FUDMA Journal of Sciences (FJS)
ISSN online: 2616-1370
ISSN print: 2645 - 2944
Vol. 10 No. 17, September, 2026, pp 221 – 227
DOI: https://doi.org/10.33003/fjs-2026-1017-5960

Friability and Erodibility of Ajali Formation-Derived Soils in Ngwo, Southeastern Nigeria: Geotechnical Implications

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Received: 14 Sept. 2026
Accepted: 16 Sept. 2026
Published: 23 Sept. 2026

ABSTRACT

Geotechnical challenges associated with erosion in the Ajali Formation at Ngwo, Enugu State, southeastern Nigeria, were assessed by characterizing the particle-size distribution, Atterberg limits, and X-ray fluorescence (XRF) of soil samples collected from exposures of the formation in the study area. Twenty samples were collected and analyzed but only four samples were for Atterberg limit test due lack of plastic materials in the majority of the samples. Particle-size distribution tests were conducted on all samples, and the results show average sand and fines contents of 88.98% and 11.04%, respectively, with average coefficients of uniformity and curvature of 3.27 and 1.11, respectively. The soil samples have an average liquid limit of 31.8% and a plasticity index of 9.88%. XRF results indicate that silica (SiO2) dominates the elemental oxides, with relatively low concentrations of Al2O3 and Fe2O3. The soils are predominantly poorly graded and exhibit low to no plasticity and weak binding characteristics. The observed properties of the soils are indicative of high erosion susceptibility in the studied soils and, consequently, to the geotechnical challenges affecting engineering structures in the area.

Keywords: Ajali Formation, Poorly Graded Soil, Erodibility, Geotechnical Challenges, Friability

INTRODUCTION

The stability of engineering structures, including roads, buildings, bridges, and railway lines, depends largely on the nature and engineering properties of the soil on which they are constructed. Where soil lacks sufficient strength to sustain imposed loads (bearing capacity), failure may occur through shear, potentially resulting in structural damage. To minimize the risks and collateral damage associated with engineering failure, geotechnical investigations are essential before construction. The determination of the mechanical properties of unsaturated soils, including consolidation, shear strength, compaction, and permeability, is critical for evaluating fluid flow and soil mechanical behavior in hillslope environments [1]. An engineering geologist can assess the suitability of a site for construction using soil index properties such as particle-size distribution, Atterberg limits, moisture content, and density. Among these properties, particle-size distribution is particularly useful for assessing coarse-grained soils. Particle size plays a major role in the strength behavior of granular materials [2, 3, 4]. Grain size influences the fabric of a soil mass and, consequently, its strength behavior. Under applied loads, soil particles rearrange to resist the imposed stresses. The ability of the soil mass to withstand these stresses depends on the behavior and interaction of individual particles because loads are transferred from particle to particle. The macroscopic response of the soil mass is therefore the cumulative result of the responses of its individual particles [5].

For these reasons, particle-size distribution curves are essential for the engineering classification of coarse-grained soils. A coarse-grained soil is one in which particles larger than 0.075 mm constitute more than 50% of the total soil mass [6]. As particle size increases, the contribution of shear resistance generally increases [7]. A particle-size distribution curve, also known as a gradation curve, represents the distribution of different particle sizes within a soil mass. The distribution of particle sizes is referred to as soil grading and is determined from the gradation curve. A curve with a pronounced hump indicates that some grain sizes are absent, and such a soil is described as gap-graded. A relatively flat S-shaped curve indicates a soil containing particles of different sizes in appropriate proportions and is characteristic of a well-graded soil. A steep gradation curve indicates that the particles are predominantly of similar size and that the soil is relatively uniform. Well-graded soils generally exhibit greater shear strength than gap-graded or uniformly graded soils because particles of different sizes can pack more efficiently. When adequately compacted, such soils become denser and consequently develop higher shear strength.

Previous studies have reported that Ajali Sandstone is geotechnically well graded, with average values of liquid limit, plastic limit, and plasticity index of 34.7%, 25%, and 9.7%, respectively, and a low moisture content of 10.8% [8]. The porosity of the sandstone has been estimated to be very high, ranging from 50% to 70%, while permeability values range from 3.74 to 724.55 m/day [9]. The sandstone also exhibits low maximum dry density (MDD) and optimum moisture content (OMC), attributed to the high presence of kaolinite, as well as low California Bearing Ratio (CBR) values, indicating low strength [10]. The groundwater level has been estimated at approximately 34 m [11]. Igwe [12] noted that Ajali Sandstone is poorly consolidated and friable, with landforms dominated by lowlands and low hills that promote the concentration of landslides near river tributaries. Despite the fact that the documented evidence of friable Ajali Formation and erosion related with geotechnical challenges within the Enugu region, the relationship between the material properties of the derived soils and their erosion response require further investigation. Friability, erodibility and erosion susceptibility are related but distinct concepts. Friability describes the tendency of soil or rock material to disintegrate under relative low mechanical forces, whereas erodibility refers to its resistance to detachment and transport by erosive agents. Erosion susceptibility, on the other hand represents the likelihood of erosion at a particular location under the combine influence of soil properties, rainfall, slope, vegetation and drainage.

This study aim is to assess the index properties of Ajali Sandstone exposed in the Anambra Basin at Ngwo, Enugu State, with particular emphasis on its erodibility and implications for engineering structures in the study area. The assessment was undertaken with specific objectives to obtain the particle-size distribution (PSD), Atterberg limits, X-ray fluorescence (XRF), and empirical parameters, including the coefficient of uniformity (Cu) and coefficient of curvature (Cc). The study area is Ngwo in Udi Local Government Area of Enugu State (Figure 1).

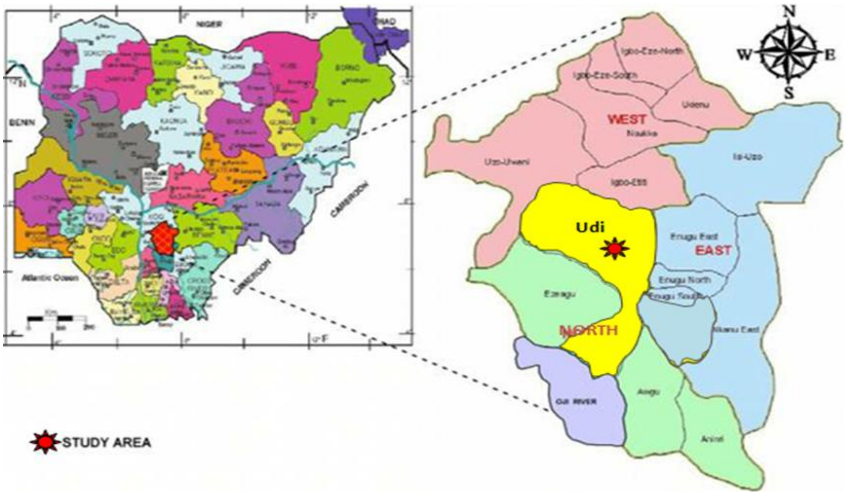

Figure 1: Map of Nigeria Showing the Study Area

Geology of the Area

The stratigraphic deposition of the Anambra Basin commenced with post-Coniacian–Santonian folding and the deposition of sediments belonging to the Campanian Nkporo Group, comprising the Enugu Shale, Nporo Shale, and Owelli Sandstone. These units are overlain by the Mamu Formation, also known as the Lower Coal Measures of Lower Maastrichtian age. The Mamu Formation is characterized by fine-grained sandstone, shale, and coal. Overlying the Mamu Formation is the Ajali Formation, formerly referred to as Ajali Sandstone [13]. It is characterized by cross-bedded sandstone with thin clay interbeds. The sandstone is highly friable, and its aquiferous nature makes it an important source of groundwater in Enugu and surrounding areas. The Upper Maastrichtian Ajali Formation is an extensive stratigraphic unit that was referred to as the false-bedded sandstone in reports of the Nigeria Geological Survey [14].

Table 1: Geology of the Study Area [16]

Age	Formation	Members	Lithologies and Facies
Paleocene	Nsukka Formation		Dark grey shales, intercalations of fine-grained sandstone and sandy shale. White sandstone, sandy shales and fine-grained clean sandstone.
Upper Maastrichtian	Ajali Formation	Sandstone	Fine, medium to coarse-grained subangular to subrounded quartzarenites. Dominant sands with milkish to greyish in colour and claystone alternating the beds
Lower Maastrichtian	Mamu Formation	Shale Sandstone	Fine to coarse-grained sandstone with band of coal alternating the sediments. And black carbonaceous ooids and shell debris. Fine to medium-grained sandstones and siltstones.
Campanian	Nkporo group	Nkporo Shale Owelli Sandstone Enugu Shale	Carbonaceous shale and concretional siltstone. Medium to coarse-grained quartz sandstone. Dark shale and mudstone with extraformational clast and shelly limestone

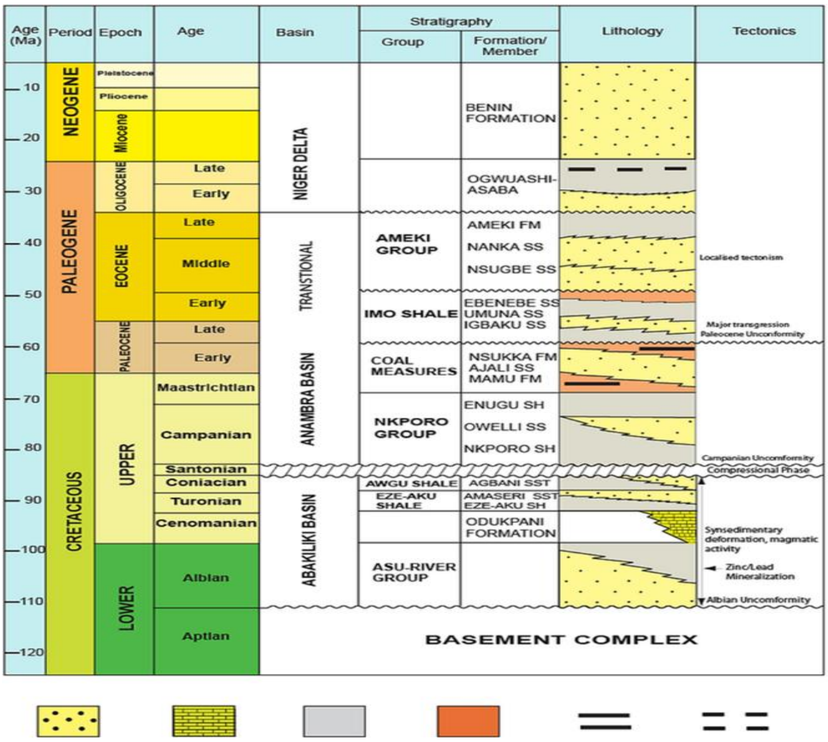

Figure 2: Stratigraphic Succession in the Anambra Basin and Outcropping Niger Delta [17]

The lithologic section of the Ajali Sandstone exposure at Ngwo is presented in Figure 3. The exposure occurs at a quarry site. The sandstone ranges from coarse to medium grained, with intercalated clay beds that occur approximately parallel to the sandstone beds. It is highly friable and readily eroded. The study area receives abundant rainfall, with an annual average of approximately 2,000 mm, which may increase to about 4,700 mm during exceptionally wet years [18]. Such rainfall can aggravate the development of gullies in the study area. The sandstone is highly aquiferous and poorly sorted. Areas containing non-plastic fines and relatively low iron-oxide contents, even under dense to moderate vegetation cover, have been reported to be more susceptible to erosion [19].

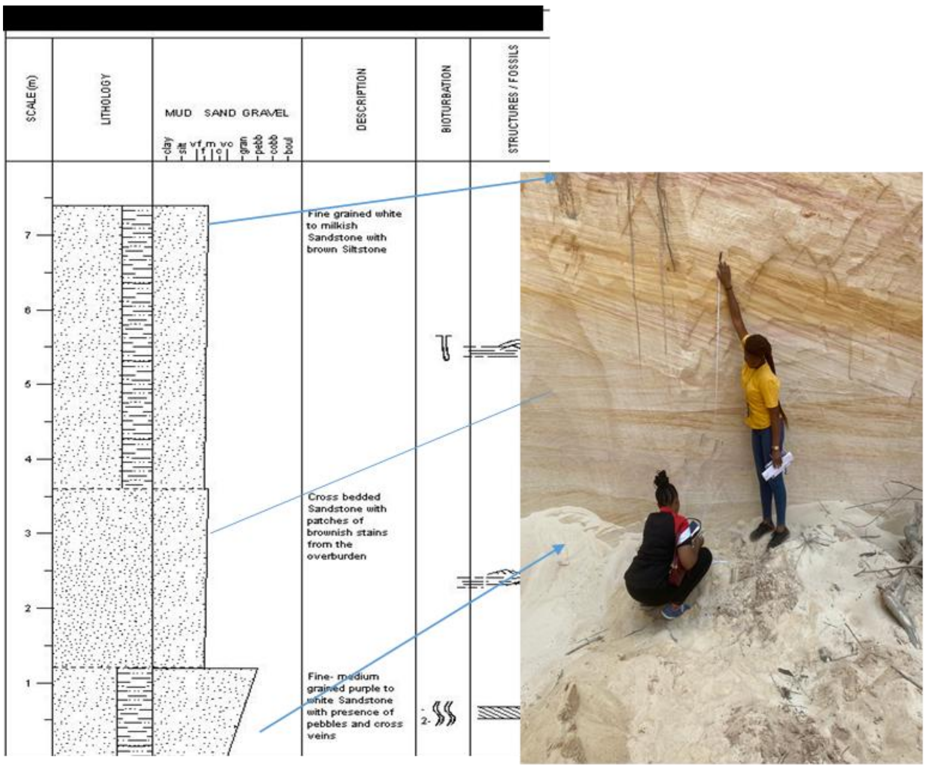

Figure 3: Logged Section Of an Ajali Formation Exposure at a Quarry Site in Ngwo.

Geomorphology of the Study Area

The landforms in Ngwo are characterized by tertiary erosion that has affected the uplifted and folded sediments exposed in the Ajali Sandstone [15]. The area is dominated by lowlands and low hills that are extensively affected by erosion associated with the region's abundant rainfall, which averages about 2,000 mm annually. The lowlands are underlain by shales of the Mamu Formation, whereas the low hills are underlain predominantly by Ajali Sandstone. The sandstone units are severely affected by erosion, posing threats to lives and property in the area. Elevation in the study area ranges from approximately 250 to 600 m above mean sea level. The hills have steep slopes, making the area susceptible to landslides and gully erosion [20]. The geology therefore exerts a strong control on both topography and gully development in the study area.

Methodology

Twenty soil samples were collected from Ajali Sandstone exposures at depths of 0.5–1.0 m within the study area (Table 2). The exposures included gully-erosion sites and quarry sites. Weathered materials were removed before the collection of relatively fresh samples, which were transported to the laboratory for particle-size distribution, Atterberg-limit, and XRF analyses. Ajali Sandstone samples were selected because of the ongoing development of gully erosion within the Ajali Formation.

Table 2: Sample Location

S/N	Location	Coordinate	Elevation	Depth(m)	Site Type
1	9th mile	6˚ 27'34"N 7˚ 24'15" E	350m	0.5	Quarry site
2	9th mile	6˚ 27'34"N 7˚ 24'15" E	350m	1	Quarry site
3	Umavulu Abor	6˚ 28'11"N 7˚ 25'03" E	460m	0.5	Quarry site
4	Umavulu Abor	6˚ 28'11"N 7˚ 25'03" E	460m	1	Quarry site
5	Amake Ngwo	6˚ 27'24"N 7˚ 23'28" E	320m	0.5	Erosion site
6	Amake Ngwo	6˚ 27'24"N 7˚ 23'28" E	320m	1	Erosion site
7	Ebe	6˚ 28'16"N 7˚ 23'29" E	400m	0.5	Road cut
8	Ebe	6˚ 28'16"N 7˚ 23'29" E	400m	1	Road cut
9	Adukwe Ebe	6˚ 28'59"N 7˚ 23'29" E	400m	0.5	Road cut
10	Adukwe Ebe	6˚ 28'59"N 7˚ 23'29" E	400m	1	Road cut
11	Ugwuto 9th mile	6˚ 24'04"N 7˚ 22'56" E	376m	0.5	Quarry site
12	Ugwuto 9th mile	6˚ 24'04"N 7˚ 22'56" E	376m	1	Quarry site
13	Amagu, Nsude	6˚ 24' 39"N 7˚ 25'09" E	459m	0.5	Quarry site
14	Amagu, Nsude	6˚ 24' 39"N 7˚ 25'09" E	459m	1	Quarry site
15	Amagu, Nsude	6˚ 24'33"N 7˚ 25'10" E	443m	0.5	Quarry site
16	Amagu, Nsude	6˚ 24'33"N 7˚ 25'10" E	443m	1	Quarry site
17	Akama, Ngwo	6˚ 28'02"N 7˚ 26'0" E	305m	0.5	Road cut
18	Akama, Ngwo	6˚ 28'02"N 7˚ 26'0" E	305m	1	Road cut
19	Onyeama Mine	6˚ 26'48"N 7˚ 26'32" E	310m	0.5	Road cut
20	Onyeama Mine	6˚ 26'48"N 7˚ 26'32" E	310m	1	Road cut

Particle Size Distribution (PSD) Test

The particle-size distribution test was conducted using British Standard sieves (BSI 1377) mounted on a mechanical sieve shaker. A balance with an accuracy of 0.1% of the sample weight was used. The samples were oven-dried to constant weight at 110 ± 5 °C and weighed. Approximately 200 g of each sample was used for the analysis. The oven-dried samples were passed through the appropriate British Standard sieves using an electric shaker. After approximately 10 minutes of shaking, the material retained on each sieve was weighed, and the cumulative percentage passing was calculated. The percentage finer for each sieve size was obtained from the cumulative percentage passing. The percentage finer was plotted on the ordinate using a natural scale, while the corresponding sieve sizes were plotted on the abscissa using a logarithmic scale to produce a semi-logarithmic gradation curve.

Atterberg's Limit Test

These tests include determining the liquid limit (LL), plastic limit (PL) and plasticity index (PI) of the samples.

The liquid limit test was conducted in accordance with the procedure specified in [21]. The samples were dried, crushed in a mortar, and passed through a 425 µm aperture sieve. The samples were then thoroughly mixed with water in a bowl to form a homogeneous soil paste. The paste was placed in the Casagrande apparatus, and a groove was made across its center using the standard grooving tool. The cup was repeatedly lifted and dropped until the groove closed. The number of blows required for closure was recorded, and a portion of the sample was collected for moisture-content determination. The moisture content was plotted against the corresponding number of blows on a semi-logarithmic graph. The liquid limit was taken as the moisture content corresponding to 25 blows. The procedure was repeated for all samples tested.

The plastic limit test was conducted following the procedure in [21]. It involved determining the moisture content at which a soil thread approximately 3 mm in diameter began to crumble. The soil was rolled into a thread on a glass plate using the palm of the hand. The average moisture content of the prepared samples at the point of crumbling was taken as the plastic limit.

X-Ray Fluorescence (XRF)

X-ray fluorescence (XRF) is a non-destructive analytical technique used to determine the elemental-oxide composition of soil samples. It establishes the chemical composition of a sample by measuring the characteristic fluorescent X-rays emitted when the sample is excited by a primary X-ray source. Each element produces a characteristic fluorescent X-ray spectrum that is unique to that element. Approximately 20 g of each sample were prepared, subjected to dispersion and sedimentation, and physically fractionated into coarse sand, fine sand, silt, and clay fractions. The samples were subsequently reduced to particle diameters below 53 µm and analyzed using an energy-dispersive XRF spectrometer (EDX-700). Spectra were obtained at 300-second intervals in a vacuum chamber using a semi-quantitative mode.

Empirical Framework

Particle-size distribution curves can be used to compare soil samples for geotechnical purposes. Three basic parameters can be derived from the gradation curve and used in the classification of coarse-grained soils: effective size (D10), coefficient of uniformity (Cu), and coefficient of curvature (Cc).

Effective size (D10): This represents the particle diameter corresponding to 10% finer material on the gradation curve. Thus, 10% of the particles are finer than D10 and 90% are coarser.

Coefficient of uniformity (Cu): This is the ratio of D60 to D10. A soil with a Cu value less than 2 is generally considered uniform, whereas a Cu value of 6 or greater is regarded as well graded. D60 is the particle diameter corresponding to 60% finer material on the particle-size distribution curve.

Coefficient of curvature (Cc): This parameter is calculated from the relationship between D10, D30, and D60.

$C_u = \frac{D_{60}}{D_{10}}$ and $C_c = \frac{D_{30}^2}{D_{10}D_{60}}$.

where D30 is the particle diameter corresponding to 30% finer material on the particle-size distribution curve.

For a soil to be classified as well graded, the value of Cc should generally range from 1 to 3.

RESULTS AND DISCUSSION

Table 3 presents the results of the particle-size distribution analysis and classification according to the Unified Soil Classification System (USCS). The sieve sizes ranged from 2.00 mm to 0.075 mm, corresponding broadly to coarse- to fine-sand fractions. The samples have average values of 88.98% coarse material, 11.04% fines, 0.26 mm for D10, 0.37 mm for D30, 0.74 mm for D60, 3.27 for Cu, and 1.11 for Cc. The corresponding ranges are 20.99–98.70%, 1.30–79.01%, 0–0.56 mm, 0–0.62 mm, 0–1.10 mm, 0–5.29, and 0–5.85, respectively. These results indicate that the study area is dominated by sand, with relatively small amounts of fines in most samples. The predominance of sand is consistent with lithological characteristics of Ajali Formation. The low proportion of fines suggests that the soil matrix contains limited amount of silt and clay-size particles. The particle size distribution of the soil influences its packing, pore structure, permeability, compressibility and shear resistance of the derived soils. This characteristic has important implication to the friability and erodibility of the soil particular during rainfall season. The results presented in Table 3 indicate that most samples contain high percentages of coarse and relatively low fines as seen in S2, S16, S17, S18 and S19 which contain approximately 95-99% of coarse sand, with fines contents generally below 5%. The absence of substantial amount of fines may reduce frictional resistance of the material thus very ease to detach from its matrix. Also dominance of a particular grain size as presented in the result is an evidence of poor grading. Based on the USCS classification, the samples comprise 45% SP-SC, 30% SP, 15% SC, 5% SM, and 5% CL. Overall, the soils are predominantly poorly graded. The fines in most samples are non-plastic and this why many were not tested for Atterberg limit. The combination of high rainfall, poor grading of the soil and geomorphology of the study area create conditions necessary for the erodibility of soils in the area.

Table 3: Particle-Size Distribution Parameters and USCS Classification of the Studied Samples

S/N	% Coarse	% fine	D10	D30	D60	Cu	Cc	USCS
S1	91.25	8.77	0.22	0.37	0.9	4.09	0.69	SP-SC
S2	96.52	3.48	0.3	0.55	1	3.33	1.01	SP
S3	87.81	12.19	0.17	0.32	0.5	2.94	1.2	SM
S4	86.85	13.15	0.18	0.3	0.9	5	0.55	SC
S5	94.74	5.26	0.28	0.45	0.95	3.39	0.8	SP-SC
S6	88.31	11.69	0.17	0.37	0.9	5.29	5.85	SP-SC
S7	87.33	12.67	0.16	0.26	0.4	2.5	1.06	SC
S8	93.68	6.32	0.27	0.4	0.95	3.52	0.62	SP-SC
S9	95.06	4.94	0.28	0.46	1	3.57	0.76	SP
S10	93.25	6.75	0.3	0.44	0.98	3.27	0.66	SP-SC
S11	93.72	6.28	0.26	0.62	1.1	4.23	1.34	SP-SC
S12	89.33	10.67	0.19	0.37	1	5.26	0.72	SP-SC
S13	20.99	79.01	0	0	0	0	0	CL
S14	90.74	9.26	0.19	0.33	0.61	3.21	0.94	SP-SC
S15	86.06	13.94	0.15	0.32	0.56	3.73	1.22	SC
S16	96.7	3.7	0.23	0.34	0.5	2.17	1.01	SP
S17	96.8	3.2	0,26	0.48	0.8	3.08	1.11	SP
S18	98.7	1.3	0.56	0.52	0.8	2.22	0.94	SP
S19	98.6	1.4	0.25	0.32	0.48	1.92	0.85	SP
S20	93.1	6.9	0.17	0.26	0.44	2.59	0.9	SP.SC
Ave	88.98	11.04	0.26	0.37	0.74	3.27	1.11	
Range	20.99-98.7	1.3-79.01	0-0.56	0-0.62	0.-1.1	0-5.29	0-5.85	

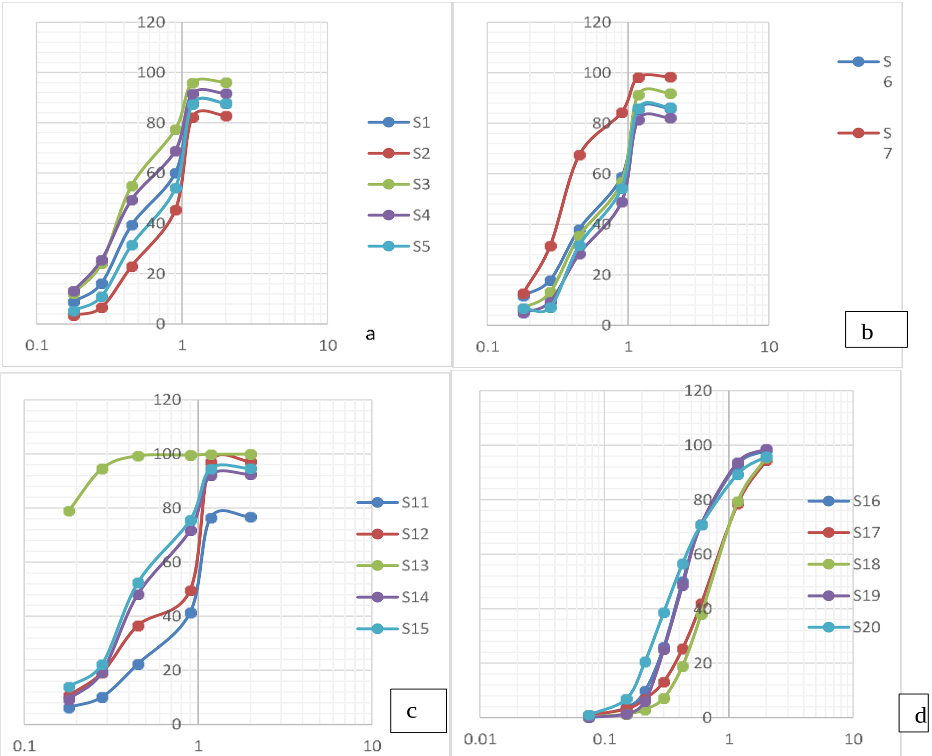

Figure 4: Particle-Size Distribution Curves of the Studied Ajali Formation-Derived Soil Samples

Atterberg's Limits

Four samples were tested for Atterberg limits because the remaining samples contained no plastic fines. The results are summarized in Table 4. The average liquid limit is 31.8%, which is indicative of low-plasticity soil according to [2]. The average plastic limit is 22.57%, while the average plasticity index is 13.17%. According to [23], soils with liquid-limit and plasticity-index values below 50% and 25%, respectively, are classified as having low swelling potential. This result of low plasticity nature of the tested soil samples indicates that the soils contain limited quantities of plastic clay capable of aiding strong cohesive behaviour.

Table 4: Atterberg-Limit Properties of Selected Ajali Formation-Derived Soil Samples

Depth (m)	LL (%)	PL (%)	PI (%)	Description of its plasticity
0.5	35.2	25.7	9.5	[2], intermediate; [23], 1980, low
0.6	43	26	17	[2], intermediate; [23], 1980, low
0.5	29	16	13	[2], low; [23], 1980, low
0.5	20	-	-	Non plastic soil
Average	31.8	22.57	13.17	

X-Ray Fluorescence (XRF)

The XRF results are presented in Table 5. The samples are dominated by high SiO2 contents, which is consistent with the particle-size distribution results indicating a predominance of sand-sized particles. The samples contain relatively low concentrations of Al2O3 and Fe2O3, consistent with the non-lateritic nature of the soils in the study area and the high silica-sesquioxide ratio (S-SR). The low concentrations of Al2O3, Fe2O3, and MgO also indicate limited cementing constituents, which is consistent with the friable nature of the Ajali Sandstone. Rossiter [24] classified soils according to the degree of laterization using the silica-sesquioxide (S-S) molar ratio, expressed as SiO2/(Fe2O3 + Al2O3). A ratio of 1.33 or less indicates laterite, a ratio of 1.33–2.00 indicates lateritic soil, and a ratio of 2.00 or greater indicates non-lateritic soil. The study area is dominated by soils with S-S ratios greater than 2.00 and is therefore classified as non-lateritic (Table 5). High content of silica and relatively low concentration of cementing oxides relate to high friability observed in the area.

Table 5. Major-Element Oxide Composition and Silica-Sesquioxide Ratios of the Studied Samples

S/N	SiO_2	Al_2O_3	Na_2O	K_2O	CaO	MgO	TiO_2	Fe_2O_3	Cr_2O_3	L.O.I	S-SR	Laterization
S1	95.42	0.24	0.05	0.31	0.28	0.03	0.51	2.0	0.04	0.72	42.6	Non lateritic soil
S2	71.5	0.19	0.24	18.34	-	-	-	1.82	2.03	1.24	35.72	Non lateritic soil
S3	93.38	0.46	0.12	0.5	0.07	0.01	0.08	1.84	0.05	1.9	40.6	Non lateritic soil
S4	83.40	7.7	1.0	5.76	0.04	-	-	0.94	0.001	1.8	9.65	Non lateritic soil
S5	79.3	10.4	0.84	6.0	0.03	-	-	1.0	0.03	1.46	6.95	Non lateritic soil
S6	96.64	1.0	0.03	0.1	0.06	0.01	0.06	0.76	0.005	0.8	54.91	Non lateritic soil

CONCLUSION

The study area is underlain by the Ajali Formation, whose sandstone member is dominated by coarse- to medium-grained sand. The coefficient of uniformity of the studied sands is generally below 6, indicating that they are predominantly poorly graded. The clay-rich fraction is characterized by low plasticity and low swelling potential. XRF analyses indicate high silica contents and relatively low concentrations of aluminum and iron oxides, consistent with the non-lateritic character of the soils. Soil strength is governed largely by cohesion and internal friction. The studied materials contain limited cementing constituents and are not densely packed because of their relatively poor grading. These characteristics may reduce the overall strength of the soil mass and contribute to its friability and susceptibility to erosion. Consequently, erosion of the underlying soil and sediment constitutes a major geotechnical challenge for engineering structures in the study area. Appropriate geotechnical investigation, drainage control, erosion protection, and, where necessary, soil stabilization should therefore be considered in engineering development within the area.

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