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Geotechnical Properties of Tropical (Lateritic) Soils and Their Implications for Road Construction: A Case Study from Bahir-Dar, Ethiopia

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ABSTRACT: The research demonstrates the geotechnical properties of tropical soils and their implications for road construction. A series of standardized geotechnical and geochemical laboratory tests on lateritic soils of Bahir-Dar (Ethiopia) were conducted. Soil samples at depths of 0.6 m and 1.5 m were collected from five sites. The silica to sesquioxide ratio indicated that soils are lateritic. The findings show invariable particle-size distribution and Natural Moisture Content range between 4.53 to 12.2%. Average Maximum Dry Density and Optimum Moisture Content were 1.563 and 20.58, respectively. The specific gravity ranges from 1.95 to 3.09. The LL, PL, and PI range from 42 to 86.3%, 28.38 to 38.4%, and 13.12 to 49.7%, respectively. The unsoaked CBR and corresponding soaked CBR values range from 4.86 to 14.36% and 1.22 to 3.88%, respectively, at 65 blows of the modified proctor. The results evaluated the suitability of soils according to the Ethiopian Roads Authority standards and implicated that partially Test Pits-C, D & E soils satisfy to be a sub-grade or embankment material.

KEYWORDS: Road construction, Laterization, Geotechnical properties, Subgrade material, and Ethiopia.

1. INTRODUCTION

A thorough and comprehensive geotechnical investigation is an important demand for the management and evaluation of engineering projects. The right style of civil engineering structures, just like the foundation of buildings, retaining walls, highways, etc., needs adequate data of subsurface conditions at the sites of the structures. Many damages to buildings, roads, and different structures supported on soils are primarily due to lack of correct investigation of substructure conditions. The town of Bahir Dar, having an adequate land area for expansion and being an important industrial, commercial, educational, and tourist center in the region, has a high potential for future development. A lot of civil engineering structures are under construction; however, there is a research gap on the soil investigation part for the intended urban development plan (Fasil, 2003), barring a few reports with limited data. A new study reports the geotechnical problems responsible for the road failure from Gilgel Beles to Bahir Dar Road Segment which is nearest to the study area (Habtamu and Maschal, 2020).

To examine the engineering behavior of the native sub-grade soils and to observe the effect of the degree of laterization (weathering), verification tests have been conducted on the samples recovered from Test Pits excavated up to a minimum depth of 1.5 m below the ground surface. Accordingly, 5 Test Pits at a depth of 0.6 m and 1.5 m (10 samples in total) have been recovered, and the necessary tests have been conducted to represent the entire project alignment of 22.3 km. Currently, Tis Esat Road project is one of the ongoing projects in the northern part of the country. The proposed road is to create enhanced access to Tis Abay (waterfall of the Blue Nile). The falls are one of the Ethiopia's best tourist attraction sites. Therefore, the main objective of the research is to determine the degree of laterization of tropical soils and their implications for road construction. After collecting the representative disturbed and undisturbed samples from proposed Test Pits, they are tested; to confirm the extent of laterization, to characterize the study area soil through chemical, index, and strength property tests, and to check the suitability of the materials for road construction under the material requirement of Ethiopian Roads Authority (ERA, 2013).

2. LITERATURE REVIEW

Soils may be thought of as the corollary of the Earth's exogenic processes. They form because of the dynamics of geomorphic systems through the interplay of climatic elements with materials forming the subsurface of the landscape (Khan and Bajpai, 2014). Residual soils usually originated with the formation of the climatic systems and are part of the geological cycle, which has been in existence for hundreds of millions of years of geological time. Exposure of rocks to exogenic processes resulted in residual soils (Bujang et al., 2012).

Laterite and lateritic soils are largely predominant in tropical areas with a moist climate. Residual soil and especially recent lateritic soils are present dominantly in major parts of Southeast Asia, Laos, Vietnam, and Malaysia. These locations generally fall between latitudes 35^{O}S and 35^{O}N (Ahmed, 2015). Residual tropical soils can be classified as lateritic or laterites, depending on the degree of laterization. Lateritic soils are severely weathered and changed residual soils developed in tropical and subtropical locations with hot, humid climatic conditions by in-situ weathering and decomposition of rocks. Their formation also consists of leaching out of free silica and bases and accumulation of oxides of iron, aluminum, or both, and this process is termed laterization.

Moreover, they are rich in sesquioxide, i.e., iron oxides, aluminum oxides, or both, and low silicate content with a considerable amount of kaolinite. Lateritic soils are usually red due to the existence of the mineral iron oxides (Fekede, 2007). Mineralization is a process of intense weathering of a parent material/mineral, which occurs under conditions favorable to tropical weathering, where the clay minerals, which are hydrous aluminum silicate, are destroyed. Due to continued weathering, silica is leached, and the remainder consists mainly of aluminum oxides such as gibbsite or hydrous iron oxide such as limonite or goethite derived from the iron. The laterization process takes place in three stages.

The first stage is the breakdown of primary rock-forming minerals occurs, and this results in the release or formation of clay minerals, mainly kaolinite, and constituent elements such as silica, alumina, iron oxides, and oxides of other elements such as calcium and magnesium. In the second stage, the silica and alkali (calcium and magnesium oxide, among others) are leached, and accumulation of sesquioxide takes place. This occurs during wet seasons of the year, and its extent depends on the pH of the groundwater and drainage conditions. Iron, being carried in ferrous form by water, is mobile until it is oxidized to Ferric ions. Following the dry season, evaporation causes ferrous ions to migrate higher, allowing for oxidation by air oxygen. After then, iron forms hydrated ferric oxides gel. Aluminum travels through the solution until dehydration or a pH change causes it to precipitate as an Alumina gel. On the surfaces of the clay minerals, sesquioxide (hydrated Ferric Oxide + Alumina gel) is adsorbed. The adsorption occurs through the interaction of positively charged sesquioxide and negatively charged clay particles. At the third stage, partial/ complete dehydration of hydrated colloidal Sesquioxide occurs (Mulugeta, 2019).

3. MATERIALS AND METHODOLOGY

The first phase was structured to introduce the research topic, to deliver a literature review on the topic concerning past research on the subject, and to formulate a simplified physical-based model to carry out the past methodologies used by researchers. The second phase dealt with the execution of chosen methodology, mainly conducting experiments and collecting data. Here, samples were collected from the selected sites, and laboratory equipment was used to determine the properties of tropical soils by conducting standard accepted tests, and those results can be compared with past research data. A conclusion with discussion hence was made based on the results.

Figure 1 Google Earth Map showing the approximate Tis Esat Road Extension and locations of the Test Pits A, B, C, D & E

Sampling areas were selected from different parts along the road segment, and five pits were excavated up to a maximum depth of one and a half meters (1.5 m). To conduct different laboratory tests, about 40 kg of disturbed soil sample was collected in bulk randomly from each site and at each depth. The undisturbed samples were collected by inserting a steel tube horizontally into the soil layers exposed on trench walls. Both ends of the steel tube were sealed with wax (melted candle) after the undisturbed samples were extracted. Both the disturbed and undisturbed samples were delivered to the Geotechnical laboratory after careful sampling.

Figure 2 Test Pit A at 0-4 km.

Figure 3 Air drying of samples and sample preparation for the test

The grain-size distribution of mixed soils was determined by combined sieve and hydrometer analyses. Hydrometer analysis was conducted with Sodium hexameta-phosphate dispersing agent for the soil samples passed on No. 200-sieve size (0.075 mm). Two methods were used for water content determinations. In the first method, samples were oven-dried at 110°C until successive weighing showed no further loss of mass. In the second method, samples were air-dried (when required) or oven-dried at a temperature of no more than 50°C and a maximum relative humidity (RH) of 30% until no additional mass loss is observed. After oven-drying for approximately 40 minutes, no further loss was observed. Around 2.2 kg of samples were prepared.

Table 1 Sample depth and the designation

Test Pit	Sample location (km)	Depth (m)	Sample designation	Visual color observed
A	0.0-4.0	0.6	A-1	Brown silty clay soil
		1.5	A-2	Black cotton soil
B	4.0-8.0	0.6	B-1	Dark Brown clay
		1.5	B-2	Brown silty clay soil with gravel
C	8.0-12.0	0.6	C-1	Red clay soils
		1.5	C-2	Brown silty clay soil with gravel
D	12.0-16.0	0.6	D-1	Dark brown with weathered gravel
		1.5	D-2	Dark brown
E	16.0-21.2	0.6	E-1	Black cotton soils
		1.5	E-2	Black cotton soils

The various property tests that were performed, including index, strength, and geochemical:

- ➢ Grain size analysis
- ➢ Moisture content
- ➢ Atterberg limit
- ➢ Free swell
- ➢ Specific gravity
- ➢ Compaction test
- ➢ CBR
- ➢ Unconfined Compressive Strength test
- ➢ Geochemical test (complete silicate analysis)

The water content from oven-dried and air-dried samples was compared, and differences ranging from 1-4% were recorded. The values of moisture content at varying temperatures are given for all the samples in Table 2. According to Fourie (2012), a difference between 4-6% moisture content measured using high heat vs. low heat/air-dried indicates the presence of “structural” water.

We conducted both soaked and unsoaked CBR tests where swell CBR is indicative of soaked CBR. A free swell test is then performed by slowly pouring 10 cm^3 of dry soil, which has passed the No. 40 (0.425 mm) sieve, into a 100 cm^3 graduated cylinder filled with tap water. After 24 hours, the final volume of the suspension is read (ASTM D1883 Standard). Compaction test results were obtained for the different CPS concentrations for soils as received using MCM. The compaction test was conducted using a modified proctor, and samples were taken from the optimum proctor results. Atterberg Limits are the water levels at which the soil transition occurs from one state to another. They are utilized to figure out how fine-grained soils are made. Soft, firm, or hard soil consistency is a term used to define the degree of hardness of the soil. It generally refers to fine-grained soils whose condition is influenced by moisture content changes (Kebede et al., 2022).

The CBR is calculated by expressing the load required to cause penetration of 2.5 mm (2.54 mm) as a percentage of 13.2 kN (6.9 MPa) or penetration of 5 mm (5.08 mm) as a percentage of 19.8 kN (10.3 MPa) whichever is the larger. CBR is commonly referred to as a strength parameter while it is also an indicator of stiffness with a considerable limitation of conventional practice towards the treatment of maximum particle size (19 mm).

For undisturbed samples, the degree of lateralization of the soil samples can be evaluated based on the Silica/Sesquioxide ratio using complete silicate analysis. The Sesquioxide, designated as R_2O_3, is the combination of Aluminum oxide (Al_2O_3) and Iron oxide (Fe_2O_3). Silica is designated by the chemical formula SiO_2. True laterites have ratios less than 1.33; lateritic soils have ratios between 1.33 and 2.00; and non-lateritic tropically weathered soils have ratios more than 2.00 (Kamtchueng et al., 2015).

4. RESULTS AND ANALYSIS

4.1 Moisture Content

According to the result, the maximum variation is 3.99% which is less than 4%, which means the soil in the study area does not have a significant amount of loosely bound structural water (Fourie, 2012). Hence, all the upcoming moisture content determination can be done by drying at an oven temperature of 110°C for all samples. Due to leaching, the left-over soil turns moisture-less and rich in aluminiferous minerals, which ultimately leads to laterization of soil. The samples of the soil advanced into laterization process and readily dried in a shorter period of heating, whereas other soil samples took a longer time.

Table 2 Moisture variation between oven-drying at 110°C and 50°C

Sample designation	MC at 110°C (%)	MC at 50°C (%)	Variation (%)
A-1	12.20	11.1	1.10
A-2	10.30	7.4	2.90
B-1	5.25	4.3	0.95
B-2	4.53	3.6	0.83
C-1	7.92	6.8	1.12
C-2	9.40	8.3	1.10
D-1	6.20	3.5	2.70
D-2	9.60	6.1	3.50
E-1	9.59	5.8	3.79
E-2	9.09	5.1	3.99

4.2 Specific Gravity (G_s) Tests

The test results vary from 1.95 to 3.09, and as previously noted, the result might be high or low. Because of the high iron concentration, the value is higher; hence specific gravity of tropical soil may be unusually low if the soil is highly leached and porous and if the soil contains high organic content or unusually high if leaching and desiccation of soil develop a high accumulation of iron oxide and aluminum oxides. Similarly, in warm and humid climatic conditions such as in the study area, where leaching causes silicate dissolution/ removal leaving aluminum and iron concentration in the topsoil, ultimately subject soil to an increasing degree of laterization.

Table 3 Values of specific gravity

Sample designation	NMC (%) at oven-drying	Specific gravity
A-1	12.20	2.02
A-2	10.30	2.29
B-1	5.25	2.35
B-2	4.53	2.47
C-1	7.92	2.37
C-2	9.40	2.34
D-1	6.20	2.07
D-2	9.60	1.95
E-1	9.59	3.09
E-2	9.09	1.99

4.3 Free Swell Tests

Based on the suggestion of Holtz (2004), soils with a free swell value of less than 50% are considered non-expansive, while those with a free swell value of 50 to 100% are considered to have an intermediate degree of expansiveness. A free swell value of greater than 100% is supposed to indicate that the soil is expansive. According to the free swell test result, all the samples except C-1 (40%) and C-2 (20%) are considered to have an intermediate degree of expansiveness and can be categorized as non-expansive. The expansive nature of soil is usually associated with a higher degree of laterization due to partial conversion into clay minerals during leaching and cation exchange.

Table 4 Free swell test values

Sample location (km)	Depth	Sample designation	Free swell (%)
0.0-4.0	0.6	A-1	55
	1.5	A-2	66
4.0-8.0	0.6	B-1	60
	1.5	B-2	65
8.0-12.0	0.6	C-1	40
	1.5	C-2	20
12.0-16.0	0.6	D-1	55
	1.5	D-2	60
16.0-21.2	0.6	E-1	70
	1.5	E-2	68

4.4 Atterberg Limits and AASHTO Classification

Based on the Atterberg limits and USCS plasticity chart, it was observed that all soil samples except Pits-C are highly plastic with LL > 50%, where A-1, A-2, B-1, D-1, and E-2 are fat clay (CH) with PI values located above A-line, whereas D-2 and E-2 are Elastic silt (MH) with PI value located below A-line. The relations are possibly affected due to comparatively higher laterization.

Table 5 Samples details along with AASHTO classification denoted as soil group-subgroup (% passing the 0.075 mm sieve)

Sample location (km)	Depth	Sample designation	Classification (AASHTO)
0.0-4.0	0.6	A-1	A-7-6(37)
	1.5	A-2	A-7-5(39)
4.0-8.0	0.6	B-1	A-7-5(58)
	1.5	B-2	A-7-6(10)
8.0-12.0	0.6	C-1	A-7-6(2)
	1.5	C-2	A-7-5(7)
12.0-16.0	0.6	D-1	A-7-6(33)
	1.5	D-2	A-7-5(49)
16.0-21.2	0.6	E-1	A-7-5(54)
	1.5	E-2	A-7-5(45)

Table 6 Atterberg limit test values

Sample location (km)	Depth (m)	Sample	LL (%)	PL (%)	PI (%)
0.0-4.0	0.6	A-1	61.0	29.6	31.4
	1.5	A-2	63.4	30.3	33.1
4.0-8.0	0.6	B-1	61.5	33.7	27.9
	1.5	B-2	67.1	28.5	38.6
8.0-12.0	0.6	C-1	42.5	28.9	13.6
	1.5	C-2	42.0	28.9	13.1
12.0-16.0	0.6	D-1	55.5	28.4	27.1
	1.5	D-2	77.8	38.1	39.6
16.0-21.2	0.6	E-1	86.3	36.6	49.7
	1.5	E-2	82.6	38.4	44.2

4.5 Particle Size Distribution

Laterization and decomposition affect the size of the soil particles. When depth increases laterization and decomposition decrease, and the soil particles remain coarser (Khan et al., 2022). During hydrometer analysis (sedimentation process), using a diluted solution of sodium hexameta-phosphate dispersing agent with a mechanical stirrer helps to eradicate the problem of flocculation on clay particles (Khan and Malik, 2019). As shown in the graph below, it contains a wide and even distribution of particle size, where well-graded Gravelly silty sand is represented as a smooth concave upward grading curve.

The graph (e.g., Figure 4) represents particles of all sizes, from gravel down to clay. This type of soil is often loosely called boulder clay, where the plasticity index (PI) shows the range over which the soil is in the plastic state. A high numerical value of the plasticity index is known to be an indicator of the presence of a high percentage of clay in the soil sample. In geological terminology, it is considered inaccurate, contains enough clay to give it cohesion, and is well-graded from clay to gravel.

Table 7 Particle size distribution by wet sieving

Sample	Depth (m)	Clay (%)	Silt (%)	Sand (%)	Gravel (%)
A-1	0.6	40.4	20.1	24.2	15.4
A-2	1.5	31.2	20.2	28.4	20.2
B-1	0.6	26.2	43.5	1.9	28.4
B-2	1.5	30.1	17.1	2.8	50.1
C-1	0.6	30.4	17.2	16.4	35.9
C-2	1.5	31.4	17.1	4.4	47.1
D-1	0.6	39.5	19.5	8.4	32.6
D-2	1.5	42.7	18.7	2.1	36.5
E-1	0.6	40.5	20.2	12.6	26.7
E-2	1.5	43.6	17.6	10.6	28.2

Table 8 Unified soil classification

Sample	Depth (m)	LL (%)	PI (%)	Percentage passes		Group symbol	Group name
				0.075 mm	4.75 mm		
A-1	0.6	61.0	31.4	98.37	99.91	CH	Fat Clay
A-2	1.5	63.4	33.1	98.33	99.78	CH	Fat Clay
B-1	0.6	61.5	27.9	99.64	100.00	CH	Fat Clay
B-2	1.5	67.1	38.6	41.67	50.27	GC	Clayey Gravel
C-1	0.6	42.5	13.1	48.60	62.80	GM	Silty Gravel
C-2	1.5	42.0	13.1	49.12	63.47	GM	Silty Gravel
D-1	0.6	55.5	27.1	97.96	99.36	CH	Fat Clay
D-2	1.5	77.8	39.6	98.19	99.76	MH	Elastic Silt
E-1	0.6	86.3	49.7	97.40	99.24	CH	Fat Clay
E-2	1.5	82.6	44.2	97.45	99.61	MH	Elastic Silt

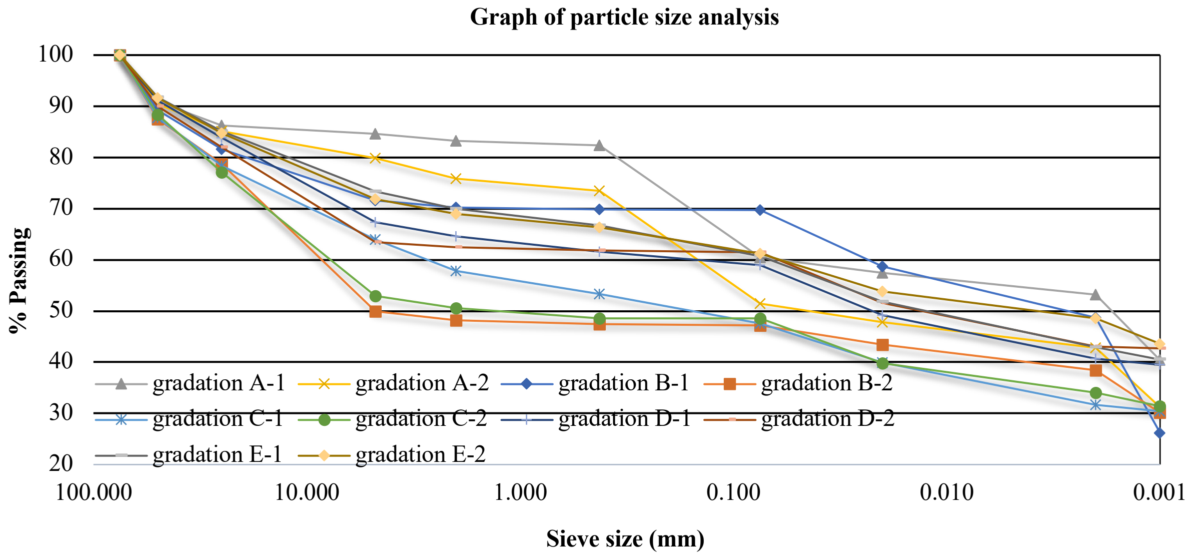


Figure 4 Grain size analysis and gradation curves

4.6 Compaction Test

Table 9 shows the modified compaction test results of all samples, which reveals that grain size and MDD increase while OMC decreases with the depth of each sample. The MDD increases with depth because the voids between gravel and soils are filled by the accumulation of the leached silica grains. Thus, the percentage of hard concretionary particles increases with depth.

In deeper parts, soil becomes coarser and denser, which results in the reduction of surface area. This reduction in surface area is caused due to decrease in OMC during compaction (Kamtchueng et al., 2015). Based on previous reports demonstrated by Lorraine M. Cahill in Highway Engineering (Second Edition, 2022), four data points can be used to develop a fairly accurate plot of dry density vs. moisture content for the soil.

Table 9 Compaction test data (for soils as received, using MCM)

Sample location (km)	Depth (m)	Method of testing	Maximum Dry Density (MDD)	Optimum Moisture Content (OMC)
0.0-4.0	0.6	Modified Proctor	1.487	24.30
	1.5	Modified Proctor	1.529	23.83
4.0-8.0	0.6	Modified Proctor	1.656	17.00
	1.5	Modified Proctor	1.698	15.85
8.0-12.0	0.6	Modified Proctor	1.510	20.70
	1.5	Modified Proctor	1.598	20.60
12.0-16.0	0.6	Modified Proctor	1.498	21.80
	1.5	Modified Proctor	1.595	19.00
16.0-21.2	0.6	Modified Proctor	1.515	22.90
	1.5	Modified Proctor	1.542	18.80

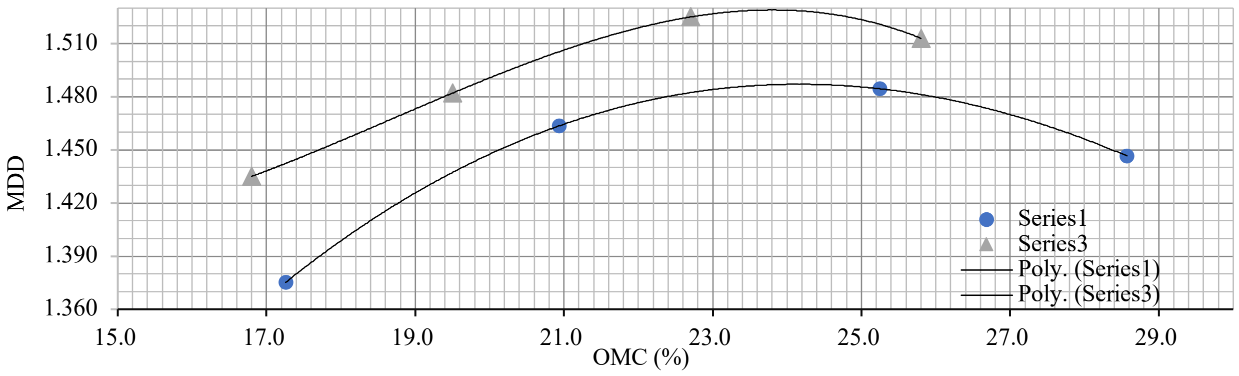


Figure 5 Effect of depth (laterization) on compaction, Test Pit-A

4.7 Unconfined Compression Strength (UCS) Tests

Test samples were brought into the laboratory in specified cylindrical tubes and extracted. Tests were conducted on these cylindrical samples. The governing factors for high unconfined compression strength for the Test Pit-C are sesquioxide strengths, moisture content, particle size constituents, and plasticity. Based on the visual and previous data observation of soils from all pits, it is confirmed that Pit C soil exhibits a lower degree of laterization which is reflected by the highest values of UCS and shear strength of this soil.

4.8 California Bearing Ratio (CBR)

Comparing CBR at 10 blows, 30 blows, and 65 blows by rammer prevail, a similar argument can be made regarding grain breakage. Generally, the increment of bearing ratio as the applied number of blows increases is related to an increase in densification. Whereas based on the effect of compaction, the rate of increase as blows progressed from 10 to 30 and 65 gives some idea about grain breakage; however, we do not have direct supporting evidence. Hence, CBR increases rapidly as the blow increases from 10 to 30 (3 times) but then from 30 to 65 (~2 times) blows, which shows that the increment is not as significant. This might be because of the diminishing effect of compaction energy.

The data in Table-10 indicates that CBR values are higher for the materials tested from Pits-C, D & E, where the latter marks the highest value as 14.38%. The data demonstrate that UCS and CBR exhibit a slightly variable relation with the degree of laterization of soils. However, it is important to observe that materials from the same Pits D & E possess the highest degree of laterization, 2.223 and 1.923, respectively, in Table 11. This variable relation is attributed to the removal of silicates from the soil and enrichment of aluminiferous oxides due to leaching and draining effects through the soil column. This phenomenon leads to soil degradation due to decomposition, laterization, and dehydration or desiccation,

4.9 Geochemical Test

Based on the results using the silica-sesquioxide ratio, it was determined that the soil samples D-2 and E-2 show the highest degree of laterization. Soil samples D-2 and E-2 are non-lateritic and lateritic soils, respectively. With increasing depth, the geological nature of the soils in Test Pits D and E is variable. The sample at a depth of 0.6 m and 1.5 m have different geological strata (soil layers). Thus, it is not an ideal condition to compare the laterization of these soils.

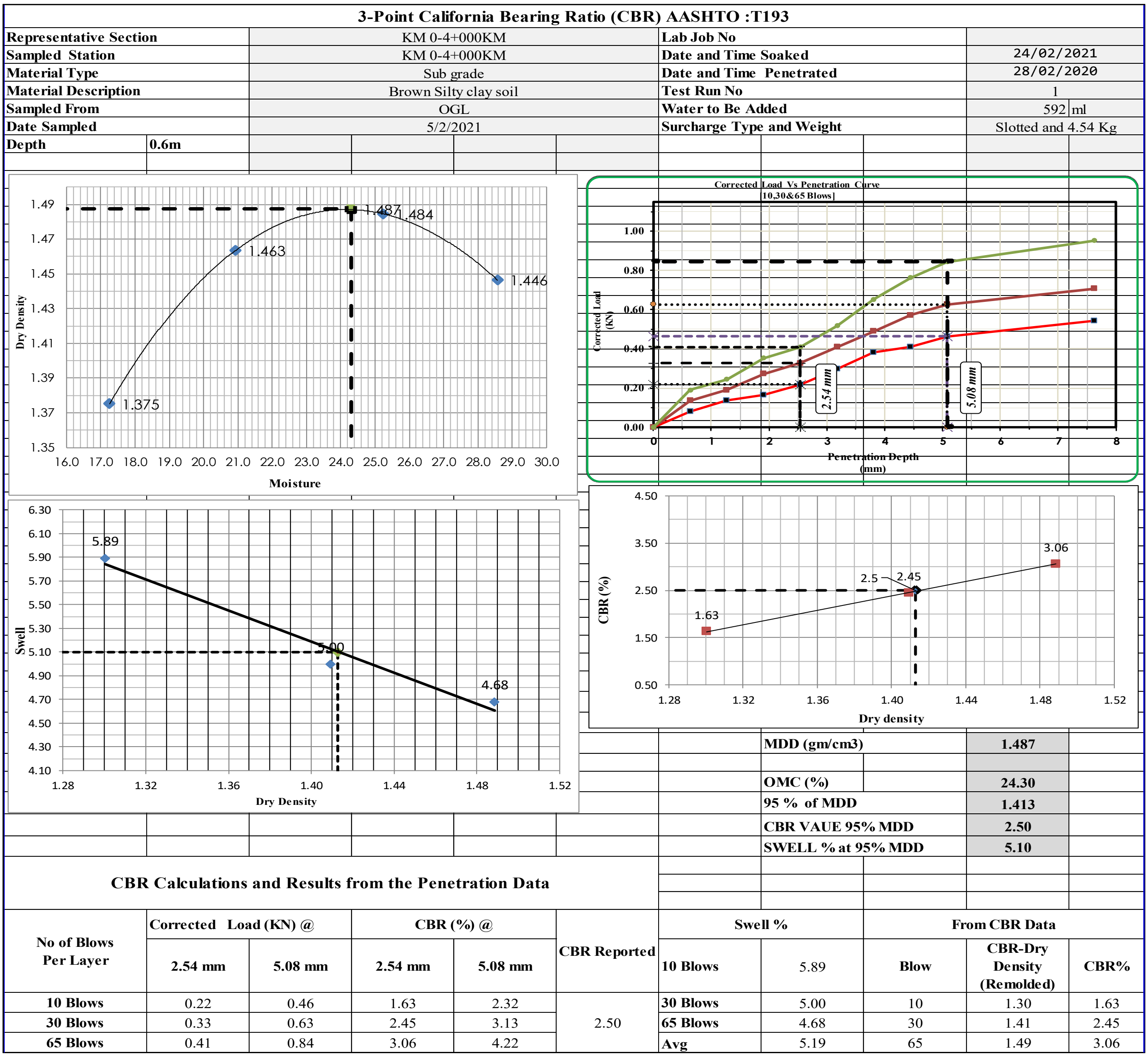
Overall, the lowest swell (1.49%) was observed as the sample was compacted using field density and natural moisture content. This arisen from its high natural water content and separated air voids or the existence of almost near to zero air voids in its in-situ condition. Further, the unsoaked CBR was the highest among all testing treatments (14.36%) at 65 blows. The maximum swell recorded was 19-20% due to the high absorption capacity of soil.

Table 10 UCS values and CBR test results showing unsoaked and their corresponding soaked values based on their respective densities

Sample location (km)	Depth (m)	Sample designation	OMC (%)	MDD	UCS, q_u (kPa)	No. of blows	CBR Unsoaked (%)	CBR Soaked (%)
0.0-4.0	0.6	A-1	24.3	1.487	40.42	10	5.89	1.63
						30	5.00	2.45
						65	4.86	3.06
	1.5	A-2	23.83	1.529	28.84	10	11.50	0.20
						30	10.53	1.02
						65	10.27	1.84
4.0-8.0	0.6	B-1	17.0	1.656	48.68	10	9.49	1.04
						30	8.71	2.04
						65	7.36	2.25
	1.5	B-2	15.85	1.698	41.36	10	5.20	2.45
						30	8.98	3.47
						65	10.31	3.88
8.0-12.0	0.6	C-1	20.7	1.51	146.26	10	4.12	2.58
						30	7.26	1.96
						65	8.58	1.64
	1.5	C-2	18.55	1.595	116.52	10	4.08	2.15
						30	9.19	1.89
						65	10.41	1.49
12.0-16.0	0.6	D-1	21.8	1.498	68.88	10	12.88	0.61
						30	12.07	2.04
						65	11.26	2.65
	1.5	D-2	19.0	1.595	46.64	10	11.55	0.41
						30	10.80	1.02
						65	9.34	1.84
16.0-21.2	0.6	E-1	22.9	1.515	74.5	10	16.10	0.41
						30	14.93	0.82
						65	14.36	1.22
	1.5	E-2	18.8	1.542	58.87	10	14.56	0.82
						30	14.02	1.22
						65	13.54	1.63

Table 11 Oxides composition in percent

Sample	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_3O_5	TiO_2	H_2O	LOI	$(SiO_2)/(Fe_2O_3+Al_2O_3)$	Remark
A-1	47.00	22.40	10.20	3.68	1.24	2.12	1.48	0.48	<0.10	0.69	3.93	8.41	1.441	**lateritic**
A-2	50.01	19.38	13.68	1.08	1.64	0.44	0.52	0.36	0.20	0.86	2.51	8.64	1.513	**lateritic**
B-1	51.20	18.72	11.68	1.28	2.00	0.56	<0.10	0.52	<0.10	0.58	5.64	8.86	1.684	**lateritic**
B-2	49.16	19.38	11.40	1.96	2.60	0.76	<0.10	0.52	0.10	0.49	5.21	7.65	1.597	**lateritic**
C-1	51.26	17.20	12.56	<0.1	1.24	<0.10	<0.10	0.16	<0.10	0.69	6.56	10.76	1.722	**lateritic**
C-2	44.06	22.66	12.92	1.64	2.32	0.80	0.48	0.16	<0.10	0.72	6.14	8.39	1.238	**laterite**
D-1	47.94	22.00	8.76	2.32	1.92	1.20	0.52	0.60	0.10	0.73	5.59	9.04	1.559	**lateritic**
D-2	57.14	13.46	12.24	0.74	2.22	0.16	<0.10	0.20	0.10	0.78	5.01	8.51	2.223	**Non-lateritic**
E-1	52.04	11.08	22.08	0.10	0.48	0.72	<0.10	0.28	<0.10	1.18	3.81	9.12	1.569	**lateritic**
E-2	51.66	13.51	13.36	3.72	2.56	0.70	<0.10	0.16	0.26	0.98	3.73	8.74	1.923	**lateritic**



3-Point California Bearing Ratio (CBR) AASHTO :T193

Representative Section	KM 0-4+000KM	**Lab Job No**	
Sampled Station	KM 0-4+000KM	**Date and Time Soaked**	24/02/2021
Material Type	Sub grade	**Date and Time Penetrated**	28/02/2020
Material Description	Brown Silty clay soil	**Test Run No**	1
Sampled From	OGL	**Water to Be Added**	592 ml
Date Sampled	5/2/2021	**Surcharge Type and Weight**	Slotted and 4.54 Kg
Depth	**0.6m**		

MDD (gm/cm3)	**1.487**
OMC (%)	**24.30**
95 % of MDD	**1.413**
CBR VAUE 95% MDD	**2.50**
SWELL % at 95% MDD	**5.10**

CBR Calculations and Results from the Penetration Data

No of Blows Per Layer	**Corrected Load (KN) @**		**CBR (%) @**		**CBR Reported**	**Swell %**		**From CBR Data**		
	2.54 mm	**5.08 mm**	**2.54 mm**	**5.08 mm**		**10 Blows**	5.89	**Blow**	**CBR-Dry Density (Remolded)**	**CBR%**
10 Blows	0.22	0.46	1.63	2.32	2.50	**30 Blows**	5.00	10	1.30	1.63
30 Blows	0.33	0.63	2.45	3.13		**65 Blows**	4.68	30	1.41	2.45
65 Blows	0.41	0.84	3.06	4.22		**Avg**	5.19	65	1.49	3.06

Figure 6 CBR test result graphs of sample A-1 obtained by using four days-soaked air-dried sample treatments.

Table 12 Comparison of this study with previous researchers

Researcher	Morin & Parry (1971)	H. Mariam (1992)	Fasil Abegna (2003)	Zelalem (2005)	Fekede Wakuma (2007)	Hanna (2008)	Eyasu Minichle (2015)	Berhane (2017)	Current Study
Location	Ethiopia	Addis Ababa	Bahir Dar	Nejo-Mendi	Assosa	Welayta Soda	Merawi	SNNPR	Bahir Dar
Soil type	Red clay	Red clay	Red clay	Lateritic	Lateritic	Lateritic	Lateritic	Red clay	Lateritic
Clay content	34-76	48-73	74-82	2-20.6	2.5-60	48-69.7	63.6-91.3	35.4-44.5	26.20-43.60
LL (%)	44-66	54-81	61-68	48-67	41-72	48-71	53-68.3	52-70	42.00-86.30
PI (%)	14-30	21-30	24-30	17-27	20-48	19-30	28.6-39.8	16-25	13.12-49.70
Free swell (%)	-	0-40	-	20-40	0-45	28-38	-	17.5-27.5	20-70
G_s	2.61-2.9	2.61-2.79	2.75-2.83	2.78-3.03	2.19-2.94	2.61-2.97	2.7-2.76	2.69-2.83	1.95-3.09
q_u (kN/m^2)	146.5-251	49-250	147-220	165-553	-	215-385	63.7-117.8	63-118	40.42-146.26
CBR (%)	-	-	-	22-79	-	-	-	-	1.22-10.41

Table 13 Ethiopian Roads Authority (ERA, 2013) material requirements

Material property	Requirement as sub-grade or embankment material	The requirement to be used as a sub-base material	Properties of soil from Test Pit C-1	Properties of soil from Test Pit C-2
Particle size	Max. 150 mm		Max. 75 mm	Max.75 mm
CBR (%)	≥ 5%	≥ 30%	8.58	10.41
Swell	≤ 2%		1.64	1.49
LL	≤ 60		42.50	42.00
PI	≤ 30	≤ 25	13.62	13.12
MDD	≥ 95%MDD	-	-	-
Remark: Soil from test samples C-1 and C-2 satisfies only to be subgrade or embankment material				

Table 14 Typical soil test results for ferrisol soils (Lyon, 1971)

Country	LL (%)	PL (%)	PI (%)	AASHTO	GI	OMC	MDD	CBR
Ghana	53	34	19	A-7-5	3	17	1.745	45
Niger	28	16	12	A-2-6	0	-	-	-
Ivory Coast	48	24	24	A-7-6	18	17	1.729	12
Mali	55	31	24	A-7-5	3	15	1.886	9
Uganda	46	21	25	A-2-7	0	14	1.894	16
Kenya	-	-	-	A-7-5	27	-	-	-
Cameron	65	37	27	A-7-5	19	-	-	-
Ethiopia	68	33	35	A-7-5	19	28	1.509	12

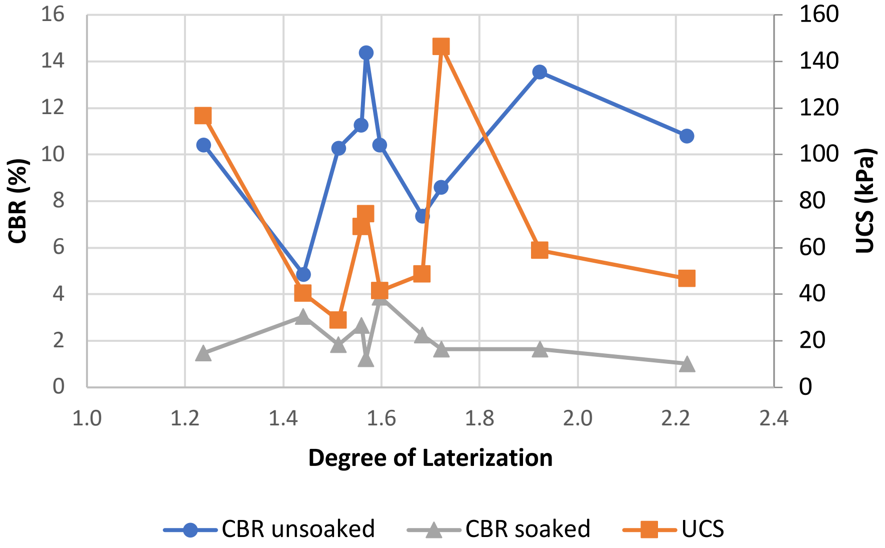


Figure 7 Degree of laterization with reference to UCS and CBR values for Pits A to E (at 65 blows)

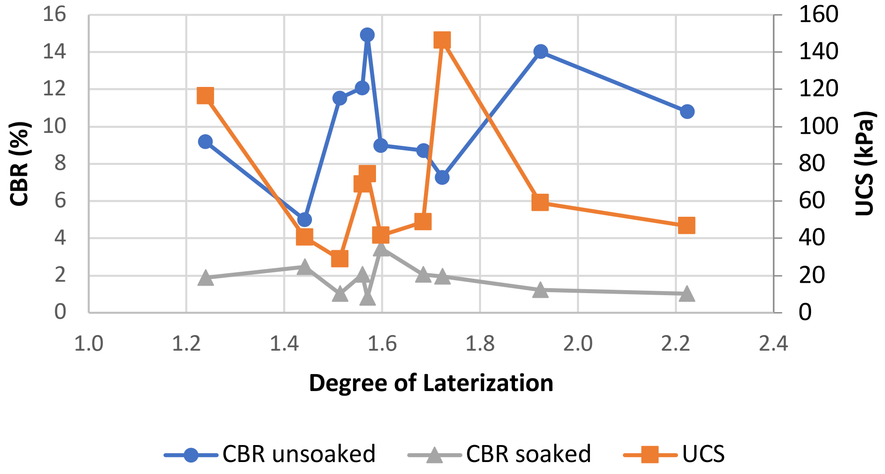


Figure 8 Degree of laterization with reference to UCS and CBR values for Pits A to E (at 30 blows)

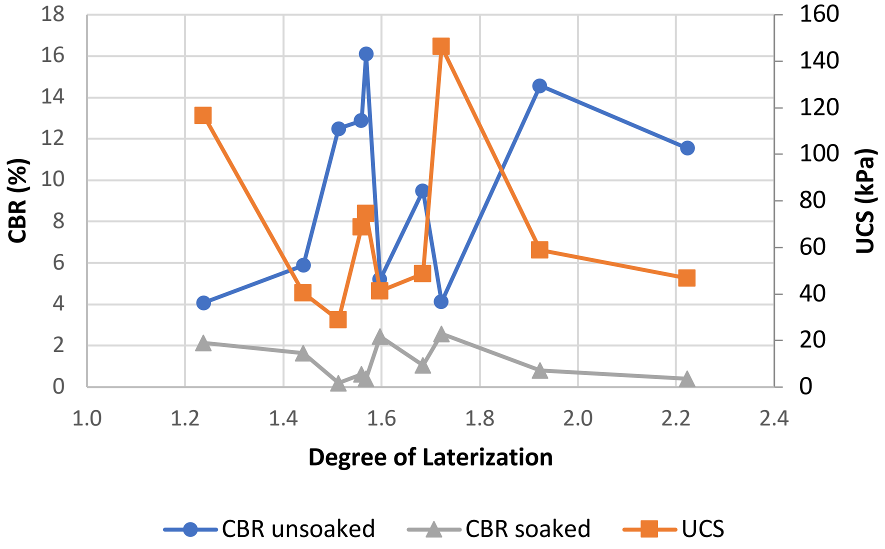


Figure 9 Degree of laterization with reference to UCS and CBR values for Pits A to E (at 10 blows)

5. SOIL SUITABILITY AS A SUBGRADE MATERIAL

According to the Ethiopian Roads Authority, "The Standard Technical Specifications and Method of Measurement for Road Works" define the limiting standard requirements in their "Geometric Design Manual" (ERA, 2013). According to ERA site investigation manual, a material with CBR value less than 5% and UCS value less than 50 kPa are very difficult to work as subgrade or pavement structure. On comparing the results of this study, we suggest that to be able to use the lateritic soil as a sub-grade/embankment sub-base, some stabilization techniques are required. After evaluation of the soil sample properties, especially laterization, CBR, and UCS, soils from Test Pits A and B were found unsuitable for subgrade if no treatments/stabilizations were carried out. Soils partially from Test Pits-C, D, and E satisfy the conditions for a suitable subgrade or embankment material; however, lateritic soils are not allowed to be used as sub-base or sub-grade material (The Geometric Design Manual, ERA, 2013).

In Table-12, a comparison of the gradation, compaction values, and Atterberg Limits values of the soil under investigation is shown, which indicates similar properties as Ferrisol soils of Ethiopia previously determined and listed in Table-14. Ferrisol soils occur in regions of between 1250 and 2750 mm of rainfall per year. The soil under investigation falls in this range of annual rainfall (Adeyeri, 2014). In Table-10, we have combinedly placed the values of UCS and CBR and compared them based on the degree of laterization against all Test pits from Table 11. For normalization, we have selected all the values of CBR and UCS for each pit from A to E. The unsoaked and soaked CBR values (at 10, 30, and 65 blows) are compared with UCS values from corresponding pits with respect to the degree of laterization as shown in their respective plots (e.g., Figures 7 to 9).

The values of the degree of laterization for all pits are calculated in Table-11 to draw a comparison with UCS and CBR. The data from Table-10 & 11 are plotted together as shown in Figures 7 to 9, where the respective graphs mark a distinct relation between laterization of soil, UCS, and soaked/ unsoaked CBR. It is observed from the plot that the values of UCS and CBR are varying with the degree of laterization in soil; however, if we compare the data of Test Pits A & B with D & E, UCS and CBR of the latter bearing a higher degree of laterization is stronger than A & B. This difference is attributed to varying effect of weathering and altered composition of material through the soil column.

6. CONCLUSIONS AND DISCUSSIONS

Geochemical test using complete silicate analysis ascertained that all soils along the Bahir Dar-Tis Esat Road project are lateritic, except soil D-2 from Pit D, which is non-lateritic. The specific gravity test results range from 1.95 to 3.09. The slightly high specific gravity is a result of a medium accumulation of heavy minerals like iron and aluminum in different forms. In contrast, low specific gravity observed on most samples indicates highly leached porous soil with high organic content. According to free swell test results, all the soil samples except Pit-C are expansive soils that are susceptible to volume change, while these soils are non-expansive with the lowest degree of laterization, which is a desired property in soils. Moreover, C-2 soil from Pit-C meets other geotechnical criteria of suitability as a sub-grade material, such as UCS and CBR. The strength parameters which were obtained from the UCS test q_u range from 40.2 to 146.26 Kpa. The CBR values are low with such high plasticity and fine-grained size. This is attributed to the sesquioxide bonds of lateritic soils being weak, leading up to low cementation between soil particles. By considering the Atterberg limits and USCS plasticity chart, it was observed that all soil samples except from Pits-C are highly plastic with LL > 50%, where A-1, A-2, B-1, D-1, and E-2 are fat clay (CH) with PI values located above A-line, whereas D-2 and E-2 are Elastic silt (MH) with PI value located below A-line (possibly affected due to comparatively higher laterization). On the other hand, soil samples of B-2 and Pits-C are coarse-grained gravelly soil, out of which the latter soils are silty gravel (GM) located below A-line. And B-2 is clayey gravel (GC) which is located above A-line, and again positively linked to a weathered soil horizon due to its coarser nature. AASHTO classification system categorizes the soils from test samples A-2, B-1, C-2, D-2, E-1, and E-2 under A-7-5 with group index >7 while the soils from test samples A-1, B-2, C-1, and D-1 are categorized under A-7-6. The Moisture-Density relationship of the soil was determined by the modified proctor test. When compacted at the modified proctor test's optimal moisture level, they produce a moderate dry density. The investigated sample's maximum dry density (MDD) value is 1.698, whereas sample B-2's optimum moisture content (OMC) value is 15.85. The discrepancy in the compaction test results may be due to the different weathering profiles in the soil and, subsequently, a varying degree of laterization. The soaked CBR values, swell percent of CBR, LL, and PI values of all soil samples except C D, and E under the material requirement of ERA-2013 implicate that these soils cannot be used for subgrade or embankment and sub-base materials, whereas soils partially from Pits-C, D & E satisfy to be sub-grade or embankment material.

Since laterization involves chemical and physicochemical changes through weathering, it tends to weaken soil structures. Also, the process of conversion of primary rock-forming minerals into compounds accelerates the weakening of soil due to formation of lattice clay minerals and laterite constituents. Moreover, the soil strength is decreased by the removal of silicate minerals, and cation exchange capacity is increased by the enrichment of oxides. These changes negatively influenced the engineering properties of soil and ultimately subjected it to high shrink-swell potential. And such soils are vulnerable to deformation due to varying temperatures and climatic factors. Due to the high water absorption tendency of clay minerals, such soils can expand by several times its original volume, which leads to the development of cracks, fractures, and fissures in the overlying structure, i.e., roads and buildings. Additionally, it can cause subsidence, slumping, ground failure, and lateral deformations to the structures. Based on the data shown in this study, most of the soils collected along the planned road trajectory have demonstrated a higher degree of laterization (due to changes in their inherent properties); however, soils from Pits-C are the exception with the least degree of laterization. Hence it is deduced from the test results (i.e., mainly free swell, laterization, CBR, and UCS) that Pits-C soils are comparatively much stronger than all other soils of the region and thus can be suitably used as sub-base or sub-grade material. Approximation to CBR value of >10% and UCS value of >100 Kpa is remarkably associated with higher degree of laterization in soils under this study and determined their suitability as a sub-grade material. Therefore, based on all parametric evaluations of the current study, it is concluded that amongst geotechnical properties, degree of laterization in soil is one of the important governing factors for the suitability of that soil as a sub-grade or embankment material and vice versa.

7. ACKNOWLEDGEMENT

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