Effects of Weathering on some Physical and Mechanical Properties of Ewekoro Limestone, South-western Nigeria

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Abstract— **The study is on the investigation of the effects of weathering on physical and mechanical properties of Ewekoro limestone, south-western Nigeria with the aim to establish the strength of the rock samples for design and engineering purposes. In order to achieve the set objectives, twenty representative samples were collected from each of the study area representing particular group of unweathered, slightly weathered, moderately weathered and highly weathered rocks using the field study indicators of colour, texture and friability, and International Society for Rock Mechanics (ISRM) classifications for the laboratory determination of physical and mechanical properties of the selected rocks. Thin sections were prepared for textural and mineralogical studies of the unweathered and weathered samples of the two rock types. The chemical composition analyses of the samples were done using X-ray Fluorescence spectrometry (XRF).The physico-mechanical variations with progressive weathering grades were statistically evaluated using Excel and Statistical Package for Social Sciences (SPSS) and mathematical models were generated. Quantitative test results show the dry and bulk densities, dry unit weight and specific gravity decreases with an increase in weathering state while the water content, water absorption and porosity increases with an increase in weathering state. The average values of dry density decreases from 2.69 g/cm³ in unweathered samples to 2.42 g/cm³ in highly weathered samples. The average porosity values increases from 7.60 % in unweathered samples to 11.27 % in highly weathered samples. The range of mechanical properties tests results decreases with an increase in weathering state with overlap of values across the different weathering grades. The average uniaxial compressive strength and point load strength values decrease respectively from 45.13 MPa and 2.30 MPa in unweathered samples to 16.30 MPa and 1.50 MPa in highly weathered samples. Textural, mineralogical and chemical studies conducted on the unweathered and weathered samples in both rock types show that noticeable textural, mineralogical and chemical changes occur in the rock fabric as a result of increase in weathering state. The results of geochemical studies show that calcium oxide (CaO) and potassium oxide (K2O) values decrease with increasing degree of weathering respectively, with 82.32 % and 0.82 % in unweathered sample to 45.21 % and 0.45 % in highly weathered samples. Silica (SiO2) and iron oxide (Fe2O3) increase as the weathering progresses respectively with 8.43 % and 2.35 % in unweathered sample to 19.93 % and 4.30 % in highly weathered sample. The regression analysis reveals strong relationships between some of the correlated parameters incorporating weathering states. The laboratory tests conducted indicate that weathering reduces strength of the rocks which could affect slope stability and performance of these rocks in engineering applications.**

Index Terms— **Carbonate rocks, Mechanical properties, Physical properties, weathering**

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I. INTRODUCTION

Weathering is an essential process that affects the physical and mechanical properties of rock material and mass at shallow depths and on the surface through chemical and physical weathering [2]. Physical weathering leads to the opening of discontinuities by rock fractures, progressively breaking down the original rock to a soil-like material representing advanced stages of weathering.
Chemical weathering results in chemical changes in minerals and both physical and chemical weathering greatly affects the engineering structures found at or near the Earth's surface [19]. The composition of sedimentary and metamorphic rocks is strongly influenced by the nature of weathering in the source area of the sediment. Chemical and physical weathering are also responsible for the formation of soils that supply nutrients to enable plant growth and control the Earth's surface morphology. Slope failures, erosion, and landslides often happen in areas that are strongly affected by weathering, and weathering is an environmental factor that impacts recent and/or historical sites. Weathering processes act as a buffer against a variety of environmental threats and also help to protect the environment [20]. Therefore, weathering is a very important process in the earth sciences.

The mechanical properties of rocks vary considerably depending on the rock types, extent of tectonism, discontinuities and weathering [17]. Weathering is the most important of these factors, affecting bearing capacity and excavatability. It is a process that involves disintegration and decomposition of rocks in nature. The different kinds of rocks which are formed under different conditions undergo disintegration and decay when exposed to the earth surface. The disintegrated and the altered products stay at the site of formation. Weathering occurs *in situ*, or "with no movement", and thus should not be confused with erosion, which involves the movement of rocks and minerals by agents such as water, ice, wind, and gravity.

Limestone are used extensively as engineering materials, including aggregates for road construction or surfacing (with or without asphalt or tar binder), manufacturing of cement, concrete and railway ballast, flux in glass making, fertilizer filler, explosives, foundation support beneath weight-bearing structures as well as dimension stone for production of slabs, tiles, ornaments and furniture etc. [16]. Generally, unweathered limestone and marble rocks have sufficient strength to meet any engineering requirement. However, the effect of weathering on this rock types variously change their physico-mechanical properties. Weathering implies decay and change in state from an original condition to a new condition as a result of external processes [6]. The process takes place in all environments but is most intense in hot, wet climates where weathering may be expected to extend to great depths. The strength of rock decreases with increase in water content due to reduction in the coefficient of internal friction of the rock particles. Presence of water in rock also increases the deformability of the rock mass [14]. While weathering may reach great depths in limestone, and rocks containing halite and gypsum, it is slow to do so and the style of weathering may change if climatic conditions change [18].

The study of the physical and mechanical characteristics of rocks depends on the physical properties and mineral composition of the weathered materials. The state of weathering resulting from physical and chemical processes may be reflected by changes in index properties such as dry density, void ratio, clay content and seismic velocity. It is thus important for rock engineering studies to estimate quantitatively the variations of these properties during weathering process. Different compositions of minerals may bring about different degree of weathering under similar conditions and show different properties [12]. On the other hand, different mechanical index tests have been used primarily to estimate the material design parameter rapidly and economically, and to characterize the degree of weathering [7]. Thus, weathering has been an important topic since the middle of twentieth century for the rock mechanics researchers. Numerous studies have been performed on many different rock types to reveal the changes in chemical, physical, and mechanical properties after weathering. The engineering interest in weathering arises because of its influence on the mechanical properties of the intact material, as well as the potential for significant effect on the coefficient of friction of the rock surface. It appears that whereas weathering causes a steady reduction in rock properties, the coefficient of friction of a surface may suffer a step reduction [4].

II. GEOLOGY OF THE STUDY AREA

The study area is Ewekoro limestone deposit as shown in Figure 1. The location is situated in Ogun State, south-western Nigeria. Ewekoro in Ogun State is bounded by Benin Republic, Lagos State, Oyo State and Ondo State in the West, South, North, and East respectively. Ewekoro lies between latitudes 6° 40´N to 6° 55´N and longitudes 3° 05´E to 3° 15´E. According to [11], geology of Ogun state in which Ewekoro the study area is a part, comprises of sedimentary rocks which underlie approximately three-quarters of the whole surface area of the state stretching from the northwest to the southeast and basement complex rocks which underlie the remaining one-quarter of the surface of the state.

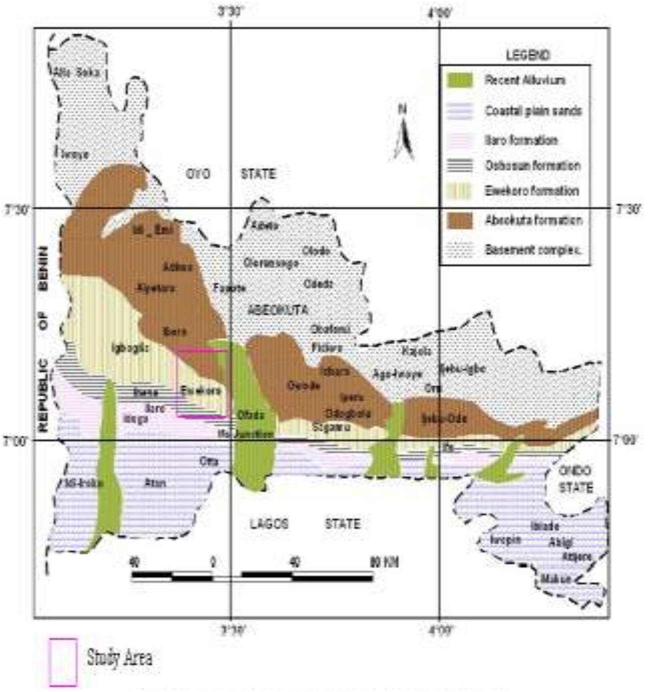

Figure1: Geological Map of Ogun State Showing Ewekoro (Adapted from [11])

III. MATERIALS AND METHODS

Sample Collection and Preparation

Twenty blocks of limestone samples representing different weathering grades were collected from the field (Ewekoro limestone deposits) in accordance to the field study and classification. The sampling of the limestone blocks of different weathering grades were performed from different pits in operation within the quarry. Samples preparations were carried out in the Rock mechanics laboratory at the Federal University of Technology Akure (FUTA). Preparation of these samples followed the relevant [1] and [8], [9] standards.

Weathering Grade Classification

In this study, the specimens were grouped qualitatively into different weathering grades based on colour, surface texture and friability (rock to soil ratio), without regard to location or depth of the specimen, and the weathering state was assigned. Quantitatively, the results of physical properties tests and strength characterization on the specimens were later used to classify them.

Laboratory Experiments

Laboratory tests were performed to determine the physical, mechanical, textural, mineralogical and chemical properties of Ewekoro limestone with different weathering grades considering the suggested methods and related standards [1],[8] and [9].

Petrographic Thin Section Analysis of the Rock Samples

The thin section of the samples was prepared and studied under the microscope. Photomicrographs of the samples were also taken to show features of geological interest. The procedures for thin section preparation are: impregnating, cutting, trimming, grinding, lapping, mounting, further grinding, lapping, further trimming, covering, washing, drying and labeling. The slides were then carefully studied under microscope to identify both the textural and mineralogical compositions of the samples. The modal analysis technique was used to estimate the percentage of each mineral present in the samples.

Major Elements Analyses of Rock Samples by X-Ray Fluorescence Spectrometry (XRF)

The procedure adopted for the determination of components was that described by [10]. There were two steps involved; sample treatment and determination of the components using X-ray Fluorescence Spectrophotometer. The X-ray fluorescence (XRF) spectrometer used was the high-resolution energy dispersive X-ray fluorescence (EDXRF) LAB X3500 model at Centre for Energy Research and Development, Obafemi Awolowo University Ile-Ife.

Determination of Rock Dry Density/Bulk Density

Ten specimens each of irregular form ranging from 25-100g were prepared from a representative sample of rock representing different weathering grades of Ewekoro limestone. The determination of the density (ρ) was carried out according to the procedures suggested by [9] using Equations 1 to 4.

$$V_{bulk} = \frac{(M_{sat} - M_{sub})}{\rho_w} \quad (1)$$

$$\rho_{bulk} = \frac{M_{bulk}}{V_{bulk}} \quad (2)$$

Dry density:

$$\rho_d = \frac{M_{dry}}{V} \text{(kg/m}^3 \text{ or g/c m}^3\text{)} \quad (3)$$

$$\text{Dry Unit weight} = \rho_d \times 9.8 \text{ (kN/m}^3\text{)} \quad (4)$$

where; V_{bulk} is the bulk volume; M_{sat} is the saturated mass; M_{sub} is the submerged mass, M_{bulk} is the bulk mass; M_{dry} is the dry mass and ρ_w is the density of water.

Determination of Moisture/Water Content

The determination of the moisture/water content (*W*) was carried out according to the procedures suggested by [9] using Equation 5.

$$\text{water content} = \frac{(M_{bulk} - M_{dry})}{M_{dry}} \times 100\% \quad (5)$$

Where; M_{bulk} is the bulk mass; and M_{dry} is the dry mass.

Determination of Water Absorption

The determination of the water absorption (W_A) was carried out according to the procedures suggested by [9] using Equation 6.

$$\text{water Absorption} = \frac{(M_{sat} - M_s)}{M_s} \times 100\% \quad (6)$$

Where; M_{sat} is the saturated mass and M_s is the solid mass.

Determination of Porosity

The saturation and buoyancy technique for determination of porosity (*n*) of irregular rock samples was adopted using Equations 7 to 8. The experimental procedures followed the standard suggested by [9].

$$\text{Pore Volume}, V_v = \frac{(M_{sat} - M_{dry})}{\rho_w} \quad (7)$$

$$\text{Porosity}, n = \frac{V_v}{V_{bulk}} \times 100\% \quad (8)$$

where; M_{sat} is the saturated surface dry mass; M_{dry} is the dry specimen mass; Vv is the pore volume; ρ_w is the density of water; and V_{bulk} is the bulk volume.

Determination of Specific Gravity

The standard procedure as specified by [3] – Standard Test for Specific Gravity (S.G) of Soil Solids by Water Pycnometer was strictly adhered to using Equation 9.

$$\text{Specific Gravity}, G_S = \frac{M_2 - M_1}{(M_4 - M_1) - (M_3 - M_2)} \quad (9)$$

where; M_1 is the mass of density bottle (pycnometer) + stopper; M_2 is the mass of density bottle (pycnometer) + stopper + sample; M_3 is the mass of water + sample + density bottle (pycnometer) + stopper; and M_4 is the mass of water + stopper + density bottle (pycnometer)

Determination of Point Load Index Strength

The point load strength (Is) values were determined for irregular samples in accordance with the procedures suggested by [8] using Equations 10 to 15.

$$Is_{(50)} = P / D^2_e \quad \text{(MPa)} \quad (10)$$

where; P is the failure load (kN), De² is the equivalent core diameter (mm)

$$D^2e = \frac{4A}{\pi} \text{(mm)} \quad (11)$$

where; A is the minimum cross sectional area of a plane through the loading points (for axial, block and lump tests)

$$A = HD \quad \text{(mm}^2\text{)} \quad (12)$$

where; D is the width of the irregular test sample; and H is the length of the sample.

Un-corrected strength Is = P/D^2 (MPa) (13)

Corrected strength Is $_{(50)}$ = FP/D^2 (14)

Where; F is the correction factor

$$F = (D/50)^{0.45} \quad (15)$$

Determination of Uniaxial Compressive Strength of Rock Materials (Unconfined Compressive Strength)

The procedures followed for the test were as stated in [9] using Equation 16. Uniaxial compressive strength test was typically characterized by loading a block (cubical) sample instead of the common cylindrical sample while maintaining the length to thickness ratio of 2.5:1 under dry conditions axially until the specimen fails.

$$C_O = P/A = P/W.D \quad (16)$$

where; C_O is the Uniaxial Compressive Strength (MPa); P is the applied peak load (kN); W is the width of the sample (m); and D is the height of the sample (m).

Determination of Tensile Strength

The tensile strength of the rock samples was estimated based on the relationship suggested by [5]s and [9] which shows the general relationship between the point load strength (Is) and the tensile strength (To) as expressed in Equation 17.

$$T_O = 1.51 \, I_{S50} \quad (17)$$

Determination of Schmidt Rebound Hardness

The determination of the hardness of the samples involves the use of Schmidt hammer on lump of the rock samples. The rebound value of the Schmidt hammer was used as an index value for the intact strength of the rock material. The measured test values for the samples were ordered in descending order. The lower 50% of the values were discarded and the average upper 50% values obtained as the Schmidt Rebound hardness. Five samples each were tested for each of the weathering grade. The procedures followed the standard suggested by [8] and [1].

Generation of Mathematical Models

Regression analysis using Statistical Packages for Social Sciences (SPSS) was used to create a mathematical model that can be used to predict the values of a dependent variable based upon the values of an independent variable. To perform the regression analyses, test data was plotted in 2 dimensions as a scatter plot. The correlations include rock strengths, density, water absorption, water content, porosity, specific gravity, Schmidt rebound hardness etc. and degree of rock weathering.

IV. RESULTS AND DISCUSSION

Qualitative Weathering Grade Determination

Weathering states 1 through 4 were assigned to all of the limestone specimens; W1 (unweathered), W2 (slightly weathered), W3 (moderately weathered), and W4 (highly weathered) based on the ISRM descriptions. As previously indicated, work by [15] demonstrated the assigning of weathering states to samples varies between professionals, especially for highly weathered specimens. In this study, limestone samples with the similar physical characteristics (colour, friability i.e. rock-soil ratio and texture) were grouped in the same grade. The classification of the Ewekoro limestone samples into different weathering grade is as presented in Table 1.

Petrographic Thin Section Analysis Results and Discussion

Table 2 respectively shows the result of textural and mineralogical analyses of Ewekoro limestone as average modal analysis.

Table 1: Typical characteristics and appearance of Ewekoro limestone in the case study.

Weathering Grade	Description	Physical Appearance
W1 (Unweathered)	Colour: Light to medium grey Texture: Fine grained with very minor pitting	Appear very competent with concrete-like appearance. 
W2 (Slightly Weathered)	Colour: Creamy colour Texture: Coarser grained with minor pitting	Appear competent with appearance of earthy-type fracture. 
W3 (Moderately Weathered)	Colour: Yellowish colour with little white colour staining noticed Texture: Even coarser compare to W2 with very evident pitting	Appear somewhat competent and somewhat fragile with earthy-type fracture appearance. 
W4 (Highly Weathered)	Colour: Yellowish colour with pronounced white staining noticed Texture: Very coarse grained texture with evident major pitting	Appear fragile with earthy-type fracture appearance. 

Table 2: Average Modal Analysis of Limestone Samples.

Sample	Bioclast	Pellets	Intraclasts	Micrite	Sparite	Quartz
W1	20	49	4	15	9	3
W2	20	46	4	15	10	5
W3	20	10	2	33	10	25
W4	32	2	3	27	8	28

Influence of Weathering on Textural and Mineral Constituents of Limestone Samples

Photomicrographs of the different weathering grades of limestone under polarized light are as shown in Figures 2 to 5.

Figure 2: Photomicrograph of Limestone (weathering grade 1)

B – Bioclast, Q – Quartz, P – Pellet, M – Micrite, S - Sparite

Figure 3: Photomicrograph of Limestone (weathering grade 2)

Figure 4: Photomicrograph of Limestone (weathering grade 3)

B – Bioclast, Q – Quartz, P – Pellet, M – Micrite, I – Intraclasts, S - Sparite

Figure 5: Photomicrographs of Limestone (weathering grade 4)

The limestone has five (5) dominant textural and one (1) mineral constituents which are; bioclasts, micrite, sparite, pellets, intraclasts and mineral quartz as shown in Table 2. Based on Figures 2 to 5, there are some noticeable textural and mineralogical changes that occur in the rock fabric as a result of increase in weathering. In the limestone, the small proportion of insoluble residue, which reflects mostly clay and fossil contents, was found to relate directly to the degree of weathering. The distribution of the different textural and mineral constituents in each of the weathering grade is shown in Figure 6.

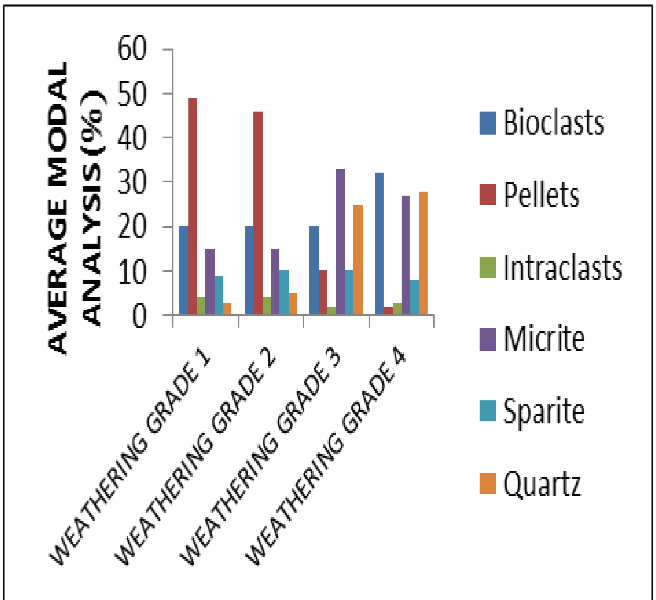

Figure 6: Average modal analysis of the major textural and mineral constituents of the different weathering grades

Geochemical Analysis Results and Discussions

The geochemical analysis of the major elements/oxide for Ewekoro limestone samples are shown in Table 3.

Table 3: Major element analyses of the Ewekoro limestone with different weathering grades.

OXIDES	W1 (%)	W2 (%)	W3 (%)	W4 (%)
K_2O	0.82±100	0.74±100	0.66±100	0.45±100
CaO	82.32±0.41	80.56±0.42	78.84±0.45	45.21±0.43
SiO_2	8.43±100	9.05±100	10.22±100	19.93±100
Fe_2O_3	2.35±100	3.05±100	4.24±100	4.30±100

The concentration of four major oxide groups has been used to classify limestone samples of different weathering profiles: calcium oxide (CaO), silica oxide (SiO_2), iron oxide (Fe_2O_3), and potassium (alkali) oxide (K_2O). The quantitative identification of these four major oxides as shown in Figure 7 is important in the characterization of the quality of the samples. SiO_2 concentration which is a reflection of the duration and intensity of weathering and destruction of other minerals during transportation shows an increasing trend as the weathering increases. High SiO_2 concentration of about 19.93 % observed in the (W4) sample may indicate a fluid inclusion which could be evidences for deep weathering of this sample.The high silica content observed could also be adduced probably to incorporation of highly siliceous shells, continental influx of silica as well as precipitation of SiO_2 from solution. CaO is the principal major oxide of most carbonate rocks and its concentration in limestone rock type can be an indication of chemical weathering. The CaO concentration unlike SiO_2 decreases insignificantly as the weathering increase. Fe_2O_3 occurs as impurity in the limestone and the higher the value, the more deteriorated or weathered the limestone samples are. In this study, the concentration increases with increasing degree of weathering. Finally, K_2O concentration value for the un-weathered (W1) sample is higher than the weathered samples i.e. decreases with increasing weathering.

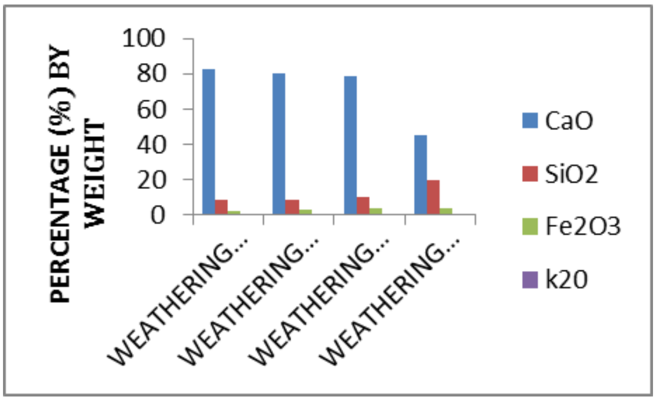

Figure 7: Major oxides distribution in limestone samples of different weathering grades

Physical Properties Results and Discussions

The summary of statistics for the physical properties of the limestone in different weathering grades is shown in Table 4. It should be noted that the results shown in the figures, are derived as average of at least 3 tests on each sample with some tests been an average of 10 tests on each sample. The results show that, almost all the physical properties of the studied rocks are affected by weathering processes.

Table 4: Summary of statistics for the physical properties of the limestone in different weathering grades.

Test Method	Specimen Breakdown	ISRM Weathering State			
		W1	**W2**	**W3**	**W4**
Bulk Density, ρ_b (g/cm^3)	Number of Specimens Tested	10	10	10	10
	Range of Values (determined)	2.67 - 2.75	2.66- 2.71	2.47- 2.62	2.42- 2.51
	Average	2.72	2.68	2.55	2.49
Dry Density, ρ_d (g/cm^3)	Number of Specimens Tested	10	10	10	10
	Range of Values (determined)	2.65 - 2.74	2.56 - 2.68	2.46 - 2.55	2.40 - 2.45
	Average	2.69	2.62	2.50	2.42
Dry Unit Weight, γ (kN/m^3)	Number of Specimens Tested	10	10	10	10
	Range of Values (determined)	25.99 -26.88	25.11 - 26.29	24.13 - 25.02	23.52 - 24.01
	Average	26.41	25.72	24.53	23.70
Specific Gravity, G_γ	Number of Specimens Tested	5	5	5	5
	Range of Values (determined)	2.66 - 2.73	2.59 - 2.66	2.46 - 2.53	2.41 - 2.46
	Average	2.70	2.60	2.52	2.43
Water Content, w (%)	Number of Specimens Tested	3	3	3	3
	Range of Values (determined)	0.27 - 0.30	0.27 - 0.36	0.34 - 0.38	0.43 - 0.46
	Average	0.28	0.32	0.36	0.45
Water Absorption, Wa (%)	Number of Specimens Tested	3	3	3	3
	Range of Values (determined)	2.64 - 2.97	2.95 - 3.15	3.69 - 3.96	4.41 - 4.71
	Average	2.79	3.05	3.85	4.52
Porosity, n (%)	Number of Specimens Tested	3	3	3	3
	Range of Values (determined)	7.19 - 8.08	7.91 -8.44	9.40 - 10.09	10.97 - 11.74
	Average	7.60	8.17	9.82	11.27

Dry density and Bulk density as Indices of Weathering in Ewekoro Limestone

Bulk and dry densities are related and the less dense rocks are also seen to have poorer performance in durability tests and in service. For bulk and dry densities, systematic trends are noted with increasing degree of weathering. The average bulk and dry densities values for the rock samples classified as unweathered (W1) are 2.72 g/cm^3 and 2.69 g/cm^3 respectively as shown in Figures 8 and 9 respectively. There are step reductions in these values for slightly weathered rock classified as W2 with the average value of 2.68 g/cm^3 and 2.62 g/cm^3 respectively. The average values for moderately weathered (W3) and highly weathered (W4) specimens are further reduced due to the increasing degree of weathering in these specimens. The average values of bulk and dry densities are 2.55 g/cm^3 and 2.50 g/cm^3; and 2.49 g/cm^3 and 2.42 g/cm^3 respectively.

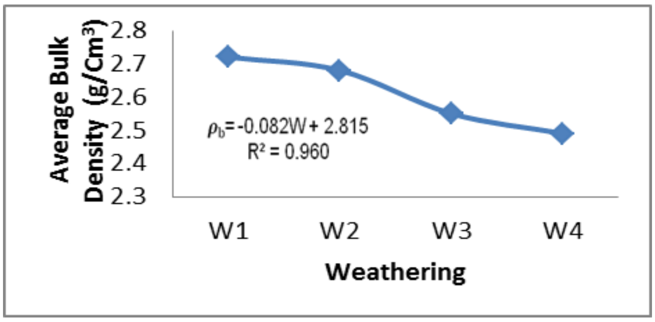

Figure 8: Average bulk density test results as a function of weathering states

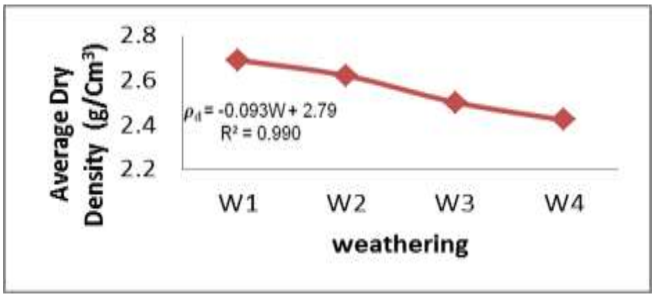

Figure 9: Average dry density test results as a function of weathering states

Dry unit weight and Specific gravity as Indices of Weathering in Ewekoro Limestone

The ranges of unit weights and specific gravity decrease with increasing weathering state as shown in Figures 10 and 11. For the samples classified as unweathered (W1), the average unit weight and specific gravity values are 26.41 kN/m^3 and 2.70respectively. For slightly weathered (W2), moderately weathered (W3) and highly weathered (W4) limestone samples, the average unit weight and specific gravity values are 25.72 kN/m^3 and 2.60; 24.53 kN/m^3 and 2.52; and 23.70 kN/m^3 and 2.43respectively.

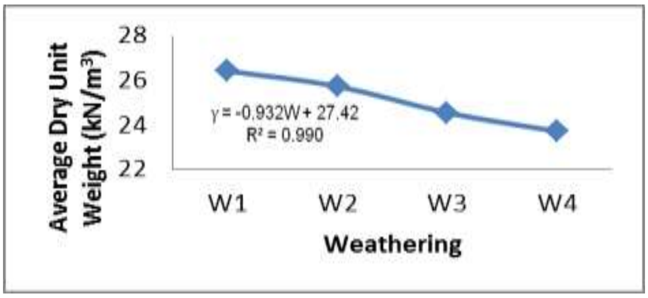

Figure 10: Average dry unit weight test results as a function of weathering states

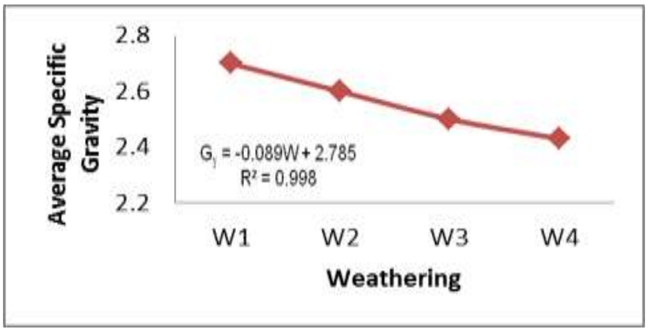

Figure 11: Average specific gravity test results as a function of weathering states

Water Absorption, Water Content and Porosity as Indices of Weathering in Ewekoro Limestone

Absorption value defines the capacity of a rock to absorb water/moisture when immersed in water till saturation. There is an increase in the absorption value as the weathering increases in the Ewekoro limestone samples as shown in Figure12. The lowest value is seen in unweathered (W1) samples with average value of 2.79 %. Slightly weathered samples (W2) which have less strength compare to W1 samples has mean values of 3.05 %. W3 and W4 samples which have lesser strength compare to W1 and W2 samples have 3.85 % and 4.52 %, 1.35 % respectively.

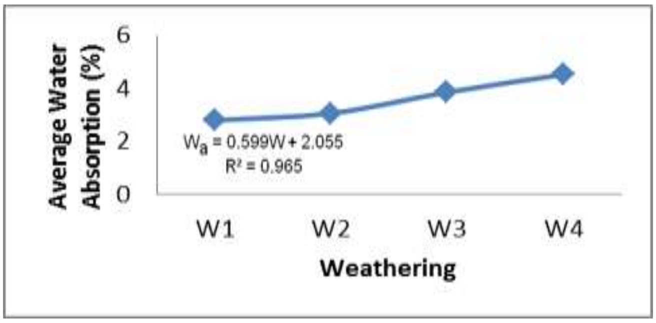

Figure 12: Average water absorption test results as a function of weathering states

Limestone samples have greater mean water content values across different weathering grades and the values increase with increasing degree of weathering. The greater values in limestone could be attributed to the fossil content and fabric or textural characteristics of the limestone samples. The unweathered samples classified as W1 have mean value of 0.28 % as shown in Figure 13. The slightly weathered (W2), moderately weathered (W3), and the highly weathered (W4) samples have mean water content values of 0.32 %; 0.36 %; and 0.45 % respectively.

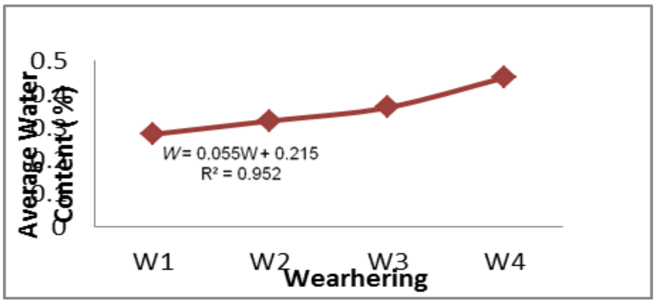

Figure 13: Average water content test results as a function of weathering states

Porosity test results are a direct indication of weathering state and weatherability in rocks. The more highly weathered the rock is, the more porous and less dense it is. The mean porosity values range from 7.60 % to 11.27 %. It is seen that the porosity values increases with increasing weathering as it is also seen with water absorption and water content results as shown in Figure 14. The highest average value of 11.27 % is seen in highly weathered (W4) samples. This high value could be attributed to the presence of wider openings in these samples. The high value obtained with limestone samples could also be attributed to the fossil content and fabric (micro-cracks and voids) of the samples. The mean porosity value for un-weathered (W1) sample is 7.60 %. Higher values are obtained with slightly weathered (W2) and moderately weathered (W3) samples with mean values of 8.17 % and 9.82 % respectively.

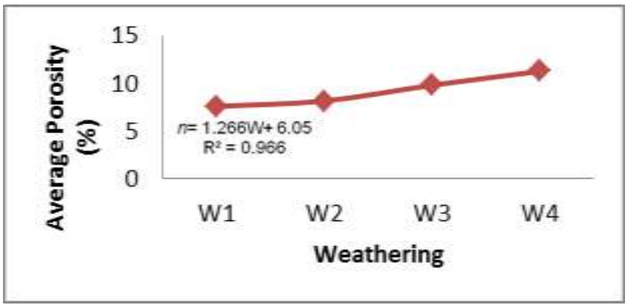

Figure 14: Average porosity test results as a function of weathering states

Mechanical Properties Tests Results and Discussions

The summary of statistics for the mechanical properties of the Ewekoro limestone in different weathering grades is shown in Table 5. It should be noted that the results shown in the figures, are derived as mean value of the tests on each sample. The results show that, almost all the mechanical properties of the studied rocks are affected by weathering processes.

Table 5: Summary of statistics for the mechanical properties of the Ewekoro limestone in different weathering grades.

Test Method	Specimen Breakdown	ISRM Weathering State			
		W1	W2	W3	W4
Point Load Strength ($Is_{(50)}$) (MPa)	Number of Specimens Tested	10	10	10	8
	Range of Values (determined)	1.28-3.89	1.25-3.56	1.36-2.24	1.25-1.70
	Average Value	**2.30**	**1.97**	**1.72**	**1.50**
Schmidt Rebound Hardness	Number of Specimens Tested	5	5	5	5
	Range of Values (determined)	37.0-39.4	33.5-35.5	31.4-33.0	25.0-26.8
	Average Value	**38.0**	**34.7**	**32.6**	**26.1**
Tensile Strength (MPa)	Number of Specimens Tested	10	10	10	8
	Range of Values (determined)	1.92-5.84	1.88-5.34	2.04-3.36	1.88-2.55
	Average Value	**3.40**	**2.91**	**2.56**	**2.25**
UCS (MPa)	Number of Specimens Tested	3	3	3	3
	Range of Values (determined)	37.5-52.8	27.3-32.5	25.1-28.2	14.0-18.5
	Average Value	**45.13**	**30.0**	**26.5**	**16.3**

The Effects of Weathering on Point Load Strength Index and Tensile Strength of Ewekoro Limestone

Point load strength index and tensile strength are important parameters in analyzing rocks weathering, strength and stability. In general, point load strength and tensile strength test result values decrease as the weathering increases as seen in Figures 15 and 16 respectively. As seen in Table5, there is a wide range of point load strength and tensile strength test results for weathering states W1, W2, W3 and W4. Weathering state W1 (10 samples each) point load strength and tensile strength test results range between 1.28 MPa to

3.89 MPa and 1.92 MPa to 5.84 MPa with mean values of 2.30 MPa and 3.40 MPa respectively. For slightly weathered W2 samples (10 samples each) point load strength and tensile strength test results range between 1.25 MPa to 3.56 MPa and 1.88 MPa to 5.34 MPa with mean values of 1.97 MPa and 2.91 MPa respectively. For moderately weathered W3 samples (10 samples each) point load strength and tensile strength test results range between 1.36 MPa to 2.24 MPa and 2.04 MPa to 3..36 MPa with mean values of 1.72 MPa and 2.56 MPa respectively. Finally, highly weathered W4 samples point load strength and tensile strength test results range between 1.25 MPa to 1.70 MPa and 1.88 MPa to 2..55 MPa with mean values of 1.50 MPa and 2.25 MPa respectively.

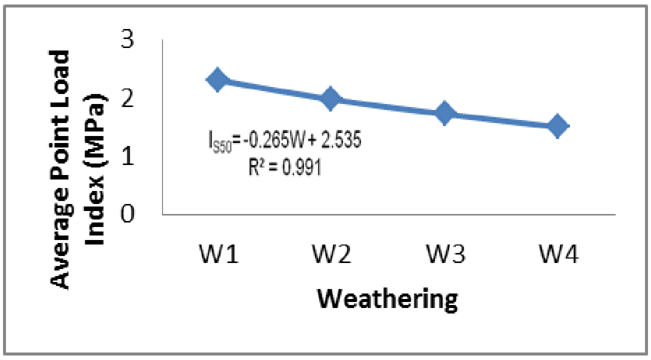

Figure 15: Average point load strength index results as a function of weathering states

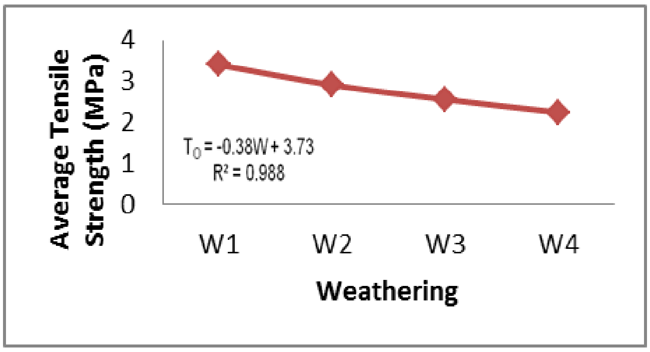

Figure 16: Average tensile strength results as a function of weathering states

The Effects of Weathering on Schmidt Rebound Hardness Number and Uniaxial Compressive Strength of Ewekoro Limestone

Schmidt rebound hardness numbers and compression results are indication of the rock strength. The results are useful to assess the quality of various mineral constituents and bond strength that exist between mineral grains of the rock and also to select rock suitable for various purposes. For Schmidt rebound hardness, there is reduction in the values as weathering increases as seen in Figure 17. The Schmidt rebound hardness value ranges between 26.1 and 38.0 with unweathered (W1) samples having a rebound hardness value results ranging between 37.0 to 39.4 with mean value of 38.0. Slightly weathered (W2) samples have values ranging between 33.5 to 35.5 with mean value of 34.7. The rebound hardness results range between 31.4 to 33.0 for moderately weathered (W3) and 25.0 to 26.8 for highly weathered (W4) with mean values of 32.6 and 26.1 for W3 and W4 samples respectively.

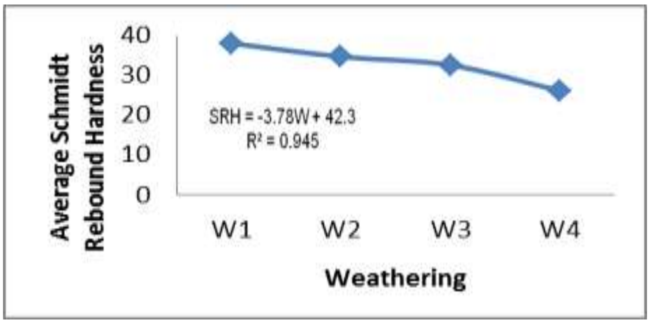

Figure 17: Average Schmidt rebound hardness results as a function of weathering states

The results in Table 5 reveals that the uniaxial compressive strength (UCS) mean value ranges from 16.3 MPa to 45.1 MPa for limestone samples. In general, UCS test result values decrease as the weathering increases as shown in Figure 18. Weathering state (W1) UCS test results values range between 37.5 MPa to 52.8 MPa with mean value of 45.1 MPa. Weathering state (W2) UCS test results values range between 27.3 MPa to 32.5 MPa with mean value of 30.0 MPa. For weathering state (W3) and (W4), UCS test results values range between 25.1 MPa to 28.2 MPa and 14.0 MPa to 18.5 MPa with mean values of 26.5 MPa and 16.3 MPa respectively.

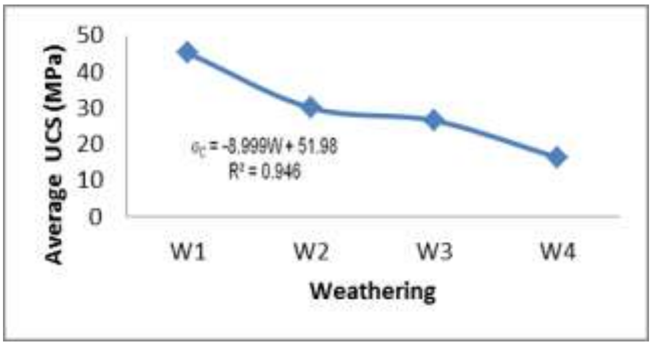

Figure 18: Average UCS results as a function of weathering states

Developed Relationships and Models

Relationships between the physical and mechanical properties and weathering states of Ewekoro limestone developed were as shown in Figures 19 to 25.

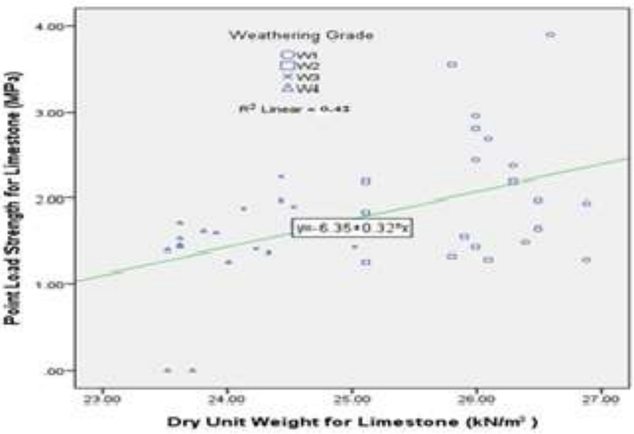

Figure 19: Relationship between point load strength and dry unit weight with weathering states.

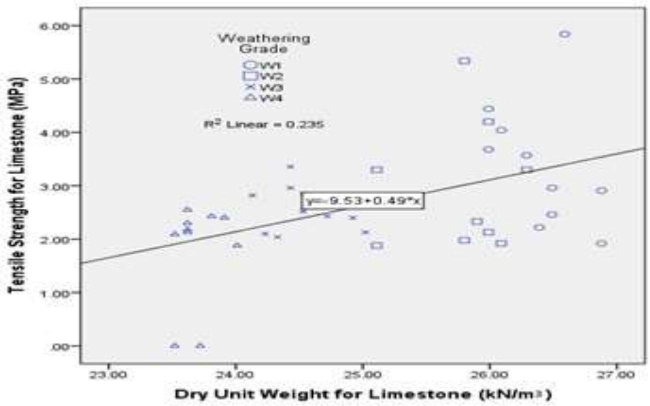

Figure 20: Relationship between tensile strength and dry unit weight with weathering states.

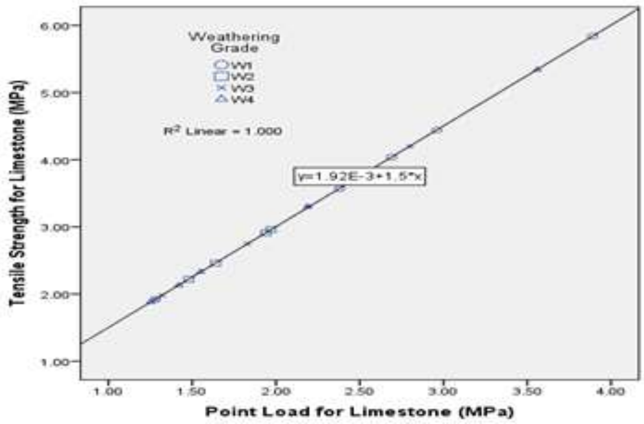

Figure 21: Relationship between tensile strength and point load strength with weathering states

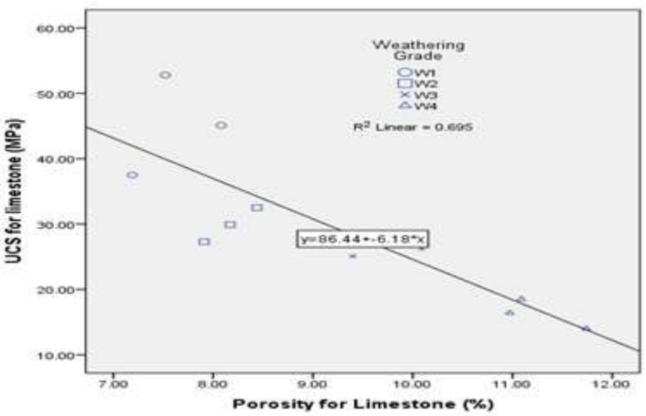

Figure 22: Relationship between uniaxial compressive strength and porosity with weathering states

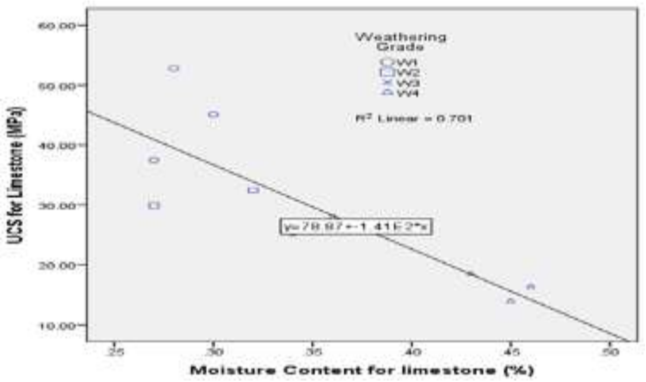

Figure 23: Relationship between uniaxial compressive strength and water content with weathering states

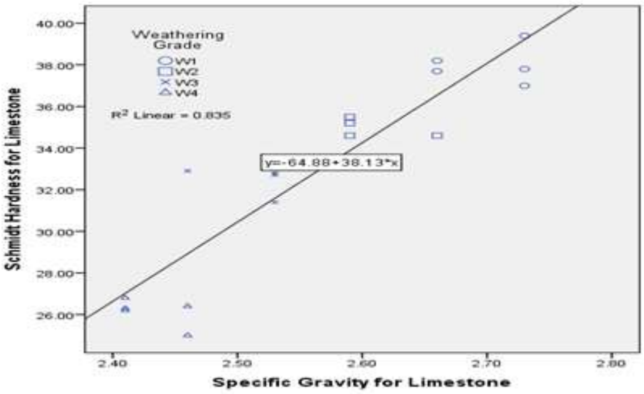

Figure 24: Relationship between Schmidt hardness and specific gravity with weathering states.

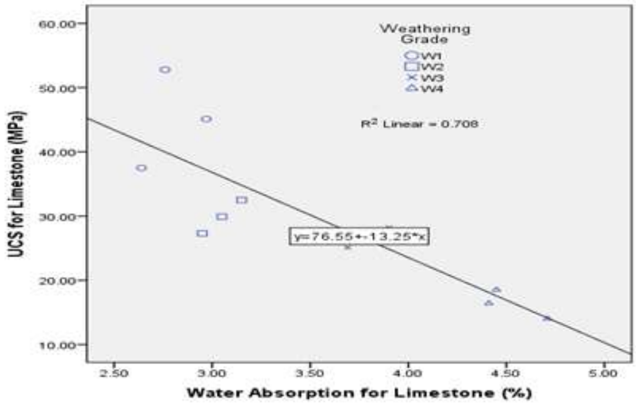

Figure 25: Relationship between uniaxial compressive strength and water absorption with weathering states

The relationship between point load strength and unit weight is linear, as shown in Figure 19. The point load strength increases with increasing unit weight in a linear form. The R^2 value for the point load strength - unit weight relationship at 0.420 is not very reliable though it can be used for prediction and hypothesis testing. Figure 20 present the relationship between tensile strength and unit weight with the R^2 value of 0.235. In general, there is an increase in tensile strength with increasing unit weight. As seen in the Figure 21, the best fit regression lines plotted for the Tensile Strength versus Point Load Strength R^2 values at 1.00 is very high. The tensile strength increases with increasing point load strength and both decrease with increasing degree of weathering. The relationship between UCS and porosity is linear, as shown in Figure 22. The UCS decreases with increasing porosity in a negative linear form. The best fit regression line plotted for the UCS versus Porosity R^2 value (0.695) is high and shows that the more porous samples are actually weaker. This correlation could mean that when rock weathers, its porosity and UCS change. The relationship between UCS and moisture content is linear, as shown in Figure 23. As shown in the figure, the UCS decreases with increasing moisture content in a negative linear form. The best fit regression line plotted for the UCS versus Moisture content R^2 value is high at 0.701. The best fit regression line plotted for the Schmidt hardness number versus Specific gravity R^2 values at 0.835 is high as seen in the Figure 24. As shown in the figure, the Schmidt hardness number increases with increasing specific gravity in a positive linear form i.e. there is positive linear correlation between the two parameters. The relationship between UCS and water absorption is linear, as shown in Figure 25. The specimens were differentiated with different shape symbols based on the weathering state. As shown in the figures, the UCS decreases with increasing water absorption in a negative linear form i.e. there is negative or inverse correlation between the two parameters. The best fit regression line plotted for the UCS versus water absorption R^2 value is high at 0.708 and is reliable for prediction purpose.

V. CONCLUSION

In this study, the weathering characteristics of Ewekoro limestone are investigated. From the results of the analyses carried out on the selected rock samples, the following conclusions are drawn:

(1) Weathering reduces some physical properties investigated: bulk density, dry density, dry unit weight and specific gravity while others as; in water/moisture content, water absorption and porosity increases with increasing degree of weathering.

(2) Weathering lowers the mechanical properties: uniaxial compressive strength, Point load strength, tensile strength, and Schmidt hardness number of the specimens. This is indicated by the generally decreasing strength values of the rock types against the weathering grades.

(4) Noticeable textural and mineralogical changes occur in the rock fabrics as a result of increasing degree of weathering on the samples.

(5) Major oxides distribution in conjunction with other determinants has been successfully used to show the effects of chemical weathering on the rock samples.

(6) Significant positive correlations were observed for most of the determined physical and mechanical properties incorporating weathering states.

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