fig 3. Variation of Unconfined Compressive Strength with Permeating Periods with Leachate as the Permeant Fluid

5. CONCLUSIONS

From the results of this investigation, the following conclusions were drawn:

i. The soil studied is classified as A-6 (11) and CL in accordance with the American Association of State Highway and Transportation Officials (AASHTO M 145-2012) soil classification system and Unified Soil Classification system (ASTM D 2487-2011) respectively.
ii. Oxide compositions of the soil determined by the X-ray fluorescence (XRF) spectroscopy method revealed that the silica sesquioxide molar ratio of iron and aluminium is 2.16, which indicates that the soil is neither classified as laterite or lateritic soil, therefore classified as other types of tropical soil.
iii. Chemical and biological characteristics of the MSW leachate revealed the presence of high concentration of non-biodegradable organic compounds due to the low BOD$_5$/COD ratio of 0.29. The trends of the compaction curves shows a general decrease in OMC with corresponding increase in MDD for the compactive efforts used.
iv. The results of the study indicate a gradual decrease in unconfined compressive strength of the specimens permeated with MSW leachate.
v. In general, none of the specimens permeated with leachate above 42 days met the minimum

unconfined compressive strength requirement of ≥ 200 kN/m^2 for a material to perform as liner in municipal solid waste containment systems. Therefore, leachate influenced the soil properties which consequently affect the satisfactory performance of a liner over time.

How to reference the authors

Chinade, A. U., Umar, S. Y. & Osinubi, K. J. (2017)……

REFERENCES

[1] Christensen, T. H. & Kjeldsen, P. (1989). Basis Biochemical Proceses in Landfills (Rev.ed.) London, UK, Academic Press.M. Young, The Technical Writer's Handbook. Mill Valley, CA: University Science, 1989.

[2] Christensen, T. H., Cossu, R. and Stegmann, R. (1994). Principles of Landfill Barrier Systems. Landfilling of Waste Barriers, Edited by T. H. Christensen, R. Cossu, & R. Stegmann, E & FN Spon, An imprint of Chapman & Hall. 3 - 10.

[3] Iaconi, C. D., Ramadori, R., Lopez, A. (2006). Combined biological and chemical degradation for treating a mature municipal landfill leachate. *Biochemical Engineering Journal.* 31: 118 - 124.

[4] Park, S., Choi, K. S., Joe, K. S., Kim, H. S. (2001). Variations of landfill leachate's properties in conjunction with the treatment process. *Journal of Environmental technology*. 22: 639 - 645.

[5] Benson, C. H., Daniel, D. E. & Boutwell, G. P. (1999). Field Performance of Compacted Clay Liners. *Journal of Geotechnical and Environmental Engineering*. 125: 390 - 403.

[6] Osinubi, K. J. & Nwaiwu, C. M. O. (2005). Hydraulic Conductivity of Compacted Lateritic Soil. *Journal of Geotechnical and Geoenvironmental Engineering.* 131: 1034 - 1041.

[7] US EPA, (1989). "Requirements for Hazardous Waste Landfills, Design, Construction and Closure," Tech. Rep. EPA-125/4-89. 022, EPA, Cincinati, Ohio, USA.

[8] Edil, T.B., Sandstrom, K. & Berthouex, P. M. (1992). Interaction of Inorganic Leachate with Compacted Pozzolanic Fly Ash. *Journal of Geotechnical Engineering,* 118(9): 1410 - 1430.

[9] AASHTO M145-91 (1991). Standard Specifications for Classification of Soils and Soil-aggregate Mixtures for Highway Construction Purposes, American association of State Highway and Transportation Officials, Washington, Wash, USA.

[10] ASTM D2487-11 (2011). Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System), ASTM International, West Conshohocken, Pa, USA.

[11] Blight, G. E. (1997). Origin and formation of residual soils. *Mechanics of Residual Soil*. 1-15.

[12] Christensen, T. H., Kjeldsen, P., Bjerg, P. L., Jensen, D. L., Christensen, J. B., Baun, A., ... & Heron, G. (2001). Biogeochemistry of landfill leachate plumes. *Applied geochemistry*, *16*(7), 659-718.

[13] Bhalla, B., Saini, M. S., & Jha, M. K. (2013). Effect of Age and Seasonal Variations on Leachate Characteristics of Municipal Solid Waste Landfill. *International Journal of Research in Engineering and Technology*. 02(08): 223 – 232.

[14] BS 1377:part 2 (1990). Methods of Testing Soils for Civil Engineering Purposes, British Standard Institution, London.

[15] Head, K. H. (1992). Manual of Soil Laboratory Testing: Soil Classification and Compaction Tests. Vol. 1, Pentech Press, London, UK.

[16] BS 1377:part 7 (1990). Methods of Testing Soils for Civil Engineering Purposes, British Standard Institution, London.

[17] Umar, S. Y., Elinwa, A. U. & Matawal, D. S. (2015). Hydraulic Conductivity of Compacted Lateritic Soil Partially Replaced with Metakaolin. *Journal of Environmental and Earth Sciences.* 5(4): 53 – 64.

[18] Umar, S. Y., Matawal, D. S. & Elinwa, A. U. (2016). Hydraulic Conductivity of Compacted Laterite Treated with Iron Ore Tailings. *Advances in Civil Engineering.* 1 – 8.

[19] Daniel, D. E. & Benson, C. H. (1990). Water content–density criteria for compacted soil liners. *Journal of Geotechnical Engineering*. 116: 1811 – 1830.

[20] Abichou, T., Benson, C. H. & Edil, T. B. (2000). Foundry green sand as hydraulic barriers: laboratory studies. *Journal of Geotechnical and Geoenvironmental Engineering.* 126(12): 1174 – 1183.

[21] Muhammad, N., Namdar, A. & Zakaria, I. B. (2011). Improving peat engineering properties by natural mineral mixture. *International Journal of Civil Engineering and Geo-environment*. 2: 23 – 27.

[22] Krishna, M. K., Chaitra, B. R., & Jjoti, K. (2016). Effect of Municipal Solid Waste Leachate on the Quality of Soil. *International Journal of Engineering Science*. 5(6): 69 – 72.

[23] Jayasekera, S., & Mohajerani, A. (2001). A study of effects of municipal landfill leachate on a basaltic clay soil. *Australian Geomechanics*, *36*(4), 63-73.

[24] Meril, G. B. (2014). *Studies on Landfill Leachate Transportation and Its Impact on Soil Characteristics* (Doctoral dissertation, Cochin University of Science and Technology).

[25] Moore, R. (1991). The chemical and mineralogical controls upon the residual strength of pure and natural clays. *Geotechnique*, *41*(1), 35-47.

[26] Alhassan, M. (2012). Effect of Municipal Solid Waste on Geotechnical Properties of Soils. *International Journal of Environmental Science, Management and Engineering Research.* 1(5): 204 – 210.