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Soil Erodibility Characterization of the Southwestern Nigerian Basement and Sedimentary Terrains Using Geochemical and Geotechnical Techniques

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Abstract
Our lack of full understanding of the factors affecting erodibility in all geological terrains, especially the combined geochemical and geotechnical effects, remains a challenge in geotechnical engineering. In this research, the erodibility of soils from basement and sedimentary terrains, Southwest Nigeria, was investigated through a combined geotechnical-geochemical approach. The soil samples from Akure (Basement Complex of Nigeria) and Ode-Irele (sedimentary basin) were tested for classification, consistency limits, compaction, California Bearing Ratio (CBR) and X-ray fluorescence (XRF). The findings reveal that basement soils have higher sesquioxides (Al_2O_3 + Fe2O_3) content, laterization, bonding, cohesion (as high as 120.2 kPa), internal friction angle (as high as 32.9°) and CBR values (as high as 70 %), well-graded, coarse grained clayey soil and classified as CI - CH soils. By contrast, sedimentary soils contain higher SiO_2, lower cohesion (2.0 kPa), well-graded, coarse grained silty sand soil and classified as CL - ML soil type. Soils found on basement terrain have better bonding, are less erodible and are more amenable to stabilization than sedimentary terrain soils (STS). In comparison, STS have lower cohesion-frictional characteristics, higher erosion, soil loss, and soil degradation potential. The greater soil loss ratio and erodibility factors for STS reflect their susceptibility to environmental degradation and landslides. These variations in soil properties reflect different geological formation histories, which result in different degrees of weathering, soil structure and permeability. This study underscores the need to consider terrain-specific soil characteristics for erosion risk analysis and infrastructure development.

***Keywords**: Terrains, Erodibility, Geochemical compositions, Laterization and Soil structure*

Introduction

Across the world, the erodibility properties of soils formed in the basement and sedimentary terrains are largely determined by soil texture, soil structure, climate and geomorphology (Ikubuwaje, *et al.*, 2023). In Nigeria, erosion is much more severe in sedimentary terrains and contact areas between basement and sedimentary terrains (Akpokodje, 2001; Teme, 2001; Okagbue & Aghamelu, 2010; Okeke & Enwelu, 2010). These two terrains are formed from different geological processes, which considerably determine their soil characteristics. Sedimentary terrains are mainly formed by intense physical weathering of pre-existing `rocks, erosion, transport, deposition and consolidation of sediments while Basement soils are formed primarily in situ from chemical weathering of the underlying basement rocks such as granite, gneiss and schist. The minerals in the rock are gradually dissolved by water and dissolved gases such as carbon dioxide, oxygen, and sulphur dioxide, via hydrolysis, oxidation and hydration, resulting in a residual soil mantle on top of the bedrock. Consequently, soils from basement terrains are greatly influenced by the parent rocks, climatic condition and drainage. (Adegoke *et al.*, 2018; Nwagha *et al.*, 2021).

The differences in particle size and mineralogical properties of the weathered products from the two terrains produce soils with very different characteristics. For example, sand displays no cohesion, silt is cohesive and clay is cohesive. Critical to erosion and transport processes in mixed sediments, in addition to the properties of individual particles, is the effects of particle interaction in terms of packing (Li *et al.*, 2022). Laboratory experiments show that sand-silt mixtures are more erodible than pure sand because of the cohesive effect of smaller particles, as well as the infilling of voids between sand particles by the smaller silt particles (Zhao *et al.*, 2020).

Besides cohesion, the network structure or packing of sediment particles plays an important role. In pure sands, network structures are formed when volume of sand exceeds the critical volume of 40-50 %. Adding water can destroy this structure by increasing the distance between particles, finally allowing flow-like behaviour once a critical water content is reached (Te

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Slaa, 2020). For mixed sediments, fine particles (silt and/or clay) can fill the pore spaces between sand grains, affecting bulk density and permeability. Typically, soils with finer particles have smaller pores, which decreases their permeability relative to coarser soils, affecting erosion rates (Wang *et al.*, 2023). On the other hand, the extent of laterization was evaluated from the silica-sesquioxide molar ratio (SSMR) of the soils. It showed that increasing laterization is indicated by lower SSMR values and decreasing laterization by higher SSMR values.

Although geotechnical and geochemical characteristics of soils are known to impact their susceptibility to erosion, there is a lack of integration of these factors in studies discussing the erodibility of soils in the basement and sedimentary terrains. This study seeks to address this by examining and integrating the geotechnical and geochemical properties of soils from these different terrains to assess their relative erodibility.

Geology of the Study Area

The Ode-Irele study areas fall within the southwestern Nigerian sedimentary basin (Eastern Dahomey Basin) while Akure south study area belongs to the region of the Precambrian Basement Complex rocks (Figure 1). The study site is located between latitudes 07° 18' and 07° 19' N and longitudes 05° 08' and 05° 09' E. The research area's topography is mildly undulating with low, rounded hills and occasionally lengthy, extended ridges that indicate the characteristics of a typical basement terrain with daily average temperatures above 30 °C.

Materials and Methods

The residual soil samples from the sedimentary and basement complex terrains within Ondo State were used in this study. These samples were collected at 1.0 m below ground level to obtain representative residual soil. The field colour was recorded as brown to greyish-brown, with a total quantity of 25 kg disturbed soil collected. Sampling was carried out in accordance with BS 1377-1:1990, and ASTM D6951/D6951M-09

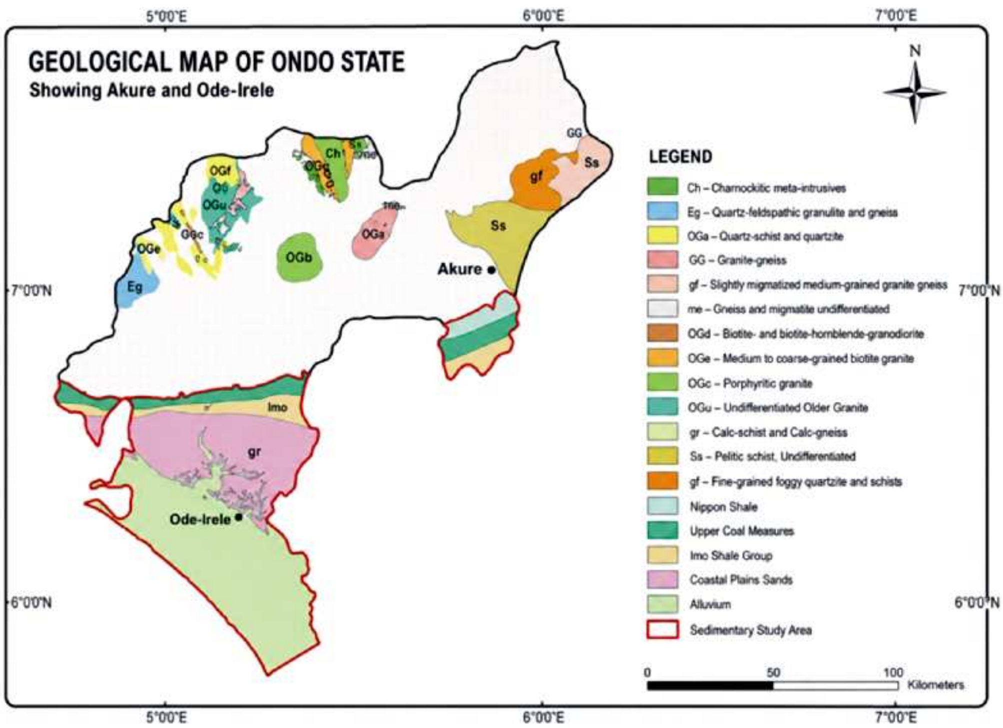

Fig. 1: Geological Map of Ondo State showing the study area (Source: NGSA, 2006).

(2015). And properly labelled and transported to Geotechnical Laboratory of Applied Geology Department, Federal University of Technology Akure (FUTA) for geotechnical analysis. The geotechnical analyses were carried out in accordance with the British Standard Institution BSI (code 1990, code 1996). The X-ray fluorescence spectrometry (XRF) method was used to analyze for the major element concentrations, in form of oxides, at the Central laboratory of the Stellenbosch University, South Africa. These oxides are as follows: SiO_2,Al_2O_3, Fe_2O_3, CaO, MgO, K_2O, MgO, MnO, Na_2O, and TiO_2. The identified Major oxides were utilized to classify and quantify key soil engineering features.

The strength and bearing capacity of both basement terrain soils (BTS) and sedimentary terrain soils (STS) were evaluated using the shear strength parameters, cohesion (c) and angle of internal friction (φ). Cohesion represents the interparticle bonding within the soil, while the friction angle reflects the resistance to sliding between soil particles. Higher c–φ values generally indicate greater shear strength and better bearing capacity.

Results and Discussion

Geochemical Studies

Major Oxides

The proportion of the major oxides determined in this study controls key engineering properties such as plasticity, permeability, and shear strength (Mitchell and Soga, 2005). Table 1 gives summary of the result of the major oxides of the samples from the sedimentary (STS) and the basement terrains (BTS). The result shows that SiO_2, Al_2O_3 and Fe_2O_3 are the dominant oxides. It was observed that SiO_2 was more in STS in comparison to BTS. On the other hand, Al_2O_3 and Fe_2O_3 were more in BTS than in STS. This implies that weathering activities is more profound in the samples from the sedimentary terrain than in those from the basement terrain. This situation may be attributed to the differences in their geological history, which gave rise to different mineralogy, geochemical compositions, soil texture and soil structure. For instance, quartz-rich sandy sediments typically exhibit high permeability and low compressibility, while clay-rich sediments show low permeability but high plasticity and compressibility, according to Mitchell and Soga (2005). This suggests that the two terrains would have differing engineering and geological characteristics. Meanwhile, Fe_2O_3 and Al_2O_3 act as cementation agents to form a hard, rock-like material with the 'in-soil' matrix. This gives rise to better bonding property in the samples from BTS when compared with those from STS. Hence, the BTS samples have more eroding resistant potential than those from STS.

Table 1a: Sedimentary terrain soil samples major oxides result

Sample/oxides (%)	ST1	ST2	ST3	ST4	ST5	ST6	ST7	ST8	ST9	ST10	ST11	ST12	ST13	ST14	ST15	AVE
SiO_2	59.44	81.48	66.36	65.00	60.29	79.76	70.97	67.75	75.06	60.97	86.65	69.87	59.86	68.72	70.67	69.52
Al_2O_3	21.14	8.32	16.44	17.37	19.86	9.55	14.11	15.85	11.20	19.16	5.86	12.52	20.49	15.53	13.99	14.76
Fe_2O_3	7.28	2.93	6.10	6.34	7.16	3.77	5.41	6.37	5.11	6.98	2.50	4.94	7.29	5.20	5.07	5.50
MnO	0.04	0.02	0.03	0.03	0.03	0.02	0.02	0.03	0.02	0.06	0.02	0.04	0.05	0.02	0.04	0.03
MgO	0.02	0.01	0.02	0.02	0.03	bdl	bdl	bdl	0.01	0.04	Bdl	0.07	0.03	0.01	0.01	0.02
CaO	0.06	0.12	0.05	0.08	0.11	0.02	0.05	0.03	0.06	0.10	0.05	0.27	0.09	0.02	0.18	0.09
K_2O	0.08	0.06	0.10	0.07	0.09	0.05	0.07	0.08	0.06	0.10	0.04	0.12	0.09	0.08	0.08	0.08
TiO_2	1.66	0.98	1.66	1.79	1.76	1.00	1.39	1.33	1.38	1.79	0.87	1.49	1.58	1.46	1.47	1.44
P_2O_5	0.12	0.07	0.10	0.09	0.11	0.06	0.07	0.08	0.06	0.14	0.05	0.16	0.40	0.07	0.20	0.12
Na_2O	bdl	0.01	bdl	0.01	0.01	bdl	0.02	bdl	bdl	0.01	Bdl	0.02	0.01	bdl	Bdl	0.01
$SiO_2/Al_2O_3+Fe_2O_3$	2.09	7.24	2.94	2.74	2.23	5.99	3.64	3.05	4.60	2.33	10.36	4.00	2.15	3.32	3.71	4.03
$Al_2O_3+Fe_2O_3$	28.42	11.25	22.54	23.71	27.02	13.32	19.52	22.22	16.31	26.14	8.36	17.46	27.78	20.73	19.06	20.26
AFMC	28.5	11.38	22.61	23.81	27.16	13.34	19.57	22.25	16.38	26.28	8.41	17.8	27.9	20.76	19.25	20.36

bdl – below detection limit

Table 1b: Basement terrain soil samples major oxides result

Sample/oxides (%)	BT1	BT2	BT3	BT4	BT5	BT6	BT7	BT8	BT9	BT10	BT11	BT12	BT13	BT14	BT15	AVE
SiO_2	48.7	44.79	35.3	32.27	38.42	46.34	46.85	42.57	50.21	50.58	49.43	44.42	43.75	39.52	45.47	43.91
Al_2O_3	23.77	22.85	19.3	17.17	21.23	19.49	22.81	17.27	28.14	22.07	28.13	30.55	30.51	22.56	31.08	23.80
Fe_2O_3	19.34	15.98	40.24	45.46	36.14	29.93	25.53	35.77	15.37	17.55	15.47	20.19	20.07	30.88	17.87	25.72
MnO	0.21	0.16	0.64	0.55	0.11	0.27	0.18	0.56	0.08	0.19	0.15	0.17	0.14	0.41	0.16	0.27
MgO	0.1	0.08	0.12	0.1	0.15	0.2	0.24	0.2	0.1	0.15	0.13	0.25	0.22	0.45	0.13	0.17
CaO	1.71	2.11	0.21	0.24	0.22	0.2	0.25	0.2	0.32	0.37	0.37	0.68	0.35	0.24	0.74	0.55
K_2O	4.51	3.62	2.13	1.85	2.25	0.97	1.34	1.12	2.24	4.95	1	0.76	1.18	0.41	1.24	1.97
TiO_2	0.18	0.07	1.84	1.98	1.47	2	2.35	2.3	0.54	0.95	3.83	1.87	2.64	2.46	2.15	1.78
P_2O_5	0.29	0.26	0.26	0.28	0.25	0.31	0.35	0.27	0.2	0.33	0.27	0.06	0.11	0.33	0.1	0.24
Na_2O	0.06	0.06	0.06	0.06	0.06	0.07	0.07	0.07	0.07	0.06	0.04	0.06	0.07	0.08	0.07	0.06
$SiO_2/Al_2O_3+Fe_2O_3$	1.13	1.15	0.59	0.52	0.67	0.94	0.97	0.80	1.15	1.28	1.13	0.88	0.86	0.74	0.93	0.92
$Al_2O_3+Fe_2O_3$	43.11	38.83	59.54	62.63	57.37	49.42	48.34	53.04	43.51	39.62	43.6	50.74	50.58	53.44	48.95	49.51
AFMC	44.92	41.02	59.87	62.97	57.74	49.82	48.83	53.44	43.93	40.14	44.1	51.67	51.15	54.13	49.82	50.24

bdl – below detection limit

Degree of Laterization

The results of silica-sesquioxide molar ratio (SSMR) values by w% of the studied soil samples are presented in Table 2 and Fig. 2. The result suggests that samples from BTS were more lateralized than those from STS. This is attributed to differences in their geochemical compositions (Table 1). Ikubuwaje et al (2023) reported that variability in the constituent major oxides within the profile of residual soil has consequential effect on the characteristic of the superficial deposits. Generally, more lateralized soils are richer in Fe_2O_3, which suggests better crystallization of accumulated sesquioxide in the pore spaces and the formation of concretionary structure of the BTS compared to the STS (Malomo, 1989), cited in Ikubuwaje *et al.* (2023). This implies that the samples from STS are more prone to soil erosion challenges and slope stability when compared with samples from BTS.

Table 2: Geochemical Quantification and Engineering Properties

Name	Sedimentary		Basement		Property
	Range	*Mean*	*Range*	*Mean*	
$SiO_2/Al_2O_3+Fe_2O_3$	2.09 - 10.36	4.03	0.52 – 1.28	0.92	Laterization
$Al_2O_3+Fe_2O_3$	8.36 - 28.42	20.26	38.83 - 62.63	49.51	Stabilization
AFMC	8.41 - 28.5	20.36	41.02 – 62.97	50.24	Bonding strength

NB: AFMC = Al_2O_3 + Fe_2O_3 + MgO + CaO

Bonding, Resistance and Stabilization Properties

Table 2 shows the results of stabilization and bonding strength. The results show that the samples from BTS have more stabilizing potential than those from STS. This is attributed to the higher Al_2O_3 and Fe_2O_3 contents in the samples from BTS than those from STS. The bonding strength results also show similar trend with the stabilization property. This indicates more cementation agents to form a hard, rock-like material, shearing resistance to soil erosion and better bearing capacity for the BTS samples compared to the STS samples. This gives rise to more vulnerability to erosion for samples from STS in comparison with those from BTS.

Classification characteristics

The summary of the grain size distribution analysis and soil loss results is presented in Table 3. The results revealed uniformly graded silty sand for the STS samples and well-graded coarse-grained clayey soils for the BTS samples. Normally, poorly graded soils are more prone to erosion than well graded coarse-grained clay soils due to lack of cohesion and proper interlocking of soil grain size, low interlocking, and moderate permeability, which may reduce bearing strength but allow good drainage. Therefore, samples from STS have lower structural stability and lower resistant which gives rise to higher detachment, dispersibility and higher soil loss in comparison to BTS. Furthermore, the results of soil erodibility factor (K) and soil loss (A) show that sedimentary terrain have more potential for soil erosion and soil loss than basement terrain soils. The ratio of the average STS soil loss to average BTS soil loss is 2.33:1, suggesting that STS is losing three times more soil than BTS. This indicates that STS soil structure greatly influences erosion susceptibility more than that of BTS. This is also due to the differences in their respective textural characteristics. This ratio variation implies that the structural integrity in STS samples significantly amplifies erosion compared to BTS samples with better stability or coarser texture.

The plasticity plot results revealed BTS samples as CI-CH soils and STS as CL-ML soils (Figs. 3a and 3b). Meanwhile, CI-CH soils are characterized with low erodibility due to their cohesive properties and high plasticity, which make them more resistant to erosion by water. In contrast, CL-ML soils have low plasticity mixed with silt, with higher erodibility because the lower plasticity and silty fraction make these soils less cohesive and more prone to dispersion and erosion (Li, 2022).

Strength Characteristics

The results of the strength and bearing capacity parameters for both BTS and STS samples (cohesion-frictional angle, c–φ, respectively), compaction (maximum dry density-optimum moisture content, MDD-OMC, respectively) and California bearing ratio (CBR) are presented in Table 4. The result shows that BTS samples have higher values than the STS samples for all the considered strength and bearing capacity parameters. This is in agreement with some previous

Tables 3: Grain Size Distributions and Soil Erodibility Factor (K) For Studied Soils

S/N	Basement Terrain Grain Size Distribution				Soil erodibility factor (K)	Soil loss A ton/ha/yr A (=2.24RH)	Sedimentary Terrain Grain Size Distribution				Soil erodibility factor (K)	Soil loss A ton/ha/yr A (=2.24RH)
	Clay	*Silt*	*Sand*	*Gravel*	*K*	*A*	*Clay*	*Silt*	*Sand*	*Gravel*	*K*	*A*
1	16	34.4	29.2	20.4	0.040	77	11.8	10.7	77.5	0.0	0.075	145
2	18	26.4	34.8	20.8	0.034	66	11.7	13.1	75.2	0.1	0.075	147
3	6	18.3	39.2	36.5	0.026	46	17.9	16.9	65.0	0.3	0.046	89
4	19	12.5	31.9	36.5	0.023	45	11.7	14.4	73.9	0.1	0.075	147
6	14	12.3	28.6	45.1	0.029	57	9.9	15.7	74.2	0.1	0.091	176
7	22	32.6	23.2	23.2	0.025	49	10.7	15.0	74.2	0.1	0.083	162
9	24	17.1	32.1	26.5	0.021	40	20.2	12.8	66.9	0.1	0.039	77
10	10	20.8	30.3	38.9	0.023	39	8.2	11.9	18.2	0.1	0.037	71
11	16	15.7	26.1	42.2	0.026	51	6.0	10.5	83.3	0.1	0.156	304
12	18	10.4	14.9	57.7	0.014	27	16.0	15.5	68.4	0.2	0.052	102
14	22	29	35.2	13.8	0.029	57	20.0	14.9	64.5	0.6	0.040	77
15	29	21.7	29.1	20.2	0.018	34	5.5	8.3	86.2	0.6	0.172	334
16	28	26	45.8	0.2	0.026	50	7.5	17.5	71.6	3.4	0.119	231
19	18	18.5	37.1	26.4	0.031	60	22.3	15.6	61.8	0.4	0.035	67
20	22	38.6	36.6	2.8	0.034	66	15.7	19.7	64.3	0.1	0.054	104
Ave	18.8	22.29	31.61	27.41	0.03	64	13.0	14.2	68.35	0.42	0.08	149

Where: RH A=2.24 RK,
R = Rainfall factor, given as 0.5H,
where H = Mean annual rainfall

$$K\ (\%) = \frac{\%\ Sand + \%\ Silt}{\%\ Clay} \times 100$$

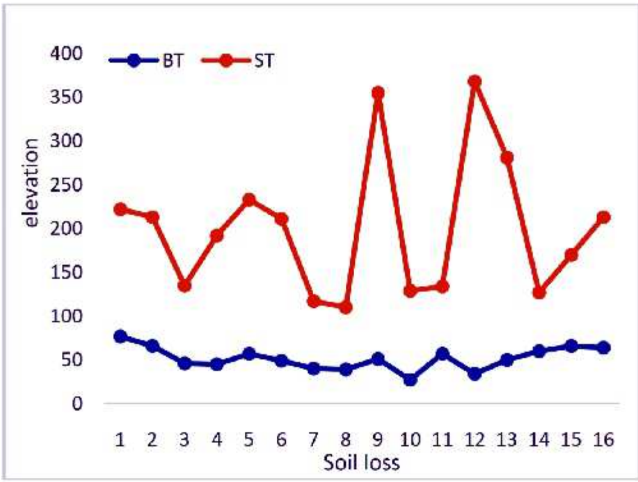

Fig. 2: Soil loss ratio relationship between BTS and STS

works (for example, Ikubuwaje, *et al.*, 2023) and the geochemical analysis results. Osinubi *et al.* (2011) reported that the soft clayey-silty layers that underlie much of the area exhibit low shear strength, high plasticity, and significant compressibility, which are common characteristics of recent sedimentary deposits. This may be attributed to degree of differences in geochemical compositions, weathering, texture and soil structure characterizations. This indicates higher erodibility potential of the STS samples than that of the BTS samples. The STS samples, with low cohesion-frictional (c–φ), less adhesion and bonding properties are thereby likely to be more vulnerable to erosion activities than the BTS samples, because the lower cohesion-frictional (c–φ) values would give rise to poorer shear resistance property that account for more susceptibility.

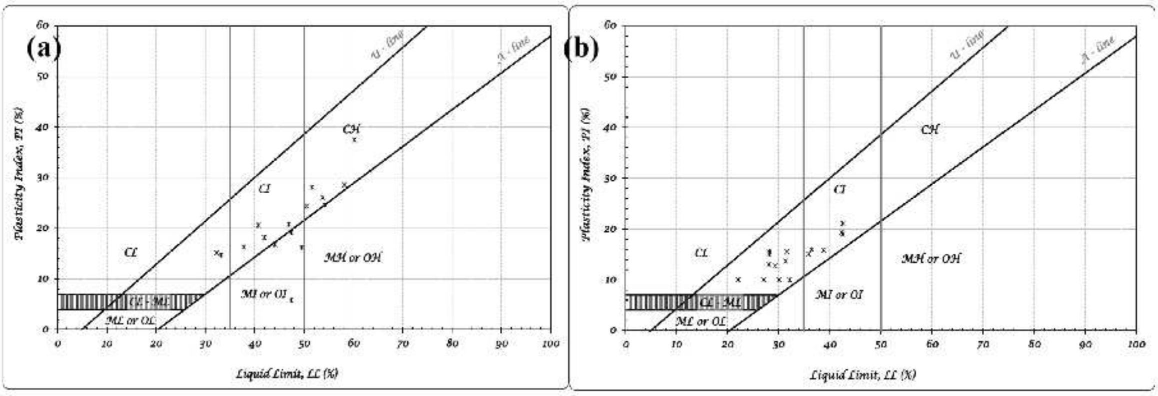

Fig. 3: Plasticity plot of (a) BTS samples, and (b) STS samples

Table 4: Strength Properties of Basement and Sedimentary Soil samples

SL	Basement Lateritic Soil					Sedimentary Lateritic Soil				
	Cohesion (KPa)	*Frictional angle (o)*	*CBR (%)*	*OMC (%)*	*MDD (kg/m³)*	*Cohesion (KPa)*	*Frictional angle (o)*	*CBR (%)*	*OMC (%)*	*MDD (kg/m³)*
1	10.6	32.9	10	20	1645	17.6	4.0	2	16.1	1636
2	30.5	14.9	22	13.95	1766	20.9	7.0	7	17.7	1935
3	24.4	26.2	70	7.71	1977	18.7	6.0	1	23.0	1787
4	99.3	18.8	25	14.3	1805	6.0	5.0	2	15.1	1743
5	79.7	16.7	65	13.83	1871	13.9	6.0	2	15.2	1735
6	77.9	29.9	14	20.15	1652	36.8	5.0	4	11.8	1698
7	43.2	29.6	31	14.34	1767	13.4	7.0	3	15.6	1557
8	35	25.9	38	15.7	1782	17.9	7.0	9	15.9	1639
9	46.4	31.9	52	15.69	1759	3.8	5.0	4	16.6	1801
10	120.2	22.3	37	17.6	1760	8.8	5.0	2	15.9	1725
11	19.2	18.2	24	18.19	1662	6.8	3.0	9	13.9	1667
12	14.9	29.9	43	19.51	1661	12.9	6.0	9	14.3	1661
13	24	21.4	14	18.65	1662	15.3	2.0	2	17.1	1868
14	31.5	22.4	27	19.13	1601	14.9	4.0	4	21.8	1683
15	9.3	20.5	22	15.8	1742	16.0	6.0	17	16.5	1630
Ave	44.41	24.10	33	16.30	1741	14.91	5.20	5.13	16.43	1718

Conclusions

This research examined the effect of terrain on the geotechnical characteristics of engineering soils in Ondo State, Southwest Nigeria. This study compares the geochemical characteristics, mineralogy and engineering properties of basement terrain soils (BTS) and sedimentary terrain soils (STS), which contribute to their reactions and stability. BTS contain higher alumina and iron oxides, which function as natural cementing agents, leading to improved bonding, stability, erosion resistance and soil strengthening compared to STS. This is evident in their well-graded, clayey texture with low erodibility and improved shear strength properties. By contrast, STS have higher silica, are silty sand textured, and have lower plasticity and cohesion-frictional properties, leading to higher erodibility, soil loss, and degradation. The higher soil loss ratios and erodibility factors for STS highlight their environmental and slope instability potential. These contrasting soil properties stem from differences in soil history, resulting in different degrees of weathering, soil structure and permeability. Consequently, BTS exhibits greater resistance and stability against environmental degradation and slope failure, while STS is more prone to erosion and may require soil stabilization or improvement techniques to enhance its strength and durability. Recognizing these differences is crucial for soil management and foundation engineering in areas where both types of terrain are found.

Recommendation

Conduct soil stabilization and erosion control treatments (e.g. binders or vegetation) on sedimentary terrain soils (STS) before construction or development to prevent environmental degradation and slope instability through improving cohesion of the soil.

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