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Review Article

Determination of Physical and Geomechanical Properties of Black Shale Hosting Lead and Zinc Ore in Eyingba, Ebonyi

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Keywords

Physical and geomechanical,
Strength properties,
Shale,
Uniaxial compressive strength,
Engineering design.

Abstract

This study was conducted to investigate the physical and geo-mechanical properties such as specific gravity, porosity, uniaxial compressive strength (UCS) etc. of shale, hosting lead and zinc ore in Enyigba, Ebonyi State, Nigeria. The strength properties of the black shale were analyzed because the variability in the strength of rock masses must be properly accounted for, to determine their utility in engineering design. Several tests were carried out on the intact shale samples, and the results were converted to bulk mass strength values using the Hoek–Brown criterion. The results showed that the UCS of the black shale ranged from 38.3 to 43.7 MPa for a geological strength index (GSI) value of 75; and from 54.2 to 60.4 MPa for a GSI value of 80. The specific gravity was 2.89 while the bulk density and porosity values were 290.3 kg/m3 and 15.56% respectively. Also, it was determined that there is a strong correlation between the UCS and specific gravity of the rock, with negligible levels of correlation, both positive and negative, between the UCS and the other mechanical properties examined. In conclusion, the black shale sample from Enyigba is characterized as a medium to hard rock that is suitable for engineering and mining projects.

1. Introduction

Rock strength is important in the design of rock structures and the stability of rock excavations because they must be able to withstand various forces applied to them. It also influences rock fragmentation in quarrying and the operation of surface and underground mines. However, because of the heterogeneous nature of rocks and diverse local geological conditions, the strength properties of rocks vary not only from rock to rock but also within the same solid mass. They also exhibit varied features in different climatic situations, owing to the action of moisture on the mineral grains, according to Ojo and Brooks (1990) [1]. Hudson and Harrison (1997) [2] showed that fractures in a rock mass have been discovered to influence the stability of near-surface structures, and this natural in situ stress governs the stability of deep structures. The determination of strength qualities and understanding how rock masses deform are critical for the safe and cost-effective construction of structures such as mines and tunnels. In situations where the rock mass is weak, fractured, or sheared, in-situ tests may be the only way to obtain accurate information about the strength and other properties of the rock mass, such as primary and residual stresses; deformation properties; shear strength parameters; anchor capacities, and permeability characteristics (Hari, 2017) [3], because laboratory tests on samples of such rocks may not be representative of the actual rock mass due to the varying fractures and discontinuities present. According to a study by Bacha et al. (2014) [4] The nature of these flaws is thought to determine the mechanical behavior of rock mass, and reliable information on this behavior, particularly shear strength of discontinuities, is critical for the design and stability analysis of civil and mining structures. The strength of a material refers to its ability to withstand stress or strain when subjected to one or more fundamental forces. Aadnøy and Looyeh (2019) [5] explained that rock strength is defined in terms of tensile strength, compressive strength, shear strength, and impact strength.

Hari (2017) [3] posited that these characteristics assist designers in doing fundamental design and stability studies of rock structures. Furthermore, in a study carried out by Bidgoli et al. (2013) [6], it was found that direct measurements of the mechanical properties of jointed rock masses using laboratory experiments are not entirely precise because of the effect of sample dimensions, discontinuities, the unknown geometry of the fracture system prior to testing, and the inherent complexity of geometric parameters.

Tse and Eyang (2016) [7] determined that shales behave differently depending on their geotechnical and mineralogical features. They are primarily composed of clay minerals that are influenced by water content, have low friction angles, and are generally poorly cemented, all of which reduce the strength of the material, making them susceptible to varying degrees of hydro-affinity and volume changes when subjected to cycles of wetting and drying, resulting in swelling during the rainy season and shrinkage during the dry season. This has resulted in a number of engineering problems such as cracking, embankment failures, slope instability, shale cut failures, and shear failure of engineering structures at various locations, necessitating investigations into the mechanical and physical properties of shale and classification methods developed to group their various characteristics in the field (Santi, 2006) [8], which is important for the analysis of the strength properties which in turn influences the measures to be adopted to mitigate failure and ensure that, regardless of its purpose, it remains feasible for use. In mining activities, the determination of the various geo-mechanical and physical properties of shale will influence the type of mining method to be used to exploit the deposit.

The reason for this research is to properly determine the geomechanical properties (Young's modulus, uniaxial compressive strength, and cohesive strength) and physical properties (porosity, specific gravity, and hardness) of black shale to aid mining projects to efficiently exploit the ores present in it and provide other engineering projects with accurate data to ensure efficient design and planning.

2. Review of Shale and Geomechanical Properties

Shale has been broadly examined over the years especially for its excellent properties as a host rock for some of the world's most economically important minerals such as petroleum, copper, lead and zinc ores etc. Yagiz (2001) [9] explained that shales are argillaceous sediments consisting of claystones, siltstones, mudstones, and marls.

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Shale is the common name given to fine-grained varieties of sedimentary rocks that are formed by the consolidation of clay, silt, and mud. Findings reveal that this type of rock is formed from silts and clays that have been deposited and compacted, or hardened.

Because of the abundance of shale materials in the Earth's crust; it is the most abundant sedimentary rock present, accounting for over 60% (Boggs, 1995) [10], it becomes expedient to utilize the use of shales because of their widespread occurrence and utility. Large quantities and numerous varieties of shale have found extensive use in various engineering applications, including construction and in mining as a host rock.

According to Okeke and Okogbue (2011) [11], shales have properties that vary in nature and can be grouped into petrophysical and geo-mechanical properties. The petrophysical properties include density, porosity, permeability, specific gravity, and clay content, whereas the geo-mechanical properties include plasticity index, slake-durability index, swelling potential, hardness, point-load strength(tensile), uniaxial compressive strength, in-situ stress, and Modulus of Elasticity (Young's modulus). Many studies have indicated that the mechanical anisotropy of shale is caused by the composition and distribution of platy clay materials and compliant organic materials (Sondergeld and Rai, 2011; Ma et al., 2017) [12-13].

The shale samples collected for the purpose of this study were sourced from the Enyigba mining district, which is located approximately 14 km southeast of Abakaliki town in Ebonyi state of southeast Nigeria and lies between latitudes 6° 07' N and 6°12' N and longitudes 8° 05' E and 8° 10E'. The region lies in a noticeably flat to gently rolling landscape within the Cross-River plain. Enyigba is characterized by a series of rolling shale formations that act as the foundation for Pb-Zn mineral deposits, and the lower Cretaceous Abakaliki shale is visible in the vicinity. The sedimentary rocks predominantly consist of black calcareous shale that is occasionally interspersed with siltstone layers (Nnabo, 2015) [14].

Hui et al. (2016) [15] also found that the mechanical properties of shale are influenced by a range of factors, including porosity, swelling potential, hardness, temperature, water content, and the Modulus of Elasticity (Young's modulus) within the rock mass.

- Stress: Stress is a tensor quantity that defines the force per unit area exerted on a rock. It possesses magnitude, direction, and a specific plane upon which it acts. Failures can be assessed by measuring the stress, and materials can simultaneously experience multiple stress factors.

Compression force is caused by an applied load that acts to reduce the length of the material.

Tensional force is caused by an applied load that tends to elongate the material.

Shear stress is caused by two forces acting in opposite directions along the plane of weakness.

Confining stress is a type of stress acting on deeply buried rock, such that it is pushed down by the weight of all the materials above it.

- Cohesive strength: This refers to the bonding strength between the particles or surfaces.

- Unconfined compressive strength: Gholami and Fakhari (2017) [16] theorized that the UCS is one of the most important mechanical properties of rocks and is widely used in different engineering-related projects to evaluate the stability of structures against loads. It is the maximum compressive stress that a rock sample can withstand under unconfined conditions.

The mechanical properties of shale are also affected by a number of factors such as confining stress, clay content, anisotropy, and bedding plane orientation etc. (Hui et al, 2016) [15].

- Effective pressure: This is defined mathematically as:

$$P_e = P_c - nP_p$$

Where Pe is the effective pressure, Pc is the confining pressure, Pp is the pore pressure, and n is the effective pressure coefficient, where the value of n can be greater than or less than 1 depending on which is more important between the pore pressure and confining pressure (Tinni et al., 2011) [17].

- Water content: Lashkaripour and Passaris (1993) [18] discovered a negative correlation between water content and compressive strength in coal mine shale. This implies that as the water content in shale increases, its compressive strength decreases. This finding was corroborated by Steiger and Leung (1989) [19], who conducted unconfined compressive strength (UCS) tests on three categories of shale rocks under both dry and wet conditions. Their results showed that shale samples with a lower water content exhibited higher unconfined compressive strength.

- Porosity: Spikes and Dvorkin (2004) [20] found that the Poisson's ratio increases with porosity using synthetic seismic modeling. Kumar et al. (2012) [21] showed that shale's Young's modulus decreases with higher porosity, and localized porosity greatly influences shale's mechanical properties.

- Clay content: Yao et al. (2010) [22] theorized that clay-rich rocks are ductile, whereas clay-deficient rocks are brittle. Sone and Zoback (2011) [23] confirmed this finding by conducting UCS tests on shale specimens and measuring the clay content using X-ray diffraction (XRD). They found that UCS decreased significantly with increasing clay content. Akrad et al. (2011) [24] observed similar results.

2.1. Stress-Strain Relations

The response of a rock to stress is determined by parameters such as the temperature, pressure, time, and type of stress. Elastic, plastic, and fracture deformations can occur in rocks. Once the external forces acting on the rock are eliminated, the elastic deformation is reversible, plastic deformation is irreversible, and fracture is permanent because the rock fails. Bogusz and Bukowska (2005) [25] demonstrated that the stress-strain behavior of rocks is non-linear. It varies with the type of rock and is affected by factors such as experimental circumstances and sample size.

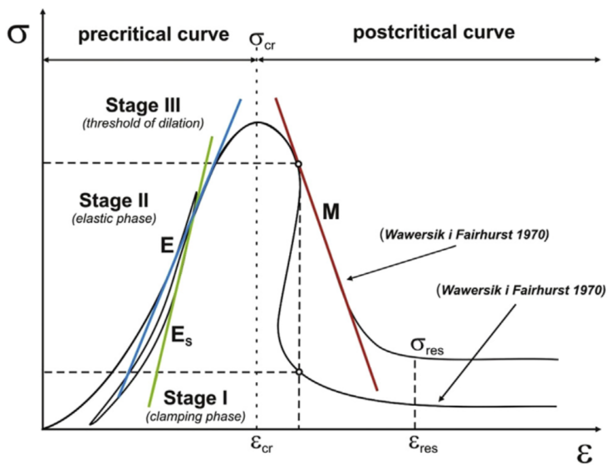

Figure 1. Ideal stress-strain characteristics of a rock under uniaxial compression (Bogusz and Bukowska, 2005) [25]

where σ is the stress; ε is the strain; σcr is the critical stress; σres is the residual stress; εcr is the critical strain; εres is the residual strain; E is the Young's modulus; Es is the elasticity modulus recovery, and M is the post-peak failure modulus.

(Bogusz and Bukowska, 2005) [25] identified multiple stages of strain in rocks across their full stress-strain characteristics when undergoing compression tests, as shown in (Fig. 1).

Stage I: the clamping and sealing phase, where the rock stiffens as pores and microcracks close.

Stage II (elastic phase): the course of the curve is linear.

Stage III: The nonlinear stress-strain curve starting from the dilation threshold to maximal strength. The tangent inclination decreased, indicating a more dynamic strain increase relative to stress. Significant transverse and volumetric strain increases occur, associated with the rock's inelastic volume expansion due to the compressive load, initiating the destruction of its structure. In the post-critical part of the stress-strain characteristics, Wawersik and Fairhurst (1970) [26] obtained two curves reflecting two different ways of rock destruction caused by loading.

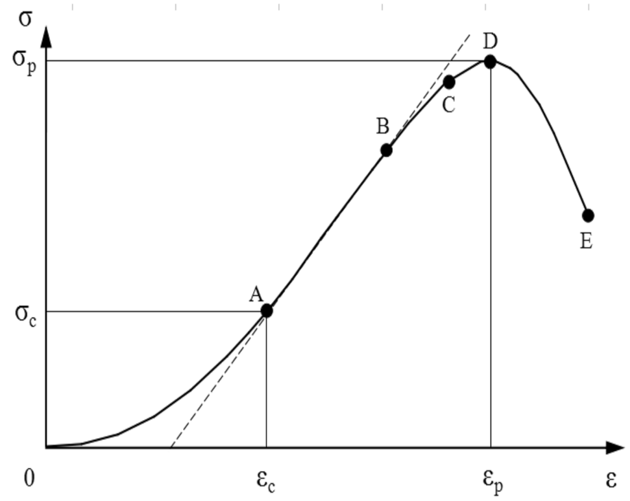

Figure 2. Typical stress–strain curves of the shale samples under uniaxial compression (Bian et al, 2018) [27]

Bian et al. (2018) [27] classified the stress-strain curves of dry and immersed shale samples subjected to uniaxial compression into five stages: void compression (OA), approximate linear deformation (AB), nonlinear deformation (BC), yield (CD), and post-peak failure and strain softening (DE).

3. MATERIALS AND METHODS

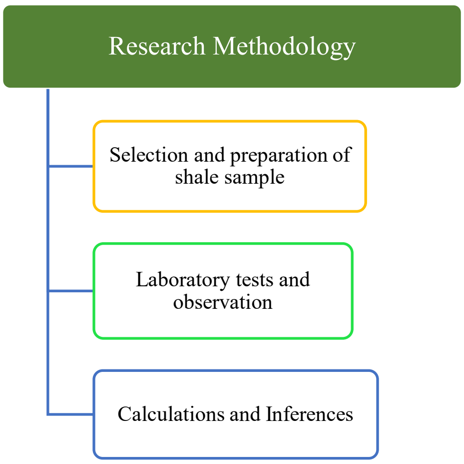

Figure 3. Flow chart of the study

3.1. Shale Sample Preparation

Coring: A rock coring machine was used to extract shale rock core samples with a diameter of 5cm and a height of 12.5cm, following the standard ratio of 1:2.5.

Figure 4. Coring Process

Cutting: This refers to trimming the cored sample to achieve a height of 12.5cm and a width of 5cm using a cutting machine, which ensures the required dimensions of the ratio 1:2.5 for laboratory testing.

Figure 5. Cutting machine

3.2. Laboratory Tests Carried Out

To achieve the aim of this study, point load, shear, water absorption, and bulk density tests were performed on the samples to assess various strength parameters of the rock, such as shear strength, tensile strength, compressive strength, and friction angle.

- ✓ Triaxial Compression Test: The triaxial test is used to simulate in-situ loads on a core soil or rock sample. The specimens were loaded axially to failure while maintaining a constant confining pressure, allowing researchers to investigate the geomaterial behavior under three-dimensional stress conditions. In this study, the Unconsolidated Undrained Triaxial test was used to determine shear strength at various confining loads.

- ✓ Bulk Density Test: The volume of the sample was calculated by comparing the difference between its submerged weight and dry weight. Water is commonly used to suspend the sample, but any incompressible fluid with a known density can be used.

4. Results and Discussions

Table 1. Triaxial strength values of intact rock

Sample ID	Max. UCS (MPa)	Min. UCS (MPa)	Avg UCS (MPa)	Tensile Strength (MPa)	Young's Modulus	Breaking Load (MPa)
Core 1	227.6	223.1	225.4	9.5	42.5	6.0
Core 2	222.6	218.2	220.4	8.9	35.7	8.9
Core 3	244.9	235.9	240.4	6.8	25.9	6.8
Core 4	226.8	221.8	224.3	8.5	40.5	5.9
Core 5	222.9	217.9	220.4	8.8	36.7	5.8
Core 6	243.1	234.3	238.7	7.8	26.4	5.0
Average	231.3	225.2	228.3	8.4	34.6	6.4
Standard Deviation	9.2	7.3	9.0	0.9	6.4	1.2

The triaxial compression test conducted on the intact rock samples revealed the following properties: the uniaxial compressive strength ranged from 220.4 MPa to 240.4 MPa, the tensile strength varied from 6.8MPa to 9.5MPa, and the Young's Modulus of the intact rock samples ranged from26.4MPa to 42.5MPa. Additionally, measurements of bulk density, porosity, specific gravity, and water absorption capacity were recorded for the core samples in Table 2.

Table 2. Bulk Density, Specific gravity and Porosity results

Sample ID	Bulk Density (kgm^{-3})	Specific Gravity	Internal Friction Angle(^{0})	Cohesive Strength	Porosity (%)	Capacity of water absorbed
Core 1	286.5	2.57	25.9	10.9	19.9	0.48
Core 2	290.2	2.56	25.8	14.4	17.9	0.54
Core 3	292.8	2.6	30.5	16.8	11.9	0.46
Core 4	286.8	2.57	24.9	8.7	11.9	0.48
Core 5	290.2	2.57	24.9	12.6	19.9	0.46
Core 6	292.8	2.6	25.4	16.3	11.9	0.46
Average	289.9	2.58	26.2	13.3	15.57	0.48
S.D	2.76	0.02	2.1	3.2	4.08	0.03

The bulk density of the intact shale rock sample has an average value of 289.9 kgm^{-3}, the specific gravity of the shale rock has an average value of 2.58 and the average of the porosity values is 15.57%.The average value of water absorption capacity was determined to be 0.48.

4.1. Conversion of Intact Rock Parameter Values To Rock Mass Values

In their paper, Bajerbaneh et al (2014) [28] argued that in order to ensure precise geotechnical applications, such as designing slopes, foundations, and underground excavations, it is critical to accurately assess the mechanical behavior of the rock mass, which includes understanding its strength and deformation properties. However, traditional engineering strength theories may be limited in their applicability to rocks, particularly under a wide range of applied compressive stress conditions. To address this, many empirical strength criteria for practical usage have been created. The Hoek-Brown criterion is a commonly used framework for isotropic rock materials and rock masses in both academic and technical contexts, and it has proven to be highly useful in providing trustworthy judgments in such circumstances. The Generalized Hoek-Brown failure criterion (Hoek et al, 2002) [29] was used to determine the rock mass characteristics of the black shale rock as expressed in.Eq. 1.

$$\sigma_1 = \sigma_3 + \sigma_{ci}(m_b \frac{\sigma_3}{\sigma_{ci}} + s)^a \quad (1)$$

Where: $\sigma_1$and σ_3 represent the major and minor principal stresses at failure, respectively, m_b is the Hoek-Brown constant, s and a are Hoek-Brown constants which depend on the characteristics of the rock mass and σ_{ci} refers to the unconfined compressive strength of the rock sample.

Obtaining the rock mass constants (m_b, s and a)using the following equations were suggested by (Hoek *et al,* 2002) [29].

$$m_b = m_1 e^{(\frac{GSI-100}{28-14D})} \quad (2)$$

$$s = e^{(\frac{GSI-100}{9-3D})} \quad (3)$$

$$a = \frac{1}{2} + \frac{1}{6}(e^{\frac{GSI}{15}} - e^{\frac{-20}{3}}) \quad (4)$$

Blasting exposes rock masses to the impacts of blast-induced damage and stress relaxation. A disturbance factor index scale ranging from 0 to 1 is utilized as an index signifying the degree of disturbance inside the rock masses to quantify the severity of blast disturbance experienced by the rock mass. To define the blast-induced disturbances within the rock, a D value of 0.6 was chosen for the current study.

4.1.1. Uniaxial Compressive Strength of Rock mass

The Uniaxial Compressive Strength of the rock mass is obtained by setting σ_3 = 0 in Eq. 1 giving:

$$\sigma_c = \sigma_{ci}(s)^a \quad (5)$$

The Geological Strength Index (GSI) estimates rock-mass strength based on geological observations of structure and rock discontinuity surface condition. The GSI value is directly applied to the Hoek-Brown failure criterion to derive rock mass properties. (Bajerbaneh et al, 2014) [27]

The Geological Strength Index (GSI) values for shale core sample was estimated to range between 75 and 80, and are used as follows in this conversion:

At GSI=75, $a = \frac{1}{2} + \frac{1}{6}(e^{\frac{-75}{15}} - e^{\frac{-20}{3}})$

$$= \frac{1}{2} + \frac{1}{6}(6.7379 \times 10^{-3} - 1.272 \times 10^{-3})$$

$$a = 0.5009$$

At GSI=80, $a = \frac{1}{2} + \frac{1}{6}(e^{\frac{-80}{15}} - e^{\frac{-20}{3}})$

$$= \frac{1}{2} + \frac{1}{6}(4.8279 \times 10^{-3} - 1.272 \times 10^{-3})$$

$$a = 0.5006$$

To obtain the value of s, we have:

$$s = e^{(\frac{GSI-100}{9-3D})} \quad (6)$$

At GSI= 75 and D= 0.6, $s = e^{(\frac{75-100}{9-1.8})}$

$$s = e^{(\frac{-25}{7.2})}$$

$$s = 0.03105$$

At GSI=80 and D= 0.6, $s = e^{(\frac{80-100}{9-1.8})}$

$$s = e^{(\frac{-20}{7.2})}$$

$$s = 0.062$$

Also, to obtain the values for s^a with the different GSI values of 75 and 80,

At GSI = 75, s= 0.03105 and a = 0.5009, hence

s^a = $0.03105^{0.5009}$

s^a = 0.1756

and at GSI = 80, s = 0.062 and a = 0.5006, hence

$s^a = 0.062^{0.5006}$

$s^a = 0.2486$

To obtain the rock mass values for the shale rock from the intact shale core samples, we multiply the values by the GSI factor as given in Eq. 5, the results are given in Table 3.

Table 3. Intact and Rock Mass values for Uniaxial Compressive Strength

Sample ID	Compressive Strength Of Intact	s^a (GSI=75)	s^a (GSI=80)	Compressive Strength of Rock mass at	Compressive Strength of Rock mass at GSI=80
Core 1	225.4	0.1756	0.2486	39.5	56.0
Core 2	220.4	0.1756	0.2486	38.7	54.8
Core 3	240.4	0.1756	0.2486	42.2	59.8
Core 4	224.3	0.1756	0.2486	39.4	55.7
Core 5	220.4	0.1756	0.2486	38.7	54.8
Core 6	238.7	0.1756	0.2486	41.9	59.3
Average	228.3			40.1	56.7

Table 3 shows that the uniaxial strength of the rock mass has an average value of 40.1MPa at a GSI value of 75, and a uniaxial compressive strength value of 56.7MPa at a GSI value of 80.

4.1.2. Deformation Modulus of Rock Mass

Using the Hoek- Brown formula,

$$E_m = E_i\left(0.02 + \frac{\frac{1-D}{2}}{1+e^{\left((60+15D-GSI)/_{11}\right)}}\right) \quad (7)$$

Where the deformation modulus of the rock mass is represented by E_m, E_i is the deformation modulus of the intact rock sample and D = 0.6.

At GSI = 75, $E_m = E_i(0.1466)$

At GSI = 80, $E_m = E_i(0.1622)$

Table 5. Intact and Rock Mass values for Uniaxial Compressive Strength

Sample ID	Deformation Modulus of Intact sample (MPa)	Deformation Modulus of Rock mass (GSI=75)	Deformation Modulus of Rock mass (GSI=80)
Core 1	335.25	49.15	54.3
Core 2	340.2	49.87	55.2
Core 3	340.3	49.89	55.2
Core 4	336.25	49.29	54.5
Core 5	340.2	49.87	55.2
Core 6	338.33	49.61	54.9
Average	338.42		54.9

The deformation modulus value at a GSI value of 75 is 49.61MPa and at GSI of 80, the deformation modulus is 54.88MPa, these two values show the range of the deformation modulus.

4.2. Deductions

4.2.1. Relationship between UCS and specific gravity

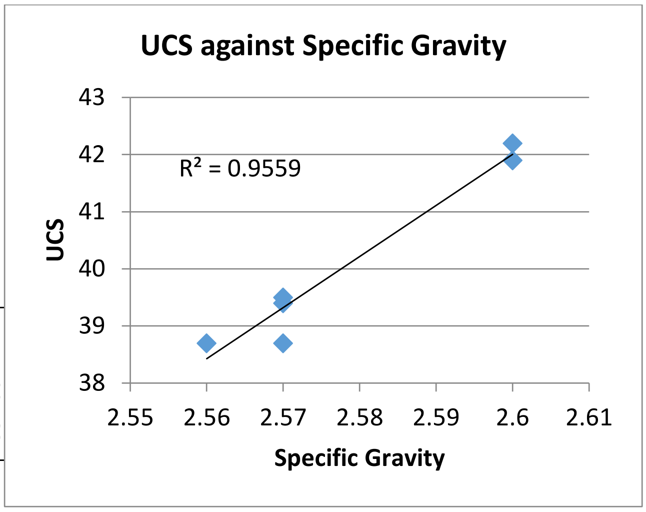

Figure 6. Graph of UCS against specific gravity

Coefficient of correlation (r) = 0.98

4.2.2. Relationship between UCS and Water absorption

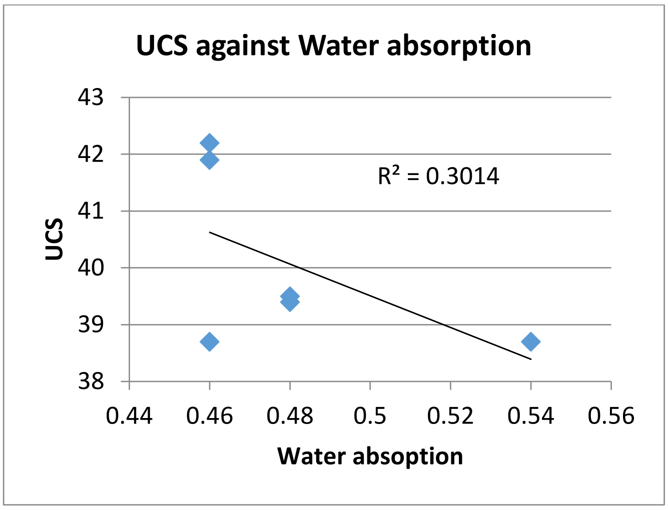

Figure 7. Graph of UCS against water absorbed

Correlation of coefficient (r) = -0.54.

4.2.3. Relationship between UCS and bulk density

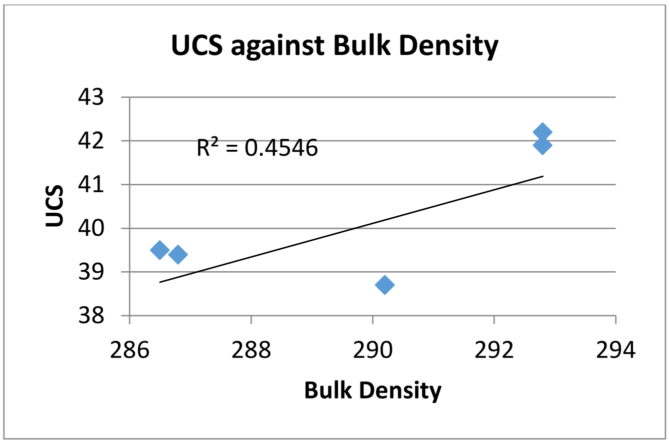

Figure 8. Graph of UCS against bulk density

Coefficient of correlation = 0.67.

4.2.4. Relationship between UCS and porosity

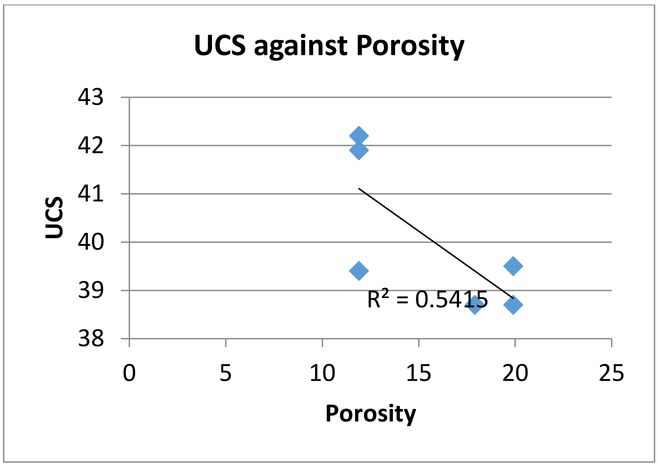

Figure 9. Graph of UCS against Porosity

Coefficient of correlation (r) = -0.73.

4.2.5. Relationship between friction angle and cohesive strength

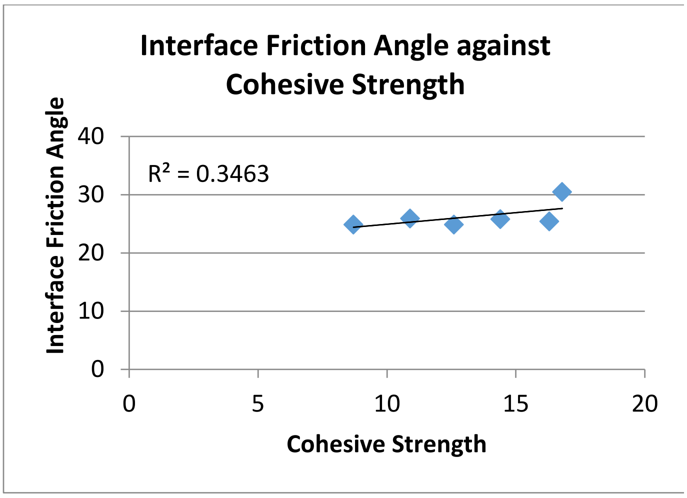

Figure 10. Graph of Friction Angle against Cohesive strength

Coefficient of correlation = 0.59

5. Conclusion

The unconfined compressive strength (UCS) assessments conducted on the black shale rock mass in the Enyigba district, Ebonyi State, yielded average values of 40.1 MPa for a GSI value of 75 and 56.7 MPa for a GSI value of 80. These results indicate that, in accordance with global engineering material standards, the rock can be classified as moderate to strong.

The black shale exhibited various properties, including an average specific gravity of 2.58, average bulk density value of 289.9 kgm^{-3}, and a porosity of 15.57%. These values were obtained from various tests conducted on the rock samples.

The calculations also revealed the some of the relationships between the different mechanical properties and the uniaxial compressive strength. A particularly strong level of correlation was shown between the UCS and the specific gravity of the shale with a coefficient of correlation value of 0.98. Lower levels of positive correlation were recorded between the UCS and parameters like the bulk density, deformation modulus, and point load strength, which indicates little or no relationship in how both parameters affect each other. Conversely, the negligible values of the coefficients of correlation between the UCS and properties like porosity, water absorption, and tensile strength do not fully define the effect that the UCS has on these properties.

Based on these findings, it is recommended to conduct further research on black shale deposits in different locations to account for the variability in shale properties. By compiling a comprehensive database, it will better serve as a basis of knowledge to be considered in future engineering and mining projects involving black shale.

Declaration of Conflict of Interests

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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