

IMPACT OF SUBGRADE SOIL VARIABILITY AND TRAFFIC LOADING ON FLEXIBLE PAVEMENT PERFORMANCE IN NIGERIA

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ABSTRACT

Subgrade soil properties critically influence the performance of flexible pavements. This study evaluates subgrade variability and its implications for pavement durability in Nigeria, using soil samples collected at depths of 3 m, 6 m, and 9 m from Akazi sand beach in Ihiala, Anambra State. Laboratory tests including sieve analysis, Atterberg limits, specific gravity, compaction, and California Bearing Ratio (CBR) were conducted to assess soil suitability. Results indicate that shallow layers (3 m and 6 m) comprise fine-grained, low-density soils with low CBR and moderate plasticity, rendering them susceptible to deformation and rutting under traffic loads. Deeper layers (9 m) exhibit higher density and improved load-bearing capacity but require elevated moisture content for optimal compaction. Significant variability in subgrade properties underscores the need for targeted interventions. Recommended measures include stabilization with lime or cement, controlled compaction, efficient drainage, traffic management during construction, and ongoing monitoring. Implementing these strategies is expected to enhance pavement resilience, reduce maintenance costs, improve traffic safety, and extend the service life of flexible pavements in regions with heterogeneous subgrade soils.

Key Words: Subgrade variability; Geotechnical investigation; Flexible Pavement Traffic loading; Pavement durability

1.0 INTRODUCTION

Pavement performance is strongly influenced by both the mechanical characteristics of the subgrade soil and the nature of traffic loading. Soil variation analysis is central in geotechnical engineering, as the subgrade forms the foundation of flexible pavements and determines their ability to withstand applied stresses. Key soil properties, including bearing capacity, shear strength, compressibility, and moisture content, directly affect subgrade performance, influencing deformation, compaction, and California Bearing Ratio (CBR) values (Anene *et al.* 2025a; Das, 2019; Holtz *et al.*, 2011; Srivastava *et al.*, 2021; Al Shukri and Al Khafaji, 2020; Olubanwo and Adeoye, 2019; Okafor and Chukwuma, 2021). Studies have highlighted significant variability in soil properties with depth, which can result in uneven load distribution and premature pavement deterioration (Anene, W. C., 2026a; Ogunjiofor *et al.* 2026a; Ogunjiofor *et al.* 2026b; Nazari and Gholami, 2022; Li *et al.*, 2018; Singh and Saini, 2023; Mohammed *et al.*, 2024; Oladapo *et al.*, 2022; Eze *et al.*, 2023).

In Nigeria, where flexible pavements are predominant, subgrade weaknesses compounded by traffic loading often led to structural failures. Variations in moisture content, plasticity, and compaction across different soil layers have been linked to reduced pavement serviceability and early deformation (Mmonwuba, *et al.* 2025; Khan *et al.*, 2022; Faheem *et al.*, 2023; Zhang and Li, 2021; Ugochukwu and Chinedu, 2020; Akinwale *et al.*,

2022; Ogunjiofor, *et al.*2026b). Laboratory and field assessments in regions such as Anambra State indicate that inconsistencies in soil characteristics at depths of 3 m, 6 m, and 9 m contribute to uneven subgrade support, increasing the risk of cracking and rutting under repeated traffic loads (Perera and Fernando, 2019; Rizwan *et al.*, 2023; Nwafor and Eze, 2021).

Traffic behavior further compounds the influence of subgrade variability. Inefficient driving practices, poor understanding of traffic signs, and inadequate adherence to safety rules can intensify pavement deterioration through irregular and repetitive loading (Anene, W. C., 2022; Olawale and Adeyemi, 2021; Balogun *et al.*, 2023; Ogunjiofor *et al.* 2026a; Ogunjiofor *et al.*2026c). Effective traffic management such as optimized signal control and congestion mitigation reduces localized pavement stresses and improves load distribution (Anene, W. C. *et al.* 2022; Anene, W. C. *et al.* 2023a; Adepoju and Bello, 2024). Specifically, congestion at critical junctions like Eke Nibo has been shown to exacerbate thermal and mechanical stresses on pavements, accelerating structural failure. Furthermore, research links poor road conditions and subgrade weaknesses directly to traffic accidents, emphasizing the dual importance of engineering subgrade integrity and traffic management in ensuring both pavement durability and road safety (Anene, W. C. *et al.* 2023b; Nwachukwu and Emeka, 2022; Olojede and Musa, 2024).

The integrated perspective emerging from these studies underscores that flexible pavement performance cannot be adequately assessed without considering both the inherent variability of the subgrade and the dynamics of traffic loading. Therefore, thorough geotechnical investigations, combined with traffic engineering interventions, are essential for designing resilient pavement structures and minimizing premature failures (Anene, *et al.*2026b; Uddin *et al.*, 2024; Basharat *et al.*, 2023; Singh and Singh, 2020; Obi and Okoro, 2023; Abiola and Adeniran, 2021).

2.0 MATERIALS AND METHODS

The research was done experimentally and includes the laboratory analysis of soil samples gotten at different depths of 3000mm, 6000mm, and 9000mm after the removal of top soil. The samples were gotten from Akazi soil beach in Ihiala, Anambra state.

Soil testing is a major step in understanding the properties and characteristics of soil which can be useful in designing, construction and performance of flexible pavements. It provides the engineering properties of soil such as; specific gravity, sieve analysis, Atterberg limits, compaction test and C.B.R test.

Sieve Analysis

Procedure

Sieve analysis is used to determine the particle size distribution of soil by separating it through a stack of standard sieves. The soil is washed, oven-dried, and mechanically shaken, after which the mass retained on each sieve is measured. This helps classify the soil and assess its suitability for engineering applications.

$$\text{Percentage Retained on Each Sieve} = \% \text{ Retained} = \frac{W_3}{W} \times 100 \dots \dots \dots (1)$$

$$\text{Cumulative Percentage Retained} = \% \text{ Cumulative Retained} = \sum \% \text{ Retained} \dots \dots \dots (2)$$

$$\text{Percentage Passing (finer)} = \% \text{ Passing} = 100\% - \text{Cumulative Retained} \dots \dots \dots (3)$$

Atterberg Limits

Procedure

• **Shrinkage limit test**

Soil samples were collected from the location and prepared as a soil paste. 30g of the above sample was placed in the evaporating dish and mixed thoroughly with distilled water. The shrinkage dish was cleaned and its weight was accurately determined to 0.1 g. The shrinkage dish was filled with wet soil. The wet and dry weight of soil, volume and dry density were determined.

$$SL = \frac{(W_w - W_d) - (V_w - V_d)}{W_d} \times 100\% \dots \dots \dots (4)$$

$$\text{Dry density, } Pd = \frac{W_d}{V_d} \dots \dots \dots (5)$$

$W_w = \text{Wet weight, } W_d = \text{dry weight, } V_w = \text{weight volume, } V_d = \text{dry volume, } p_w = \text{density of water}$

• **Plastic limit test**

Soil mixtures at different moisture content were turned over with palm on a glass plate into threads till it began to break at 3mm. The threads were placed in containers like that of liquid limit test, measured and documented. They were placed in oven for twenty-four hours to dry and then put in a closed glass vessel containing a desiccant to cool and then re-measured. The weights were used to know their moisture content.

$$\text{Moisture Content} = W = \frac{W_w - W_d}{W_d} \times 100\% \dots \dots \dots (6)$$

• **Liquid limit test**

A clay sample was placed in a standard cup to make a groove using a spatula. The cup was dropped till the separation vanished. Water content of the soil was gotten from the sample. The test was repeated by increasing the water content.

$$\text{Moisture Content} = W = \frac{W_w - W_d}{W_d} \times 100\% \dots \dots \dots (7)$$

$$w = a - b \log N \dots \dots \dots (8)$$

$N = \text{Number of blows; } a, b = \text{Constant from the flow curve}$

Specific Gravity

Specific gravity (Gs) of soil is defined as the ratio of the density of soil solids to the density of water at a standard temperature. It is an important parameter in geotechnical engineering used in determining void ratio, degree of saturation, and unit weight relationships. The density bottle method (also called pycnometer method) is commonly used for fine-grained soils. In this procedure, the weights of the bottle in different conditions (empty, with soil, with soil + water, and with water only) are measured to determine the relative density of the soil solids

$$G_s = \frac{W_2 - W_1}{(W_2 - W_1) - (W_3 - W_4)} \dots \dots \dots (9)$$

$W_2 - W_1 = \text{Weight of dry soil}$
 $(W_3 - W_4) = \text{Weight of water displaced by soil solids}$

Compaction Test

Procedure

3000 g of soil was weighed and mixed with varying water contents (4%, 8%, 12%, 16%, and 20%). The sample was compacted in three layers using the British Standard Light method with 27 blows of a 2.5 kg rammer. The compacted soil and mould were weighed, and samples were taken for moisture content determination. These samples were oven-dried at 105–110°C for 24 hours and reweighed. The results were used to calculate moisture content and dry density, and a graph of **dry unit weight versus moisture content** was plotted to determine compaction characteristics.

$$\text{Bulk density, } \gamma = \frac{W}{V} \dots \dots \dots (10)$$

$$\text{Dry density, } \gamma_d = \frac{W}{V} \dots \dots \dots (11)$$

$$\text{Degree of Saturation, } S = \frac{wG_s}{e} \dots \dots \dots (12)$$

$$\text{Air Voids, } V_a = \left(1 - \frac{\gamma_d}{G_s \gamma_w}\right) \dots \dots \dots (13)$$

California Bearing Ratio (CBR)

Procedure

The principle of California bearing ratio is to get the relationship between force and penetration when a cylindrical plunger of a standard cross-sectional area is made to penetrate the soil at a given rate. It is often used to estimate the bearing capacity of pavement sub-grade and sub base soil. CBR was carried out on two samples and were soaked for 4 days.

5kg of each of the soil sample was placed in the metal tray respectively, the required amount of water according to the moisture content was added and then mixed thoroughly and was divided into three layers. The wet soil sample was compacted with 7.2kg rammer with 62 blows each. The collar was removed and the top was levelled. For the un-soaked CBR test proceed to CBR machine to carry out the test. For the soaked CBR test, a filter was placed at the top and bottom of the mould, the mould was placed in the water tank for 96 hours, then the mould was retrieved from the tank and was allowed to air dry. The specimen was placed under the penetration piston and the stress and strain values were recorded. A graph of penetration (In) versus force was plotted and the CBR value was calculated.

3.0 RESULT AND DISCUSSION

The results of various tests for the study conducted in the laboratory are presented in tables 1 to 5 and figures 1 to 5. Table 6 contains the revised AASHTO system of soil classification and table 7 is the Federal Ministry of Works and Housing general specifications for roads and bridges.

Table 1: Sieve Analysis of The Trial Samples

SAMPLE NUMBER	SAMPLE DEPTH	SIEVE ANALYSIS(%PASSING)
A	3	88.74
B	6	89.26
C	9	82.66

The sieve analysis indicates that all samples contain high fines, suggesting predominantly fine-grained soils. In line with the AASHTO, such soils likely fall within silt-clay groups (A-4 to A-7), which are generally weak as subgrade materials. Samples A and B show similar gradation in the upper layers, while Sample C is slightly coarser with depth, indicating minor subgrade variability. According to the Federal Ministry of Works Nigeria, these soils are prone to low bearing capacity and high moisture sensitivity, making them susceptible to deformation and rutting. This condition adversely affects traffic flow by causing uneven road surfaces, reduced vehicle speeds, increased travel time, and higher vehicle operating costs. In severe cases, pavement distress can lead to traffic congestion and safety hazards. Therefore, stabilization and proper drainage are necessary to enhance subgrade strength and ensure smooth and efficient traffic movement

Table 2: Specific Gravity of The Trial Samples

Sample Number	Samples Depths (M)	Specific Gravities
A	3	2.56
B	6	2.71
C	9	2.75

The specific gravity increases from 2.56 (Sample A) to 2.75 (Sample C), indicating a transition from weaker, lighter soils at the surface to denser, stronger soils at depth. In line with the AASHTO, higher specific gravity values ($\approx 2.6-2.8$) reflect better mineral composition and improved load-bearing capacity under traffic loading.

According to the Federal Ministry of Works Nigeria, the weaker upper layer (Sample A) is critical because it directly supports vehicular traffic loads, including repeated axle loads from cars, buses, and heavy trucks. Its low strength makes it more susceptible to deformation and rutting under continuous traffic movement. This condition can negatively impact traffic flow by causing uneven pavement surfaces, reduced vehicle speeds, increased travel time, and higher vehicle operating costs, especially on heavily trafficked roads. Thus, stabilization or improvement of the surface subgrade is necessary to ensure adequate pavement performance and smooth, safe, and efficient traffic movement.

Table 3: The Laboratory Result Summary for Atterberg Limits

Sample Number	Sample Depth	Liquid Limit (Ll)	Plastic Limit (Pl)	Plasticity Index (Pi)
A	3	34	30.38	3.62
B	6	28	26	2.0
C	9	20	18.5	1.5

The Atterberg limits decrease with depth, indicating reduced plasticity and improved soil stability. With low PI values (1.5–3.62), the soils fall within low-plasticity groups under the AASHTO, making them generally suitable as subgrade materials.

According to the Federal Ministry of Works Nigeria, such soils have low compressibility and minimal swelling risk, favouring good pavement performance. However, the slightly higher plasticity at the surface (Sample A) may weaken under moisture and repeated traffic loads, causing minor deformation and affecting traffic flow. Thus, light stabilization and proper drainage are recommended to ensure durable pavement and smooth traffic movement.

Compaction

Table 4: The Laboratory Result Summary for Compaction Test

Sample Number	Samples Depths (M)	Max. Dry Density (G/Cm ³)	Opt. Moisture Content (%)
A	3	20.033	11.53
B	6	18.106	9.64
C	9	19.163	12.80

The compaction results show variability in Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) with depth. Sample A (MDD = 20.033 g/cm³) is well-compacted and strong, Sample B (MDD = 18.106 g/cm³) is weaker, and Sample C requires more moisture for optimal compaction (OMC = 12.80%). In line with AASHTO and Federal Ministry of Works Nigeria, higher MDD improves load-bearing capacity, while lower MDD and poor moisture control reduce subgrade stability. Weak or unevenly compacted layers can lead to rutting, settlement, and reduced traffic flow. Proper moisture management, uniform compaction, and stabilization are therefore essential to ensure durable pavement and smooth traffic movement.

California Bearing Ratio

Table 5: The Laboratory Result Summary for C. B.R Test

Sample Numbers	Samples Depths (M)	Unsoaked	Soaked
A	3	3.57	16.435
B	6	3.35	13.2
C	9	2.53	4.97

The CBR test for Samples A (3 m) and C (9 m) shows low values at standard penetrations (2.5 mm and 5.0 mm), indicating weak subgrade soils. According to AASHTO and Federal Ministry of Works Nigeria, such soils are unsuitable for direct pavement construction. Without improvement, they are prone to rutting and deformation under traffic, affecting road safety and flow. Stabilization (e.g., cement, lime, or granular fill) is recommended to meet standard subgrade requirements and ensure durable pavement performance.

Table 6: Revised AASHTO System of Soil Classification

General Classification	General Materials (35% or less passing 0.075mm)							Silt-clay materials (more than 35% passing 0.075mm)			
Group Classification	A-1		A-3	A-2				A-4	A-5	A-6	A-7
	A-1-a	A-1-b		A-2-4	A-2-5	A-2-6	A-2-7				
Sieve Analysis % passing 2.00mm (No10)	50max										
0.425mm (No40)	30max	50max	51min								
0.725mm (No200)	15max	25max	10max	35max	35max	35max	35max	36max	36max	36max	36max
Characteristics of friction			N.P	40max							
Passing	6max										
Liquid limit			N.P	40max	41max	40max	41max	40max	41min	40max	40min
Plastic Index				10max	10max	11min	11min	10max	10max	11min	11min
Usual types of significant	Stone fragment		Fine	Silty or clayey gravel and sand				Silty soils	Clayey soils		
Constituent material	Gravel and sand		sand								
General rating	Excellent to Good							Fair to Poor			

Table 7: Nigerian Standard of Soil Classification for Roads and Bridges

Sample	A	B	C
L.L (<35%)	34 Pass	NIL	NIL
P.I(<12%) comment	3.62 Pass	NIL	NIL
C.B.R. soaked for sub-base (>30%)	16.435 Fail	NIL	4.9 Fail
C.B.R. unsoaked base course (>80%)	3.57 Fail	NIL	2.53 Fail
Overall Rating	Sub base		Sub base

4.0 CONCLUSION AND RECOMMENDATIONS

The study demonstrates that subgrade soil variability significantly influences flexible pavement performance in Nigeria. Laboratory tests reveal predominantly fine-grained soils with high fines, low plasticity, and variable compaction characteristics. Surface layers (Samples A and B) are weaker, with lower specific gravity and CBR values, making them susceptible to deformation and rutting under repeated traffic loads. Deeper layers (Sample C) are denser and slightly stronger but require higher moisture for optimal compaction. Overall, the findings indicate that without subgrade improvement, flexible pavements are vulnerable to early distress, reduced load-bearing capacity, and compromised traffic flow.

Recommended Measures to Enhance Pavement Performance:

1. **Subgrade Stabilization:** Improve weak subgrade soils using lime, cement, or other suitable stabilizers to increase strength and reduce susceptibility to deformation.
2. **Controlled Compaction:** Ensure optimal compaction of subgrade layers in accordance with laboratory-determined moisture content and density specifications to enhance load-bearing capacity.
3. **Effective Drainage Design:** Incorporate adequate surface and subsurface drainage systems to prevent water accumulation, minimize soil moisture variability, and protect pavement integrity.
4. **Traffic Management During Construction:** Restrict heavy vehicle movement on newly constructed pavements until the subgrade attains sufficient strength to support traffic loads safely.
5. **Routine Monitoring and Maintenance:** Implement regular inspection programs to detect early signs of distress, enabling timely maintenance interventions and prolonging pavement service life.

Implication: Implementing these measures will improve flexible pavement durability, enhance traffic flow, and increase road safety, even on weak and variable subgrade soils.

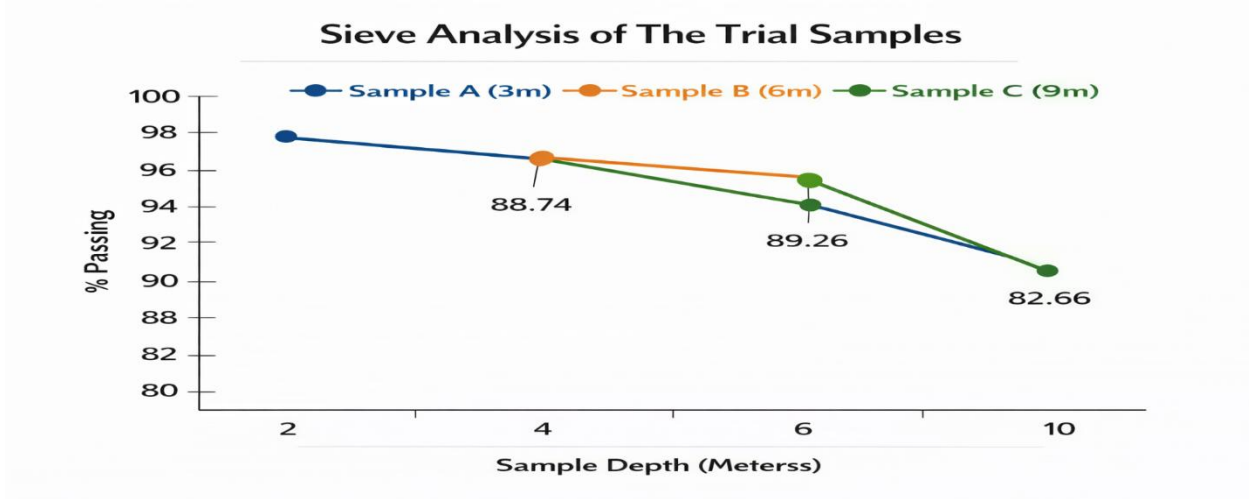


Figure 1: Sieve Analysis of the Trial Samples

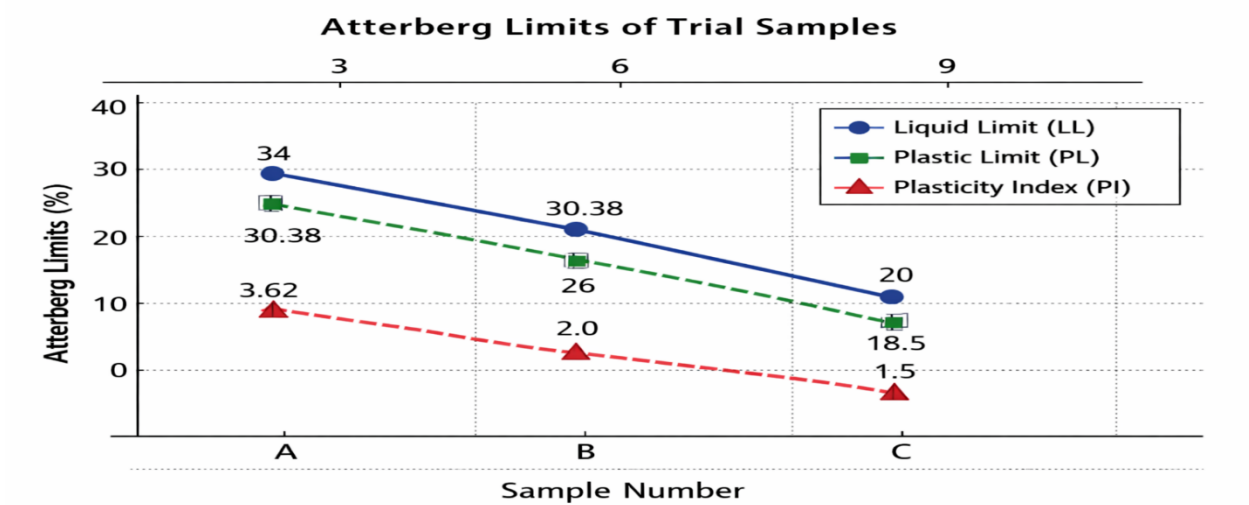


Figure 2: Atterberg Limit of the Trial Samples

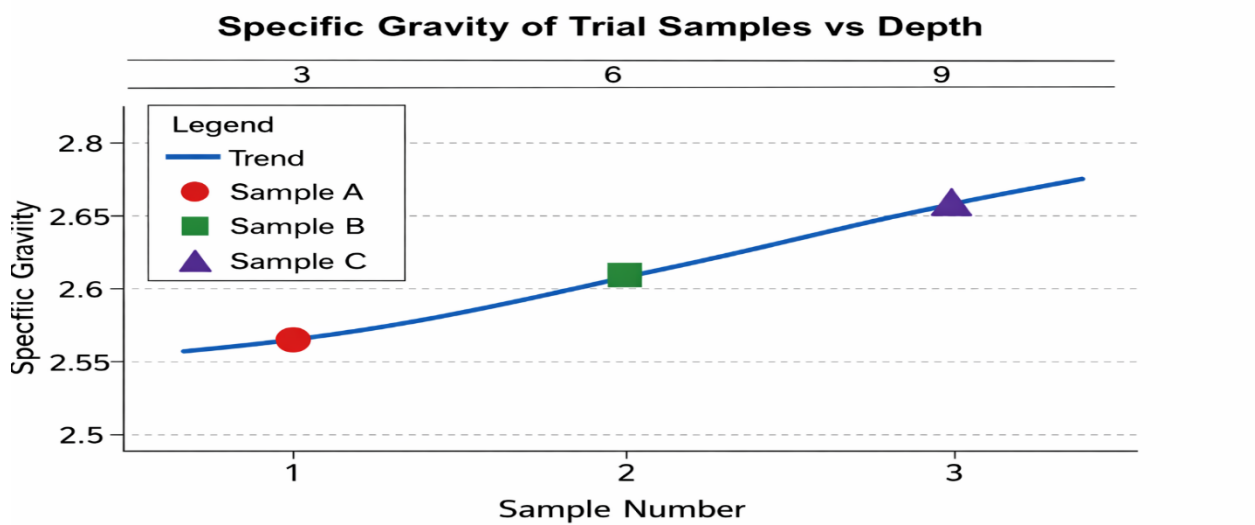


Figure 3: Specific Gravity of the Trial Samples

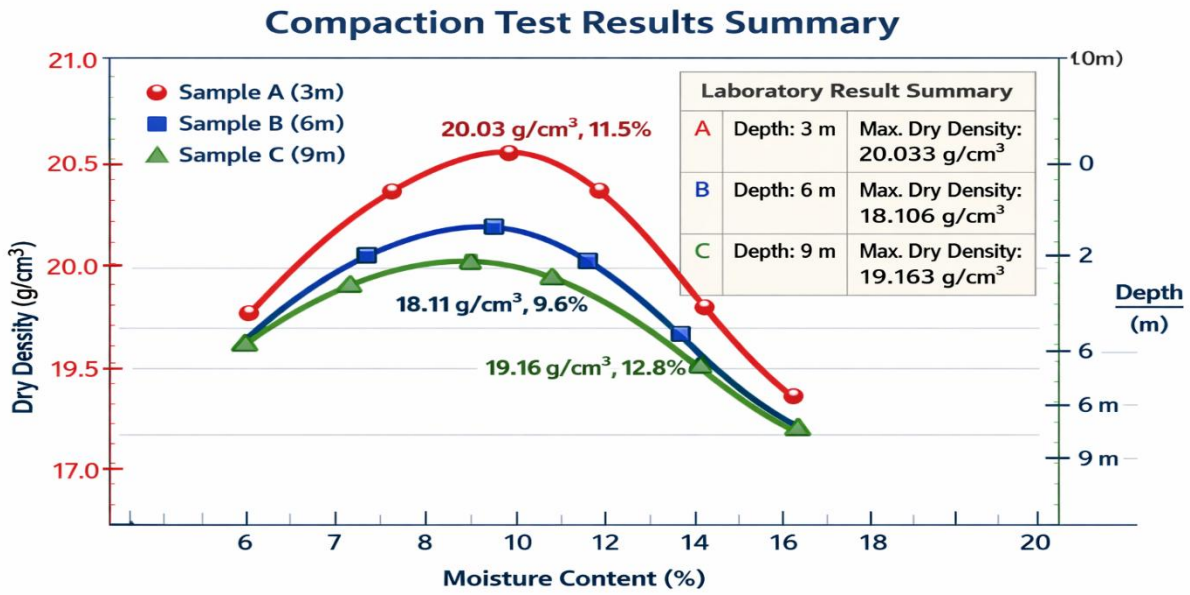


Figure 4: Compaction Graph of Trial Samples

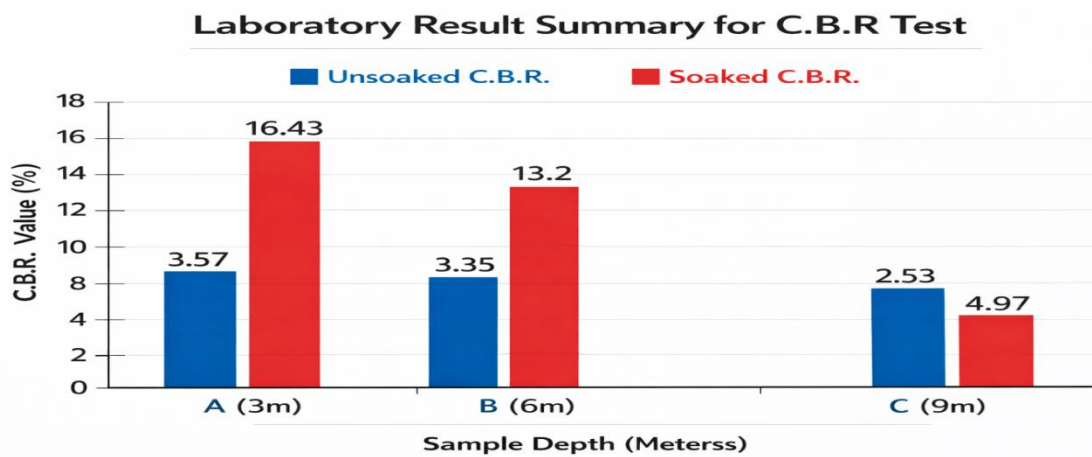


Figure 5: Bar Chart Reorientating C.B.R Test of the Trial Samples

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