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IN-SITU ASSESSMENT OF THE RELATIONSHIPS BETWEEN VARIABLE SOIL MOISTURE AND SUBGRADE SOIL STRENGTH PARAMETERS

*,[1]Ikubuwaje, C. O., [2]Adebayo, A. E., & [3]Adewumi, O. A.
[1,2, & 3] Department of Minerals and Petroleum Resources Engineering Technology
Federal Polytechnic Ado-Ekiti, Ekiti State, Nigeria
*Corresponding author email: cikubuwaje@gmail.com

ABSTRACT

The mechanical properties and terrain features that reflect the soil-forming environment are important for pavement design. Experimental laboratory data demonstrate the relationship between soil moisture and soil strength, but this relationship largely ignores in-situ soil conditions. This study examines the effects of varying soil moisture on in-situ soil strength parameters of subgrade soils using a dynamic cone penetrometer. The experiment was performed on granite-derived lateritic soils with constricting grain sizes. Soil samples were collected at an interval of 450mm, 650mm, and 900mm down the soil profile to examine changes in the moisture content and the effect on soil strength parameters. The DCP sounding was performed at an established location and the acquired penetration index was converted to CBR and M_R values. The result revealed that increases in moisture content resulted in a high penetration index. Change in the California Bearing Ratio (CBR) and resilient modulus (M_R) values is directly proportional to the amount of moisture content absorption. M_R is more susceptible to the ingress of water compared to CBR. Moisture content has a significant effect on cohesive soil type in dry-wet conditions. In-situ dynamic soil strength properties could be used to measure a range of soil moisture conditions while a dynamic cone penetration device could be used to evaluate moisture content conditions. Adequate information on either M_R or CBR can give good inferences and help to deduce the engineering performance of soils. In addition, the findings improve how soil moisture content and soil strength parameters are analyzed to have an impact on next-generation mobility models. They also enable remote evaluation of subgrade soil under soil moisture circumstances based on pedogenetic characteristics.

KEYWORDS: Dynamic cone penetrometer; In-situ test; California Bearing Ratio; Resilient modulus; Granite-derived lateritic soils

INTRODUCTION

California Bearing Ratio (CBR) and resilient modulus (M_R) are essential strength structural parameters utilized in pavement design. Although California Bearing Ratio (CBR) measures the strength of the subgrade of a road, as well as the materials used in its construction, resilient modulus (M_R) measures the stiffness of subgrade materials. To calculate the stress and strain deflection in pavement design, resilient modulus (M_R) needs input, while CBR is a key prerequisite for pavement design. Typically, natural subgrades serve as the foundation layer and integral layer of the entire road surface, acting as support, limiting deformation to considerable levels, and promoting uniformity of support for the long-term performance of the roadways.

The features of the subgrade soil have an impact on how well the pavement performs (Yoder & Witczak, 1975). According to O'Reilly and Brown (1991), subgrade might be made up of natural soil that has been removed or filled in to support the pavement systems. These soils are a result of the underlying rocks' intense chemical weathering. The amount of moisture in the soil, the soil's texture, mineralogy, structure, density, and strength all have an impact on the structure's strength. Climate change will always have an impact on the subgrade because it is so near to the soil surface (Baladi et al., 2009). It also causes water levels to change, which will have an impact on the stability and strength of the soil, particularly clay soil. According to Ovik et al., (1999), changes in the state of moisture in the subgrade will affect the stiffness on a seasonal basis. Some scholars have investigated the impact of soil moisture content on resilient modulus throughout the last few decades (Maher et al., 2000; Zaman & Khoury 2007). One of the most crucial factors to consider when predicting the resilient modulus (M_R) value is the moisture content of subgrade soils (Fleming et al., 2000; George 2004). Empirical laboratory studies demonstrate the link between soil moisture and soil strength, although these relationships are mostly unaffected by in-situ soil conditions (Brad et al., 2022). Murthy (2003) asserts that the highly structured nature of lateritic soils has a significant impact on the geotechnical performance of these materials. Site characterization is crucial since site sampling and transportation of soils to the lab usually influence their structure along with sample preparation techniques. Indian Roads Congress (IRC): SP 72(2015) suggests using a dynamic cone penetration (DCP) test to get around this. This was supported by Pinard (2016), who found that the DCP test works superbly in the geotechnical evaluation of in-situ stiffness and strength of pavement materials. Research on geotechnical investigation had produced excellent empirical connections between DCP resistance and CBR measures, including those by Kleyn (1975), Smith & Pratt (1983), Livneh & Livneh (1994), and Amadi et al., (2018). This study aims to demonstrate how moisture content affects subgrade properties such as resilient modulus value (M_R) and California Bearing Ratio (CBR) value using a dynamic cone penetrometer. The relationship between resilient modulus and California Bearing Ratio (CBR) will be established, which can be highly useful in pavement design.

MATERIALS AND METHOD

Study Area

Latitude 07°16.00'N to 7°28.00'N and Longitude 005°10.00'E to 005°17.00'E outlined the research area. The investigation points established have residual soils that are brownish with both fine-grained and coarse-grained textures. The lateritic soil was found developed over granitic rocks of the Precambrian basement complex that form the geological setting of the highway.

Method

For this study, coarse-grained and fine-grained (CG and FG) soil types were used. Depending on the size of its particles, the soil has different engineering properties. As a result, the soils for this investigation were carefully selected to comprise defined narrow-range particle sizes (e.g. CG and FG soil types). Second, only soil types derived from granite were used in other to eliminate the impact of mineralogical variations. Integrated strategies that included laboratory, field, and soil sampling were explored. To identify and categorize the samples, index tests such as moisture content and particle size determination were carried out.

Field test

Dynamic Cone Penetrometer (DCP), as specified in ASTM D6951/D6951M-09 (2015), was used for an in-situ geotechnical study. The DCP used in this study is equipped with the following extras: a steel rod with a cone at one end that has an apex angle of 60° and a base diameter of 20 mm. A sliding hammer that weighed 8 kg was used to push it into the subgrade from a height of 575 mm. For the in-situ geotechnical investigation, nine (9) test pits were established to collect soil samples. The soil samples were collected at depths of 450, 650, and 900mm, to determine changes in moisture content and the relative effect on soil structural properties down the soil profile. Polythene bags with labels and seals were used to store and transport the obtained soil samples to the lab for analysis.

Laboratory test

Moisture content determination

The natural moisture content of the soil samples was determined immediately after they were brought from the field to the laboratory to determine the amount of moisture present in the natural state and setting. Apparatus like moisture cans, paper tapes, weighing balances, oven, and permanent markers were used.

The aluminum cans used were cleansed, dried, and labeled for easy identification. They were weighed (M_1) and their masses were recorded against their labels on the datasheet. Sample representatives of the wet soils were put into the cans and their masses, with that of the moisture cans were then taken and recorded (M_2). The moisture can and the samples were then put into the oven, already set to a temperature of 105°C, and left overnight to allow the sample to achieve a constant mass. The dried samples were then taken out of the oven the next day and their masses were obtained by weighing them on a weighing balance (M_3) using Equation (1).

$$Wn = \frac{Ww}{Ws} \times 100 \tag{1}$$

Where Wn is moisture content;

Ww is the weight of water present in the soil mass

Ws is the weight of the soil mass

Particle size test

The particle size test of the soil samples was carried out on a mechanical sieve shaker in accordance with wet sieving British Standard, BS 1377 (1990) test 7a standard. The sample materials were allowed to drain carefully transferred to a tray and placed in the oven to dry at a temperature of 105 to 110 °C overnight. The dry soil was then passed through a nest of the complete range of sieves to cover the size of particles present down to 63 μm sieve. The percentage weight retained and the percentage passing in the sieves were determined. The percentage passing versus particle size distribution is plotted as shown in Figures 3 and 4 respectively.

DCP software was used to interpret DCP readings and convert them to CBR values, while the Resilient modulus (M_R) value was determined using formulae presented by George and Uddin (2000).

RESULTS AND DISCUSSION

Moisture content analysis

Table 1 presented the result of the natural moisture content analysis, the mean ranged from 9.30 % to 18.00 % for CG and ranged from 10.19 % to 17.21 % for FG. The result of the natural moisture content (NMC) analyses shows that both soil types (CG and FG) are vulnerable to changes in moisture content conditions. According to Ikubuwaje et al., (2022), all derived soils are susceptible to the ingress of water with a consequential reduction in strength. It was observed that variation in the moisture content across the different horizons and especially along the soil profiles gave rise to corresponding consequences on soil strength parameters. For instance, No. 2 and No. 3 for CG-derived soil and No. 6 and No. 7 for FG-derived soil with almost the same moisture content value have almost the same strength values according to Table 2. However, No. 4 and No. 5 for CG-derived soil and No. 6 and No. 9 for FG-derived soil with the same range of particle sizes depending on their soil types but with different moisture content values exhibit corresponding consequences with strength properties. This implies that moisture content tendencies are the main impetus of the studied soil characteristics, especially in terms of the strength parameters. In addition, there exists an inverse relationship between moisture content and strength parameters of the soils, it was observed that increases in the soil moisture content reduce the soil strength parameter while, decreases in the soil moisture content increases the soil strength parameter Figures 1 and 2. The result revealed that soil moisture content values at 13.08%, 15.67%, and 17.21% give rise to CBR values higher than the 10% recommended for soaked CBR for Nigerian roads. FMWH (1997) recommended that CBR values for subgrade should not be < 10%, under soaked conditions.

Geotechnical reports obtained from Ekeocha & Akpokodje (2012), Nweke & Okogbue (2017), and Amadi et al., (2018) revealed that if a sub-grade has a CBR value < 10%, both the sub-base and subgrade materials will deform under traffic loadings leading to the pavement or material deterioration. The result also corroborates Underwood (1967) recommendation of soil with NMC ranging from 5% to 15% as suitable in engineering works. Subgrade can significantly be affected by variations in moisture content, and this may be a contributory factor to road failure. Meanwhile, the degree of CBR reduction is an expression of the moisture content differences in the soil types among other factors.

Textural analysis

The result of the particle size distribution analysis for the samples tested for different trial pits is shown in Table 2. This gives the percentage occurrence of different grain sizes within the soil mass, which in turn is used to describe the soil. The result of the sieve analyses shows that the range of coarse fraction for the coarse-grained (CG) derived soil samples lies between 60 % and 67 %, while the range of fine fraction is from 32 to 42%, similarly, the range of coarse fraction for the fine-grained (FG) derived soil samples lies between 32 and 42 %, while the range of fine fraction is from 58 to 68 %. It is interesting to note that the granite-derived soil result revealed that CG and FG investigation trial pits have soil grain size distribution which generally has a close range of particle sizes depending on their soil types. This is to minimize the effect of soil texture. For instance, No 2 and No 3 for CG-derived soil and No 6 and No 7 for FG-derived soil with almost the same moisture content value have almost the same penetrating index (PI) as presented in Table 2. This result indicates that the effect of grain sizes may not account for any significant effect on the studied soil characteristics.

Strength parameters relationships

The result of strength parameters (PI, CBR, and M_R) and the relationship among them in response to the moisture conditions are summarized in Table 3, Figure 1, and Figure 2. The values of PI, CBR, and M_R ranged from 5 - 30 mm/blow, 6.5 - 52 %, and 47-110 psi respectively for CG-derived soil, while for FG-derived soil the values of PI, CBR, and M_R ranged from 7.7 - 18 mm/blow, 11.8 - 34 % and 60 – 89 psi respectively. The result showed that the strength parameters within the soil profile respond to variations in the moisture content conditions. The results also revealed that CBR and M_R have lower values at higher moisture content and higher values at lower moisture content. Secondly, the degree of change (reduction) in the CBR and M_R values is directly proportional to the amount of moisture content absorption. However, the degree of response to the change in moisture content conditions by M_R is relatively higher in comparison to that of CBR with an average of 50 psi. This implies that M_R is more susceptible to ingress of water compared to CBR. According to Fleming et al., (2000) and George (2004), the moisture content of subgrade soils is one of the most important variables to predict the resilient modulus (M_R) value. Generally, it was observed that strength parameters M_R and CBR of both soil types have a direct relationship in terms of the trend but both have an inverse relationship with PI. Furthermore, a current climatic change that has given rise to increasing rainfall would further affect ingress in groundwater conditions of subgrade soils and consequential reduction in the strength properties for both M_R and CBR values. The subgrade is close to the soil surface, the conditions will always be affected by changes in climate (Baladi et al., 2009). It causes water levels to rise and so affects the soil strength and stiffness, especially on clayey soils. This causes a decrease in axial strength properties, which gives rise to the deformation of the flexible pavement.

CONCLUSIONS AND RECOMMENDATIONS

The resilient modulus (M_R) and California Bearing Ratio (CBR) have lower values at higher moisture content and higher values at lower moisture content. M_R is more susceptible to the ingress of water compared to CBR. The strength parameters M_R and CBR of both soil types have a direct relationship in terms of the trend but both have an inverse relationship with Penetration Index (PI). Moisture content has a significant effect on cohesive soil type in dry-wet conditions. In-situ dynamic soil strength properties could be used to measure a range of soil moisture conditions while a dynamic cone penetration device could be used to evaluate moisture content conditions. Generally, both resilient modulus (M_R) and California Bearing Ratio (CBR) have an inverse relationship with the Penetration Index (PI). Adequate information on either M_R or CBR can give good inferences and help to deduce the engineering performance of soils.

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Table 1: Summary of MC, PI, MR and CBR

S/N	Parameter	45mm	65mm	90mm	Mean	Texture
1	MC	15.7	15.61	15.7	15.67	Coarse
	PI	17	17	16	17	
	M_R	61	61	63	62	
	CBR	12.5	12.5	13.4	13	
2	MC	10.8	10.07	12.08	11	
	PI	7	6	8	7	
	M_R	93	100	88	91	
	CBR	34.9	36.9	27.2	33	
3	MC	6.88	11.9	13.88	10.89	
	PI	5	7	10	7	
	M_R	93	88	88	90	
	CBR	48.1	33	22.2	34	
4	MC	8.5	9.7	9.7	9.30	
	PI	5	5	5	5	
	M_R	110	110	110	110	
	CBR	52	52	52	52	
5	MC	17.8	18.96	17.47	18.	
	PI	28	35	27	30	
	M_R	48	43	49	47	
	CBR	7	5.4	7.4	6	
6	MC	9.69	8.18	12.7	10.2	Fines
	PI	6	5	12	7.7	
	CBR	36.9	48.1	18.6	34.5	
7	MC	**6.9**	**11.3**	**12.7**	10.3	
	PI	5	8	10	7.7	
	CBR	**48.1**	**27.2**	**22.2**	32.5	
8	MC	12	13.06	14.19	13.1	
	PI	14	17	18	16.3	
	CBR	**15.2**	12.5	11.2	13.0	
9	MC	15.3	17.76	18.58	17.2	
	PI	13	20	21	18.0	
	CBR	16	10	9.5	11.8	

Where, MC - Moisture content, PI – Penetration index, M_R - Resilient modulus, and CBR - California Bearing Ratio

Table 2: Summary of Grain Size Analysis Result

SN	Gravel (%)	Sand (%)	Coarse (%)	Silt (%)	Clay (%)	Fines (%)	MC (%)	PI	Texture
1	23.2	37.2	60.4	38.4	1.3	39.7	15.67	17	CG
2	35.9	25.2	61.1	22.4	16.5	38.9	11.02	7	
3	40	27.2	67.2	30.5	2.3	32.8	10.89	7	
4	30.2	32.9	63.1	19.3	17.6	36.9	9.30	5	
5	37.3	26.9	64.2	25.7	10.1	35.8	18	30	
6	3.8	38.5	42	56	1.8	58	10.19	7.7	FG
7	5.8	26.2	32	54.2	13.8	68	10.3	7.7	
8	5.5	33.7	39	46.1	14.8	61	13.08	16.3	
9	19.7	22.4	42	56.9	1	58	17.21	18	

Where Coarse grained (CG) Fine grained (FG)

Table 3: Summary of MC, PI, CBR & M_R

SN	MC (%)	PI (mm/blow)	MR (Psi)	CBR (%)	Different in (MR-CBR)	Texture
1	15.67	17	62	13	49	Coarse
2	11.02	7	91	33	58	
3	10.89	7	93	34	59	
4	9.30	5	110	52	58	
5	18	30	47	6.5	41	
ave	12.976	13.2	80.6	27.7	53	
6	10.19	7.7	89	34	55	Fines
7	10.3	7.7	89	33	56	
8	13.08	16.3	63	13	50	
9	17.21	18	60	11.8	48	
ave	12.695	12.425	75.25	22.95	52	

Where; MC: Moisture content, CBR: California Bearing Ratio, PI – Penetration index M_R: Resilient modulus and CBR for fine-grained soil

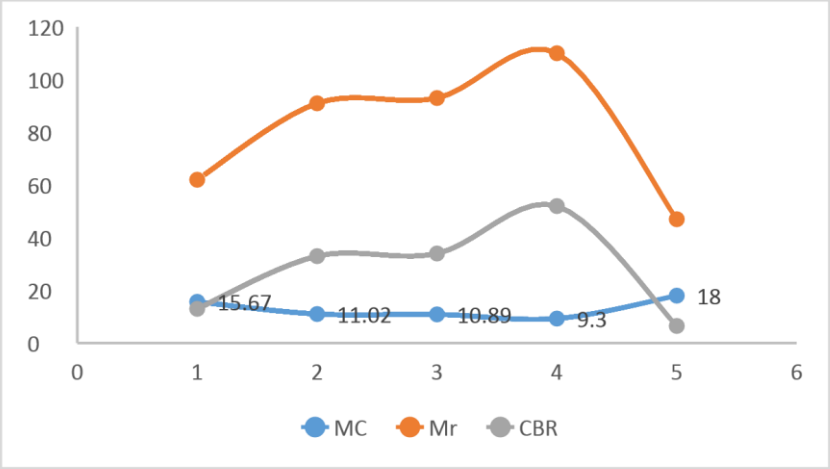

Figure 1. Graph showing the relationship between MC, Mr, and CBR Coarse soil

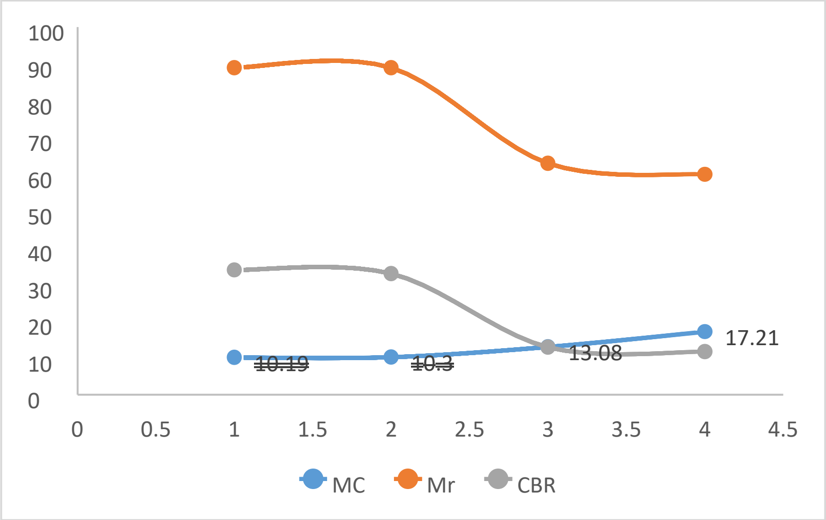

Figure 2. Graph showing the relationship between MC, Mr, and CBR of fine-grained soil