Assessment of Rock Aggregate for Construction Using Comminution Theory

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Abstract— In this research, grinding energy of selected rock samples collected from South West Nigeria was determined using comminution theory in order to evaluate suitability of rock for aggregate production. Bond Work Index (BWI), Aggregate Impact Value (AIV) and Aggregate Crushing Value (ACV) of samples was characterized and correlated. The work index of the charnockitic rock, granite gneiss, porphyritic granite –labelled PG1 and porphyritic granite –labelled PG2 of samples was found to be 17.12 kWh/t, 13.72 kWh/t, 13.64 kWh/t and 12.76 kWh/t respectively. The ACV of the charnockitic rock, granite gneiss, porphyritic granite (PG1) and porphyritic granite (PG2) was determined to be 26.2 %, 27.3 %, 27.6 % and 27.8 % respectively; while the AIV of the samples, in same order, was 11.2 %, 13.2 %, 19.1 % and 18.4 % respectively. Following high correlation coefficient of 0.98% between BWI and ACV, hardness of rock materials are classified as ‘very difficult’, ‘difficult’, ‘medium’, ‘easy’ and ‘very easy’ for grinding energies in the range of >18 kWh/t, 14-18 kWh/t, 10-14 kWh/t, 7-10 kWh/t and 0-7 kWh/t respectively. Based on the classification, rock materials with grinding energy >10 kWh/t could be suitable for aggregate production and usable for civil construction purposes.

Keywords- Aggregate, Aggregate impact value, Aggregate crushing value, Comminution, Grinding energy.

1 INTRODUCTION

In most mineral processing plants, hardness is a measure used in evaluating the resistance of a mineral/ore sample to comminution and useful in the design of mineral processing circuits. Readings from hardness tests are also used to evaluate crushing and grinding efficiency (Aksani and Sonmez, 2000; Wills and Napier-munn, 2006). Bond work index is a size reduction parameter proposed by F.C Bond in 1952 (Wills & Napier-munn, 2006), which expresses the resistance of a material to comminution or grinding. The knowledge of the Bond work index is useful for design of comminution plants for metal extraction or mineral processing (Aksani and Sonmez 2000; Hafiez 2012; Wills and Napier-munn 2006). For efficient separation of valuable minerals, the surface area to be subjected to process treatments must be large enough for faster actions and particle size analysis. Various researchers have made useful recommendations on comminution plant design by the determination of Bond work index for several minerals and ores (Egbe and Abubakre 2013; Gupta and Yan 2006; Oyelola et al. 2012).

On the other hand, the strength of an aggregate is a vital measure for consideration before adoption for specific uses. Essentially, the hardness of a rock has critical effect on the durability, resilience, dependability and quality of the aggregate produced from it, especially when put to use in road pavements. Selecting aggregate with the essential quality is, therefore, significantly important. Experimental analysis such as aggregate crushing value (ACV) and aggregate impact value (AIV) is useful in assessing the load bearing capacity of aggregate for flexible road pavement before failure may occur (Adebola & Abdulazeese, 2014; Egesi & Tse, 2012; Harrison & Bloodworth, 2006).

Since Bond work index helps to determine the resistance of a deposit to size reduction (Kahraman & Toraman, 2008; Mwasha, 2009; Wills & Napier-munn, 2006), evaluation of the reluctance of a rock specimen to grinding could be used to predict its fitness for aggregate production and utilization in flexible road pavement. Hence, this research aims to use Bond work index to estimate the suitability of selected Nigerian rocks for the production of aggregate for use as construction materials –particularly in making flexible road pavement.

2 MATERIALS AND METHODS

2.1 LOCATION OF THE STUDY AREA

The study areas are Ita-ji-Ekiti (Ekiti State, Nigeria, 7°34’28.5”N 5°20’05.2”E); Ikere-Ekiti (Ekiti State, Nigeria, 7°27’01.7”N 5°13’38.5”E); Iitaogbolu (Ondo State, Nigeria, 7°20’47.5”N 5°14’59.0”E); Akure (Ondo State, Nigeria, 7°16’38.8”N 5°20’05.2”E).

2.2 MINERALOGICAL ANALYSIS

Mineralogical analysis on specimens was carried out at the Petrology Laboratory, Department of Advanced Geology, Federal University of Technology, Akure (FUTA), Ondo State, Nigeria. The mineralogical analysis showed that sample from:

- Ikere-Ekiti, Ekiti State, Nigeria is porphyritic granite (labelled as PG1)
- Iitaogbolu, Ondo State, Nigeria is porphyritic granite (tagged as PG2)
- Ita-ji-Ekiti, Ekiti State, Nigeria is granite gneiss, and
- Akure, Ondo State, Nigeria is charnockite rock

2.3 DETERMINATION OF AGGREGATE CRUSHING VALUE

The Aggregate Crushing Value (ACV) was determined using the standard procedure suggested in BS 812-110: 1990 (BS 812-110, 1990).

2.4 DETERMINATION OF AGGREGATE IMPACT VALUE

The Aggregate Impact Value (AIV) was determined using the standard procedure suggested by BS 812-112: 1990 (BS 812-112, 1990).
2.5 Determination of Work Index
The modified Fred C. Bond’s theory popularly called the comparative method was used to measure the work index values (grinding energy) of selected samples (Gupta and Yan; Oyelola et al. 2012; Wills and Napier-munn 2006). Quartz samples from Ijero-Ekiti, Ekiti State, Nigeria was used as the reference sample of known work index for analyzing the selected rock samples under observation (Gupta & Yan, 2006).

Representative samples of selected rocks as well as the reference sample (quartz from Ijero, Ekiti State, Nigeria) were obtained and broken manually with a hammer to produce aggregate sizes passing through 14mm sieve aperture but retained on 10 mm sieve size and the experiment carried out according to the following procedure:
1. 500g each of the selected test samples (and the reference sample) were pulverised with laboratory jaw pulverizer.
2. The pulverized test and reference samples were sieved by sieving into a number of size fraction i.e. +2000 μm, +1180 μm, +600 μm, +500 μm, +425 μm, +300 μm, +212 μm, +150 μm and +75 μm using the automatic sieve shaker, weighed and the values noted as “feed” (F).
3. The “feed” test and reference samples were each further ground by introducing into the laboratory ball mill and milled for 15 minutes.
4. The milled test and the reference samples were then sized by sieving into a number of size fractions i.e. +600 μm, +425 μm, +300 μm, +150 μm, +106 μm and +75 μm using the automatic sieve shaker, weighed and the value noted as the “product” (P).

The work index was determined using equation (1) (Berry & Bruce, 1966; Oyelola et al., 2012; Wills & Napier-munn, 2006).

\[ W_{it} = \frac{W_{ir}(\frac{1}{F_{t80}} - \frac{1}{F_{r80}})}{\frac{1}{P_{t80}} - \frac{1}{P_{r80}}} \]  \hspace{1cm} (1)

Where:
- \( W_{it} \) is the work index of the test material (in kWh/tonne)
- \( P_{t80} \) is the size of the test material through which 80 percent of the Product passes (in μm)
- \( P_{r80} \) is the size of the of the reference material which 80 percent the products passes (in μm)
- \( W_{ir} \) is the work index for the reference ore (quartz) used, \( W_{ir} \approx 13.57\text{kWh/tonne} \) (Wills & Napier-munn, 2006)
- \( F_{t80} \) is the size of the reference material which 80 percent the products passes (in μm).
- \( F_{r80} \) is the size of the of the reference material which 80 percent of the feed passes (in μm)

3 Results
3.1 Aggregate Crushing Value (ACV)
The porphyritic granite (PG2) sample showed the highest ACV reading of 27.8% while the charnockite rock sample gave the strongest ACV reading of 26.2% (Table 1). The standard ACV for aggregate is ≤ 30 % (Mwasha, 2009). Therefore all tested rock samples are appropriate for aggregate production.

3.2 Aggregate Impact Value (AIV)
The charnockite rock sample also gave the highest strength property from the aggregate impact test by maintaining the lower value of AIV. In the same vein, the porphyritic granite (PG2) and porphyritic granite (PG1) samples revealed a close range of the highest values of the AIV, i.e. lesser strength properties (Table 2). Nevertheless, AIV values for all selected samples fell within the range considered strong enough for use in different types of road pavements (BS 812-112, 1990).

3.3 Work Index
Tables 3-6 show the results of the sieve analysis on test materials.

Table 1. Result of ACV Test

| Test Samples               | Aggregates, ACV (%) |
|----------------------------|---------------------|
| Porphyritic granite (PG1)  | 27.6                |
| Porphyritic granite (PG2)  | 27.8                |
| Granite gneiss             | 27.3                |
| Charnockite rock           | 26.2                |

Table 2. Result of AIV Test

| Test Samples               | Aggregates Impact Value, AIV (%) |
|----------------------------|---------------------------------|
| Porphyritic granite (PG1)  | 19.1                            |
| Porphyritic granite (PG2)  | 18.4                            |
| Granite gneiss             | 13.2                            |
| Charnockite rock           | 11.2                            |

Table 3. Sieve analysis for porphyritic granite (PG1) sample “feed”

| Sieve size (μm) | Wt (g) retained | Wt% retained | Cumulative wt% retained | Cumulative wt% passing |
|-----------------|----------------|-------------|-------------------------|------------------------|
| +2000           | 1.6            | 0.32        | 0.32                    | 99.68                  |
| +1180           | 53.5           | 10.70       | 11.02                   | 88.98                  |
| +600            | 131.5          | 26.30       | 37.32                   | 62.68                  |
| +500            | 27.1           | 5.42        | 42.74                   | 57.26                  |
| +425            | 36.1           | 7.22        | 49.96                   | 50.04                  |
| +300            | 55.8           | 11.16       | 61.12                   | 38.88                  |
| +212            | 57.1           | 11.42       | 72.54                   | 27.46                  |
| +150            | 84.4           | 16.88       | 89.42                   | 10.58                  |
| +75             | 42.2           | 8.44        | 97.86                   | 2.14                   |

Fig. 1: “Feed” Cumulative wt (%) Passing against Sieve Size (μm) for the porphyritic granite (PG1) sample.
As shown on the graph (Fig. 1), equation for the determination of the 80% cumulative passing is:

\[ y_F = 32.21\ln(F_t) - 143.6 \]  

(2)

Where:

- \( y_F \): cumulative weight passing (%) of ‘feed’ test sample of porphyritic granite (PG1) pulverized,
- \( F_t \): Particle size of porphyritic granite (PG1) pulverized, in \( \mu m \)

From equation (2), the size of the ‘feed’ sample at which 80% of the test sample passes (i.e. when \( y_F = 80\% \)) is \( F_{t80}=1032.77 \mu m \)

### Table 4. Sieve analysis for porphyritic granite (PG1) sample “product”

| Sieve size (μm) | Wt (g) retained | Wt% retained | Cumulative wt% retained | Cumulative wt% passing |
|-----------------|----------------|-------------|-------------------------|------------------------|
| +600            | 12.5           | 2.90        | 2.90                    | 97.10                  |
| +425            | 48.6           | 11.28       | 14.18                   | 85.82                  |
| +300            | 87.1           | 20.22       | 34.40                   | 65.60                  |
| +150            | 132.4          | 30.73       | 65.13                   | 34.87                  |
| +106            | 60.3           | 14.00       | 79.13                   | 20.87                  |
| +75             | 37.0           | 8.59        | 87.72                   | 12.28                  |
| sieve base      | 52.9           | 12.28       | 100.00                  | 0.00                   |

As shown on graph (Fig. 2), equation for the determination of the 80% cumulative passing is:

\[ y_F = 42.75\ln(P_t) - 176.3 \]  

(3)

Where:

- \( y_F \): cumulative weight passing (%) of porphyritic granite (PG1) milled and
- \( P_t \): Particle size (μm) of ‘product’ test sample, i.e. porphyritic granite (PG1).

From equation (3), the particle size of the “product” sample at which 80% of the test sample passes (i.e. when \( y_F = 80\% \)) is \( P_{t80}=403.43 \mu m \)

### Table 5. Sieve analysis for charnockite rock sample “feed”

| Sieve size (μm) | Wt (g) retained | Wt% retained | Cumulative wt% retained | Cumulative wt% passing |
|-----------------|----------------|-------------|-------------------------|------------------------|
| +2000           | 5.7            | 5.7         | 1.14                    | 98.86                  |
| +1180           | 81.5           | 81.5        | 17.44                   | 82.56                  |
| +600            | 120.1          | 120.1       | 41.46                   | 58.54                  |
| +500            | 22.8           | 22.8        | 46.02                   | 53.98                  |
| +425            | 22.1           | 22.1        | 50.44                   | 49.56                  |
| +300            | 46.8           | 46.8        | 59.8                    | 40.2                   |
| +212            | 40.9           | 40.9        | 67.98                   | 32.02                  |
| +150            | 48.4           | 48.4        | 77.66                   | 22.34                  |
| +75             | 75.4           | 75.4        | 92.74                   | 7.26                   |
| sieve base      | 36.3           | 32.3        | 100.00                  | 0.00                   |

### Table 6. Sieve analysis for charnockite rock sample “product”

| Sieve size (μm) | Wt (g) retained | Wt% retained | Cumulative wt% retained | Cumulative wt% passing |
|-----------------|----------------|-------------|-------------------------|------------------------|
| +600            | 27.9           | 6.04        | 6.04                    | 93.96                  |
| +425            | 89.8           | 19.43       | 25.47                   | 74.53                  |
| +300            | 120.7          | 26.11       | 51.58                   | 48.42                  |
| +150            | 101.6          | 21.98       | 73.56                   | 26.44                  |
| +106            | 49.4           | 10.69       | 84.25                   | 15.75                  |
| +75             | 28.3           | 6.12        | 90.37                   | 9.63                   |
| sieve base      | 44.5           | 9.63        | 100.00                  | 0.00                   |

As shown on graph (Fig. 3), equation for the determination of the 80% cumulative passing is:

\[ y_F = 28.08\ln(F_t) - 118.1 \]  

(4)

Where:

- \( y_F \): cumulative weight passing (%) of the ‘feed’ test sample of the charnockite rock pulverized
- \( F_t \): Particle size of ‘feed’ test sample, i.e. charnockite rock pulverized, in \( \mu m \)

From equation (4), the particle size of the “feed” test sample at which 80% of the test sample passes (i.e. when \( y_F = 80\% \)) is \( F_{t80}=1152.86 \mu m \)
Here, the equation for the determination of the 80% cumulative passing is:

\[ y_p = 40.43 \ln(P) - 171.8 \quad (5) \]

Where:
- \( y_p \) is cumulative weight passing (%) of charnockite rock milled and
- \( P \) is Particle size (µm) of ‘product’ test sample, i.e. charnockite rock

From equation (5), the particle size of the “product” sample at which 80% of the test sample passes (i.e. when \( y_p = 80\% \)) is \( P_{80} = 507.76 \) µm

In the same vein, \( P_{80}, F_{80} \) of the reference sample (i.e. Quartz) and \( P_{80}, F_{80} \) of the remaining two test samples (Granite gneiss and porphyritic granite, PG2) where determined as shown in Table 7. These values were then substituted in equation (1) to determine work index as presented in Table 8.

Table 7. Values of \( P_{80}, F_{80}, P_{80}, F_{80} \) of samples

| Sample                | Particle sizes at 80% Cumulative wt pass ('feed' and 'product') | Values (µm) |
|-----------------------|-----------------------------------------------------------------|-------------|
| Quartz (Reference Sample) | \( P_{80} \) = 411.68                                          | \( F_{80} \) = 1074.92 |
| Porphyritic granite (PG1) | \( P_{80} \) = 403.43                                          | \( F_{80} \) = 1032.77 |
| Porphyritic granite (PG2) | \( P_{80} \) = 399.41                                          | \( F_{80} \) = 1107.65 |
| Charnockite Rock      | \( P_{80} \) = 507.76                                          | \( F_{80} \) = 1152.86 |
| Granite Gneiss        | \( P_{80} \) = 395.44                                          | \( F_{80} \) = 992.27 |

Table 8. Work index values of samples

| Test Samples           | Work Index (kWh/t) |
|------------------------|-------------------|
| Porphyritic granite (PG1) | 13.64             |
| Porphyritic granite (PG2) | 12.76             |
| Charnockite rock       | 17.12             |
| Granite gneiss         | 13.72             |

3.4 CORRELATION BETWEEN WORK INDEX AND AGGREGATE CRUSHING VALUE (ACV)

Fig. 5 shows the correlation between Aggregate Crushing Value of the different tested samples and their bond work index. The figure reveals that Bond work index has an inverse relationship with Aggregate Crushing Value according to equation (6).

\[ Wi = 1775e^{-0.17X_{acv}} \quad (8) \]

\[ R_{acv} = 0.98 \]

Where:
- \( Wi \) = Work index in kWh/t
- \( X_{acv} \) = Aggregate Crushing Value (%)
- \( R_{acv} \) = Correlation coefficient between work index and Aggregate Crushing Value

![Fig. 5: Correlation between aggregate crushing values of the different studied samples and work index](image)

3.5 CORRELATION BETWEEN WORK INDEX AND AGGREGATE IMPACT VALUE (AIV)

Fig. 6 shows the correlation between Aggregate Impact Value of the different tested samples and their bond work index. From this figure, the work index has an inverse relationship with aggregate impact value according to equation (7).

\[ Wi = 21.30e^{-0.02X_{aiv}} \quad (7) \]

\[ R_{aiv} = 0.63 \]

Where:
- \( Wi \) = Work index in kWh/t
- \( X_{aiv} \) = Aggregate Impact Value (%)
- \( R_{aiv} \) = Correlation Coefficient between work index and aggregate impact value

![Fig. 6: Effect of aggregate impact value of the different studied samples on Work index](image)
4 DISCUSSION

In order to predict aggregate quality, work index, ACV and AIV values were analyzed using correlation method. The exponential correlation between work index and ACV is shown in equation (6) with correlation coefficient of 0.98; while the exponential relation between Work Index and AIV was rather too weak to be used for this prediction with correlation coefficient of 0.63 (i.e. equation 7).

Table 9 was generated from equation 6. From the table, predicted ACV values within the range of 32.5% and above; and 32.5 -30.5% are classified, in terms of their hardness property, as “very easy” and “easy” respectively. The energy required to achieve crushing for the “very easy” and “easy” classification was found to be between 0-7 kWh/t and 7-10 kWh/t respectively which are too low. Aggregates within these classifications (0-7 kWh/t and 7-10 kWh/t) are not qualified for use in flexible road pavements due to their low strength. On the other hand, the work index for the “medium”, “difficult” and “very difficult” classification was predicted to be 10-14kWh/t, 14-18kWh/t and >18kWh/t respectively. From these values, ACV values of 30.5-28.5%, 28.5-27.0% and >27% are predicted from equation 6 (see Table 9). Aggregates with 10-14kWh/t grinding energy (i.e. “medium” classification) were observed to have a relatively considerable ability to resist grinding and has reasonable strength properties for aggregates production and usable for road pavement. In the same vein, aggregates with work index values of 14-18kWh/t and >18kWh/t classified as “difficult” and “very difficult” respectively were used to predict aggregate strength property (ACV) according to equation 6 to the range of 28.5-27.0% and < 27.0% as shown in Table 9.

Table 9. Classification of aggregate strength quality for road pavement

| Classification | Bonds Work Index (kWh/t) | ACV (Determined by substituting Bond Work Index values into equation 6)% |
|----------------|--------------------------|---------------------------------------------------------------|
| very easy      | 0-7                      | 32.5 and above                                                |
| Easy           | 7-10                     | 32.5-30.5                                                    |
| Medium         | 10-14                    | 30.5-28.5                                                    |
| difficult      | 14-18                    | 28.5-27.0                                                    |
| very difficult | 18 and above             | Below 27.0                                                   |

In essence, aggregates classified as “difficult” and “very difficult” in ability to resist crushing possess sufficient hardness property and suitable for various types of road pavements (Egbe & Abubakre, 2013; Metso Minerals Finland, 2006). Most standard specifications for aggregate indicate ≤ 30% as a suitable value for ACV in roadways (BS 812-110, 1990; Egesi & Tse, 2012). The predicted value of < 30.5% for the “medium” hardness classification (see table 9) is therefore applicable for use in flexible pavement. The classification shown in Table 9 is found to conform with related research results (Egesi & Tse, 2012; Metso Minerals Finland, 2006; Mwasha, 2009).

5 CONCLUSION

Work Index values of rocks from four different quarry sites were determined and correlated with the resulting Aggregate Crushing Values (ACV) and Aggregate Impact Values (AIV) and a strong relationship between Work Index and ACV was found which was used classify the hardness of rocks as shown in Table 9. Rocks with work Index values >10 kWh/t (i.e. ACV < 30.5 %). Table 9 are classified as appropriate for aggregate production. This shows that the suitability of aggregates for construction purposes (e.g Aggregate Crushing Value) can be evaluated from the determination of grinding energy.

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