Effect of Textural Characteristics of Rock on Bit Wear

Babatunde Adebayo

Department of Mining Engineering, Federal University of Technology Akure, Ondo State, Nigeria
E-mail: <baayoakinola@yahoo.com>

Abstract

The relationship between textural properties of selected Nigerian rocks and bit wear rate was investigated. These rock samples were tested in the laboratory for mineral composition, silica content and porosity. Also, average grain size and packing density were determined from photomicrograph of the samples using empirical equations proposed by researchers. Wear rates for each rock sample obtained on field were correlated with the textural properties to establish their relationships. The percentages of quartz and biotite are 42%, 30.56% for feldspar granite; 51.11%, 17.78% for biotite hornblende granite; and 57.14%, 26.98% for coarse biotite granite; respectively. The results show that all textural characteristics have high coefficient of correlation for all the samples. The highest wear rate was experienced on coarse biotite granite having mean packing density of 93.46%. This has revealed that wear of rock drill bit in quarries is related to textural rock properties and this will be necessary to have an overview of rock response to drilling.

Keyword: *Textural properties, circularity factor, wear rate, drill bit, quarry.*

Introduction

Investigations of nature, characteristics as well as properties of rock are essential for determination of response of rock mass to mechanical fragmentation in quarries and mines. Also, rock engineers are eager to know or make projection before and during exploitation of a particular rock type. Bilgin *et al*. (2006) opined that the ability of excavation machines to operate and cut effectively in hard rock is limited by system stiffness and the ability of the cutting tool to withstand high forces. The variation in the resistance experience on different rock types depends on the textural characteristics of the rocks. However, the design of mechanical equipment for drilling operation, excavation, hauling and crushing relies to a large extent on the quality and quantity of textural characteristics data available. This will help the mine managers in the selection of appropriate machinery for their different levels of operation and guarantee optimum performance of the equipment.

Williams *et al.* (1982) define rock texture as the degree of crystallinity, grain size or granularity and fabric or geometrical relationship between the constituent of a rock. Ersoy and Waller (1995) explained that textural characteristics refer to the geometrical features of rock particles such as grain size, grain shape, grain orientation, relative areas of the grain and matrix (packing density) and compositional features such as mineral content, cement type, degree of cementation or crystallization and bond structure and concluded that textural characteristics are a major factor in determining the mechanical behaviour of rocks which can be used as a predictive factor for assessing the drillability and cuttability, mechanical and wear performance of rocks. In addition, Ulusay *et al*. (1994) described all these properties as petrographic characteristics affecting the behaviour of rock and can be readily measured in the laboratory and determined during routine thin-section studies.

It had been examined that grain boundaries, or contact relationships, are complex (Bieniawski 1967). Deketh (1995) in his study of wear of rock cuttings discovered that tool wear is predominantly affected by microscopic rock properties and the degree of mineral interlocking. Thuro (2003) in an effort to investigate wear of cutting tools correlated some geological factors with road header pick wear. Some groups of researchers expressed the opinion that mineral composition and fabric have a key effect on the damage mechanism of rocks and identified two mechanisms throughout the loading process as compaction and micro-cracking (Gatelier *et al*. 2002). Therefore, a progressive loss of button materials on the surface of the bit is called wear. This can also be explained as material response of cutting elements of the bit to external load, a rock abrasive effect which will ultimately result in drill bit deterioration and replacement. Mechanical abrasive wear is damaged by solid surfaces due to relative motion. Beste *et al*. (2004) observed that rock is normally considered rather hard and the contact leads to erosion and point fatigue. He was of the view that wear mechanisms of tools are often complex and vary in character depending on rock type, and the wear of the tip was found to be correlated to the hardness of rocks, but was also influenced by grain size, quartz content and isotropy.

This contribution is a continuation of a series of papers on the properties of Nigerian rocks (Adebayo and Okewale 2007; Adebayo 2008; and Adebayo *et al*. 2010).

Materials and Methods

Rock samples

Feldspar granite, *biotite hornblende granite* and *coarse biotite granite* were used for the various tests required for this work.

Determination of Mineral Composition

The thin sections prepared from the rock samples were viewed under a polarizing microscope and the mineral compositions of the rocks were estimated as presented in Tables 1-3.

Determination of Average Grain Size

The average grain size was measured from the photomicrograph of the samples. In addition, all the completed grains in the reference area were measured and the average of the grain size measured was calculated for all the samples.

X- Ray Fluorescence Test for Determination of Silica Content

The palletized samples which were inserted into the sample holder were prepared in accordance with (ASTM C-118), so that the beams of *X*-ray light can fall on the flat surface of the palletized sample. The RIX 3100 *X*-ray spectrometer, equipped with a monitor, processed each sample inserted, analysed the percentage presentation of each element present in the sample and displayed the results as presented in Table 5.

Determination of Porosity

Porosity was determined using saturation and caliper technique as suggested by ISRM (1989). The representative sample of the rock was machined to conform to cubiod. The bulk volume V_b was calculated from caliper reading for each dimension. The sample was saturated by water immersion for a period of 5 days. The sample was removed, the surface was dried, and the saturated surface dry mass was determined. The sample was dried to a constant mass at a temperature of 105°C, cooled in a desiccator and its mass determined to give grain mass *Ms*. The pore volume and porosity were obtained using Eqs. (1) and (2) as shown in Table 6:

$$V_p = (Msat - Ms)/\rho_w, \quad (1)$$

where: ρ_w = Density of the saturated fluid (Water); and V_p = Pore volume; therefore

$$Porosity\ (n) = 100\ V_p/V_b. \quad (2)$$

Determination of Packing Density

The packing densities for the samples were determined using Eq. (3) proposed by Kahn (1956) and the results are presented in Table 7:

$$PD = (Summed\ Length\ of\ Grains\ Measured\ Along\ the\ Traverse)/(Length\ of\ Traverse). \quad (3)$$

Determination of Wear Rate of Gauge Button

The lengths of both gauge buttons were measured at regular intervals on the quarry site. This was used to determine average wear rate of gauge buttons for the bit and the results are presented in Table 8.

Results and Discussion

Textural Properties

The mineral composition of feldspar granite, biotite hornblende granite and coarse biotite granite are shown in Tables 1-3. The results show that the percentage of quartz, biotite and plagioclase are 42%, 30.6% and 13.1% for feldspar granite; 51.11%, 17.78% and 6.66% for biotite hornblende granite and 57.14%, 26.98% and 3.17% for coarse biotite granite. Table 4 presents the average grain size of the samples. The results show that the average grain size varies in the following millimetre ranges of 0.94 mm - 0.99 mm, 0.65 mm - 0.68 mm and 0.65 mm - 0.68 mm for feldspar granite, biotite hornblende granite and coarse biotite granite, respectively.

Table 5 presents the silica content of the samples. The result shows that the silica content varies in the following ranges of 57.16-57.21%, 82.5-82.72% and 76.04-76.12% for feldspar granite, biotite hornblende granite and coarse biotite granite, respectively. Table 6 shows the porosity of the samples. The results revealed that porosity varies in the following ranges of 1.03-1.07%, 0.87-0.93% and 0.72-0.74% for feldspar granite, biotite hornblende granite and coarse biotite granite, respectively. Table 7 shows the packing density of the samples. The results show that the packing density varies in the following ranges of 92.18-94.53%, 91.60-94.40% and 92.82-94.24% for feldspar granite, biotite hornblende granite and coarse biotite granite, respectively.

Wear Rate for the Samples

The wear rate of the gauge buttons for all the samples varies from 0.0163 mm/m for feldspar granite to 0.0234 mm/m for biotite hornblende granite as presented in Table 8.

Table 1. Mineral composition of feldspar-granite.

Rock Code	Minerals	Proportion (%) Location 1	Proportion (%) Location 2	Proportion (%) Location 3	Proportion (%) Location 4	Proportion (%) Location 5
IK01	Biotite	30.60	30.56	30.64	30.64	30.62
	Quartz	42.00	42.10	41.90	42.12	41.95
	Plagioclase	13.10	13.06	13.12	13.14	13.30
	Opaque	3.80	3.80	3.80	3.80	3.80
	Orthoclase	10.70	10.48	10.54	10.30	10.33
Total		100.00	100.00	100.00	100.00	100.00

Table 2. Mineral composition of biotite hornblende-granite.

Rock Code	Minerals	Proportion (%) Location 1	Proportion (%) Location 2	Proportion (%) Location 3	Proportion (%) Location 4	Proportion (%) Location 5
IB02	Microcline	6.67	6.67	6.67	6.67	6.67
	Hornblende	8.89	8.89	8.89	8.89	8.89
	Biotite	17.78	17.80	17.75	17.81	17.82
	Quartz	51.11	51.09	51.18	51.14	51.07
	Plagioclase	6.66	6.66	6.64	6.66	6.66
	Orthoclase	2.22	8.89	8.87	8.83	8.89
Total		100.00	100.00	100.00	100.00	100.00

Table 3. Mineral composition of coarse biotite-granite.

Rock Code	Minerals	Proportion (%) Location 1	Proportion (%) Location 2	Proportion (%) Location 3	Proportion (%) Location 4	Proportion (%) Location 5
DE03	Hornblende	12.70	12.70	12.70	12.70	12.70
	Biotite	26.98	27.00	27.01	27.01	26.96
	Quartz	57.14	57.10	57.12	57.09	57.16
	Plagioclase	3.17	3.20	3.17	3.20	3.18
Total		100.00	100.00	100.00	100.00	100.00

Table 4. Average grain size of selected rocks in South Western Nigeria.

Rock Name and Code	Average Grain Size (mm) Location 1	Average Grain Size (mm) Location 2	Average Grain Size (mm) Location 3	Average Grain Size (mm) Location 4	Average Grain Size (mm) Location 5
Feldspar-Granite (IK01)	0.94	0.99	0.96	0.99	0.95
Biotite Hornblende-Granite (IB02)	0.67	0.66	0.69	0.69	0.65
Coarse Biotite-Granite (DE03)	0.68	0.66	0.68	0.65	0.68

Table 5. Silica content of selected rocks in South Western Nigeria.

Rock Name and Code	Silica Content (%) Location 1	Silica Content (%) Location 2	Silica Content (%) Location 3	Silica Content (%) Location 4	Silica Content (%) Location 5
Feldspar-Granite (IK01)	57.17	57.19	57.16	57.21	57.17
Biotite Hornblende-Granite (IB02)	82.64	82.60	82.72	82.7	82.50
Coarse Biotite-Granite (DE03)	76.09	76.04	76.12	76.06	76.10

Table 6. Porosity of selected rocks in South Western Nigeria

Rock Name and Code	Porosity(%) Location 1	Porosity(%) Location 2	Porosity(%) Location 3	Porosity(%) Location 4	Porosity(%) Location 5
Feldspar-Granite (IK01)	1.05	1.06	1.043	1.07	1.03
Biotite Hornblende-Granite (IB02)	0.91	0.87	0.92	0.93	0.87
Coarse Biotite-Granite (DE03)	0.73	0.72	0.74	0.72	0.74

Table 7. Packing density of selected rocks in South Western Nigeria.

Rock Name and Code	Packing Density(%) Location 1	Packing Density(%) Location 2	Packing Density(%) Location 3	Packing Density(%) Location 4	Packing Density(%) Location 5
Micro Feldspar-Granite (IK01)	92.96	93.75	92.96	94.53	92.18
Biotite Hornblende-Granite (IB02)	91.95	91.95	93.00	94.40	91.60
Coarse Biotite-Granite (DE03)	92.88	93.52	92.82	94.24	92.82

Table 8. Wear rate of selected rocks in South Western Nigeria.

Rock Name and Code	Wear Rate (mm/m) Location 1	Wear Rate (mm/m) Location 2	Wear Rate (mm/m) Location 3	Wear Rate (mm/m) Location 4	Wear Rate (mm/m) Location 5
Feldspar-Granite (IK01)	0.0163	0.0164	0.0163	0.0164	0.0163
Biotite Hornblende-Granite (IB02)	0.0233	0.0233	0.0234	0.0234	0.0233
Coarse Biotite-Granite (DE03)	0.0212	0.0211	0.0212	0.0211	0.0212

The Relationship between Wear Rate and Textural Characteristics

Wear Rate and Quartz Percentage

The results of the relationship between wear rate and quartz content are presented in Figs. 1-3. It was observed that a logarithmic relationship exists between wear rate and percentage of quartz for feldspar granite, while the relationship between wear rate and percentage of quartz is shown in linear equations for biotite hornblende granite and coarse biotite granite, and these are expressed in Eqs. (4-6):

$$Wg = 0.022 \ln(QZ) - 0.067, \quad (4)$$
$$Wg = 0.001\, QZ - 0.034, \quad (5)$$
$$Wg = 0.001\, QZ - 0.072, \quad (6)$$

where:

Wg - Gauge button wear rate (mm/m);
QZ - percentage of quartz.

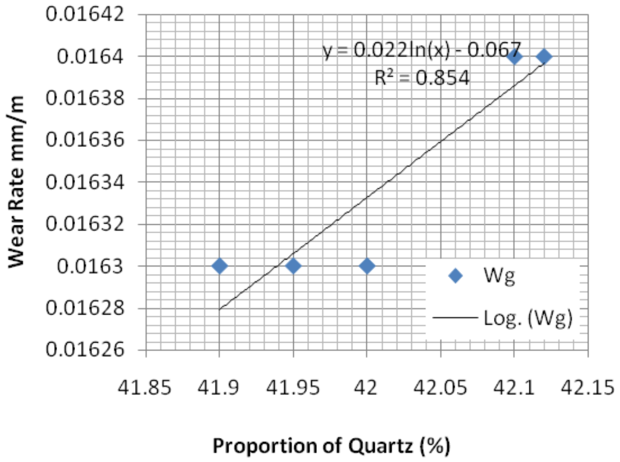

Fig. 1. Plot of wear rate against quartz (%) for *feldspar granite*.

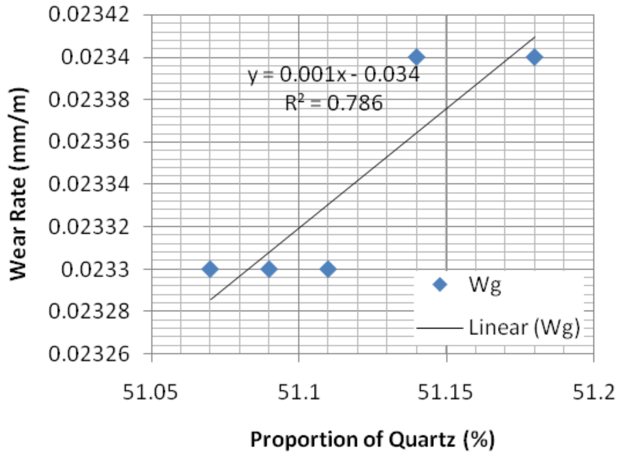

Fig. 2. Plot of wear rate against quartz (%) for *biotite hornblende-granite*.

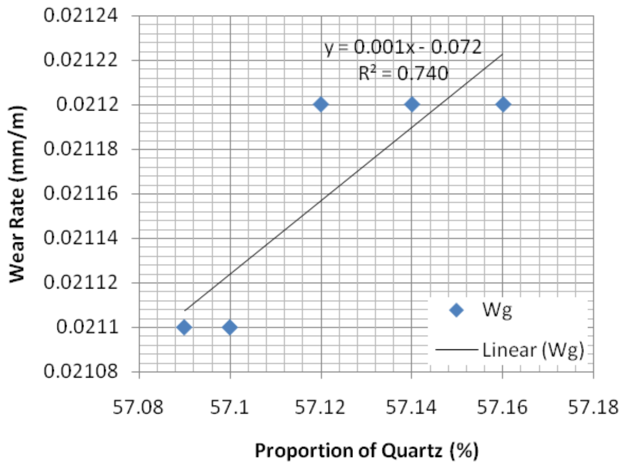

Fig. 3. Plot of wear rate against quartz (%) for *coarse biotite-granite*.

Wear Rate and Average Grain Size

The results of the relationship between wear rate and average grain size are presented in Figs. 4-6. It was observed that the equation connecting wear rate and average grain size for feldspar granite is in exponential form, while relationships existing between wear rate and average grain size for biotite hornblende granite and coarse biotite granite are linear, and these are expressed in Eqs. (7-9). The coefficients of correlation for feldspar granite, biotite hornblende granite and coarse biotite granite are 0.905, 0.843 and 0.937, these show that strong relationship exist between wear rate and average grain size for all the samples:

$$Wg = 0.014\, e^{0.138\, Avg}, \qquad (7)$$

$$Wg = 0.002\, Avg + 0.021, \qquad (8)$$

$$Wg = 0.003\, Avg + 0.018, \qquad (9)$$

where:

Wg - Gauge button wear rate (mm/m);

Avg - Average grain size (mm).

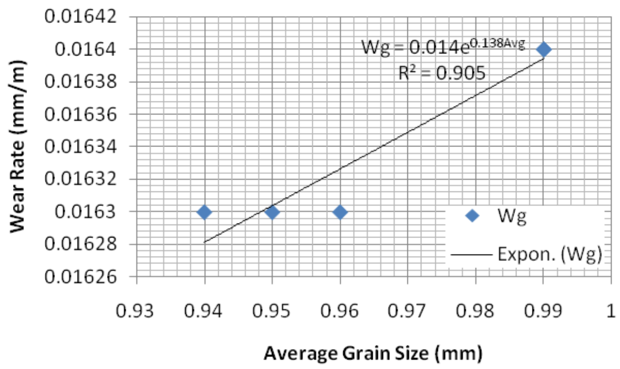

Fig. 4. Plot of wear rate against average grain size for *feldspar granite*.

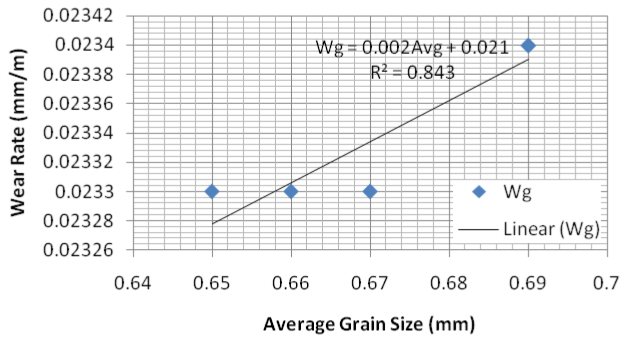

Fig. 5. Plot of wear rate against average grain size for *biotite hornblende-granite*.

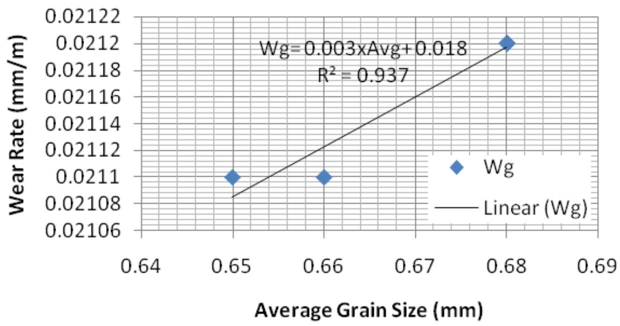

Fig. 6. Plot of wear rate against average grain size for *coarse biotite-granite*.

Wear Rate and Silica Content

The results of the relationship between wear rate and silica content are presented in Figs. 7-9. It was observed that the equation connecting wear rate and silica content for biotite hornblende granite is in exponential form, while relationships existing between wear rate and silica content for feldspar granite and coarse biotite granite are linear, and these are expressed in Eqs. (10-12). The coefficients of correlation for feldspar granite, biotite hornblende granite and coarse biotite granite are 0.833, 0.656 and 0.836, these show that strong relationship exist between wear rate and silica content for all the samples:

$$Wg = 0.002\, Sio_2 - 0.126, \qquad (10)$$

$$Wg = 0.003\, e^{0.021\, Sio_2}, \qquad (11)$$

$$Wg = 0.001\, SiO_2 - 0.098, \qquad (12)$$

where:

Wg - Gauge button wear rate (mm/m);

SiO_2 - Silica content (%).

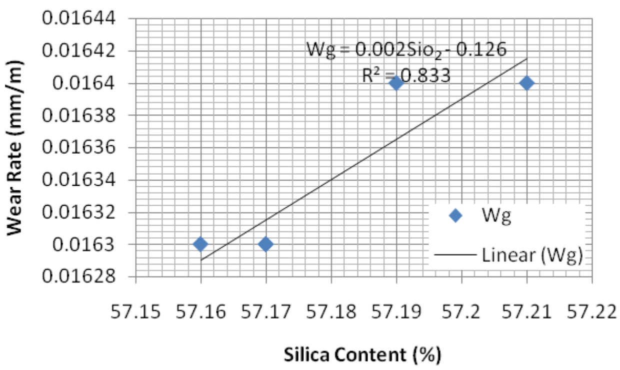

Fig. 7. Plot of wear rate against silica content for *feldspar granite*.

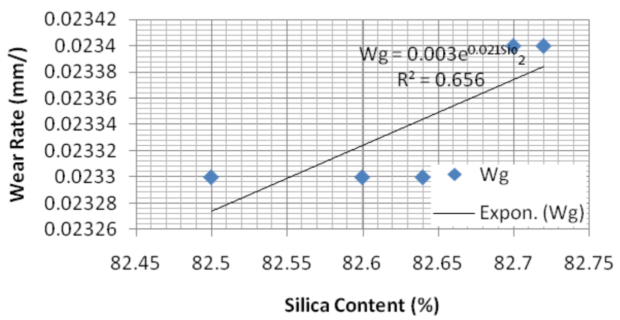

Fig. 8. Plot of wear rate against silica content for *biotite hornblende-granite*.

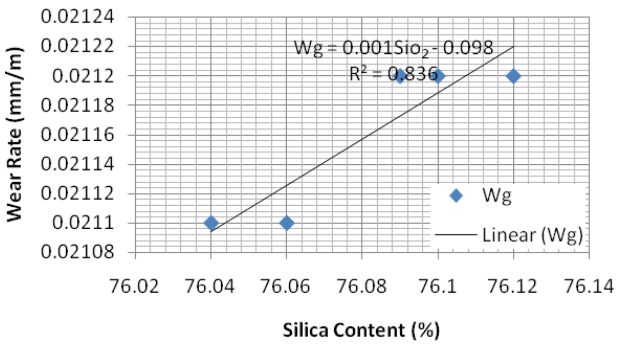

Fig. 9. Plot of wear rate against silica content for *coarse biotite granite*.

Wear Rate and Porosity

The results of the relationship between wear rate and porosity are presented in Figs. 10-12. It was observed that equations connecting wear rate and porosity for exhibit linear relationship for all the samples and are expressed in Eqs. (13-15). The coefficients of correlation for feldspar granite, biotite hornblende granite and coarse biotite granite are 0.729, 0.651 and 0.833, respectively, these show that strong relationship exist between wear rate and porosity for all the samples:

$$Wg = 0.003\ n + 0.013, \quad (13)$$

$$Wg = 0.001\ n + 0.021, \quad (14)$$

$$Wg = 0.005\ n + 0.017, \quad (15)$$

where:

Wg - Gauge button wear rate (mm/m);

n - porosity (%).

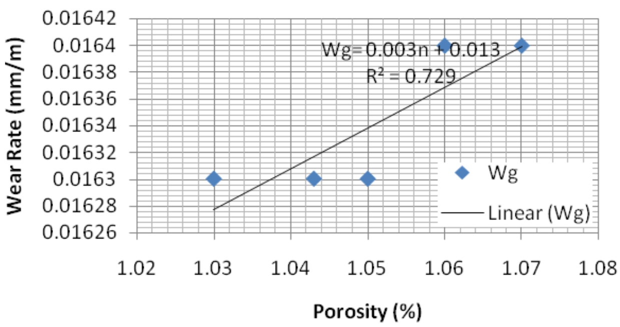

Fig. 10. Plot of wear rate against porosity for *feldspar granite*.

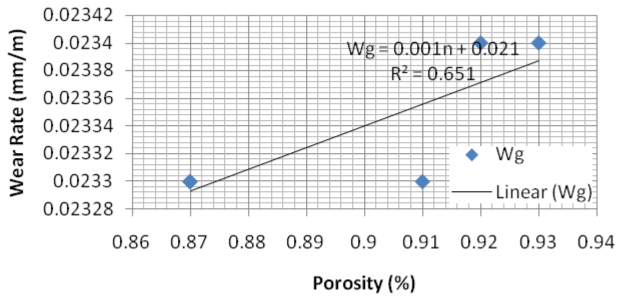

Fig. 11. Plot of wear rate against porosity for *biotite hornblende-granite*.

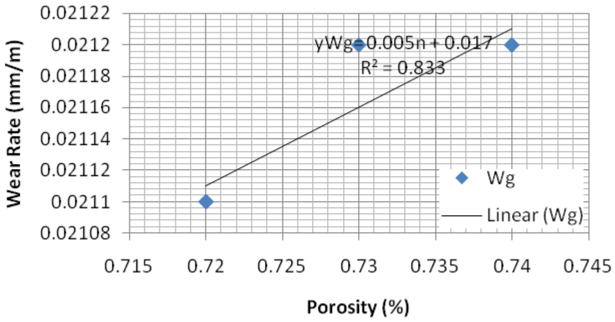

Fig. 12. Plot of wear rate against porosity for *coarse biotite granite*.

Wear Rate and Packing Density

The results of the relationship between wear rate and packing density are presented in Figs. (13-15). It was observed that the equation connecting wear rate and packing density for biotite hornblende granite is in logarithmic form, while relationships existing between wear rate and packing density for feldspar granite and coarse biotite granite are linear, and these are expressed in Eqs. (16-18). The coefficients of correlation for feldspar granite, biotite hornblende granite and coarse biotite granite are 0.778, 0.799 and 0.832, respectively, these show that strong relationship exists between wear rate and packing density for all the samples:

$$Wg = 5E\text{-}05\ PD + 0.011, \quad (16)$$

$$Wg = 0.004 \ln(PD) + 0.005, \quad (17)$$

$$Wg = -8E\text{-}05\ PD + 0.028, \quad (18)$$

where:

Wg - Gauge button wear rate (mm/m);

PD - Packing density (%).

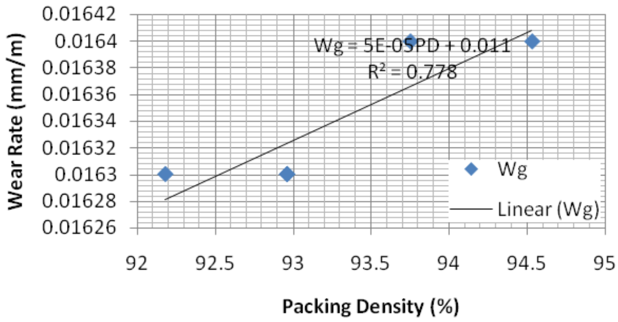

Fig. 13. Plot of wear rate against packing density for *feldspar granite*.

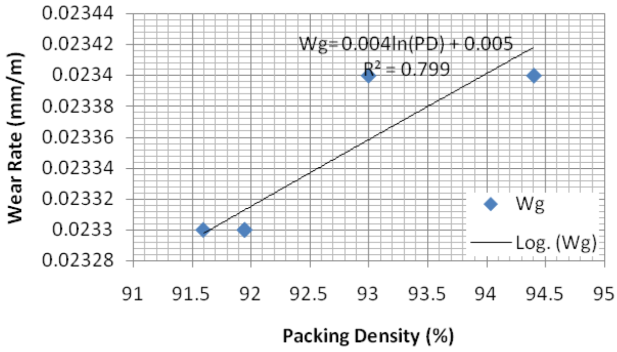

Fig. 14. Plot of wear rate against packing density for *biotite hornblende-granite*.

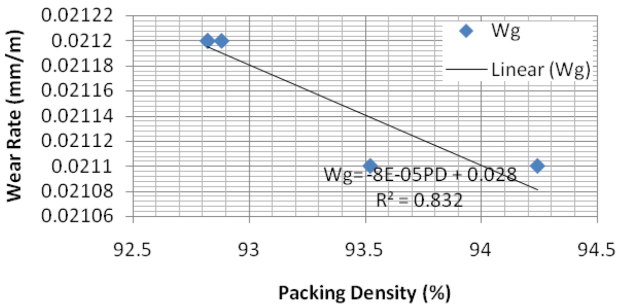

Fig. 15. Plot of wear rate against packing density for *coarse biotite granite*.

Conclusion

Investigating the relationship between wear rate and textural properties of rocks are essential to understand the behaviour of rock under mechanical loading. The wear rate is an important variable to be able to project drill bit consumption in mines or quarry. Among the textural characteristics selected for this study are quartz proportion, silica content, average grain size, porosity and packing density. All these properties were found to have strong relationship with wear rate. Also, wear rate is highest in coarse biotite granite with mean pack density of 93.46% which incidentally is the highest packing density. It could be concluded that rock drill bit responses are different because of variation in the textural characteristics of these rocks.

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