

The Inter-relationship of Bulk Density and Porosity of Some Crystalline Basement Complex Rocks: A Case Study of Some Rock Types In Southwestern Nigeria.

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ABSTRACT

The inter-relationship of bulk density and porosity of some crystalline rocks in southwestern Nigeria was investigated. Six crystalline basement complex rock types from two localities in Nigeria (three each from Akure and Igarra) were sampled and tested for their petrography (mineralogy, texture and microstructures), bulk density and porosity. *ImageJ* was used for image analysis of the photo-micrographs, the bulk density was calculated from the determined specific gravity while the porosity was determined by water saturation technique. From the results of the analyses, the rocks were found to contain quartz, feldspar, hornblende, mica and minor minerals in various proportions. Micro-structures such as bent twin lamellae, undulose extinctions, distorted and incomplete twinning and platy mineral alignment were observed in the thin sections of the rocks. The bulk density values ranged from 2.63 to 2.81 and the porosity from 0.03 to 0.16. The correlation coefficient relating the two parameters is -0.9713 indicating a very high negative correlation. The square of Pearson Product moment correlation coefficient is 0.9434. A mathematical model was derived from the relationship between the two parameters. The standard error of 0.02 and the Ftest of 0.98 were determined for the model. It was deduced that the porosity of a crystalline rock is affected mainly by its bulk density and possibly by the degree of weathering.

Keywords: *bulk density, correlation coefficient, micro-structures, porosity, relationship*

1. INTRODUCTION

The anisotropic nature of rocks is believed to be caused by variations in their petrography (mineralogy, texture and micro-structures) and physical properties. These variations have been discovered to occur even in locations which are only a few centimetres apart on an outcrop. As a result of this, similar rock types in the same locality may not yield the same engineering properties and therefore may not be suitable for the same use. This explains why confirmatory tests on rocks require lots of test samples and are therefore very expensive, time consuming and tedious (Teme, 1983). Bulk density and porosity are two of the physical properties that have been found to significantly affect the mechanical properties, particularly Uniaxial Compressive Strength (UCS), of crystalline rocks. Slight variations in these parameters, particularly porosity, have been discovered to correspond to significant variations in UCS (Ademeso, 2011). Porosity of a crystalline rock is the sum of micro-fractures, intra-granular pores and fluid inclusions (Tullborg and Larson, 2006). Generally, crystalline rocks are believed to exhibit extremely low porosity values (as low as < 1%) because intra-granular pores and fluid inclusions are rare occurrences in them.

Researchers usually take porosity of crystalline rocks for granted, by not testing for it, perhaps as a result of its extremely low values whereas a slight variation in this parameter can lead to significant variation in UCS which can cause serious disruption of engineering designs. The establishment of a relationship between the two important parameters of bulk density and porosity will, however, provide a way out of the possible impasse. This can also lead to a reduction in the cost and time required to test for them during reconnaissance surveys as the bulk density (which is an essential test parameter) can be used to estimate the porosity of the rock. Furthermore, such estimations make it possible to identify areas that require further survey, as well as to demarcate those that could possibly cause a future failure of engineering structures.

The two study areas (Akure and Igarra) for this project, where six rock types have been selected as case study, are located within the Basement Complex of South-western Nigeria (Fig.1). The rocks of this complex have been variously classified by Rahaman (1976, 1988); Odeyemi (1988); Adekoya (1996) and Adekoya *et al.* (2003). Adekoya *et al.*, (2003) classified the rocks as (a) the gneiss-migmatite-quartzite complex; (b) the schist belts which are low to medium grade supracrustal and meta-igneous rocks; (c) the Pan African granitoids (Older Granites) and other related rocks such as

charnockitic rocks and syenites; and (d) minor felsic and mafic intrusives. The major rock types exposed in the Akure area consist of the following: (i) migmatite-gneiss; (ii) medium to coarse grained biotite granite; (iii) charnockitic intrusives and (iv) coarse porphyritic biotite and biotite-hornblende granites. The major rock groups exposed in Igarra study area are the metasediments and the intrusives. The Igarra metasediments consist of intercalating bands of phyllite, calcgneiss, quartzite, and metaconglomerate which are well exposed in the northern part of the area. The bands vary in width from about 50 to 200m. The Igarra metasedimentary rocks have been intruded by igneous rocks including the Igarra older granite batholith which ranges for over 5km and is over 1000m above sea level. Occurrences of metasediments were recorded at the very top of the granite batholith. Inselbergs of older granite and syenite outcrop in the northern and southern parts of the area. The minor intrusions include the lamprophyres which intruded the metasediments as dykes in various parts of the area. Other minor intrusives such as quartz, pegmatite and aplite dykes and veins, commonly with N-S orientation, occur in various rock types in the area.

2. METHODOLOGY

2.1 Petrographic Study

Prepared thin sections were studied with petrographic microscope taking care to capture the photomicrographs of pertinent characteristics.

2.2 Determination of Bulk Density

The bulk density of the rock types was determined by first finding out the specific gravity of the samples using Archimedes principle. The specific gravity, which is dimensionless, was calculated as follows:

$$\text{Specific Gravity} = \frac{\text{Weight in air}}{\text{Weight in air} - \text{Weight in water}} \quad \text{-----} \quad (1)$$

The density (g/cm^3) of the rocks is then calculated from the established specific gravity. Since specific gravity or relative density is the ratio of the density of the substance to the density of the reference material [in this case water (1g/cm^3)], then

$$\text{Specific Gravity of rock} = \frac{\text{Density of rock}}{\text{Density of water}}$$

$$\therefore \text{Density of rock} = \text{Specific Gravity of rock} \times \text{Density of water}$$

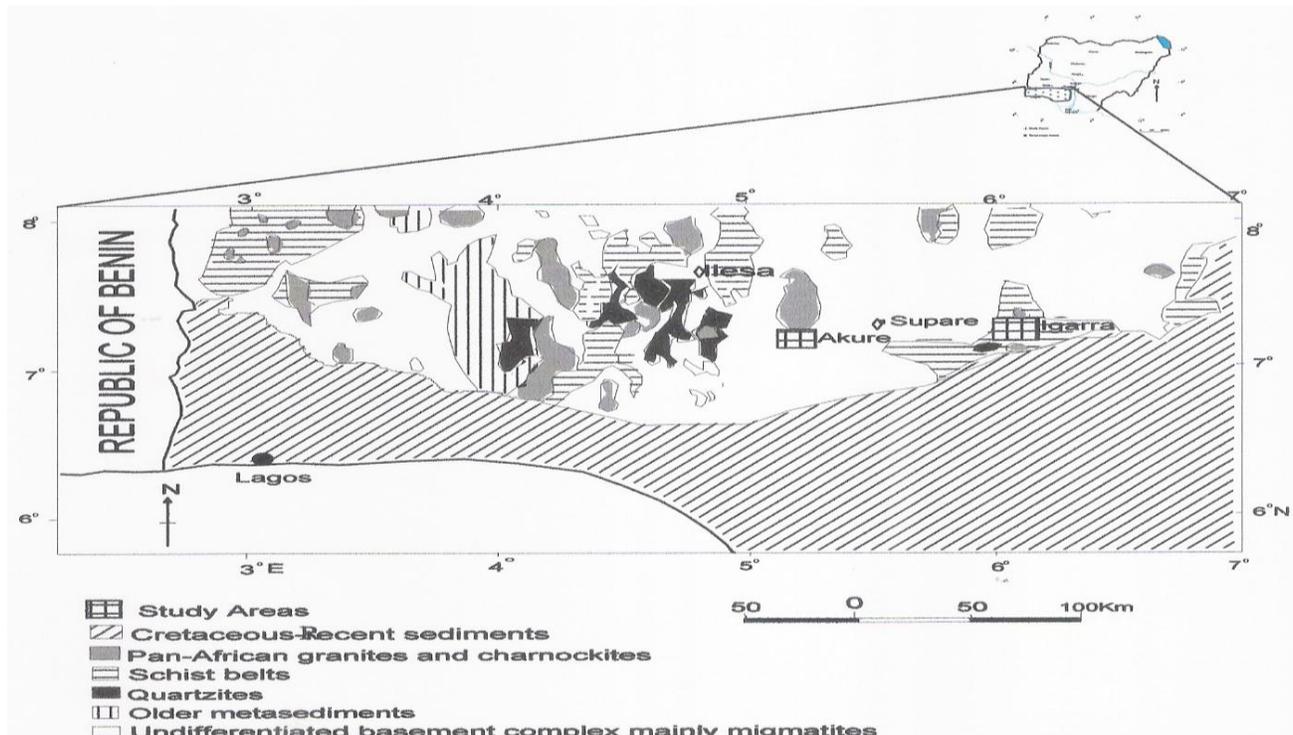


Fig. 1: Geological Map of South-western Nigeria Showing Study Areas.

2.3 Determination of Porosity

The sample was weighed dry, then soaked in water for twenty-four hours and re-weighed (Brown, 1981). The porosity of the sample was determined as the percentage of the ratio of the difference in the soaked and the dry weight to the dry weight as follows:

$$\text{Porosity } (\rho) = \frac{\text{Soaked Weight} - \text{Dry Weight}}{\text{Dry Weight}} \times 100 \text{ ----- (2)}$$

2.4 Determination of Mathematical Model relating Bulk Density with Porosity.

A chart of the scatter diagram with regression line correlating the two parameters for the rock types was also plotted with the software. The determined regression equation was thereafter used in determining the model relating the two parameters. The square of Pearson product moment correlation coefficient (R^2) and the correlation coefficient (r) between two sets of data were determined with the aid of Microsoft Excel 2007.

2.5 Test of reliability of the Model.

The porosity of selected rock types from the study areas was estimated with the model using the bulk density values derived from the laboratory and the result was compared with the porosity values determined in the laboratory. The variance, standard deviation, standard error and F-test were evaluated for the two sets of values in accordance with James (1999), with the aid of Microsoft Excel 2007.

3. RESULT

3.1 Petrographic study

3.1.1 Mineralogy

(i) Gneiss, Ondo road, Akure.

The rock consists of the following minerals (with estimated modal content): plagioclase (36%), quartz (25%), biotite (21%), hornblende (7%), microcline (6%), hypersthene (3%), muscovite (1%), pyroxene (1%) and mymerkite (0.3%) (Table 1).

(ii) Granite gneiss, Igbatoro road, Akure

Microscopically, quartz, biotite, plagioclase, microcline and hornblende constitute the major minerals in thin section of the rock while mymerkite occurs sporadically. The modal percentages of the minerals are 29%, 23%, 21%, 19%, 8%, 4%, and 1% (Table 1). Generally, the platy minerals tend to be arranged in preferred orientation that defines the foliation of the rock (Fig. 2B).

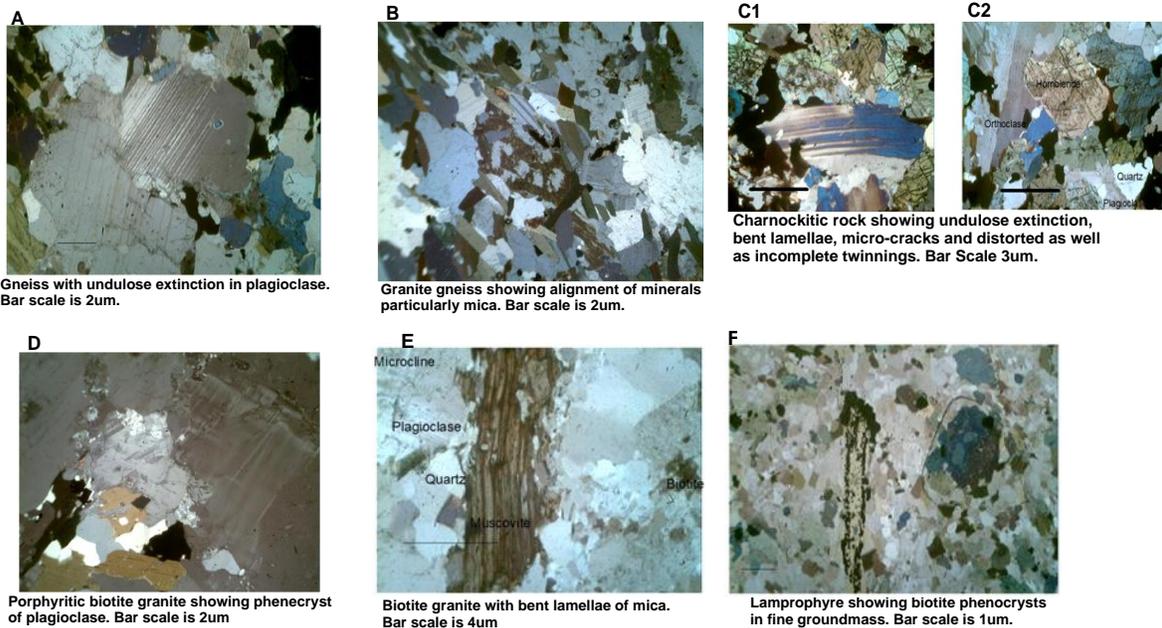


Fig. 2: Photomicrographs of the rock types: A = Gneiss, B = Granite gneiss, C1, C2 = Charnockitic rock, D = Porphyritic Biotite Granite, E = Biotite Granite and F = Lamprophyre.

(iii) Charnockitic rocks, Akure

Plagioclase, biotite, quartz, hypersthene, hornblende, muscovite and orthoclase are the major minerals while opaque minerals (probably iron oxide) and zircon are the accessories identified in the thin section of the rock. The modal analysis of the thin sections of the rock gives 32%, 16%, 16%, 16%, 11%, 4%, 3%, 1% and 1% respectively for the minerals (Table 1).

(iv) Porphyritic Biotite Granite, Somorika Road, Igarra

Biotite, plagioclase, quartz, microcline and hornblende are the major minerals in the thin section of the rock while mymerkite and zircon constitute the accessories. The modal analysis of the minerals in the thin section is 31%, 30%, 23%, 10%, 4%, 3% and 1%, respectively (Table 1).

(v) Biotite granite (leucocratic), Ibillo road, Igarra

The occurrence of microcline, plagioclase and quartz as major minerals with biotite and hornblende as subordinate minerals is revealed from the microscopic examination of the thin sections of the rock. The modal composition of the rock is 37%, 30%, 27%, 5% and 1%, respectively (Table 1).

(vi) Lamprophyre, Igarra

Biotite, quartz, plagioclase, hornblende, microcline and opaque minerals are the major minerals identified in the thin section of the rock while zircon is the accessory (Fig. 2F). The result of the modal analysis is 41%, 23%, 21%, 6%, 5%, 5% and 0.5%, respectively, for the minerals (Table 1).

Table 1: Summary of modal analyses of selected rock samples.

S/No	Sample No	Modal (%) Content of Minerals												Total
		Qtz	Pla	Mic	Ort	Bio	Hyp	Mus	Hnb	Pyx	Zir	Mym	Opa	
1.	Gn(Ak001)	25	36	-	6	21	3	1	7	1	-	0.3	0.1	100.4
2.	Ggn(Ak002)	29	21	18	-	23	-	-	8	-	-	1	-	100
3.	Chk (Ak003)	16	32	-	3	16	16	4	11	-	1	-	1	100
4.	Pgr(Ig001)	23	30	10	-	31	-	-	4	-	1	4	-	100
5.	Gr(Ig002)	27	30	37	-	5	-	-	-	-	1	-	-	-
6.	Lam(Ig003)	23	21	4	-	41	-	-	6	-	-	-	5	100

Note: Gn = gneiss; Ggn = granite gneiss; Chk = charnockitic rock; Pgr = porphyritic biotite granite; Lam = lamprophyre; and Gr = biotite granite.

Qtz = quartz; Pla = plagioclase feldspar; Mic = microcline; Ort = orthoclase; Bio = biotite; Mus = muscovite; Hnb = hornblende; Hyp = hypersthene; Mym = mymerkite and Opa = opaque minerals.

3.1.2 Texture

Generally, three of the rock types (gneiss, granite gneiss and biotite granite) exhibit medium to coarse grained texture. The grains display irregular shape with sutured margins indicating that they are strongly interlocked. The charnockitic rock is largely coarse grained while the porphyritic biotite granite displays very large crystals of feldspar in finer groundmass of quartz, biotite and feldspar. The charnockitic rocks and porphyritic biotite granite possess grains with sutured boundaries. The Lamprophyre possesses coarse biotite grains in a groundmass of very fine grains of biotite, quartz, feldspar and hornblende, indicating porphyritic texture.

3.1.3 Microstructures

(i) Gneiss

The rock exhibits mineral inclusions, micro-cracks, twinning, partly deformed twinning, cleavages and undulose extinction as micro-structures (Fig. 2A).

(ii) Granite gneiss

The rock petrography revealed cleavage, micro-cracks, mineral inclusions, twinings and mymerkite as the micro-structures exhibited by the rock (Fig. 2B).

(iii) Charnockitic rocks

The charnockitic rocks exhibited the following micro-structures: cleavage, distorted cleavage, mineral inclusions, micro-cracks, bent twin lamellae and compressed twin plane (Fig. 2C).

(iv) Porphyritic biotite granite

The micro-structures that were observed in the thin section of the rock include: cleavages, mineral inclusions, twinings and micro-cracks (Fig. 2D).

(v) Biotite granite

Micro-structures such as bent lamellae, cleavage, bent cleavage, twinning and mineral inclusions were observed in the thin sections of the rock (Fig. 2E).

(vi) Lamprophyre

This rock type exhibited cleavage and twinning as micro-structures in thin section (Fig. 2F).

3.2 Bulk Density

The result of the bulk density tests is presented in Table 2 (A). The values range from 2.63 for biotite granite to 2.81g/cc for charnockitic rocks.

3.3 Porosity

The porosity tests on the samples of the selected rock samples gave results that range from 0.03 to 0.16% for charnockitic rocks and biotite granite respectively [Table 2 (A)].

3.4 Mathematical Model

The Correlation coefficient (r) and the square of Pearson Product Moment Correlation coefficient (R²) for the relationship between the bulk density and the porosity of the selected rock types were determined as presented in Table 2 (B).

The scatter diagram with regression line correlating the two sets of values was plotted (Fig. 3). The regression equation, $Y = 0.7562X + 2.1564$, was calculated (Fig. 3). The R² (0.9434) (Fig. 3) that was calculated tallies with that of Table 2 (B).

Table 2: Table of the bulk density and porosity of the rock types.

(A)				
S/No	Sample No	Rock Type	Density (g/cc)	Porosity (%)
1	Ak001	Gn	2.67	0.15
2	Ak002	Ggn	2.67	0.12
3	Ak003	Chk	2.81	0.03
4	Ig001	Pgr	2.69	0.14
5	Ig002	Gr	2.63	0.16
6	Ig003	Lam	2.78	0.05

(B)		
Density	R ²	r
Porosity	0.9434	-0.9713

Note: Gn = gneiss, Ggn = granite gneiss, Chk = charnockitic rock, Gr = biotite granite, Pgr = porphyritic biotite granite and Lam = lamprophyre.

Density = bulk density of rock types and Porosity = the porosity of the rock types.

R² = the square of Pearson product moment correlation coefficient.

r = the correlation coefficients between two sets of data.

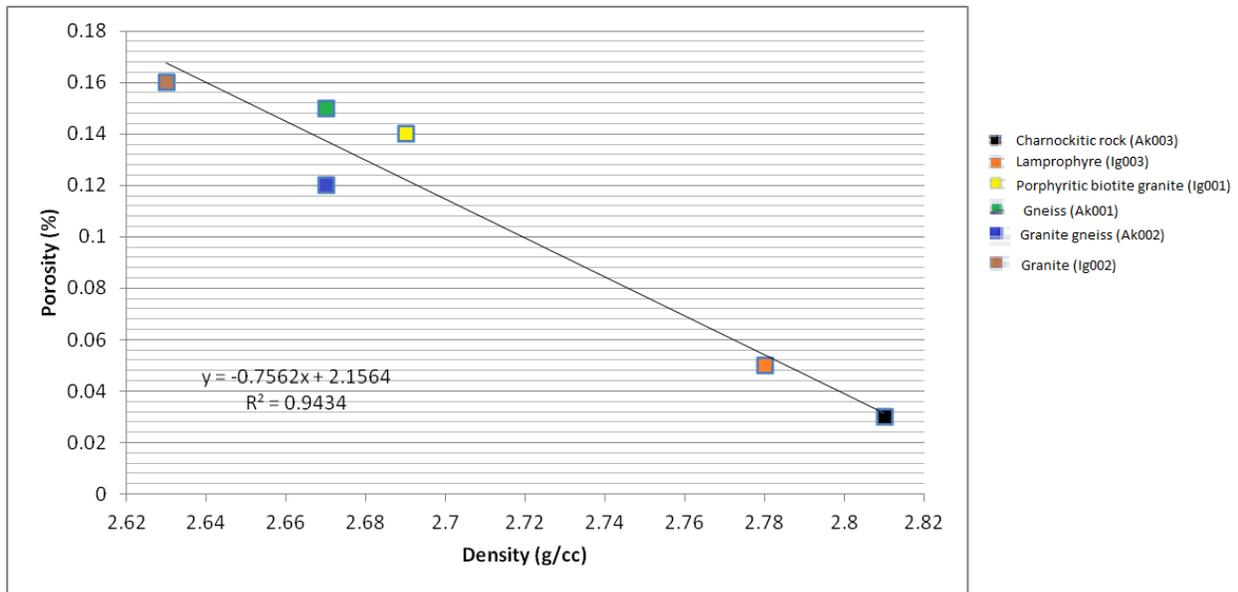


Fig. 3: Scatter diagram with regression line correlating Porosity with Bulk Density for the rock types

4. Discussion

A study of the relationship between bulk density and porosity shows a very high correlation coefficient value [$r = -0.9713$ (Table 2(B))]. This indicates a very high negative correlation between the two parameters which implies that the higher the bulk density, the lower the porosity and vice-versa. This correlation coefficient is consistent with the discovery of Gates and West (2008) that bulk density and UCS decrease with increase in vesicularity of basalt. Since vesicularity can be considered as indication of porosity, it can therefore be said that porosity increases as bulk density decreases. Table 2(A) shows that (i) charnockitic rocks and lamprophyre with very low porosity values (0.03% and 0.05%) have very high bulk density values (2.81g/cc and 2.78g/cc); (ii) biotite granite with the highest porosity value has the lowest bulk density (0.16% and 2.63g/cc); and (iii) granite gneiss, porphyritic biotite granite and gneiss with similar porosity values also exhibit similar bulk density values.

Biotite granite, with the highest porosity and lowest bulk density values, shows indications of incipient weathering petrographically (Fig. 2E). Charnockitic rocks with micro-structures like micro-cracks, bent lamellae, undulose extinction and distorted/deformed twinnings (Fig. 2C) have a porosity value that is close to that of lamprophyre that does not possess such micro-structures (Fig. 2F). The two rocks possess porosity values that are lower than those of the gneiss, granite gneiss, porphyritic biotite granite and biotite granite (Fig. 2A, D, E) that have fewer micro-structures. The implication of this is that microstructures do not seem to have any serious influence on porosity and bulk density of the rocks.

The charnockitic rocks and lamprophyre with similar porosity values exhibit diverse mineralogical characteristics and therefore it can also be deduced that mineralogy does not seem to influence porosity. In the same vein, the texture does not seem to impact on the porosity as the two rocks differ substantially in this characteristic.

The characteristics that are common to the two rocks with very low porosity values are (i) bulk density and (ii) absence of signs of incipient weathering. Other rock types that possess higher porosity values have lower bulk density and some of them show signs of incipient weathering.

Since the correlation coefficient (r) of porosity and bulk density is very high, the model derived from the regression equation would serve to give a good estimate of one parameter if the other parameter is known.

The regression equation of the relationship (Fig.3) is

$$Y = -0.756X + 2.156 \quad \text{----- (3)}$$

which can be re-written as

$$\text{Porosity} = -0.756D + 2.156 \quad \text{----- (4)}$$

where D is the determined bulk density.

This is a mathematical model expressing the inter-relationship between the two parameters.

The model was used to estimate the porosity of the rock types using the determined bulk density values. The result was compared with the determined porosity values and a test of reliability was conducted by determining the mean, variance, standard deviation, standard error and F-test for the two sets of porosity values. The results are: mean of 0.11 for the two sets of values; variance of 0.0002; standard deviation of 0.014; Standard Error of 0.02; and an Ftest of 0.98 (Table 3). The standard deviation is very small compared to the mean indicating that the data are fairly tightly packed around the

mean. The range 0.05 – 0.17 [mean ± 4(standard deviation)] accommodates all estimated values except 0.03 which can be regarded as an outlier. This however does not mean that the value is wrong. The model can therefore be said to be reliable.

Table 3: Relationship between the Porosity values determined in the laboratory and those estimated with the derived model using bulk density of the rock types

Model: $P = -0.756D + 2.156$

S/No	Rock Type/Sample Code	D	P	P ¹	P – P ¹	[P – P ¹] ²
1.	Gn (Ak001)	2.67	0.15	0.14	0.01	0.0001
2.	Ggn (Ak002)	2.67	0.12	0.14	-0.02	0.0004
3.	Chk (Ak003)	2.81	0.03	0.03	0.00	0.0000
4.	Pgr (Ig001)	2.69	0.14	0.12	0.02	0.0004
5.	Gr (Ig002)	2.63	0.16	0.17	-0.01	0.0001
6.	Lam (Ig003)	2.78	0.05	0.05	0.00	0.0000
Sum			0.65	0.65		10.1859
Mean			0.11	0.11		
Var						0.0002
Std						0.014

Standard Error = 0.02 Ftest = 0.98

where:

P = Porosity of rock determined in the laboratory;

P¹ = Porosity of rock estimated with model;

D = Bulk density of rock determined in the laboratory;

Var = Variance;

Std = Standard deviation.

Note: Gn = gneiss; Ggn = granite gneiss; Chk = charnockitic rock; Pgr = porphyritic biotite granite; Gr = biotite granite and Lam = lamprophyre.

The deduction therefore is that the porosity of a crystalline rock is affected mainly by its bulk density and possibly the state of weathering.

CONCLUSION

Conclusively, the higher the bulk density of a crystalline rock, the lower the porosity. It was also discovered that weathering increases porosity in that rocks that show signs of incipient weathering tend to have higher porosity values.

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