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Engineering Characterization of Selected Nigerian Limestone Deposits Using Rock Mass Rating and Geotechnical Analysis

Omonaye Joseph[1]; Olaleye B. M.[2]; Okewale I. A.[3]; Gata Thomas Bulus[4]

[1]Nigerian Institute of Mining and Geosciences Jos, Plateau State, Nigeria.
[2,3]Federal University of Technology Akure, Ondo State, Nigeria.
[4]Federal Polytechnic Ekowe, Bayelsa State. Nigeria Mineral and Petroleum Resources Engineering Technology Department.

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Abstract: Reliable rock mass characterization is essential for safe and economical engineering design in carbonate terrains; however, systematically integrated geomechanical datasets for Nigerian limestone formations remain limited in peer reviewed literature. This study presents a comprehensive geotechnical and rock mass evaluation of selected limestone deposits in Iluagba (Kogi State), Okpella (Edo State), Gboko (Benue State) and Ewekoro (Ogun State) Nigeria. A total of 300 core specimens were prepared and tested in accordance with International Society for Rock Mechanics (ISRM) and ASTM standards. Laboratory investigations included uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), porosity, bulk density, rebound hardness value (RHV), and water absorption, while field-based structural mapping was conducted to determine Rock Quality Designation (RQD) and Rock Mass Rating (RMR) parameters. The limestones exhibit low porosity (1.21–2.75%), high bulk density (2.60–2.80 g/cm³), and minimal water absorption (0.42–1.05%), indicating compact microstructures with limited pore connectivity. UCS values range from 38.2 to 82.0 MPa (moderately strong to strong rock), while tensile strength varies between 3.11 and 7.45 MPa, representing 7–12% of UCS and confirming brittle carbonate behavior. The average RQD of 80.26% and RMR values between 62 and 78 classify the rock mass predominantly as Class II (Good Rock), reflecting favorable discontinuity conditions despite locally damp to wet groundwater environments. Mineralogical and geochemical analyses reveal dominant calcite composition (CaO 48–54%) with minor silica and moderate MgO content, indicating localized dolomitization and compositional control on strength variability. The integration of intact mechanical properties, structural characterization, and mineralogical assessment provides a robust geomechanical framework for evaluating engineering suitability in Nigerian carbonate terrains. The investigated deposits are mechanically competent for foundation systems, quarry slope design, aggregate production, and cement manufacturing. This study contributes one of the most comprehensive standardized rock mass datasets for Nigerian limestone formations, thereby enhancing design reliability and supporting sustainable infrastructure development.

Keywords: *Rock Mass Characterization; Nigerian Limestone; Uniaxial Compressive Strength; Brazilian Tensile Strength; Rock Quality Designation; Rock Mass Rating; Geomechanics; Carbonate Rocks; Engineering Suitability; Mineralogical Control.*

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I. INTRODUCTION

Limestone is one of the most extensively utilized sedimentary rocks in civil engineering, mining, and infrastructure development due to its abundance, workability, and generally favourable mechanical properties (Zhang *et al*., 2022; Wang *et al*., 2023; Gad *et al*., 2025). It constitutes a primary raw material for cement production, dimension stone, structural aggregates, road base materials, and foundation systems worldwide (Salami and Adeyemi, 2021; Ademila and Olayinka, 2020). However, despite its widespread industrial relevance, limestone exhibits substantial variability in engineering behavior, which is controlled by both intrinsic properties such as mineralogical composition, pore structure, grain fabric, density, and degree of diagenesis—and extrinsic structural characteristics, including discontinuity spacing, joint persistence, bedding orientation, weathering grade, and groundwater conditions (Zhao *et al.,* 2021; Wang *et al.,* 2023; Erharter *et al.,* 2025). This inherent heterogeneity necessitates comprehensive geotechnical and rock mass characterization prior to engineering utilization. From a rock mechanics standpoint, the mechanical response of limestone under stress is governed not only by intact rock parameters such as uniaxial

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compressive strength (UCS), tensile strength (TS), Young's modulus, and Poisson's ratio, but also by the geometry, frequency, roughness, infilling, and orientation of discontinuities that define the rock mass structure (Alejano, 2025; Niu *et al*., 2024). Experimental investigations have demonstrated that carbonate rocks display wide strength variability depending on depositional environment, fossil content, recrystallization intensity, dolomitization processes, and microcrack density (Zhang *et al.,* 2022; Wang *et al.,* 2023; Gad *et al.,* 2025). In addition, karstification and secondary dissolution features may significantly weaken the rock matrix and introduce anisotropic mechanical behavior (Chen *et al.,* 2020; Xu *et al*., 2021). Moisture content further plays a critical role in controlling limestone strength and deformability. Laboratory studies indicate that saturation can reduce UCS and tensile strength by 10–40% depending on pore connectivity and clay mineral content (Zhao *et al*., 2021; Li *et al.,* 2022). The water-weakening effect is particularly pronounced in porous and micro-fractured limestone varieties, where capillary forces and mineral dissolution accelerate crack propagation (Xu *et al*., 2021). Consequently, reliance solely on intact rock strength parameters may lead to overestimation of in-situ stability conditions. Integrated rock mass evaluation approaches are therefore essential for reliable engineering design (Niu *et al.,* 2024; Erharter *et al.,* 2025). Rock mass classification systems remain fundamental tools in applied rock mechanics. The Rock Mass Rating (RMR) system developed by Bieniawski (1989) integrates intact rock strength, Rock Quality Designation (RQD), discontinuity spacing and condition, groundwater effects, and orientation factors to generate a quantitative index for design applications. Contemporary reviews highlight the continued global application of RMR and related systems in tunneling, slope engineering, and mining excavation projects (Alejano, 2025; Erharter *et al.,* 2025). However, recent research emphasizes that carbonate terrains require context-specific calibration due to their complex interaction between lithological fabric and structural discontinuities (Wang *et al.,* 2023; *Sun et al*., 2022). Furthermore, emerging approaches incorporating statistical modeling and machine learning techniques demonstrate improved predictive capability when mineralogical and index properties are integrated into classification frameworks (Niu *et al.,* 2024; Li *et al*., 2023). In Nigeria, limestone deposits occur within major sedimentary basins, notably the Benue Trough and Dahomey Basin, and serve as critical feedstock for the national cement industry and construction sector (Ademila, 2020; Salami and Adeyemi, 2021). Large-scale industrial operations depend on these carbonate formations for raw material supply, underscoring their strategic economic importance. Nevertheless, comprehensive and systematically documented geotechnical datasets for many Nigerian limestone formations remain scarce in peer-reviewed literature. Existing studies frequently emphasize geochemical suitability for cement production, with comparatively fewer investigations addressing intact strength variability, structural characterization, and rock mass quality assessment under standardized testing protocols (Ademila, 2020; Olaleye *et al*., 2019). This data limitation poses challenges for engineering design, particularly in foundation construction, quarry slope stability analysis, blasting optimization, and potential underground excavation works. In carbonate terrains where discontinuity patterns, weathering profiles, and hydrogeological conditions exhibit strong spatial variability, the absence of detailed geomechanical characterization can lead to conservative support design, increased construction costs, or underestimated instability risks (Alejano, 2025; Erharter *et al*., 2025). Moreover, as infrastructure expansion accelerates across Nigeria and other developing regions, the demand for reliable, site-specific geomechanical data to inform sustainable engineering practice continues to grow (Li *et al*., 2023; Niu *et al*., 2024). Accordingly, this study aims to provide an integrated geotechnical and rock mass characterization of selected limestone deposits in Nigeria using standardized laboratory testing and field-based structural mapping. The resulting dataset contributes to improved design reliability in carbonate environments and provides a regionally relevant reference framework for future rock mechanics investigations.

II. MATERIALS AND METHODS

Representative limestone samples were collected from four major carbonate outcrops in Nigeria: Iluagba (Kogi State), Okpella (Edo State), Ewekoro (Ogun State), and Gboko (Benue State). These locations fall within prominent Nigerian sedimentary basins and exhibit varying lithological and structural characteristics. Geographic coordinates were recorded using a handheld GPS device at each sampling point. Detailed field investigations were conducted to evaluate lithological variability and structural controls influencing rock mass behavior. Geological mapping included identification and measurement of bedding planes, joints, fractures, weathering grades, and karst features. Discontinuity orientation (dip and dip direction) was measured using a Brunton compass, while spacing, persistence, aperture, roughness, and infilling conditions were documented following ISRM suggested methods. Groundwater conditions were qualitatively assessed based on seepage evidence and surface moisture observations. A total of 300 cylindrical specimens were prepared from block samples collected from fresh outcrops. Cylindrical specimens were cored and trimmed in accordance with ISRM (2007) and ASTM standards, maintaining a length-to-diameter (L/D) ratio between 2.0 and 2.5. End faces were ground parallel within acceptable tolerances to ensure uniform stress distribution during loading. Specimen diameters ranged from 38 to 54 mm. Samples were oven-dried at 105 ± 5°C for 24 hours prior to physical testing, except for specimens designated for saturated-condition testing. Physical properties were determined using standardized laboratory procedures. Bulk density was calculated from the dry mass-to-volume ratio, with specimen volume computed from measured dimensions. Effective porosity was obtained using the saturation and buoyancy method based on Archimedes' principle, while water absorption was determined from the percentage increase in mass after saturation. These parameters provided insight into pore structure characteristics and fluid sensitivity of the limestone. Mechanical properties were evaluated through uniaxial compressive strength (UCS) and Brazilian tensile strength (BTS) testing following ISRM and ASTM D7012 and D3967 standards, respectively. UCS

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tests were conducted at a constant stress rate in accordance with ISRM recommendations. Peak load and corresponding stress values were recorded to compute compressive strength. Indirect tensile strength was determined using the Brazilian disc method, with failure loads recorded and converted to tensile strength values based on specimen geometry. Rebound hardness values were obtained using a Schmidt hammer, with multiple impact readings averaged to reduce local heterogeneity effects and correlated with UCS results for validation purposes. Rock Quality Designation (RQD) was determined from core logging as the percentage of core pieces longer than 100 mm relative to the total core run length, providing a quantitative measure of fracturing intensity. Rock mass quality was subsequently evaluated using the Rock Mass Rating (RMR) classification system, incorporating ratings for intact rock strength (UCS), RQD, discontinuity spacing, discontinuity condition, groundwater condition, and orientation adjustment. The final RMR values were computed as the summation of these parameters, enabling engineering assessment of slope stability, foundation competence, and excavation support requirements. Mineralogical composition was determined through X-ray diffraction (XRD) analysis of pulverized samples (<75 µm), allowing identification of dominant carbonate phases such as calcite and dolomite, as well as accessory minerals including quartz and clay phases. Major oxide concentrations (e.g., CaO, SiO_2, MgO, Fe_2O_3) were determined using geochemical analysis to evaluate compositional controls on mechanical behavior. This integrated methodological framework combined field-based structural characterization, standardized laboratory testing, mineralogical analysis, and rock mass classification to provide a comprehensive geotechnical evaluation of selected Nigerian limestone formations.

III. RESULTS AND DISCUSSION

Table 1 Summary of Physical Properties of the Investigated Limestone Deposits

Location	P(%)	BD (g/cm³)	WA (%)	RHV
A1	1.21–2.10	2.72–2.80	0.42–0.85	38–46
A2	1.35–2.45	2.65–2.78	0.50–0.92	35–44
A3	1.60–2.75	2.60–2.72	0.65–1.05	32–40
A4	1.30–2.20	2.68–2.79	0.48–0.88	36–45
Range	1.21–2.75	2.60–2.80	0.42–1.05	32–46

NOTE: ILUAGBA (A1), OKPELLA (A2), GBOKO (A3), EWEKORO (A4). Porosity (P), Bulk Density (BD), Water Absorption (WA), Rebound Hardness Value (RHV).

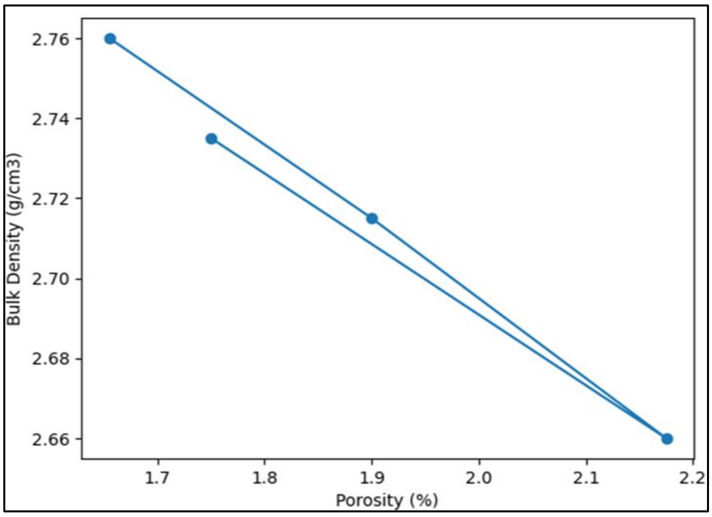

Fig 1 Relationship Between Porosity and Bulk Density

➤ *Physical Properties*

The results of laboratory-determined physical properties of the investigated limestone deposits are shown in Table 1**.** The limestones exhibit low effective porosity ranging from 1.21% to 2.75%**,** indicating a compact pore structure with limited interconnected voids. Bulk density values vary between 2.60 and 2.80 g/cm³**,** consistent with dense calcitic limestone formations. Water absorption values remain low (0.42–1.05%), indicating minimal pore connectivity and reduced susceptibility to moisture induced deterioration. The highest bulk density values were recorded at Iluagba and Gboko, corresponding to lower porosity ranges, whereas slightly higher porosity and water absorption values were observed in Ewekoro samples. This inverse relationship between porosity and density indicates that microstructural compactness strongly controls the physical integrity of the rock.

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Table 2 Mechanical Properties of the Limestone Samples

Location	UCS (MPa)	TS (MPa)	TS/UCS Ratio (%)	Strength Class
A1	55.4–82.0	5.10–7.45	8–11	Strong
A2	48.6–75.3	4.20–6.80	8–10	Moderately Strong–Strong
A3	38.2–60.5	3.11–5.20	7–9	Moderately Strong
A4	50.1–78.4	4.50–7.10	8–11	Strong
Range	38.2–82.0	3.11–7.45	7–12	Moderate–Strong

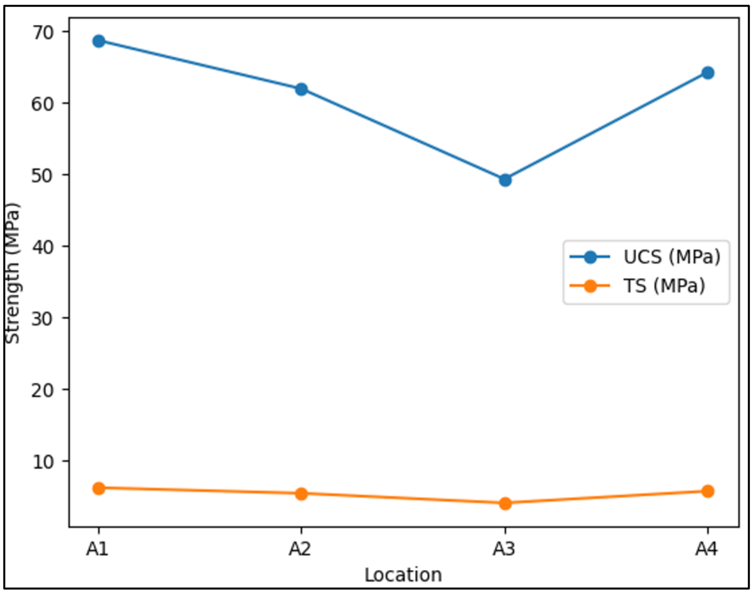

Fig 2 Variation of Uniaxial Compressive Strength and Tensile Strength

➢ *Mechanical Properties*

The mechanical strength parameters obtained from UCS and Brazilian tensile strength testing are presented in Table 2. The uniaxial compressive strength (UCS) values range from 38.2 MPa **to** 82.0 MPa, classifying the limestone as moderately strong to strong rock according to ISRM standards. The highest compressive strengths were recorded at Iluagba and Gboko, whereas relatively lower values were observed at Ewekoro. Brazilian tensile strength (BTS) values range from 3.11 MPa to 7.45 MPa, representing approximately 7–12% of the UCS values, which is characteristic of brittle carbonate rocks. The tensile to compressive strength ratio confirms the expected brittle failure behavior, with axial splitting observed in UCS tests and central crack propagation in Brazilian disc specimens. The variability in strength values across locations reflects differences in mineralogical composition, degree of recrystallization, and micro-fracture distribution. Samples with lower porosity and higher density consistently recorded higher UCS and BTS values, confirming the strong influence of pore structure on mechanical performance. The rebound hardness values (RHV) range from 32 to 46**,** reflecting moderate to high surface hardness. Samples with higher RHV consistently corresponded to higher UCS values, indicating good reliability of Schmidt hammer measurements for rapid field-based strength estimation.

Table 3 Rock Mass Rating (RMR) Classification Parameters

Parameter	Observed Range	Rating Contribution
UCS (MPa)	38.2–82.0	7–12
RQD (%)	72–88	13–17
Discontinuity Spacing	Moderate–Wide	10–15
Discontinuity Condition	Rough, Slightly Weathered	15–20
Groundwater Condition	Damp–Wet	4–10
Orientation Adjustment	Favorable–Fair	-2 to 0
Final RMR	62–78	Class II (Good Rock)

➢ *Rock Quality Designation (RQD) and Rock Mass Rating (RMR)*

Rock Quality Designation values range between 72% and 88%, with an overall average of 80.26%, classifying the deposits as good quality rock mass. The relatively high RQD values indicate low fracture intensity and favorable block size distribution. Rock Mass Rating (RMR) results are shown in Table 3. Final RMR values range between 62 and 78, placing the deposits predominantly within Class II (Good Rock). The classification reflects the combined influence of strong intact rock strength, moderate to wide discontinuity spacing, rough joint surfaces, and generally favorable structural orientation.

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Although groundwater conditions were locally damp to wet, their effect on overall RMR was moderate due to limited clay infilling and strong intact rock properties. The RMR results suggest stable conditions for surface excavations and moderate support requirements for underground openings.

Table 4 Major Oxide Composition of the Limestone Deposits

Location	CaO (%)	SiO_2 (%)	MgO (%)	Fe_2O_3 (%)
A1	51–54	2.0–4.5	1.5–3.2	0.6–1.2
A2	50–53	3.5–6.0	1.8–3.5	0.8–1.5
A3	48–52	4.5–7.5	2.0–4.0	1.0–1.8
A4	50–54	2.5–5.0	1.6–3.0	0.7–1.3

➢ *Mineralogical and Geochemical Characteristics*

Major oxide composition results are presented in Table 4. The limestone deposits are dominated by high CaO content (48–54%), confirming calcite as the principal mineral phase. SiO_2 values remain relatively low (2.0–7.5%), while MgO values (1.5–4.0%) indicate partial dolomitization in certain locations. Higher silica content observed in Ewekoro samples corresponds with slightly reduced UCS values, suggesting localized heterogeneity. However, the overall dominance of calcite and limited clay minerals contribute to high density and strength values across all study areas. The geochemical composition confirms suitability for cement production due to high calcium content and acceptable impurity levels.

➢ *Integrated Engineering Implications*

The integrated assessment combining intact rock mechanical testing, detailed structural mapping, and mineralogical characterization provides a comprehensive evaluation of the engineering competence of the investigated limestone deposits. The results demonstrate that the formations exhibit moderate to high uniaxial compressive strength values ranging from 38.2 to 82.0 MPa, coupled with low porosity and minimal water absorption, indicating a dense and mechanically stable rock fabric. Furthermore, the average Rock Quality Designation (RQD) of approximately 80% and Rock Mass Rating (RMR) values predominantly within Class II confirm generally good rock mass conditions with favorable discontinuity characteristics and limited structural weaknesses. Collectively, these geotechnical attributes indicate that the studied limestone deposits are structurally competent and mechanically reliable for a wide range of engineering applications, including shallow and deep foundation systems, quarry slope design, aggregate production, and cement manufacturing. The integration of laboratory-derived strength parameters with field based rock mass classification enhances the reliability of design predictions and reduces uncertainty associated with carbonate terrain variability. Consequently, the dataset generated in this study establishes a robust geomechanical framework to support safe, economical, and sustainable engineering development within limestone dominated regions of Nigeria.

IV. CONCLUSION

This study presents an integrated geotechnical and rock mass characterization of selected limestone deposits in Iluagba (Kogi State), Okpella (Edo State), Ewekoro (Ogun State), and Gboko (Benue State), Nigeria, using standardized laboratory testing and field-based structural assessment. The results demonstrate that the investigated limestone formations exhibit moderate to high uniaxial compressive strength values (38.2–82.0 MPa) and Brazilian tensile strength values (3.11–7.45 MPa), classifying them as moderately strong to strong rocks according to ISRM standards. The consistently low porosity (1.21–2.75%), high bulk density (2.60–2.80 g/cm³), and minimal water absorption indicate a compact microstructure with limited susceptibility to moisture-induced weakening. Rock mass evaluation revealed average RQD values of approximately 80%, reflecting good rock quality with relatively low fracture intensity. The computed Rock Mass Rating (RMR) values ranging from 62 to 78 place the formations predominantly within Class II (Good Rock), suggesting favorable structural conditions for engineering applications with minimal to moderate support requirements. Although localized damp to wet groundwater conditions were observed, their influence on overall rock mass competence remains limited due to strong intact rock properties and generally rough, slightly weathered discontinuities. Mineralogical and geochemical analyses confirm dominant calcite composition with minor quartz and moderate MgO content, indicating partial dolomitization in certain locations. The high CaO content and acceptable impurity levels further validate the suitability of these deposits for cement production. Variations in silica content correspond with minor reductions in mechanical strength, highlighting the influence of mineralogical heterogeneity on engineering behavior. The integration of laboratory derived physical and mechanical properties with rock mass classification provides a reliable framework for evaluating engineering suitability in carbonate terrains. The investigated limestone deposits are mechanically competent and suitable for foundation construction, quarry slope development, aggregate production, and cement manufacturing. This study contributes a comprehensive, standardized geomechanical dataset that enhances design reliability and supports sustainable infrastructure development in limestone-dominated regions of Nigeria. Future research should incorporate deformability parameters, durability testing under cyclic wetting–drying conditions, and advanced predictive modeling approaches to further refine engineering performance assessments in Nigerian carbonate formation.

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