

Determination of Comminution Work Index and Physical Properties of Ebiti Phosphate Rock in Ogun State Southwestern Nigeria

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Abstract

The study determined the physical properties and comminution work index of Ebiti phosphate rock and analysed its particle size and mineralogical properties. These were with a view to generating data baseline for further advanced characterisation of the rock for use in some industrial engineering applications. The phosphate rocks were sourced from Ebiti Village, Ifo Local Government Area, Ogun State. The rocks were crushed and ground with Pascal Engineering crusher and ball mill, respectively. Textural forms, colour, water absorption capacity, specific gravity, Moh hardness tests were performed to determine their physical properties. Comminution work index was also carried out to determine the energy required to reduce the phosphate rock samples to a specific particle size. Thereafter, petrographic analysis was performed to determine their mineralogical and textural features. The study showed that Ebiti phosphate rock occurs as nodular and vesicular form with dead white or creamy colour. It has 5.0 hardness on the Moh's Scale, which indicates a medium resistance to abrasion and crushing. Its apparent specific gravity was 2.65 and water absorption capacity was 12.74%. Particle size analysis showed that percentage of cumulative weight retained increases down the sieve series. Thin Section Microscopy revealed nodules, vesicles with dark spots. The study concluded that Ebiti phosphate rock is sedimentary and has comminution work index of 16.97 Kwh/tons.

Keywords

Comminution, Work Index, Specific Gravity, Absorption Capacity,

Phosphate Rock

1. Introduction

Phosphate rock, also known as phosphorite, occurs naturally as sedimentary or igneous ore that contains large amount of phosphate minerals. It represents the major origin of phosphorus, an important element in agriculture and other applications like animal feed, electronics, cosmetics etc. [1]-[3]. It typically contains 3% - 15% phosphorus and 18 - 40 wt.% P_2O_5 and can also be a host of rare earth elements and uranium 65 - 200 ppm, sometimes as high as 800 ppm, which adds to its potential for energy-related applications. According to Obaje *et al.* [4], the dominant mineral found in phosphate rock is apatite commonly fluorapatite ($Ca_5(PO_4)_3F$), along with other forms like chlorapatite [$Ca_9(PO_4)_6CaCl_2$] and hydroxyapatite [$Ca_9(PO_4)_6Ca(OH)_2$].

The physico-chemical characterization of Ogun and Sokoto phosphate rocks has been reported by Fayiga and Obigbesan [5]. The researchers reported that the phosphate rocks in Oja-Odan area of Ogun State exist as nodules, granules, pellets and vesicles with hardness value of 5, specific gravity of 1.52, and water absorption capacity of 24.4. However, out of four phosphate deposits in Eastern Dahomey Basin in Ogun State, Southwestern Nigeria (Igbeme, Oja-Odan, Ososun, Ebiti), this research was carried out on only one deposit (Oja-Odan).

Adesanwo *et al.* [6] wrote that the phosphate rock from junction between Ifo and Ososun areas of Ogun state contained diffused reddish brown iron stain which indicated the presence of primary sedimentary ferrous minerals (siderite, pyrite, and glauconite), while the fine grains found in the thin section revealed nodular phosphorites and presence of shell fragments with bioclastic materials, which confirmed granular phosphorites. The characterization methods were limited to XRF, XRD and petrographic analyses, and the specific phosphate rock deposit among the four found in Ogun state was not specified.

Olanipenikun and Bolanrinwa [7] reported petrographic analysis on phosphate rocks in Eastern Dahomey Basin in Ogun State, Southwestern Nigeria. The result from the study identified fluorapatite as the major phosphate mineral with calcite, quartz, glauconite, gypsum, and hematite. Granular phosphorites which are majorly at Ososun and Ebiti areas were observed to have high to low spherically rounded granules with oolitic and pelletal structures, subangular to angular grains, and clasts of fluorapatite have opaline silica and calcite in them. The study also reported that nodular phosphorites from Ososun and Ebiti areas appear to be coarser than the granular type and have either perfect or imperfect ellipsoidal, spherical, cylindrical, and rectangular shapes which appear to be pebble conglomeratic. They also have dead-white or cream colour and the fluorapatite that contains in them has brown-coloured or yellowish-brown nodules inside sparite and glauconite, among others. However, the researchers based their observations on petrographic analy-

sis alone.

Comminution, a process whereby a mineral is reduced into smaller sizes required for downstream processing using sequence of blasting, crushing, and grinding [8] [9]. On the other hand, comminution work index is described as ore grindability or the resistance of a particular ore to crushing and grinding. That is, the ease with which a particular ore is been comminuted [10].

Comminution work index of Sokoto phosphate rock in Nigeria has been reported to be 56.73 Kwh/t by Umar *et al.* [11]. However, the comminution work index of Ogun phosphate rock has not been reported, even though it has been reported to be economically viable [12].

The present research therefore determines the comminution work index and physical properties of Ebiti Phosphate rock in Ogun State Southwestern Nigeria to provide empirical data for further characterization and beneficiation.

2. Materials and Methods

2.1. Sample Collection

About 13 kg phosphate rocks used for this research was collected from Ebiti village in Ogun State Nigeria. Ebiti phosphate rock is one of the four phosphate rock locations of the Eastern Dahomey Basin in Southwestern Nigeria (Igbeme, Oja-Odan, Ososun, Ebiti). It is located at Ebiti Village in Ifo Local Government, Ogun State with latitude and longitude of 6.816089° and 3.237346°. The rock samples were collected randomly.

2.2. Sample Preparation

The phosphate rock samples collected above were sorted, washed and oven dried at 100°C [5] to remove moisture. Some oven-dried samples were crushed and ground with Pascal Engineering crusher (model number: 18862) and dry ball mill (Sturtevant, London and Manchester, Machine number: C. 374975) respectively for further analysis.

2.3. Physical Observation and Mohs' Hardness Test

The physical observation of samples was performed after they were sorted and washed for the textural forms and color while hand scratch method was used to determine Mohs' hardness. Clean, dry and smooth surface rock samples were selected; they were gently scratched with the fingernail (Mohs hardness of 2.5), thereafter iron nail (Mohs hardness of 4.5) and finally steel knife blade (Mohs hardness of 5). After each scratch, the surface of phosphate rock was wiped with clean cloth to confirm the scratch.

2.4. Specific Gravity and Water Absorption Capacity Test

They were performed according to the ASTM C128-15 standard [13]. Oven dried phosphate samples crushed with Lab mill were sieved through 4.75 mm sieve and 1 kg of the undersized phosphate samples were soaked for 24 hours in water. They

were sieved out, poured into a tray and air-dried with the hand dryer for an hour until it reached saturated surface dry (SSD) condition. 500 g SSD each was weighed as mass A and 500 g SSD poured into the pycnometer plus water as mass B. The content regarded as mass B was poured, filtered, oven dried, weighed and recorded as mass C. Finally, the mass of pycnometer filled with water was weighed and recorded as mass D. Values from each process were tabulated and specific gravity and water absorption test were calculated.

2.5. Comminution Work Index

This was performed based on modified Bond work index method by Bruce and Berry [14] as described by Oji *et al.* [9] [10] which necessitates the use of reference ore of known work index or grindability. In this research granite was used as a reference since the phosphate rock samples were in solid forms. Granite was selected as a reference material because is widely available, hard and crystalline igneous rock with a typically high Bond Work Index (15.13 kWh/t), reflecting its strong interlocking silicate mineral framework. In contrast, sedimentary phosphate rock generally exhibits a lower work index (9 - 13 kWh/t), due to its higher porosity, weaker cementation, and the presence of softer minerals such as apatite and carbonates. This clear and consistent contrast in grindability makes granite an effective upper-bound reference material for this research. Although granite and phosphate rock differ in geological origin; however, both materials undergo brittle fracture under the controlled conditions of the bond crushing work index test. It is mineralogically stable, and exhibits low variability in mechanical properties compared with many sedimentary ores. This makes it a reliable and reproducible reference material. When used consistently, granite provides a stable baseline against which the relative milling behavior of phosphate rock can be evaluated with confidence. The validity of using granite lies in the fact that the comparative work index test does not require identical breakage mechanisms, but rather a consistent testing framework and a reference material with well-characterized grinding behavior. Granite satisfies these criteria, and the observed differences in energy requirement between granite and phosphate rock can be directly attributed to their intrinsic material properties.

The starting samples for both the test ore (Ebiti phosphate rock) and reference ore were crushed for 15 minutes and allowed to pass through 1.18 mm sieve for homogeneity. 100 g each undersized samples of 1.18 mm sieve were then subjected to sieve analysis for 15 minutes with sieve sizes ranging in descending order from +1000 μm , +710 μm , +500 μm , +355 μm , +200 μm , +150 μm , +106 μm , +75 μm , by Endecott sieve shaker (E.F.L 2 M K 11); each size fraction for test and reference ores were weighed as “feed”. Also, the undersized samples were ground in a ball mill for 15 minutes and 100 g each were subjected to sieve analysis with the same set of sieves for 15 minutes and each fraction for both test and reference sample were weighed as “product”. Finally, the weight from each sieve analysis was tabulated against each sieve size.

2.6. Particle Size Analysis

Sieve analysis was conducted on 300 g of crushed Ebiti phosphate rock, and the sieves were 4750 μm , 2360 μm , 1180 μm , 710 μm , 300 μm , 250 μm , 125 μm , and 75 μm based on the square root of 2 rules. An auto-sieve shaker (MATEST S p. A, Treviolo 24048, Italy with Serial number AC60-01/AC/0154) was used for the analysis and the over-size fraction for each sieve after 10 minutes were recorded.

2.7. Petrographic Analysis

The washed and oven-dried phosphate rock samples of nodular and vesicular samples were machined and mounted on a thin section by glazing with araldite glue. The mounted samples thereafter underwent lapping. Lapping is the grinding and polishing of rock into a flat, smooth and uniform surface on a thin section. Finally, they were examined under a microscope, and the photomicrograph was captured.

3. Results and Discussion

3.1. Physical Observation

As shown in **Figure 1** and **Table 1**, the textural form of Ebiti phosphate rock is nodular and vesicular represented with N and V respectively, with dead white or creamy colour, with hardness value of 5.0 which indicates that it has high rock strength. These results corroborate that of Olanipekun and Bolarinwa [7], and Fayiga and Obigbesan [5], respectively.

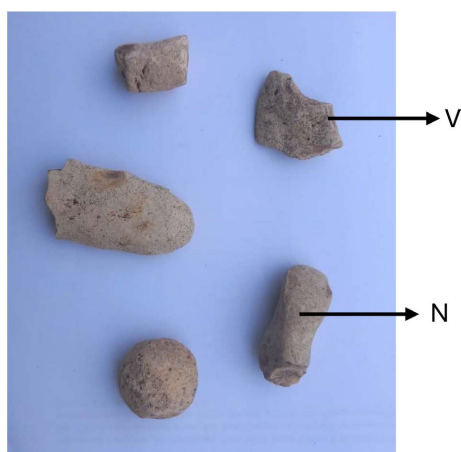


Figure 1. Texture and colour of Ebiti phosphate rock.

Table 1. Colour, textural form and hardness value of Ebiti phosphate rock.

Properties	Ebiti Phosphate Rock
Color	Dead white or creamy in color
Textural form	Vesicular and nodular
Hardness value	5.0

3.2. Specific Gravity and Water Absorption Capacity

Table 2(a) and **Table 2(b)** revealed that Ebiti Phosphate rock has bulk specific gravity for saturated surface dry (SSD) of 2.23, bulk specific gravity for oven-dried sample of 1.98 and apparent specific gravity of 2.65 which agrees with the literature [11]. The water absorption capacity is 12.74 which is lower than the 24.4 recorded for Oja Odan phosphate rock in the literature. The 12.74% water absorption indicates high strength relative to other specific phosphate deposits, and this value generally suggests significant porosity in rock mechanics contexts. This lower rate in water absorption capacity indicated that Ebiti phosphate rock possesses high strength. However, this water absorption capacity value is good for agricultural purposes as it will aid the dissolution of the phosphate rock during its direct application in agriculture.

Table 2. (a) Readings for specific gravity and water absorption capacity of ground Ebiti phosphate rock; (b) Specific gravity and water absorption capacity of ground Ebiti phosphate rock.

(a)					
Pycnometer	Saturated Surface-Dry Mass (W_1) (g)	Pycnometer Mass + SSD Sample + Water (W_2) (g)	Oven-Dry Mass (W_3) (g)	Pycnometer Mass + Water (W_4) (g)	Empty Pycnometer Mass (W_5) (g)
A	500	903	443	627	130
B	500	903	444	627	130
(b)					
Pycnometer	Bulk Specific Gravity (SSD) $\frac{W_1}{W_1 + W_4 - W_2}$	Bulk Specific Gravity (OD) $\frac{W_3}{W_1 + W_4 - W_2}$	Apparent Specific Gravity $\frac{W_3}{W_3 + W_4 - W_2}$	Water Absorption Capacity (%) $\frac{W_1 - W_3}{W_3} \times 100$	
A	2.23	1.98	2.65	12.87	
B	2.23	1.98	2.64	12.61	
Average	2.23	1.98	2.65	12.74	

3.3. Comminution Work Index

Tables 3-6 show the result for sieve analysis of crushed and ground samples for reference and test ore performed during the comminution work index.

From the analysis, using Berry and Bruce [14] method, the comminution work index is 16.97 Kwh/tons, which is above the values (9.92 - 13.00 Kwh/ton) reported in the literature [8] [11], for the work indices of other phosphate ores but lower than the value of 56.73 Kwh/ton for Sokoto phosphate rock as recorded in the literature [11]. This implies that Ebiti phosphate rock in Ogun requires less

energy to comminute than Sokoto phosphate rock.

Table 3. Sieve analysis of feed to ball mill for test ore.

Sieve Size Range (μm)	Weight of oversize (g)	% Weight retained	Cumulative % weight of oversize	Cumulative % weight undersize
1000	8.08	8.13	8.13	91.87
-1000+710	10.32	10.38	18.51	81.49
-710+500	13.56	13.64	32.16	67.84
-500+355	13.64	13.72	45.88	54.12
-355+200	5.81	5.85	51.73	48.27
-200+150	21.72	21.85	73.58	26.42
-150+106	10	10.06	83.64	16.36
-106+75	7.82	7.87	91.51	8.49
-75	8.44	8.49	100.00	0.00

Table 4. Sieve analysis of feed to ball mill for reference ore.

Sieve Size Range (μm)	Weight retained (g)	% Weight retained	Cumulative % weight oversize	Cumulative % weight undersize
1000	8.54	8.57	8.57	91.43
-1000+710	11.33	11.37	19.94	80.06
-710+500	12.71	12.75	32.69	67.31
-500+355	11.66	11.70	44.40	55.60
-355+200	2.62	2.63	47.02	52.98
-200+150	22.87	22.95	69.97	30.03
-150+106	12.55	12.59	82.57	17.43
-106+75	12.56	12.60	95.17	4.83
-75	4.81	4.83	100.00	0.00

Table 5. Sieve analysis of product to ball mill for test ore.

Sieve Size Range (μm)	Weight retained (g)	% Weight retained	Cumulative % weight oversize	Cumulative % weight undersize
1000	0.15	0.15	0.15	99.85
-1000+710	0.93	0.94	1.09	98.91
-710+500	3.52	3.55	4.64	95.36
-500+355	12.05	12.16	16.80	83.20
-355+200	7.99	8.06	24.86	75.14
-200+150	28.1	28.35	53.20	46.80
-150+106	29.74	30.00	83.20	16.80
-106+75	13.23	13.35	96.55	3.45
-75	3.42	3.45	100.00	0.00

Table 6. Sieve analysis of product to ball mill for reference ore.

Sieve Size Range (μm)	Weight retained (g)	% Weight retained	Cumulative % weight oversize	Cumulative % weight undersize
1000	0.22	0.22	0.22	99.78
-1000+710	0.25	0.25	0.47	99.53
-710+500	1	1.00	1.48	98.52
-500+355	5.35	5.37	6.84	93.16
-355+200	3.18	3.19	10.03	89.97
-200+150	38.6	38.73	48.77	51.23
-150+106	34.22	34.34	83.10	16.90
-106+75	13.99	14.04	97.14	2.86
-75	2.85	2.86	100.00	0.00

From **Table 3**, if $710 \mu\text{m} = 81.49\%$

$$X \mu\text{m} = 80\%$$

$$X = \frac{80 \times 710}{81.49} = 697.02 \mu\text{m}$$

Therefore, $F_t = 697.02 \mu\text{m}$

From **Table 4**, if $710 \mu\text{m} = 80.06\%$

$$X \mu\text{m} = 80\%$$

$$X = \frac{80 \times 710}{80.06} = 709.47 \mu\text{m}, \text{ Therefore, } F_r = 709.47 \mu\text{m}$$

From **Table 5**, if $710 \mu\text{m} = 98.91\%$

$$X \mu\text{m} = 80 \%$$

$$X = \frac{710 \times 80}{98.91} = 574.26 \mu\text{m}, \text{ Therefore, } P_t = 574.26 \mu\text{m}$$

From **Table 6**, if $710 \mu\text{m} = 99.53\%$

$$X \mu\text{m} = 80\%$$

$$X = \frac{710 \times 80}{99.53} = 570.68 \mu\text{m}, \text{ Therefore, } P_r = 570.68 \mu\text{m}$$

where X represent sieve in μm .

$$\text{The modified bond equation is: } W_{ir} = \frac{W_{ir} \left(\frac{10}{\sqrt{P_r}} - \frac{10}{\sqrt{F_r}} \right)}{\left(\frac{W}{\sqrt{P_t}} - \frac{W}{\sqrt{F_t}} \right)} = \frac{W_{ir} \left(\frac{10}{\sqrt{P_r}} - \frac{10}{\sqrt{F_r}} \right)}{\left(\frac{10}{\sqrt{P_t}} - \frac{10}{\sqrt{F_t}} \right)},$$

[10]

where,

P_r is the reference ore product diameter of 80% passing through $710 \mu\text{m}$ aperture;

F_r is the reference ore feed diameter of 80% passing through $710 \mu\text{m}$ aperture;

P_t is the test ore product diameter of 80% passing through $710 \mu\text{m}$ aperture;

F_t is the test ore feed diameter of 80% passing through $710 \mu\text{m}$ aperture;

W_{ir} = Work index of reference ore (*i.e.* granite) = 15.13 Kwh/tons.

$$\text{Therefore, } W_{ir} = \frac{W_{ir} \left(\frac{10}{\sqrt{570.68}} - \frac{10}{\sqrt{709.47}} \right)}{\left(\frac{10}{\sqrt{574.26}} - \frac{10}{\sqrt{697.02}} \right)} = 16.97 \text{ Kwh/tons.}$$

From the analysis, using Berry and Bruce method is 16.97 Kwh/tons which is above the values (9.92 - 13.00 Kwh/ton) for the work indices of other phosphate minerals ores and lower than the value of 56.73 Kwh/ton for Sokoto phosphate rock as recorded in textbook and literature respectively [8] [11].

3.4. Particle Size Analysis

Table 7 and **Figure 2** show the results for particle size analysis. From the analysis, crushed phosphate rocks are distributed majorly in the coarse particle size range. 10.1% were retained on 4750 μm , 31.80% were retained on -4750+2360 μm range, and 31.56% was retained on -2360+1180 μm range which give 73.46% in the coarse range but in the finer range; 1.07% was retained on -300+250 μm , 3.60% was retained on -250+125 μm , 1.60% was retained on -125+75 μm and 2.14% was retained on -75 μm which resulted to less than 10% in the finer range. The percentage of cumulative weight retained increases down the sieve series which indicated that the size analysis of the sample was completed. Likewise, the cumulative percentage weight passing decreases; indicating that smaller fraction decreases as size decreases and proved that crushed Ebiti phosphate rock is coarse-grained.

In conclusion, the result revealed that for Ebiti phosphate rock to be used for industrial applications, it needs further grinding to have a higher percentage of finer grains.

Table 7. Sieve analysis for 300 g crushed Ebiti phosphate rock.

Range of Sieve Size (μm)	Weight retained (g)	% Weight retained	Cumulative % weight oversize	Cumulative % weight undersize
4750	30	10.01	10.01	89.99
-4750+2360	95.3	31.80	41.81	58.19
-2360+1180	94.6	31.56	73.37	26.63
-1180+710	32	10.68	84.05	15.95
-710+300	22.6	7.54	91.59	8.41
-300+250	3.2	1.07	92.66	7.34
-250+125	10.8	3.60	96.26	3.74
-125+75	4.8	1.60	97.86	2.14
-75	6.4	2.14	100.00	0.00

3.5. Petrographic Analysis

The photomicrographs for nodular, vesicular and ground Ebiti phosphate rocks are presented in **Figures 3(a)-(c)** respectively. **Figure 3(a)** revealed distinct

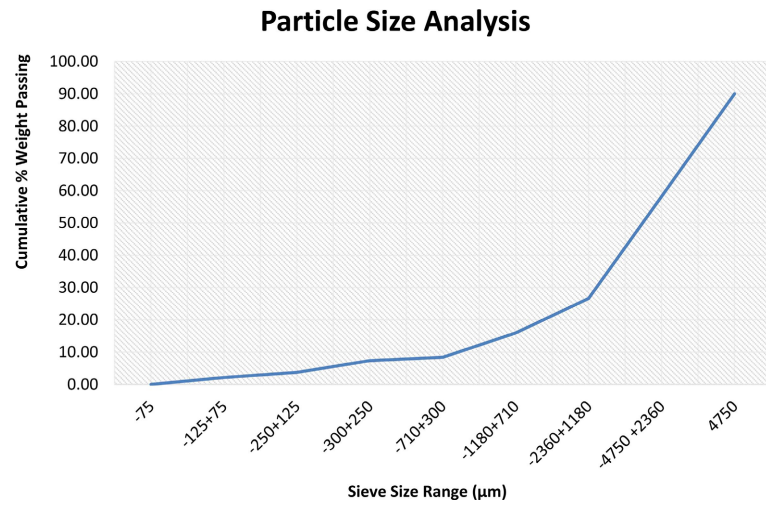


Figure 2. Particle size analysis graph.

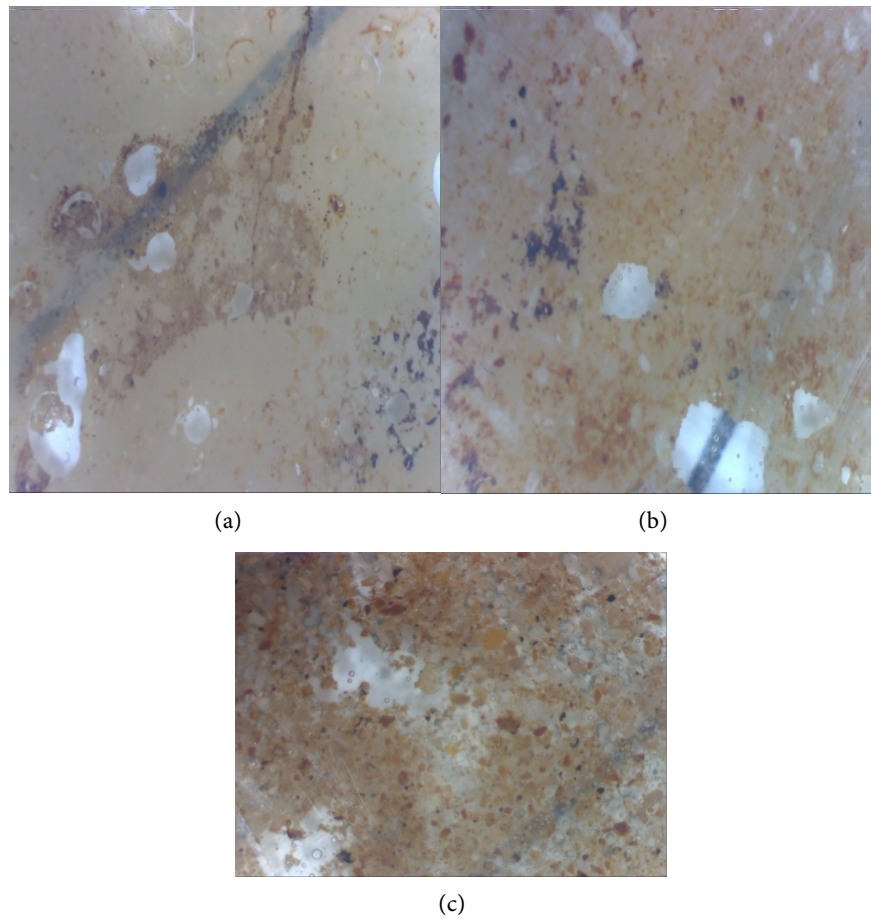


Figure 3. Photomicrograph of (a) Nodular, (b) Vesicular and (c) Ground Ebiti Phosphate Rock.

nodule-like structures with some nodules darker than others which confirm the presence of an apatite mineral with light surrounding matrix which signifies possibility of calcite spar. It also revealed pitted surface confirming that it contained

fossils. **Figure 3(b)** revealed distinct vesicles with some vesicles partly filled. It has a dark spot within the vesicle that indicates iron or aluminum replacement minerals such as hematite or wavellite and **Figure 3(c)** revealed a small equal grain which is closely packed. The identification of specific replacement minerals such as hematite, wavellite is tentative, as the study relies on optical microscopy without confirming it with geochemical analysis such as XRD or XRF.

These results were in agreement with that of Olanipekun and Bolarinwa [7], who work on petrographic analysis of the four phosphate rock deposits in Ogun State.

4. Conclusions

The following conclusion can be drawn from the results of this research:

a) The comminution work index of Ebiti phosphate rock is 16.97 Kwh/tons, which means that it requires less energy to comminute that Sokoto phosphate rock whose comminution work index is 56.73 Kwh/ton;

b) The water absorption capacity of Ebiti phosphate rock is 12.74, meaning that it is suitable for direct application in agriculture as it will aid the dissolution of the phosphate rock. This lower water absorption capacity indicates lower porosity, which implies better strength for industrial uses. This will also aid beneficiation and industrial handling;

c) Ebiti phosphate rock requires adequate grinding to generate finer grains for advanced characterization and beneficiation due to its high hardness value;

d) The textural form of Ebiti phosphate rock is nodular and vesicular, with dead white or creamy colour.

The results of this research revealed that Ebiti phosphate rock is suitable for direct use as fertilizer in agriculture. This research would benefit from further advanced characterization, such as x-ray fluorescence, x-ray diffraction analysis, Fourier Transform Infrared Spectroscopy and Scanning electron microscopy/Energy Dispersive Spectroscopy. These analyses would provide better characterisation of this rock for industrial applications.

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Data Availability Statement

No data was used for the research described.

Conflicts of Interest

The authors declare that 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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