Journal of Mining and Geology Vol. 59(1) 2023. pp. 59 - 70 0022-2763
© Nigerian Mining and Geosciences Society (NMGS) - Printed in Nigeria.

Influence of Acid, Base and Salt Contamination on Geotechnical Properties of Lateritic Soils from Southwestern Nigeria

Owoyemi, O.O.
Department of Geology, College of Pure and Applied Science, Kwara State University, Malete, PMB 1530, Ilorin, Nigeria.
Corresponding E-mail: lade. owoyemi@gmail. com

Abstract

Pore water quality is often overlooked in geotechnical works and research. Samples of quartz schist-derived lateritic soil (S1) and granite gneiss-derived lateritic soils (S2) were mixed with solutions of varying pH spanning between pH 2 -12 and saltwater containing varying amounts of dissolved sodium chloride. The effect of this contamination on Atterberg limits, specific gravity, bulk density, compaction, California bearing ratio (CBR), shear strength, permeability and matric suction were investigated. Both soils contain kaolinite, quartz and goethite in varying proportions. Chemically, they contain silica, alumina, iron and titanium in order of abundance. Salt contamination resultsin reduced plasticity, specific gravity and bulk density. S1 samples which have higher kaolinite content exhibited greater reduction in these properties. Specific gravity and bulk density are highest for both soils when contaminated with alkaline water at pH 9. Optimum moisture content, permeability, cohesion and CBR reduced while maximum dry density and angle of internal friction increased with increasing salt contamination. Lateritic soils with the same mineralogy react differently to acid and base contamination due to variations in the minerals' percentage abundance. The presence of sodium chloride in the pore fluid of the soils caused agglomeration, a decrease in the diffuse double layer of their clay particles and cohesion.

Keywords: *Soil contamination, geotechnical properties, agglomeration, kaolinite, mineralogy, pH*

Introduction

Lateritic soils are residual soils readily available in humid tropical areas of the world. They form the foundations of most civil engineering structures such as roads, bridges, sanitary landfills and buildings in these areas(Gidigasu, 1976; Owoyemi and Adeyemi 2017; 2021). Industrial wastes eventually end up in soils, important groups of thesecontaminantsare acids, alkalis and salts which have been proven to modify soil properties (Rao and Chittaranjan, 2010; Liuand Zhang, 2014; Abuzeid and Abd El-Aal, 2016; Ying *et al.*, 2021). Research has shown that soil properties can be influenced by pore water chemistry (Mitchell and Soga, 2005; Abuzeid *et al.*, 2016; Matsumoto *et al.*, 2018; Momeni *et al.*, 2022). Acid rain, leachates from dumpsites, leakages from industries, acid mine drainage and soil liming for agricultural purposes and soil stabilization can change the pH of soil pore water. The pH of acid mine drainage contaminated soil can be lower than 3, while that of stabilized soil can be higher than 12 (Eades and Grim 1966; Galhardi and Bonotto, 2016; Jhaand Sivapullaiah, 2020; Zhang, *et al.*, 2020).

Salinization of groundwater and soil can result from both natural and human-induced processes (Ding *et al.*, 2011; Mahlknecht *et al.*, 2017; Jia *et al.*, 2017; Krishan, 2019; Cui *et al.*, 2019; Said *et al.*, 2021; Li *et al.*, 2022). Human activities leading to soil and water salinization include mining, oil extraction, steel production, pulp production, cement production improper irrigation practices, application of fertilizers; over-exploitation of groundwater in coastal areas, industrial brine discharge (Mahlknecht*et al.*, 2017; Schuler *et al.*, 2018; Litalien and Zeeb, 2020). The natural processes include the dissolution of salt deposits, deposition of weathered minerals rich in salt, drought and capillary rise of saline groundwater in low-water areas (Herczeg *et al.*, 2001; Shokrikuehni *et al.*, 2017; Cui *et al.*, 2019). Accidentalsalt and acid discharge during haulage and storage can also cause soil contamination.

Research by Gori (1994) on Atterberg limits of kaolinite at varying pH stated that the liquid limit of kaolinite is not dependent upon the pH of pore fluids while Wang and Siu, (2006) observed that kaolinite increases its compressibility at high pH values. Ghobadi *et al.*, (2014) reported that the shear strength of clay soil improved significantly when thepore fluid pHwas increased to 9 or decreased to 3. Gratchev and Towhata, (2009) investigated the effect of acid contamination on marine soils in Japan and reported that long-termclay-water interaction can alter compressibility properties. Ajalloeian *et al.*, (2013) showed that the Atterberg limits, compression index and swelling index offine-grained soil from Iran decreased while consolidation coefficient and shear strength parameters increased as pore water salinity increased. Mansouri *et al.*, (2017) investigated the effect of water salinity on the geotechnical properties of fine-grained soil and quartz sandstones and gathered that the compressibility index reduced while permeability and shear strength increased with increased salinity.

Other research has been conducted on the effect of pore water chemistry on the mechanical propertiesof clay and clay-basedsoils (Siddiqua *et al.*, 2014; Zhanget., 2015; Estabragh et al; 2018; Shabanianand Ouria, 2022), however, research on the influence of pore water chemistry on lateritic soil behaviour is still scanty. Standard methods for soil testing involving the addition of water to soil usually recommend distilled water or demineralized water. Sometimes, the water of this specification is not readily available and the effect of using mineralized and contaminated water is overlooked. There is a need to investigate the effect ofusing mineralized, seawater and non – neural water due to pollution in the determination of soil physical properties. In this work, the effect of acid, alkali and salt contamination on some important geotechnical properties of lateritic soil from Nigeriawas investigated.

The soil specimens used for this work were prepared from two bulk lateritic soilstaken from Oro (S1) and Ajase (S2). S2 is developed over granite gneiss of the Southwestern Basement Complex and S1 is developed over quartz shist bedrock(Figure 1). Both bedrocks belong to the Precambrian Basement Complex Rocks of Nigeria.

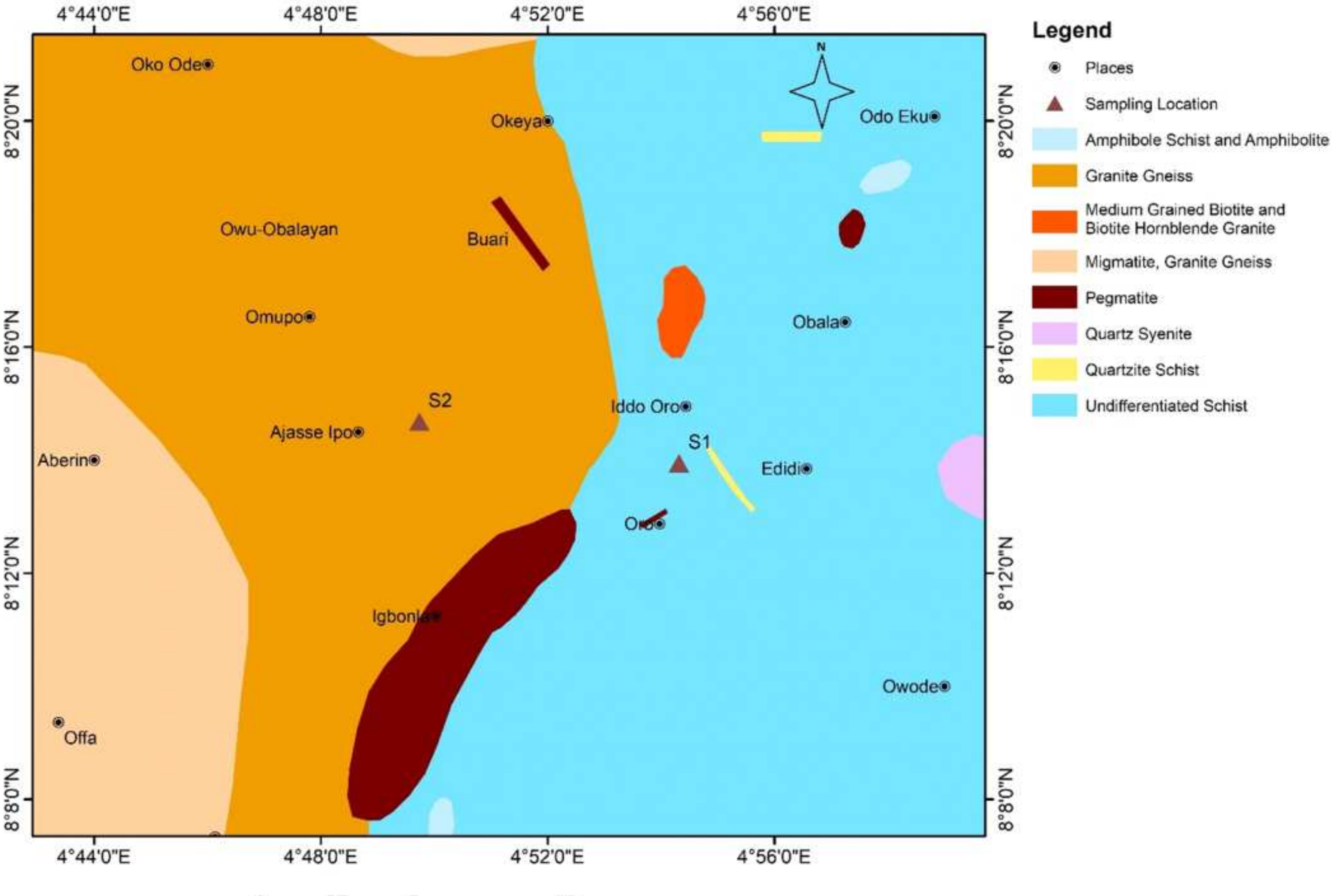

Fig. 1: Geology map showing the location of sampling sites(modified from NGSA, 2004)

Materials and **Methods**

Bulk samples were taken from active burrow pits where lateritic soils were being quarried for construction at 1 m depth. The samples were air-dried until a constant weight was achieved. The mineralogical, geochemical and geotechnical properties of the natural soilswere determined. Mineralogy was determined using the X-ray diffractometry (XRD) method using atheta-theta goniometer configured diffractometer at the Department of Geology, University of free State, South Africa. Data collection was done using Collector v. 3. 0c and Highscore v. 3. 0e equipped with the ICDD PDF-2 database for the evaluation of diffractograms.

Geochemistry of the natural soil was carried out using the X-ray fluorescence method (XRF) at the Department of Geology, University of free State, South Africa. Sodium components and other elements were determined using pellet disc and fusion disc respectively.

Natural moisture content, specific gravity, bulk density and consistency limits were carried out by British standard 1377 (1990). Grain size distribution analysis was carried out the Landmark University using D422-63 (2007) standard test method. Soil particles finer than 423µm were used for the determination of liquid and plastic limits. The liquid limit was carried out using the Casagrande method. Specific gravity was carried out using the pycnometer method while bulk density was carried out using a graduated cylinder. The soils were compacted using standard Proctor energy and compaction mould. Thereafter themoisture-dry density relationshipand soaked and unsoaked California Bearing ratio (CBR) were determined. Samples at the optimum moisture content (OMC) and maximum dry density (MDD) continuously sheared at a constant rate of 1. 25 mm/min were used for CBR determination. Unsoaked and soaked CBR of the soils were obtained at penetrations of 2. 5 and 5. 0 mm, while 48 hours of soaking was done before the determination of soaked CBR. Shear strength parameters were determined using a shear box while permeability was determined using a falling head permeameter using British Standard methods 1377 – 7 (1990) and 1377– 5 (1990) respectively. Samples compacted at standard Proctorlevel were soaked in water until they were fully saturated before connecting them to the permeameter. The samples used for theshear box test were compared at OMC using the standard Proctor compaction effort and they were sheared at arate of 0. 03 mm/min until maximum horizontal displacement or failure is reached. Normal stresses of 5, 10 and 15kPawere applied during the shearing of the specimens. Matric suction was carried out on Standard Proctor compacted samples at OMC and MDD using the standard method specified in ASTM D 5298 – 03 method. Grade 42 Whatman filter paper was used and matric suction in kPa was obtained from the standard calibration curve for Whatman Grade 42 paper based on the wetting testing procedure modified after ASTM D5298-10 cited in Kim *et al.*, (2017). This calibration curve was originally proposed by Greacen *et al.*, (1987) and it has a correlation coefficient greater than 0. 99 for filter paper moisture content and suction in kPa.

Differentsalts (NaCl) weights were dissolved in one litre each of demineralized water to give solutions of different salinities (20g/l, 35g/l, 50g/l and 70g/l). Two litres of these four saltwatersolutions were mixed with 6kg ofeach of the soils and allowed to sit in the laboratory for seven days. Distilled water contaminated with acid (H_2SO_4) and base (NaOH) was used to prepare water of different pH(s). The acid-contaminated water has pHs of 2 and 5 while the base-contaminated water has pHs of 9 and 11 respectively. 6 kg of soil samples were mixed with two litres of each water at pH 7, 2, 5, 9 and 11. The resulting contaminated and uncontaminated soils were then air-dried to constant weight before re–testing. Atterberg limits, specific gravity, bulk density, compaction, shear box, permeability and matric suction tests were repeated on air-dried contaminated soils to determine the influence ofpH and salinity variation on the soil samples.

The two soils used for this work have simple compositions comprising onlythree minerals namely, kaolinite, quartz and goethite. They are both rich in kaolinite with less than 40 % quartzcontent (Figure 2). The X-ray diffractograms of the soils are shown in Figure 3. In terms of chemistry, the major oxide in both soils includes silica, alumina, iron and titanium in order of abundance (Table 1). Apart from the reddish-brown colour of samples, the geochemistry of the samples (Table 1) shows that both soils are depleted in silica and enriched in sesquioxide (TiO_2, Fe_2O_3 and Al_2O_3) with a high loss on ignition. This is a basic characteristic of lateritic soils (Owoyemi and Adeyemi 2021). The total sesquioxide content in S2 is 39. 16% while that of S1 is 41. 01%. The geotechnical properties of the two soils are presented in Table 2.

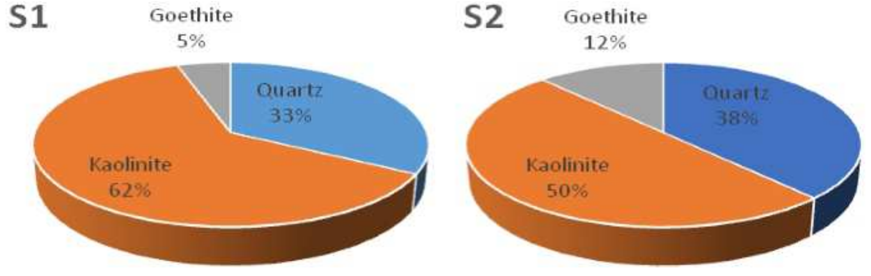

Fig. 2: Mineralogical composition of the soils

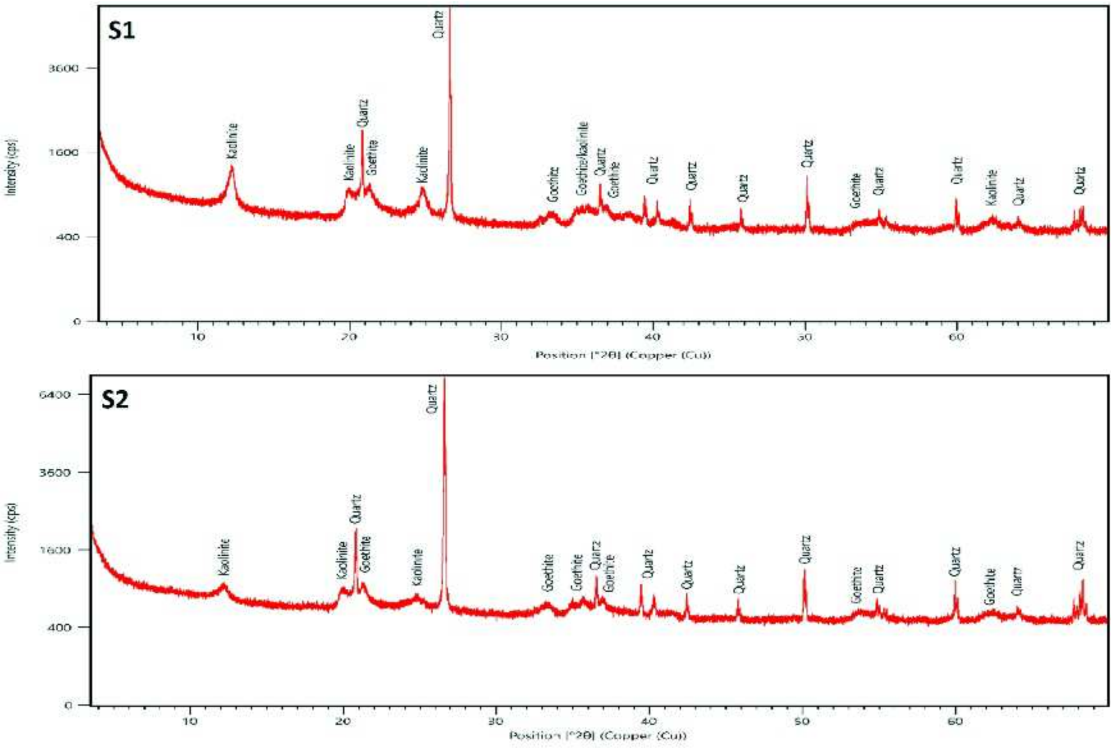

Fig. 3: X-ray diffractograms of the soils

Table 1: Elemental composition of the soils

XRF Major Elements (wt%)	S2	S1
SiO_2	50. 46	46. 63
TiO_2	1. 41	1. 74
Al_2O_3	20. 47	23. 43
Fe_2O_3	17. 28	15. 84
MgO	0. 09	0. 09
MnO	0. 15	0. 10
CaO	0. 10	0. 12
Na_2O	0. 01	0. 01
K_2O	0. 37	0. 16
P_2O_5	0. 07	0. 06
LOI	9. 12	10. 27
Total	99. 52	98. 46

Table 2: Physical properties of the natural soil soaked with water at pH 7.

S/N	S1	S2
NMC (%)	7. 3	4. 52
Gravel (>2mm)	1	6
Sand (<2mm)	57	49
Fines (<0. 075mm)	42	45
UCS class	CL	CL
Liquid limit (%)	45. 0	40. 0
Plastic limit (%)	34	29
plasticity index	11	11
specific gravity	1. 83	2. 29
Bulk density(kg/m^3)	1290	1268
The angle of internal friction (^{0})	5	10
Cohesion(kPa)	43	70
Permeability(m/sec)	9. 13932E-07	1. 54647E-06
Unsoaked CBR	13	57
Soaked CBR	3	13
Matric suction (KPa)	269. 4	269. 4
MDD (%)	1983. 3	1883. 4
OMC (%)	15. 2	18. 9

Results and **Discussion**

Atterberg Limits

Liquid limit and plasticity indexarehighest inS1 soil (62 % kaolinite) when contaminated with acid at pH 2. On the other hand, for S2 soil (50% kaolinite) the highest Atterberg limits are recorded in the control sample (CS) soaked with neutralwater(Figure 4). Generally, liquid limit values and plasticity index are higher in S2 soil when soaked with acid solutions. This implies that soil withthe same mineralogy will react differently to acid and base contamination due to variations in their percentage mineral composition. Liquid limitand plasticity indexeswere reduced with increasing salt content in both soils as shown in Table3. Irrespective of soil type, salt contamination leads to a decrease in plasticity. This is like the observation of previousresearch (Shariatmadari *et al.*, 2011; Ayininuola *et al.*, 2013; Ike, 2020). The addition of salt increasesthe ionic concentration in the pore fluid of the soil specimens, thereby, reducing the thickness ofthe diffusedouble-layer structure around the surfaces of the soil mineral grains. This enhances attraction between the clay mineral grains leading to agglomeration which in turn reduces plasticity. It is also noted that S1 samples which have higher clay content exhibit greater loss of plasticity

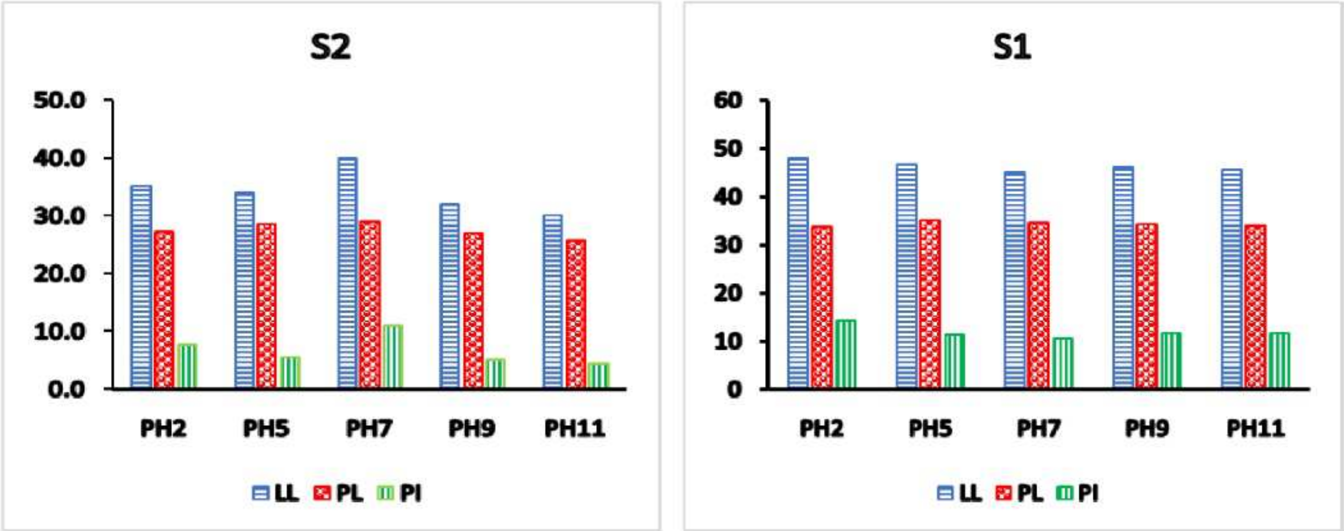

Fig. 4: Variation of Atterberg limits with pH*LL (Liquid limit), PL (Plastic limit), PI (Plastic limit).

Table 3: Variation of Atterberg limits with salt contamination

Sample	S1					S2				
Salt con. (g/l)	0	25	35	50	70	0	25	35	50	70
LL (%)	44	34	31	26	23	40.6	36	32	30	28
PL (%)	28	25.6	24.3	20	21.1	25.4	25.7	23.1	22	20
PL (%)	16	8.4	6.7	6	1.9	15.2	10.3	8. 9	8	8

Bulk Density **and** ***Specific Gravity***

Bulk density is influenced by both pore space and soil grain properties. The addition of salt increased the bulk density and specific gravity of both soils as shown in Figure5. The increase in specific gravity is because of an increase in the amount of dissolved solute in the soil. The increase in bulk density is because of the increase in the weight of the soil because of the additional weight of salt. Bulk density and specific gravity do not follow a specific pattern with variations in the pH of the contaminating solution. However, S1 soil samples containing higher amounts of kaolinite consistently exhibit lower bulk density and specific gravity values in comparison to the S2 samples. This might be because S2 samples have more quartz and iron content than S1 samples. Quartz and iron are denser than kaolinite which is the dominant mineral in the S1 soil. It is also observed that bulk density is highest for both S1 and S2 soils when contaminated with alkaline water at pH 9. Specific gravity is high in samples contaminated with alkali solutions for both soils (Figure 6). This might be due to increased dispersion in soil structure due to increased alkalinity in the soil which enables more soil solids to be packed into a small volume)..

Compaction Parameters

The S2 soil soaked with water at pH 7 (CS) exhibits higher MDD and OMC than S2 soil (Figure7). This

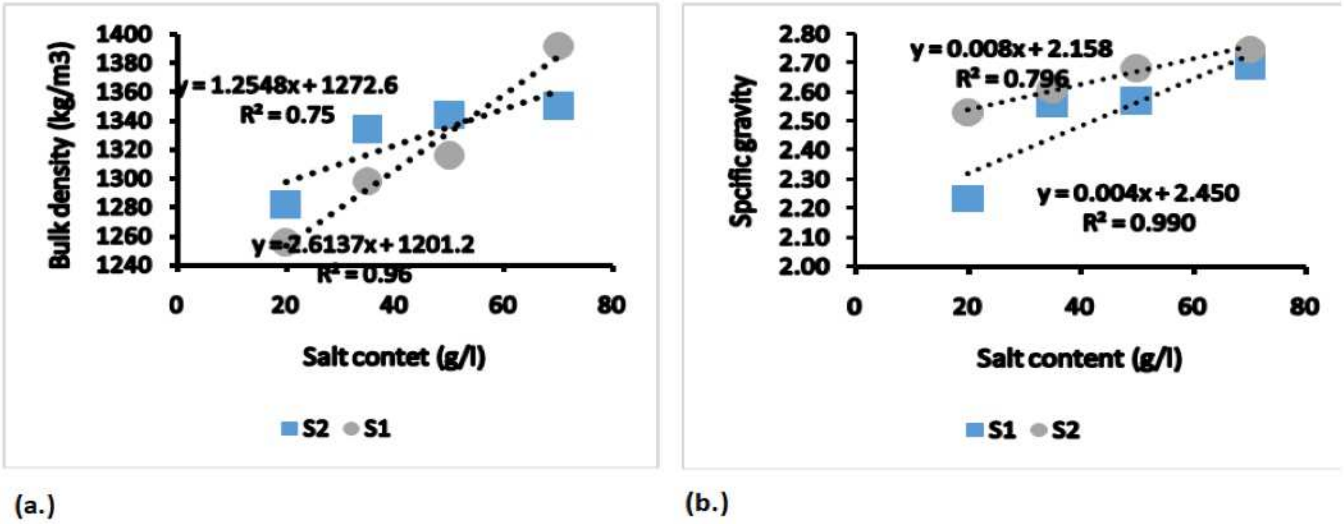

Fig. 5: Variation of (a.) bulk density and (b.) specific gravity with salt contamination

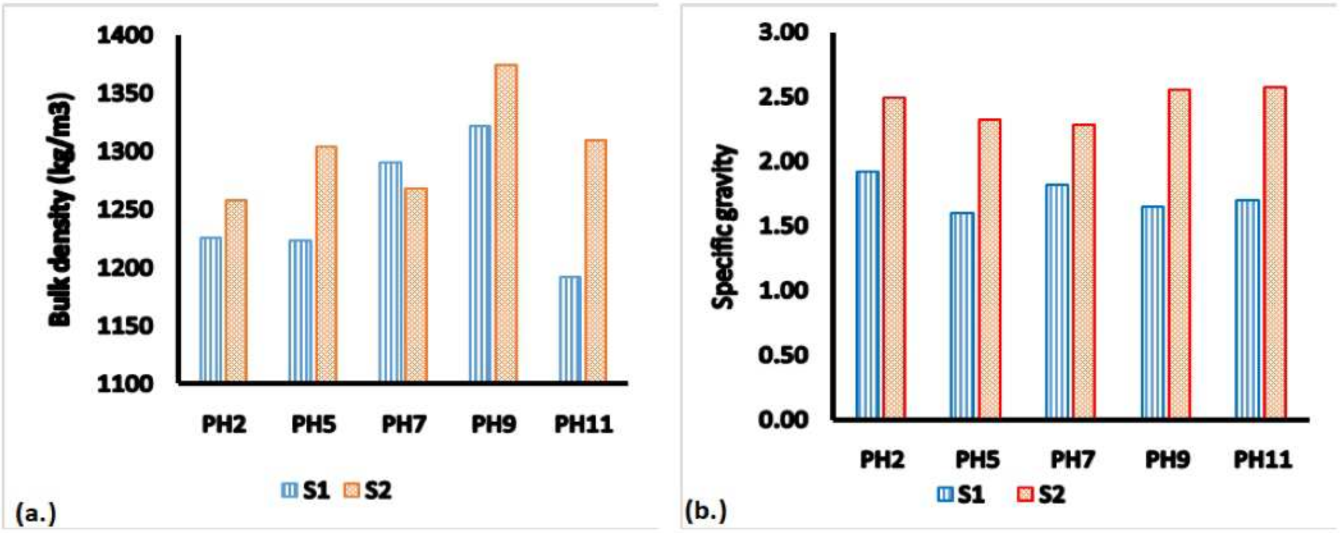

Fig. 6: Variation of (a.) bulk density and (b.) specific gravity and with pH

reflects the difference in their mineralogy, for example, S2 has higher quartz content than S1. OMC and MDD are minimum in both soils when contaminated with a basic solution at pH 11. The OMC and MDD of both soils contaminated with an acid solution at pH 5 yieldthe same OMC and MDD. Figure8shows the moisture-dry density relationship curves of both soils at different salt contamination levels. There is an increase in MDD anda decrease in OMC with an increase in salt content for both soils. This contrasts with the findings of Liu and Zhang, 2014who reported a reduction in both MDD and OMC in salt-contaminated soils with a 3% to 8% clay size fraction. However, this result is similar to the findings of Abood *et al.,* 2007*;* Shariatmadari *et al.,* 2011*;* Durotoye *et al.,* 2016cited in Ying *et al.,* 2021 who reported increased MDDand reduced OMC in highly plastic soils rich in clay minerals. The rise in MDD is however expected because of the increase in bulk density and decrease in plasticity of both soils with increasing salt contamination. The rise in MDD is because of clay particle agglomeration while the decrease in OMC is a result of the hydrophilic nature of NaCl.

Permeability

Soil samples contaminated with acid did not show significant variation in permeability. S2 soil samples soaked with a neutral solution and contaminated with a basic solution however show clearly that permeability is higher in S2 than in S1(Figure9a). Permeability increased with increasing salt contamination (Figure9b). This can be attributed to the increased flocculation of clay particles in the soils as salt

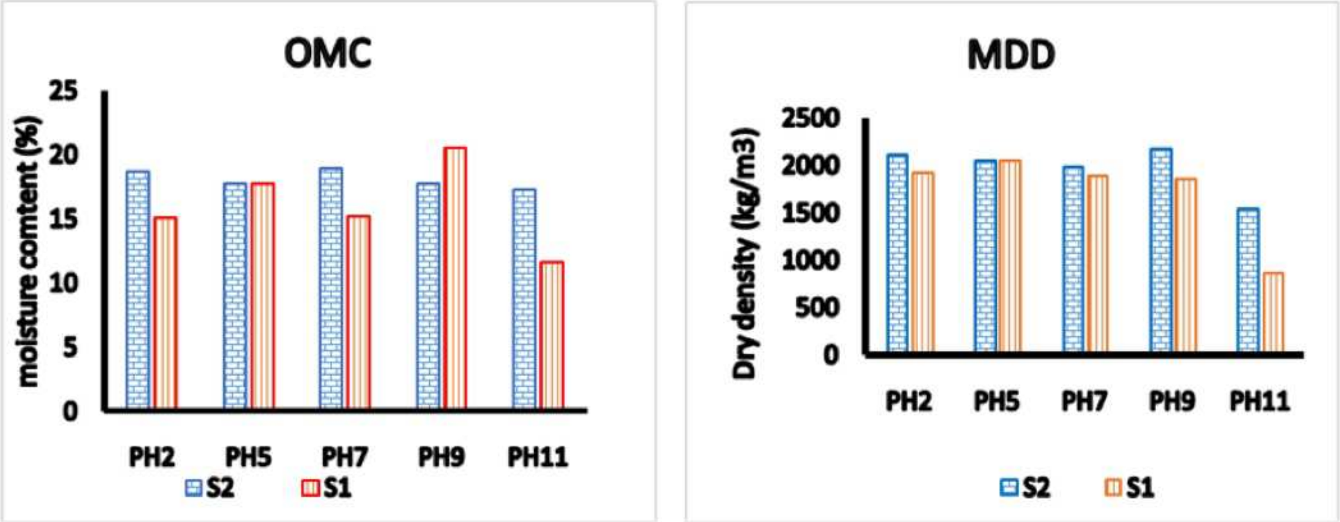

Fig. 7: Variation of optimum moisture content (OMC) and maximum dry density (MDD) with pH

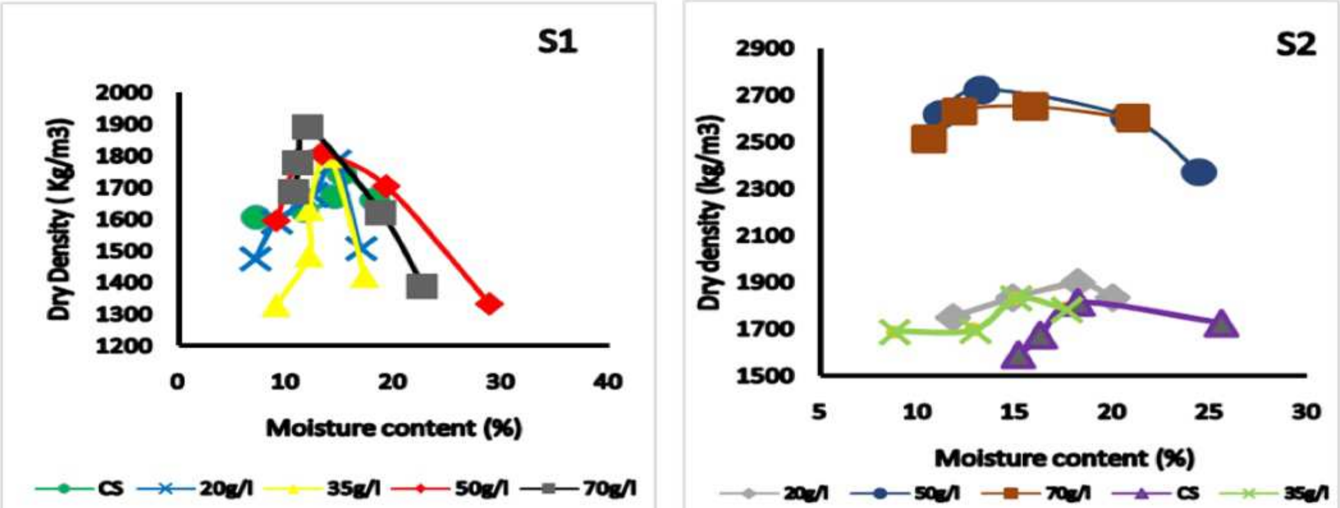

Fig. 8: Variation of compaction parameters with salt content

concentration increases. This increases available pore spaces in the soil samples, thereby inducing higher permeability in them. (Jose *et al.,* 1989, Wada *et al.,* 1989; Xu, 2020).

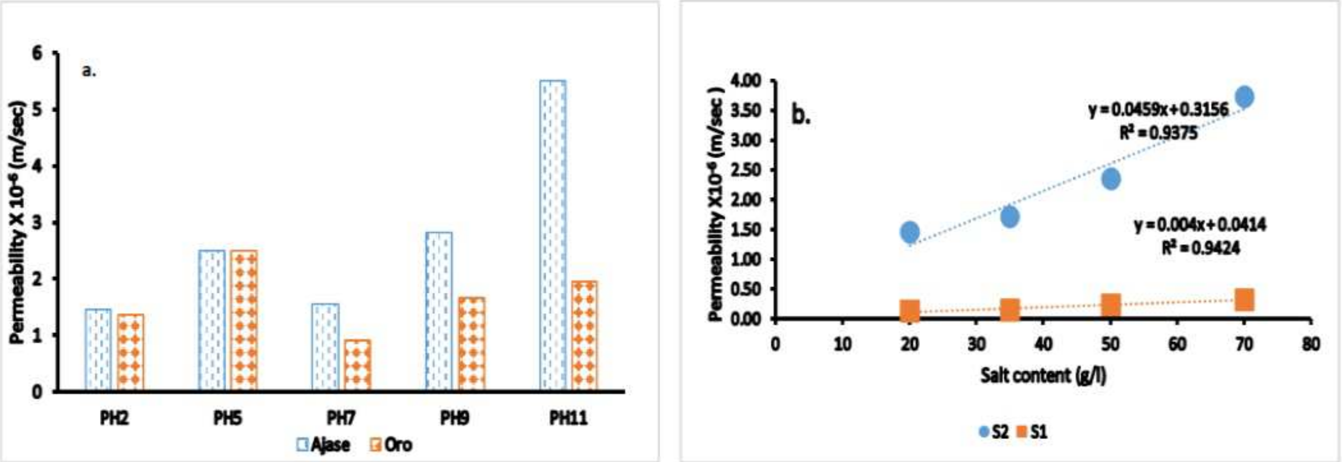

Fig. 9: Variation of permeability with (a.) pH (b.) salt content

soaked with neutral water (Figure 4). Generally, liquid limit values and plasticity index are higher in S2 soil when soaked with acid solutions. This implies that soil with the same mineralogy will react differently to acid and base contamination due to variations in their percentage mineral composition. Liquid limit and plasticity indexes were reduced with increasing salt content in both soils as shown in Table3. Irrespective of soil type, salt contamination leads to a decrease in plasticity. This is like the observation of previous research (Shariatmadari *et al.*, 2011; Ayininuola *et al.*, 2013; Ike, 2020). The addition of salt increases the ionic concentration in the pore fluid of the soil specimens, thereby, reducing the thickness of the diffuse double-layer structure around the surfaces of the soil mineral grains. This enhances attraction between the clay mineral grains leading to agglomeration which in turn reduces plasticity. It is also noted that S1 samples which have higher clay content exhibit greater loss of plasticity previous research (Shariatmadari *et al.*, 2011; Ayininuola *et al.*, 2013; Ike, 2020). The addition of salt increases the ionic concentration in the pore fluid of the soil specimens, thereby, reducing the thickness of the diffuse double-layer structure around the surfaces of the soil mineral grains. This enhances attraction between the clay mineral grains leading to agglomeration which in turn reduces plasticity. It is also noted that S1 samples which have higher clay content exhibit greater loss of plasticity.

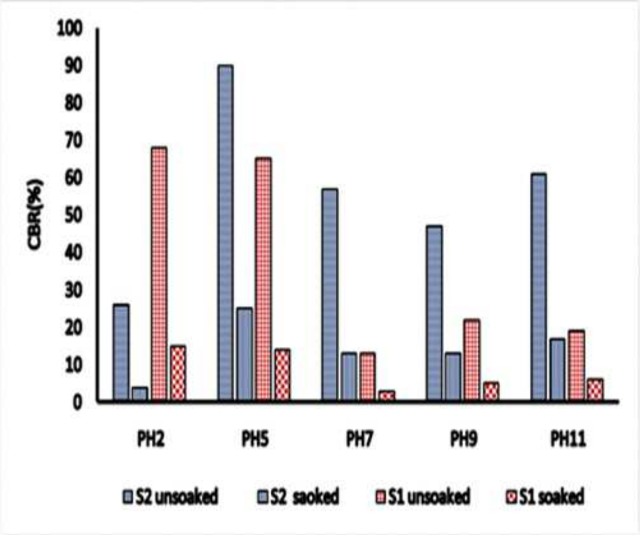

Fig. 10: Variation of CBR with pH

Table 4: Variation of CBR with salt contamination

Salt Contamination (%)	S2CBR (%)		S1 CBR (%)	
	Unsoaked	*Soaked*	*Unsoaked*	*Soaked*
0	81	24	50	14
20	62	17	56	18
35	55	15	35	8
50	45	13	18	5
70	37	10	16	5

Table 5: Variation of shear strength parameters with pH

pH	S1		S2	
	C (KN/m^2)	Ø°	C (KN/m^2)	Ø°
pH2	30	9	33	18
pH5	39	20	31	20
pH7	43	6	30	23
pH9	61	5	28	26
pH11	43. 5	21	27	30

Matric Suction

Soil suction helps to determine the moisture condition of unsaturated soils. It can also be used to predict their shear strength (Mahmood *et al.*, 2016; Pujiastuti *et al.*, 2018 cited in Owoyemi and Afolagboye, 2021). Both natural soils soaked with water at pH 7exhibit the same matric suction (Figure 12a). Samples contaminated with the base at pH 9 also exhibit the highest matric suction for both soils. Apart from the sample contaminated with the basic solution at Ph9, S2 samples show very little variation with contaminant pH. S1, on the other hand, exhibits lower pH when contaminated withlow-pH water. S2 samples also do not show variation in matric suction due to salt contamination (Figure 12b). However, for S1 samples, matric suction increased with an increase in salt contamination to a peak at 35% salt contamination and then decrease with a further increase in salt contamination. The matric suction of S2 soil seems to be insensitive to both the pH and salt content of the contaminant while that of S1 is sensitive. This might also be due to the difference in the proportion of kaolinite in them.

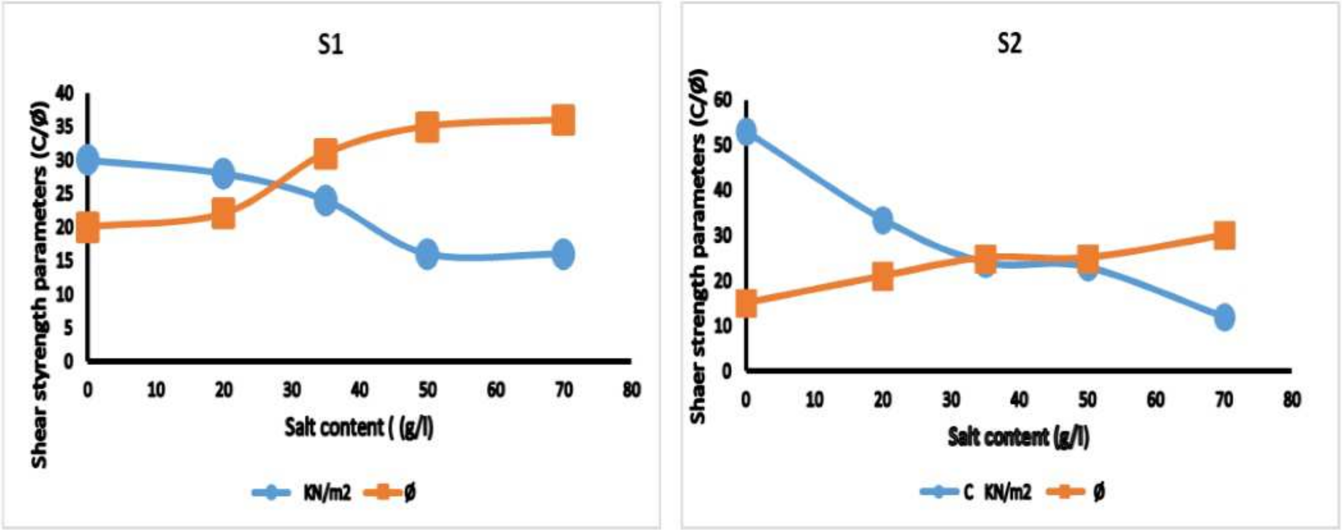

Fig. 11: Variation of shear strength parameters with salt contamination.

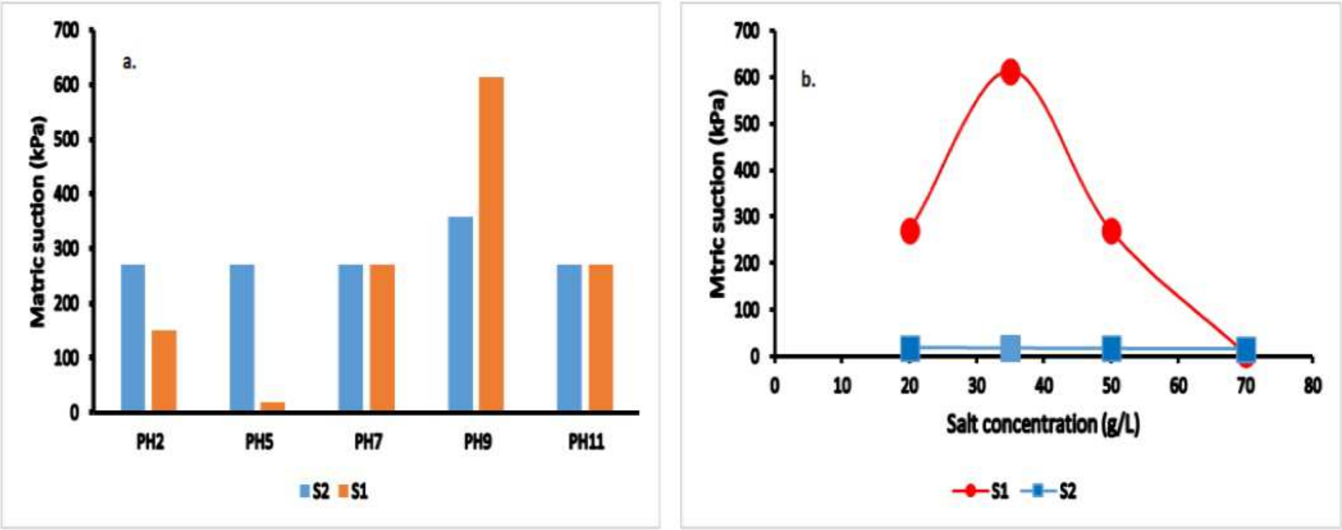

Fig. 12: Variation of matric suction with(a) pH, (b.) Salt concentration

Conclusion

The effectof acid, base and saltwater contamination on the geotechnical properties of lateritic soils was investigated in this work. Reduction in plasticity was recorded with increasing salt content irrespective of soil type. Liquid limit and plasticity index tend to be higher inacid-contaminated samples than in those contaminated with alkali solution. This implies a reduction in plasticity in alkali-contaminated soils depending on mineral components. An increase in specific gravity recorded with alkaline solution contamination for soil type can be attributed to increased dispersion in soil structure due to increased soil alkalinity which enables more soil solids to be packed into a small volume. Soils with the same mineralogy will react differently to acid and base contamination due to variations in percentage abundance. An increase in permeability, angle of internal friction, bulk density specific gravity and decrease in plasticity with an increase in salt contamination can be linked with agglomeration because ofan increase inionic concentration in the pore fluid of the soil specimens which reduces the thickness of the diffuse double layer structure around the surfaces of the soil mineral grains. The impact of variation in pore water chemistry is more severe in S1 soil because of the higher kaolinite content in it.

References

Abood, T.T., Kasa, A.B. and Chik, Z.B. (2007). Stabilisation of silty clay soil using chloride compounds. J. Eng. Sci. Technol. 2 (1), 102-110.

Abd El-Aal, A. K. and others. (2017). Effect of salinity of groundwater on the geotechnical properties of some Egyptian clay. *Egyptian Journal of Petroleum*, *26*(3), 643–648.

Abu zeid, M.M. and El-Aal, A.K.A. (2016). Effect of salinity of groundwater on the geotechnical properties of some Egyptian clay, Egypt. J. Petrol. http://dx. doi. org/10. 1016/j. ejpe. 2016. 09. 003.

Ajalloeian, R., Mansouri, H. and Sadeghpour. A.H. (2013). Effect of Saline Water on Geotechnical Properties of Fine-grained Soil. 18, 1419-1434.

ASTM D5298-10. (2010). Standard test method for measurement of soil potential (suction) using filter paper, annual book of ASTM standards. *ASTM International*. West Conshohocken

ASTM D 422-63. (2007). Standard Test Method for Particle Size Analysisof soils*ASTM International, West Conshohocken, PA. Doi:10. 1220/D0422*

ASTM D 5333 – 03. (2003). Standard Test Method for Measurement of Collapse Potential of Soils *Annual Book of ASTM Standards*, Vol 04. 09.

Ayininuola, G.M. and Agbede, O.A. (2013). Influence of Inorganic Salts on Soils Liquid and PlasticLimits., 15(1), pp. 51–60.

British Standard 1377 (1990). *Methods of testing for soils for civil engineering purposes*. London: BritishStandards Institution.

BS 1377:part 7 (1990). Methods of Testing Soils for CivilEngineering Purposes, British Standard Institution, London.

BS 1377:part 5 (1990). Methods of Testing Soils for CivilEngineering Purposes, British Standard Institution, London.

Cui, G., Lu, Y., Zheng, C., Liu, Z. and Sai. J., (2019). Relationship between soil salinization and groundwater hydration in Yaoba Oasis, NorthwestChina, "*Water*, vol. 11, no. 1, p. 175, Jan., Doi: 10. 3390/w11010175.

Ding, J., Wu, M., Tiyip, T., (2011). Study on soil salinization information in arid regionsusing remote sensing technique. Agric. Sci. China 10 (3), 404–411.

Durotoye, T.O., Akinmusuru, J.O., Ogbiye, A.S. and Bamigboye, G.O. (2016). Effect of common salt on the engineering properties of expansive soil. Int. J. Eng. Technol. 6 (7), 233e241.

Eades, J.L. and Grim, R.E. (1966). A quick test to determine lime requirements for lime stabilization. Highway Res. Rec. 139, 61–72.

Estabragh, A R., Soltani, A. and Javadi, A A. (2018). Effect of pore water chemistry on the behaviour of kaolin–bentonite mixture during drying and wetting cycles, European Journal of Environmental and Civil Engineering, DOI: 10. 1080/19648189. 2018. 1428691

Galhardi, J.A. and Bonotto, D.M. (2016). Hydrogeochemical Features of Surface Water and Groundwater Contaminated with Acid Mine Drainage (AMD) in Coal Mining Areas: A Case Study in Southern Brazil. Environmental Science and Pollution Research, 23, 18911-18927. https://doi. org/10. 1007/s11356-016-7077-3.

Gidigasu, M.D. (1976). Laterite soil engineering: pedogenesis and engineering principles. Amsterdam Elsevier Scientific, New York

Ghobadi, M.H., Abdilor, Y. and Babazadeh, R. (2014). Stabilization of clay soils using lime and effect of pH variations on shear strength parameters. Bull Eng Geol Environ 73, 611–619 https://doi. org/10. 1007/s10064-013-0563-7.

Gori, U. (1994). The pH influence on the index properties of clays. Bull. Int Assoc Eng Geo 50:37–42.

Gratchev, I.B. and Towhata, I. (2009). Effects of Acidic Contamination on the Geotechnical Properties of Marine Soils I Japan. " Paper presented at the Nineteenth International Offshore and Polar Engineering Conference, Osaka, Japan.

Greacen, E.L., Walker, G.R. and Cook, P.G. (1987). Evaluation of the Filter Paper Method for Measuring Soil Water Suction, International Conference on Measurement of Soil and Plant Water Status, 138.

Herczeg, A.L., Dogramaci, S.S. and Leaney, F.W J. (2001). Origin of dissolved salts in a large, semi-arid groundwater system: Murray Basin, Australia. Marine and freshwater Research 52, 41-52. https://doi. org/10. 1071/MF00040.

Ike, E. (2020). Effect of Ionic Concentrations andpHon the Atterberg Limitof Cohesive SoilGlobal Journal of Pure and Applied Sciences Vol. 26, 73-85DOI:https://dx. doi. org/10. 4314/gjpas. v26i1. 9.

Jha, A.K. and Sivapullaiah, P.V. (2020). Lime Stabilization of Soil: A Physico-Chemical and Micro-Mechanistic Perspective. Indian Geotech J 50, 339– 347 https://doi. org/10. 1007/s40098-019-00371-9.

Jia, Y., Guo, H., Xi., B., Jiang, Y., Zhang, Z., Yuan, R., Yi., W. and Xue., X. (2017). Sources of groundwater salinity and potential impact on arsenic mobility in the western Hetao Basin, Inner Mongolia. Science of the Total Environment 601–602 (2017) 691–702. http://dx. doi. org/10. 1016/j. scitotenv. 2017. 05. 196.

Jose, U.V., Bhat, S.T. and Nayak B.U. (1989) Influence of salinity on permeability characteristics of marine sediments, Marine Geotechnology, 8:3, 249-258, DOI: 10. 1080/10641198909379871.

Kim, H., Prezzi, M. and Salgado, R. (2017). Calibration of Whatman Grade 42 filter paper for soil suction measurement. *Can. J. Soil Sci.*, *97*, 93–98 dx. doi. org/10. 1139/cjss-2016-0064.

Krishan, G. (2019). Groundwater Salinity. Curr. World Environ. 14, 186–188.

Li, Z., Xie, Y., Ning, X., Zhang, X. and Hai, Q, (2022). Spatial distributions of salt-based ions, a case study from the Hunshandake Sandy Land, China. PLoS ONE 17(8): e0271562. doi:10. 1371/journal. pone. 0271562

Litalien., A. and Zeeb., B. (2020). Curing the earth: A review of anthropogenic soil salinization and plant-based strategies for sustainable mitigation. Science of the Total Environment 698 134235.

Liu, J. Y. and Zhang, L. J. (2014). The microstructure characteristics of saline soil in the QarhanSalt Lake area and its behaviours of mechanics and compressive strength. Arabian J. Sci. Eng. 39 (12), 8649e8658.

Mahlknecht, J., Merchán, D., Rosner, M., Meixner., A. and Ledesma-Ruiz. (2017). Assessing seawater intrusion in an arid coastal aquifer under high anthropogenic influence using major constituents, Sr and B isotopes in groundwater. Sci. Total Environ. 587–588, 282–295.

Mansouri, H., Jorkesh, Z., Ajalloeian, R. and Sadeghpour, A.H. (2017). Investigating effects of water salinity on geotechnical properties of fine-grained soil and quartz in a sandstone case study: Ajichayproject in northwest Iran. Bull Eng Geol Environ 76:1117–1128. DOI 10. 1007/s10064-016-0920-4.

Matsumoto, S., Ogata, S., Shimada, H., Sasaoka, T., Hamanaka, A. and Kusuma, G. J. (2018). Effects of pH-induced changes in soil physical characteristics on the development of soil water erosion. Geosciences (Basel Switzerland) 8, 134. doi 10. 3390/geosciences8040134.

Mitchell, J. K. and Soga, K. (2005) Fundamentals of Soil Behaviour, 3rd ed. John Wiley and Sons, Inc., New York, NY, USA.

Momeni, M., Bayat, M. and Ajalloeian, R. (2022). Laboratory investigation on the effects of pH-induced changes on geotechnical characteristics of clay soil, Geomechanics and Geoengineering, 17(1), 188-196, DOI: 10. 1080/17486025. 2020. 1716084.

Naeini, S. A., Jahanfar, M. A. (2011). Effect of salt solution and plasticity index on undrained shear strength of clays. *International Journal of Materials* and *Metallurgical Engineering* 5(1), 92-96.

NGSA (Nigerian Geological Survey Agency) (2004) Map 1: 100000. NGSA, Abuja, Nigeria.

Owoyemi, O.O. and Adeyemi, G.O. (2017). Variability in the Highway Geotechnical Properties of Two Residual Lateritic Soils from Central Nigeria. *J GeolGeophy*. 6 (3): 1- 9. doi: 10. 4172/2381-8719. 1000290.

Owoyemi, O.O. and Adeyemi, G.O. (2021). Characterization of soils derived from different parent rocks from north central Nigeria. *Proceedings of the Institution of Civil Engineers – Construction Materials* 174(6): 275-288. https://doi. org/10. 1680/jcoma. 18. 00027.

Owoyemi, O. O and Afolagboye, L. O. (2021). Mineralogy and collapse behaviour of compacted lateritic soils from North-central Nigeria. *Technoscience Journal for Community Development in Africa* 2:1 109–120. ISSN 2659-0573.

Pujiastuti H., Rifa'I , Adi, A.D. and Fathani, T.F. (2018). The effect of matric suction on the shear strength of unsaturated sandy clay. *International Journal of GEOMATE, 14*(42), 112-119. DOI: https://doi. org/10. 21660/2018. 42. 72825ISSN

Rao, A.V. and Chittaranjan, M. (2010). Harmful effects of certain Industrial wastes on geotechnical properties of soils - A review. Nature Environment and Pollution Technology. 9. 799-804.

Said, I., Salman, S.A. and Elnazer, A.A. (2022). Salinization of groundwater during 20 years of agricultural irrigation, Luxor, Egypt. Environ Geochem Health 44, 3821–3835 https://doi. org/10. 1007/s10653-021-01135-2.

Schuler, M.S., Cañedo-Argüelles, M., Hintz, W.D., Dyack, B., Birk, S. and Relyea, R.A. (2019). Regulations are needed to protect freshwater ecosystems from salinization. Philos. Trans. R. Soc. B: Biol. Sci. 374: 20180019. doi:10. 1098/rstb. 2018. 0019.

Shabanian, M. and Ouria, A. (2022). Effect of the steady-state pH of kaolinite pore fluid on its microstructure and geotechnical properties. Arab J Geosci 15, 1437 https://doi. org/10. 1007/s12517-022-10689-z https://link. springer. com/article/10. 1007/s12517-022-10689-

Shariatmadari, N., Salami, M. and Fard, M.K. (2011). Effect of inorganic salt solutions on some geotechnical properties of soil-bentonite mixtures as barriers. Int. J. Civ. Eng. 9 (2), 103e110.

Shokrikuehni, S.M.S., Norouz Rad, M., Webb, C. and Shokri, N. (2017). Impact of type of salt and ambient conditions on saline water evaporation from porous media. Adv. Water Resource., 105, 154–161.

Siddiqua, S., Siemens, G., Blatz, J., Man, A. and Lim, B.F. (2014). Influence of Pore Fluid Chemistry on the MechanicalProperties of Clay-Based Materials. Geotech Geol Eng. DOI 10. 1007/s10706-014-9778-z

Wada, K. and Beppu, Y. (1989). Effect of Aluminum Treatments on Permeability and Cation Status of a Smectitic Clay. Soil Science Society of America Journal. 53(2). https://doi. org/10. 2136/sssaj1989. 03615995005300020015x

Wang, Y. and Siu, W. (2006). "Structure characteristics and mechanical properties of kaolinite soils. 1. Effects of structure on mechanical properties. " Canadian Geotechnical Journal. 43 (6). 587-600, DOI: 10. 1139/t06-026.

Xu, P., Zhang, Q., Qian, H. and Qu, W. (2020). Effect of Sodium Chloride Concentration on Saturated Permeability of Remolded Loess. Minerals, 10(2), 199; https://doi. org/10. 3390/min10020199

Ying, Z., Cui, Y., Benahmed, N. and Duc, M. (2021). Salinity effect on the compaction behaviour, matric suction, stiffness and microstructure of a silty soil. Journal of Rock Mechanics and Geotechnical Engineering. 13(4). 855-863. https://doi. org/10. 1016/j. jrmge. 2021. 01. 002.

Zhang, T.W., Deng, Y.F., Liu, S.Y. and Zhang, D.W. (2015). Preliminary Study of Pore Water Chemistry Effect on the Physical and MechanicalBehaviour of Artificial Mixed Soil. IFCEE March 17-2 San Antonio Texas 133-141https://doi. org/10. 1061/9780784479087. 014.

Zhang, Y., Daniels, J.L., Cetin, B. andBaucom, I.K. (2020). Effect of Temperature on pH, Conductivity and Strength of Lime-Stabilized Soil. J. Mater. Civ. Eng., 32(3). DOI: 10. 1061/(ASCE)MT. 1943-5533. 0003062.