FUOYE Journal of Pure and Applied Sciences

Available online at https://fjpas.fuoye.edu.ng/

Comparative Study of Geotechnical Assessment of Highway Subgrade Using *In Situ* DCPT and Laboratory Engineering Parameters

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ARTICLE INFO

Received: Feb. 2024
Accepted: April 2024

Keywords:
UCS, CBR, Permeability, Geotechnical, Characterization.

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DOI: 10.55518/fjpas.BJZK9266

Abstract

A comparative study of the geotechnical assessment of subgrade soils using *in situ* Dynamic Cone Penetrometer (DCP) Test and laboratory tests were carried out. The study was aimed at establishing the suitability of selected tropical soils as subgrade materials using the conventional laboratory test and *in-situ* DCPT method. The study involved sampling a total of 15 soil samples taken in a hand-dug pit at a minimum depth of 0.5m along Osogbo-Ilobu road. The *in-situ* test involved the use of a DCP in estimating the *in-situ* California Bearing Ratio (CBR) of the soil at 100m intervals through the 1.5 km stretch of the road. Laboratory tests carried out includes the grain size analysis, hydrometer test, Atterberg limits and specific gravity, CBR, permeability and Unconfined Compressive Strength (UCS). The results revealed a well-graded soils which are mostly clayey and silty sand (SC & SM) according to the Unified Soil Classification System (USCS) and A-2-4, A-2-6 to A-7 category of the American Association of State Highway and Transportation Officials (AASHTO) classification. The coarse fraction ranged between 48.3 - 90.5 % and fine fraction between 9.5 - 44.6 %. The UCS ranged from 148.8 - 214.5 kPa; unsoaked CBR from 54 – 148 %; soaked CBR from 42 – 106 %, reduction in strength due to soaking between 2.8 and 31.1 %; DCPT estimated CBR between 70 and 185. Conclusively, the soils were fairly suitable as subgrade, except for the clay contents in them, accounting for a very low rate of permeability which may be responsible for ponding and excessive soaking of the subgrade.

1.0 Introduction

Dynamic Cone Penetrometer (DCP) is a simple instrument used to measure the strenght of *in-situ* soil, the thickness, location of underlying soil layers and pavement evaluation. Two typical *in-situ* penetration tests for estimating the shear strength of soil include the Standard Penetration Test (SPT) and the Cone Penetration Test (CPT). The evaluation of subgrade strength plays a major role in the design of pavements since traffic loads need to be transmitted in a manner in which the subgrade deformation is within elastic limits and the shear forces developed are within safe limits under adverse climatic and loading conditions. One of the important steps in site investigation for road construction is the determination of subgrade material strength with different *in-situ* and laboratory tests such as the Dynamic Cone Penetrometer (DCP) test and the California Bearing Ratio (CBR) test [1]. In this connection, subgrades need to be evaluated for soil stiffness and strength. In addition to this, an investigation into the influence of the soil properties of the subgrade on pavement performance is also essential in checking for the cause of road failure [2]. Nigerian roads are known for persistent failure even shortly after construction, this has been attributed to poor construction materials, bad design, usage factor, poor drainage network which are considered to be factors that causes road failure [3], [4] and [5].

California Bearing Ratio (CBR) is popularly used as a critical test of the strength of subgrade soils especially for road constructions [6]. The laboratory determination of CBR is costly and require a considerable time to carry out. In order to overcome this time and cost in-efficiency, a reliable *in situ* CBR estimation will be the solution. The basic index properties of soil (e.g. grain sizes, Atterberg limits, density and moisture contents) are some of the factors that influences the CBR of soil [7]. Various correlations to estimate the CBR and Allowable Bearing Pressure (ABP) values from the index and engineering properties have been widely investigated by several authors [1], [6], [7], [8], [9], [10], [11] and [13]. These relations however vary for different types of soil and as well climates. Dynamic Cone penetrometer test (DCPT) according to [13] and [14] is a fast, effective, and relatively inexpensive instrument for collecting important soil parameters during a geotechnical site investigation or subsoil exploration. DCP can be effectively employed in the determination of the sub-grade soil strength for both flexible and rigid pavements. This paper therefore made an attempt to develop a generalized correlation between laboratory CBR value and estimated DCP CBR value, in a typical tropical residual soil in Nigeria.

1.1 Description of the Study Area

The study area is located between latitude $07^0$48N and $7^0$47N and Longitude $004^0$32 and $004^0$33E in the southwestern part of Nigeria (as shown in Figure 1). The study area covered 1.5 km stretch of Osogbo - Ilobu road. The study area can be accessed by road. Osogbo-Ilobu road is a federal road that connects other neighboring Communities such as Ifon, Ilajue, Oko down to Ogbomoso. The climate of the study area lies within the tropical savannah climate of the middle belt and southwestern parts of the Koppen climate classification [15 and 16] and is marked by alternating wet (rainy) and dry (harmattan) seasons. The rainy season occurs between March/April and October/November, during

which humidity and rainfall are high [15]. The coolest period is in the middle of raining season with an average temperature of 25^0C. The mean annual rainfall is about 1500 mm to 2500 mm [15]. The mean annual temperature is about 28°, with an annual variation of 3° and an average relative humidity of 90 percent across the year [15]. The dry season occurs from November – February. The dry season is usually characterized by dry northeast cool wind which is known as 'harmattan' and keeps humidity low. The drainage system is mainly dendritic and ranges from rivers, streams, springs, wells, runoff waters and swamp/wetlands [16]. Many rivers, including the Osun River from which the state coined its name, have their source in the northern part of the state.

In terms of geology, Osogbo lies within the Precambrian Basement Complex of southwestern Nigeria that forms part of the Pan-African Mobile and Ilesha/Iwo schist belts east of the West African Craton. Lithologies within this area include migmatite/gneiss and pegmatite schists (Figure 2). Low-temperature regional metamorphism coupled with hydrothermal alteration was responsible for the development of the varieties of schist in the area [17], [18], [19] and [20]. Besides this, rocks within the area of study form the parent material for the surficial soils characterized by strongly weathered residual profiles forming lateritic soils as a result of the chemical weathering of the parent rock material.

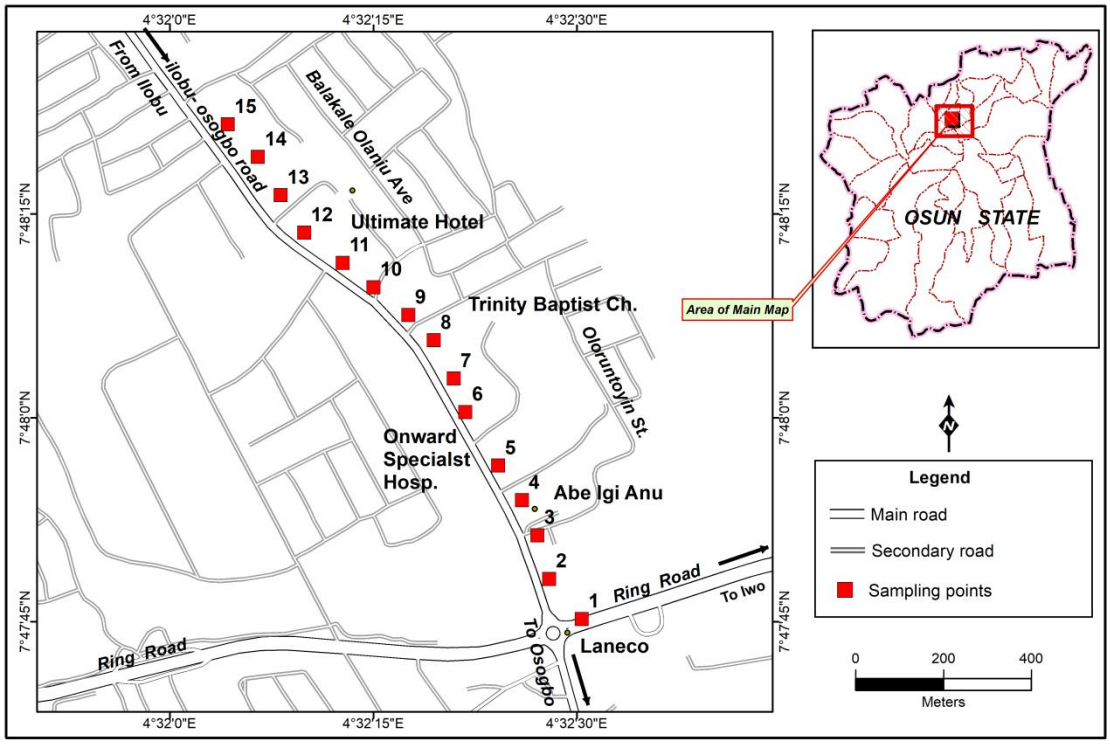


Figure 1: Location map of the Study area (extracted from Iwo Topo. Map sheet 242SE)

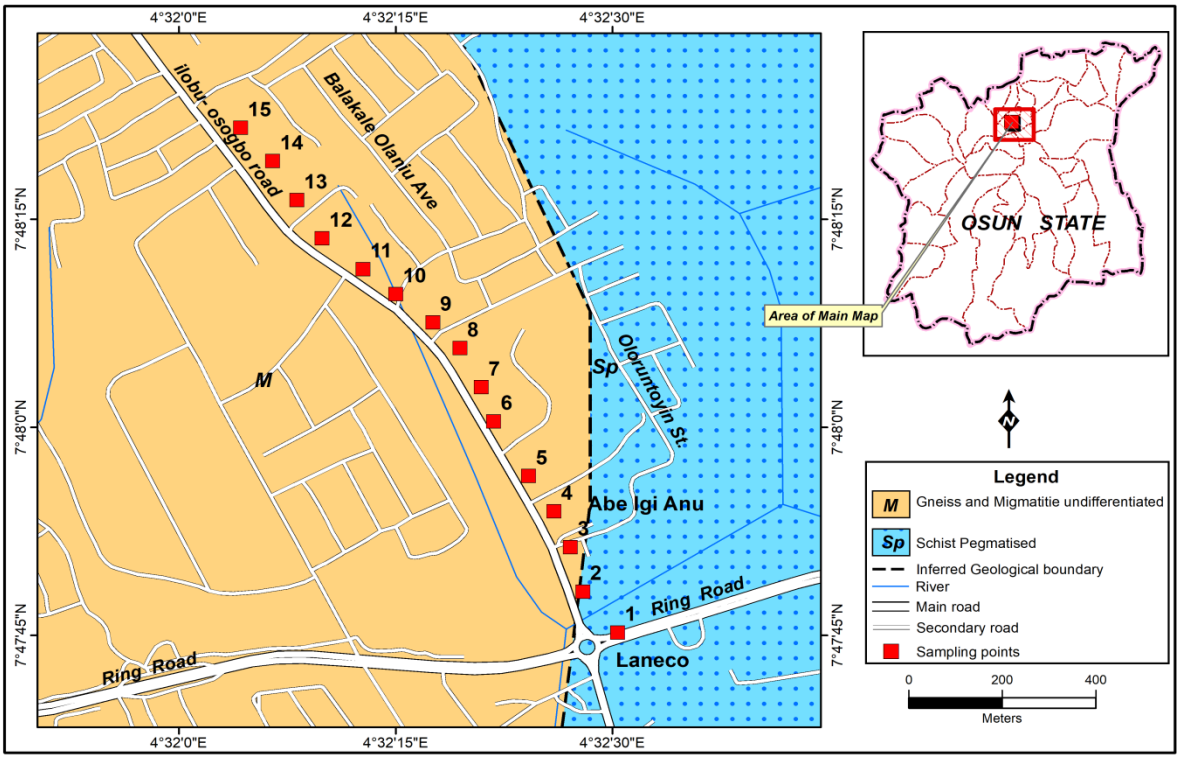


Figure 2: Geological map of the Study area (extracted from [21])

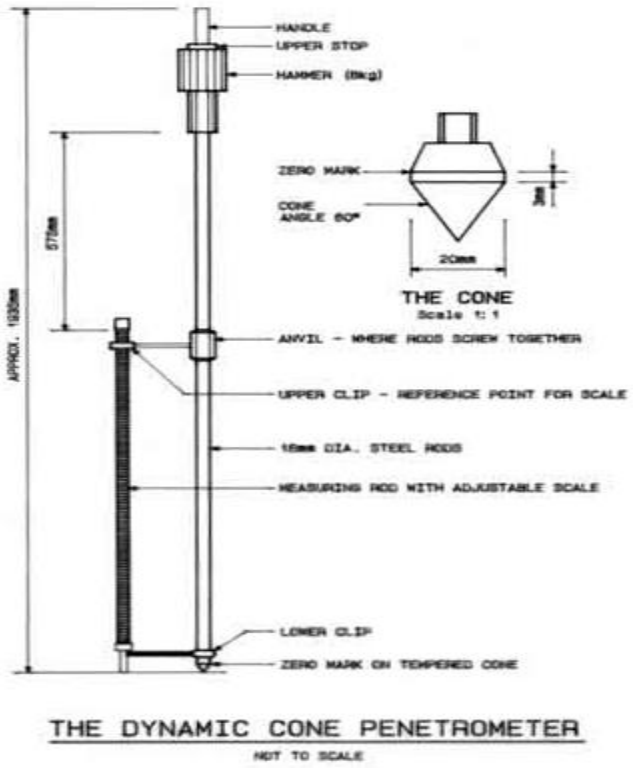


Figure 3: Diagram showing the part of DCP

2.0 Materials and Methods

The study involved an in-situ assessment of the shear strength of the soil using the Dynamic Cone Penetrometer (DCP) to determine its California Bearing Ratio (CBR). The DCP in this case is a slide hammer-driven rod with a replacement 20 mm diameter and 60° included angle cone that is inserted into the soil. For reasons of durability, the 60° cone was introduced and is preferred to the earlier 30° cone ([22] in [13]). At the desired depth, the 8 kg hammer was dropped repeatedly through a standard height of 575 mm onto an anvil attached to the rod with the cone at the end, with each drop or series of drops being measured for penetration depth. The kinetic energy associated with the falling mass was transferred to the conic tip through the rod upon impact at the anvil. The soil failed under shear and the cone moves forward if the energy (about 144 kNm per unit cone area) was high enough in comparison to the soil strength. As a result of the energy transmitted, the cone's ability to penetrate the soil was correlated with the density of the soil. According to ASTM D6951/D6951M, the DCP test's standard operating method is described. The strength of layers deeper than the reach of the DCP can be measured by removing some or all of the overlying material with a pick and spade or using a hand auger. At the start of the test the depth below the original datum level of the material to be tested is measured, using a trace measure and recorded (extracted from the DCP MANUAL).

2.1 Soil Sampling

A total of 15 (Fifteen) soil samples were collected within a distance of about 2-4m away from the riding surface of the road pavement. The samples were taken within a hand-dug pit at a minimum depth of 0.5m and a distance of 100m apart, the pits were labelled according to the pit number representing each soil samples. The soil samples were taken at depth of 0.5m below and labelled as OIR1, OIR2, OIR3… OIR15 respectively. The physical appearance of the soils, location of pits and depths were recorded during the collection of soil samples. Samples for moisture content determination were taken and preserved in polythene bags so as to prevent loss of moisture on exposure to air.

2.2 *In situ* Sampling (DCPT)

Field DCP tests were performed on subgrade soils at Osogbo-Ilobu road. The test carried out through the use of dynamic cone penetrometer (DCP) is to establish the depth to competent soil and estimate the *in-situ* CBR for the flexible pavement, the tests were done on the existing subgrade soils exposed by the road shoulders. The DCP tests were conducted at 100m intervals through the 1.5 km stretch of the road and each locations are labeled OIR1 - OIR15 respectively. For each location, there is a plot of DCP log as shown in Figure 4.

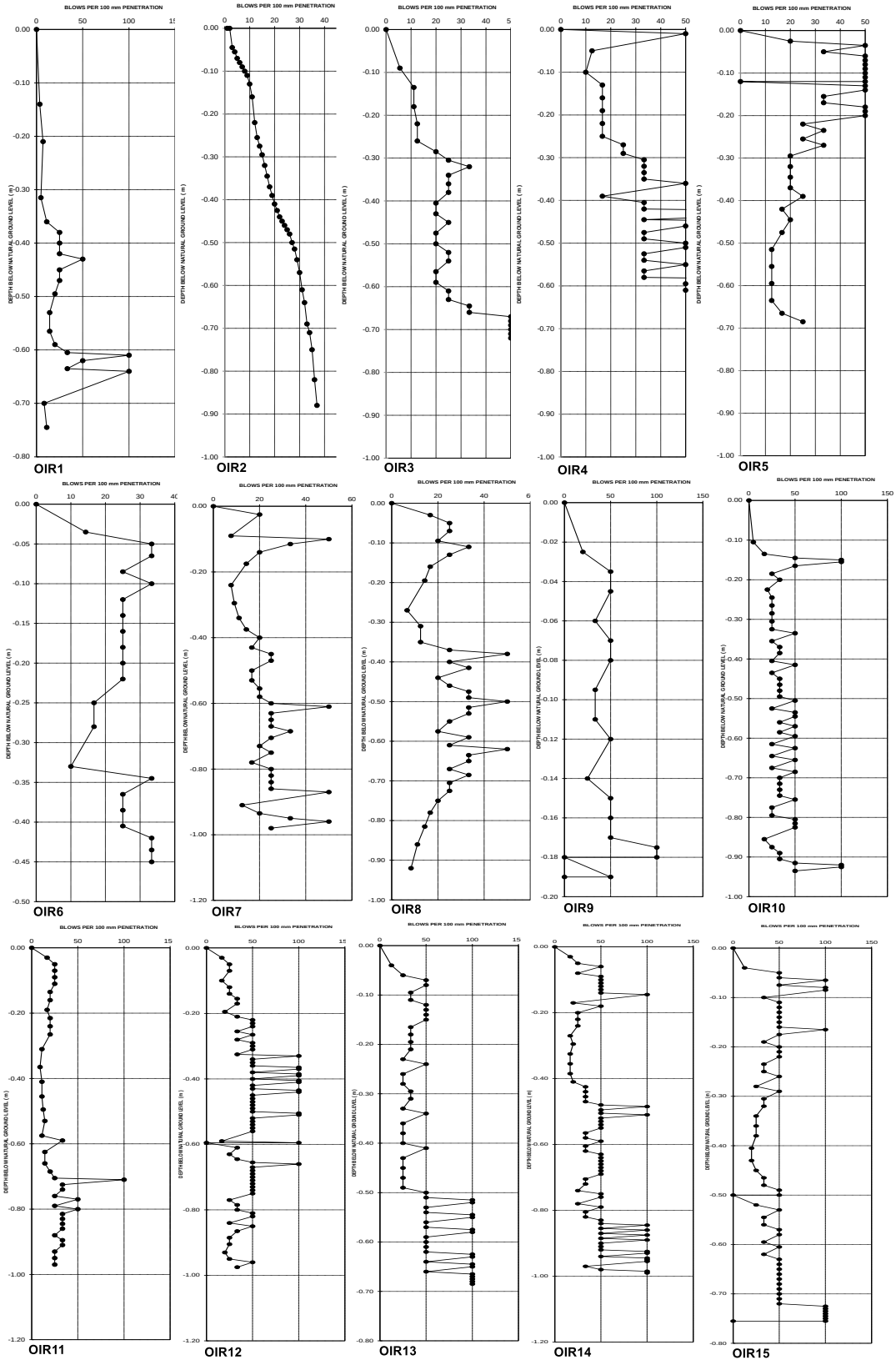


Figure 4: DCP plots

3.0 Results and Discussion

3.1 Index Properties

The results of the index properties of the soil are presented in Table 1. These are the parameters on which the CBR value depends. The moisture contents of the soil vary from low to moderate with values ranging from 5.2% to 18.3%. This could be attributed to the slightly gentle slope of the ground along the study area with variable depths to water table. Olubanjo [23] inferred that samples with low moisture content in their natural state indicates the soil has moderate percentage of clay which suggests that there is no interaction of sub base soils with the ground water which could increase the tendency of the soil getting wet. This condition would increase the shear strengths of the soil resulting to the prevention of the failure of the riding surface.

The soils in the study area were predominantly clayey/silty sand according to the Unified Soil Classification (USCS) systems and American Association of State Highway and Transportation Officials (AASHTO). The amount of fines (which corresponds to particle sizes from < 0.002 mm to 0.06 mm) ranges generally between 9.5 and 44.60 % with an average of 31.04%. The coarse particle (which corresponds to sand and gravel particle sizes, 0.06–20 mm) contents ranged between 48.3 and 90.5% with an average of 68.9 % for the soils. These results are typical of soils derived from rocks that are mostly felsic in origin, and the soils from all sample areas reflect the mineralogical and textural characteristics of the parent rock [24], [25]. Figure 5 shows the particle size distribution curve reflecting a well-graded soil. The soils mostly satisfy the specification as proposed by the [26], which stipulates that percentage passing sieve 200 must be less than 30%. The Atterberg Limits reveals a liquid limit value ranging from 20.0 to 44.3 % with an average of 30.58%, plastic limits between 21.1 and 24.2 %.

The specific gravity ranges from 2.617 to 2.677. Adeyemi [27], justified the use of specific gravity as a valuable parameter in assessing subgrade materials especially in terms of determination of the degree of laterisation in order to evaluate laterite aggregates used in pavement construction.

Texturally, the soils are mostly suitable for sub grade soils in road construction except very few like OIR 7.

Table 1: Index properties of the soil samples along Osogbo - Ilobu roa

SAMPLE NO/ LOCATION	MOISTURE CONTENT	SPECIFIC GRAVITY	GRAVEL %	SAND %	SILT %	CLAY %	AMOUNT OF FINES %	AMOUNT OF COARSE %	LIQUID LIMIT %	PLASTIC LIMIT %	PLASTICITY INDEX %	LINEAR SHRINKAGE %	USCS	AASHTO
OIR 1	5.2	2.622	0.7	89.8	2.5	7.0	9.5	90.5	20	-	-	7.1	SM	A-2-4
OIR 2	16.3	2.650	6.1	50.3	17.5	26.1	43.6	56.1	38.5	21.3	17.25	7.9	SC	A-2-6
OIR 3	12.6	2.617	1.4	76.4	20.3	1.8	22.1	77.8	27.1	21.1	6.00	4.3	SC	A-2-6
OIR 4	8.5	2.631	1.6	63.8	24.3	10.4	34.6	65.4	33.4	23.1	10.35	2.9	SC	A-2-5
OIR 5	6.2	2.641	0.8	81.6	15.4	2.3	17.7	82.4	22.4	-	-	1.4	SM	A-2-4
OIR 6	5.2	2.628	19.7	59.1	15.5	5.7	21.2	78.8	23.0	-	-	2.1	SM	A-2-4
OIR 7	18.3	2.677	0.0	48.3	28.9	22.8	51.7	48.3	44.3	24.2	20.15	9.3	CL	A-7-5[a]
OIR 8	10.3	2.643	4.6	63.2	21.2	10.9	32.2	67.8	28.3	21.1	7.20	5.7	SC	A-2-4
OIR 9	16.7	2.658	10.5	47.5	23.8	18.2	42.0	58.0	41.1	23.1	18.00	8.6	SC	A-2-5
OIR 10	10.3	2.638	6.3	77.5	13.0	3.2	16.2	83.8	23.0	-	-	2.1	SM	A-2-4
OIR 11	13.6	2.654	7.5	50.7	22.3	19.5	41.8	58.3	39.8	21.3	18.55		SC	A-2-6
OIR 12	15.3	2.670	4.1	51.3	24.8	19.8	44.6	55.4	41.2	22.6	18.60	5.0	SC	A-2-7
OIR 13	12.2	2.653	7.8	48.4	26.2	17.6	43.8	56.2	31.4	22.6	8.80	5.7	SC	A-2-4
OIR 14	11.2	2.641	0.1	79.1	17.9	2.9	20.7	79.2	23.1	-	-	2.9	SM	A-2-4
OIR 15	8.8	2.634	0.1	75.9	20.1	3.9	24.0	76.0	22.2	-	-	1.4	SM	A-2-4

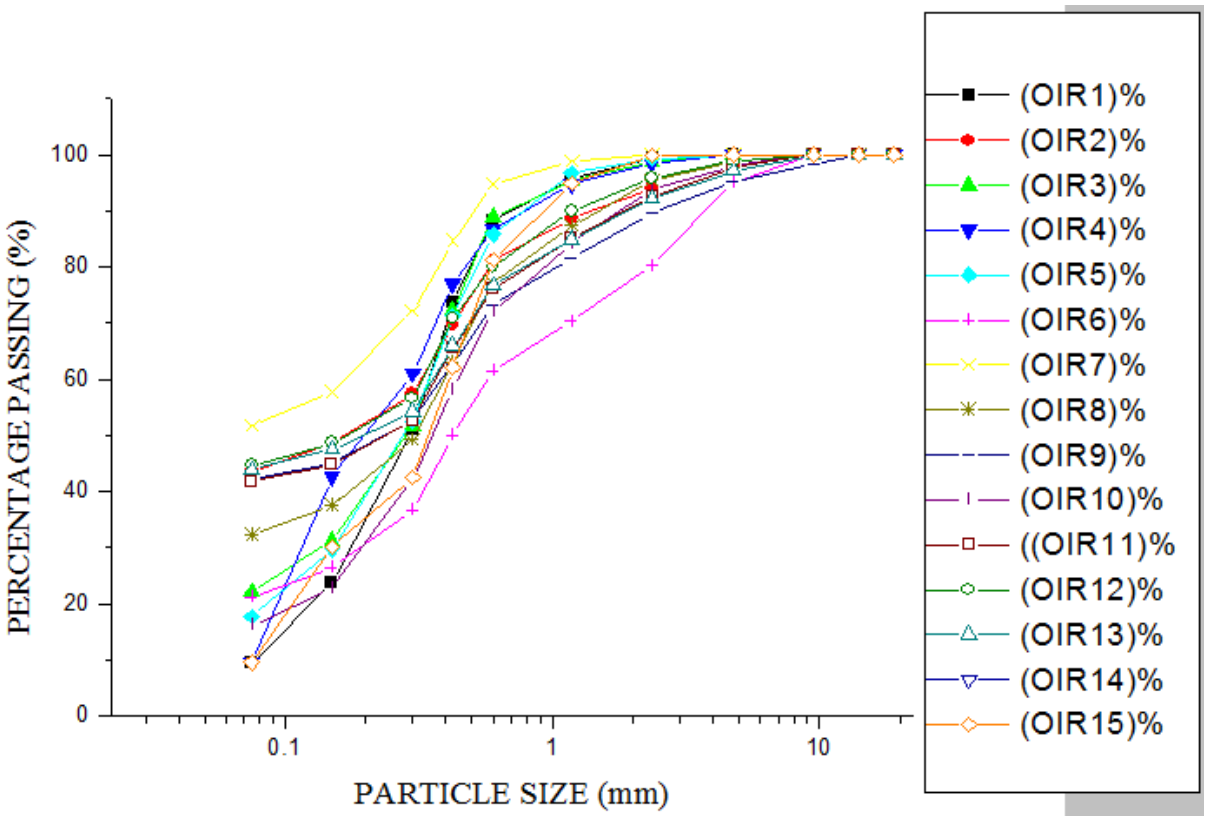


Figure 4: Particle size distribution curve of soil samples of the study area

Table 2: Engineering properties of the soil samples

S/N	Sample Code	Shrinkage Limit (%)	UCS (kPa)	CBR (%)		Red. In Strength (%)	Est. CBR (DCPT)	Permeability	
				Soaked	Unsoaked			K_T(cm/s)	K_{T20}(cm/s)
1	OIR 1	10.6	157.4	88	92	4.3	110	0.00947	0.00784
2	OIR 2	10.1	195.5	99	103	3.8	102	0.0000074	0.0000061
3	OIR 3	12.5	148.8	106	109	2.8	170	0.000659	0.000546
4	OIR 4	13.4	161.7	89	94	5.3	110	0.0000214	0.0000177
5	OIR 5	14.4	151.5	42	55	23.6	70	0.001520	0.001260
6	OIR 6	13.9	214.5	46	54	14.8	70	0.000698	0.000578
7	OIR7	9.1	206.6	86	97	11.3	115	0.00000030	0.00000025

8	OIR 8	11.5	206.6	88	115	23.5	175	0.0000305	0.0000252
9	OIR 9	9.6	210.5	102	148	31.1	185	0.0000143	0.0000118
10	OIR 10	13.9	166.3	78	102	23.5	102	0.001149	0.000952
11	OIR 11	9.6	195.5	98	120	18.3	165	0.00000906	0.00000750
12	OIR 12	12.0	164.2	96	108	11.1	170	0.00000313	0.00000259
13	OIR13	11.5	177.1	86	102	15.7	180	0.00000734	0.00000608
14	OIR 14	13.4	174.3	82	98	16.3	150	0.0009886	0.0008192
15	OIR15	14.4	148.8	42	56	25.0	75	0.0009704	0.0008042

3.2 Engineering Properties

The results of the Unconfined compressive strength (kPa) shown in table 2 ranges from 148.8 kPa to 214.5 kPa with an average range value of 178.6kPa. Generally, the higher the compressive strength the better the soil. According to Mathur [28], soils having unconfined compressive strength value of 50-100 kPa is considered relatively firm and soils having values of 100-200 kPa are considered stiff while soils with values between 200 kPa and 400 kPa is considered very stiff while any soil with unconfined strength of over 400 is considered hard. Therefore, soil samples within the study area are considered to be stiff and very stiff soil and their compressive strength are good, even though, water retention and inadequate drainage can quickly weaken such soil samples leading to incessant road failure.

The permeability of the soil samples ranges from 0.00000030 cm/s to 0.00947cm/s. From the results, few soil drains more due the high content of sand and gravel. The clay particles in other samples makes them retain more water because clay is impermeable. According to Lambe [29] the degree of permeability of the soil samples are rated as very low for OIR 2, 7, 11, 12 & 13, low for OIR 3, 4, 6, 8, 9, 14 & 15 and medium for OIR 1, 5 & 10. The result show that the sub-grade soil of OIR have very low to medium permeability which result in low infiltration rate, poor drainage and this is responsible for the frequent failure of the road.

The CBR was determined at the Maximum Dry Density (MDD) and OMC on both unsoaked and soaked conditions. Soaking was carried out with the aim of simulating the response or behaviour of soil to moisture under soaking condition. CBR value for natural soil (unsoaked) ranged between 54% to 148 % while soaked CBR value ranged from 42 to 106 %. The reduction in strength due to soaking vary accordingly from about 2.8 to 31.1 %. This indicates the response of the soil to ingress of water or increase in moisture content. The results are in agreement with the earlier findings of Oyelami and Van Rooy [30] where they opined that the presence of clay particles in the tropical lateritic soils were responsible for the swelling when it comes in contact with

water. This is responsible for the significant reduction in strength observed in the study area.

The estimated CBR from DCPT are presented in table 2 according to the earlier estimations from numerous previous authors as mentioned in the introduction. The estimated values ranged from 70 to 185.

3.3 Correlation between the unsoaked CBR and DCPT estimated CBR

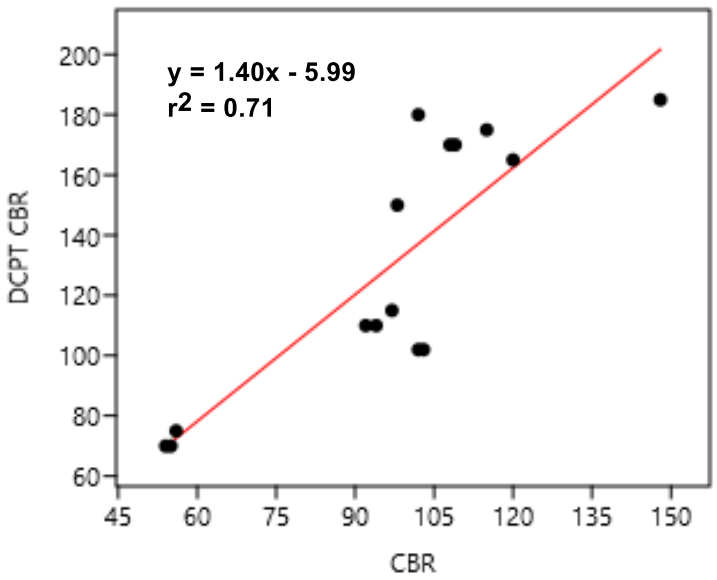


Figure 5: Correlation between CBR and DCPT derived CBR

The variation between *in-situ* CBR values and the laboratory CBR values were compared as shown in Figure 5 above using regression analysis. A linear regression as shown above presents a fairly strong correlation between the two parameters with a coefficient of determination (r^2) of 0.71.

The result reflects a significant level of confidence in the usage of DCPT CBR derived *in-situ* as a viable alternative for the laboratory CBR.

4.0 Conclusions

The geotechnical assessment of Osogbo – Ilobu road has been carried out using *in-situ* dynamic cone penetrometer and conventional laboratory tests with the aim of comparing the efficiency of in-situ test over the conventional laboratory tests. Most of the studied subgrade soils are not suitable in their natural state as materials for highway pavement but could be enhanced by stabilization.

On the efficiency of the *in-situ* and laboratory CBR, it was found that the DCPT CBR value estimated in the filed may be a viable alternative for the laboratory CBR. DCPT CBR for road geotechnical assessment is cost

and time effective as established in the regression analysis presented in this paper.

Other important parameter to be considered is the rate of permeability of the sub grade soil; results in this paper revealed mostly non-permeable soils having very low - medium permeability which makes them unsuitable as materials for subgrade in road construction, such material as this will expose the highway to ponding which will eventually weaken the highway pavement from the subgrade up to the riding surface. A significant reduction in strength was observed in some of the soil samples based on the results of soaked and unsoaked CBR, as previously opined, this is due to the effect of fine particles in the sub grade soil which swells when it comes in contact with water. This can be reduced by the providing adequate drainage for the highway.

Based on the results of the geotechnical assessment, the following recommendation are proposed:

- *In-situ* DCPT CBR has been proven to be a viable alternative to understanding the strength of sub grade soil.
- A proper drainage system should be constructed in the study area. The drainage would help control the water flow and would reduce accumulation of water on the road.
- A quick and cost efficient geotechnical/engineering investigations should be carried out on roads before any maintenance/repair works.
- Proper remediation should be done by removing the clay layer and replacing it with a more competent soil especially for the subgrade layer.

Declarations

Ethics approval: Not applicable

Consent for publication: Not applicable

Competing interests: The authors declare that there are no competing interests on the manuscript.

Funding: The work is self-funded.

Authors contributions: CAO conceptualized this work, supported by OAO, the fieldwork and laboratory analyses were carried out by OOO and SA. All the authors drafted the manuscript and all authors read and approved the final manuscript.

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