Journal of Metals, Materials and Minerals, Vol.29 No.2 pp.51-57, 2019

Evaluating the grinding process of granitic rocks using the physico-mechanical and mineralogical properties

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Received date:
27 December 2018
Revised date:
1 January 2019
Accepted date:
18 May 2019

Keywords:
Grinding
Mean particle size
Granites
Physico-mechanical properties
Abrasive mineral content

Abstract

Granitic rocks are sometimes ground for different purposes. Predicting the mean particle size (d_{50}) is useful for planning and cost estimation of purposes. In order to investigate the possibility of predicting the d_{50} of ground rock from the physico-mechanical rock properties, six different granites were tested in the laboratory. First, the d50 values were correlated with the corresponding physico-mechanical properties. The simple regression analysis showed that there were no good correlations between the d_{50} and the physico-mechanical properties. Then, the multiple regression analysis was carried out and strong prediction equations were developed. It was also shown that the dominant parameter in grinding was the abrasive mineral content of rock. It is concluded that the d50 of granites can be predicted from the derived multiple regression equations especially for preliminary investigations. The developed estimation equations including index test values are especially useful since they are easy to use.

1. Introduction

The grinding of rocks or ores is a common method executed in several industrial plants such as cement factory, calcite plants and ore dressing plants. It is known that the mechanical and mineralogical characteristics of rocks strongly affect their grindability. Mean particle size (d_{50}) is a tool to investigate the grindability of rocks. The development of some estimation equations for d_{50} of granites will be useful for engineers especially during feasibility studies.

Although it is known that the mechanical and mineralogical properties of rock have a strong effect on the crushing and grinding, there are limited studies on this issue in the literature. Berry et al. [1] investigated the correlations between a jaw crusher performance and rock properties. They carried out porosity test, strength tests, and elastic modulus test and found some correlations between the rock properties and the performance of the crusher. Bearman et al. [2] studied the effect of feed size, closed side setting and rock strength on the performance of laboratory scale cone crusher. They correlated the strength of rock to the energy consumption and material size in crushing test, and found strong correlations between the rock strength and the performance of the cone crusher. They also presented three dimensional plots to estimate the power and product size according to the different operational parameters. Heikkila [3] revealed the effect of geological characteristics, the feeding style and the shape of fragments on the fracturing of rocks in crushing. Briggs and Bearman [4] investigated the effects of different forms of crushing and showed that the stress field applied to the rock fragment depended on the type of crusher plate and the shape of the rock fragment. Evertsson [5] suggested a method for the prediction of the product size distributions and total capacity of cone crusher performance. Raisanen and Torppa [6] pointed out the significance of the evaluation of inhomogeneous rock mass in order to supply different size and quality of aggregates for individual usage areas. Whittles et al. [7] studied the influence of strain rate, impact energy and the fragmentation degree on the efficiency of energy in crushing. They indicated that increasing strain rate increases the energy necessary to break rock. Kekec et al. [8] investigated the influence of the textural properties on the crushability of rocks using statistical analysis. They derived some correlations between the textural characteristics and the physico-mechanical properties of the rocks. Toraman et al. [9] tested different rocks types such as igneous, sedimentary and metamorphic in order to predict the crushability using impact strength index and concluded that rock crushability could be easily predicted from the impact strength index.

There are some studies on the effect of mechanical properties of rocks on their grindability in the literature. The correlation between Bond grindability index and point load index was investigated by Deniz et al. [10] for coals. They derived an inverse relation between the two parameters. The mechanical properties of rocks were correlated to grindability by Bearman et al. [11] and a good correlation was established between indirect tensile strength and grindability. Deniz and Ozdag [12] studied the

DOI: 10.14456/jmmm.2019.18

relations between dynamic elastic properties and both the Bond grindability and work index. They developed estimation equations for Bond grindability and work index for sedimentary and volcanic rocks. The Bond grindability and work index were also correlated to the friability value for some rocks [13]. Another study was carried out by Sengun et al. [14] in order to investigate correlations between the Bond grindability index and the Shore hardness and point load index for sedimentary rocks and marbles. They presented some estimation relations for Bond grindability index. Some researchers [15, 16] investigated the correlations between the Hardgrove grindability index and the mechanical properties for coals and derived some empirical prediction equations.

There are some studies on the relations between the grindability and some properties of coals and some rocks in the literature. However, there is no published study on the grindability of granites. Granites behave differently from coals during grinding, because coals have too much cleat planes and therefore, they are very fragile. On the other hand, granites have different textural properties from other rock types and other igneous rocks as well. They are also brittle, and have hard and abrasive minerals such as quartz and feldspar. For this reason, the grindability of granites should be investigated. This paper presents the investigation on the correlations between the d_{50} and physico-mechanical and mineralogical properties of granitic rocks.

2. Sampling

Some natural stone processing plants were visited, and six different granitic rock blocks were sampled. The selected rock blocks were transported to the laboratory for the tests. The names and locations of the sampled rocks are given in Table 1.

3. Mineralogical analysis

The mineral contents were determined as a result of analysis under polarized light microscopy. In order to determine the type and the amount of minerals in each rock type, a thin section of 0.002 mm thickness was prepared from the rock specimens. When the light sent to the thin cross-section under the polarized light microscope, it is reflected in the eye in different colors depending on the type of mineral. This color is the color of the mineral in the polarizing microscope. The mineral percentages were determined by point counting method. The grids are generated periodically in point counting method. A dark spot is placed on the corner points of the grid. When we compare the number of points corresponding to the same kind of minerals to the total number of points, it gives us the total percentage of the same kind of mineral.

Figure 1 presents the rational mineral distribution of granite (Kaman rosa). The minerals with high hardness scale (according to Mohs Hardness Scale) have been identified and labeled on thin section microphoto. Quartz (Mohs HS: 7 and Orthoclase (Mohs HS: 6) constitute approximately % 75 of the Kaman rosa granite.

The mineral contents and percentages of each rock type are given in Table 1. The abrasive mineral percentages such as quartz and feldspar are given in Table 1 for each rock type. The minerals with Mohs hardness of 5 and higher than 5 were accepted as abrasive, and the total of abrasive minerals was described as the abrasive mineral content.

Table 1. Mineral contents and percentages of the tested rocks.

Rock type	Location	Quartz (%)	Orthoclase (%)	Plagioclase (%)	Biotite (%)	Amphibole (%)	Nepheline (%)	Sphene (%)	Abrasive mineral content (%)
Granite (Anadolu grey)	Ortakoy/ Aksaray	42	29	15	14	–	–	–	86
Granite (Kaman rosa)	Kaman/ Kirsehir	22	36	17	21	4	–	–	79
Syenite (Kircicegi)	Kaman/ Kirsehir	–	63	–	–	12	22	3	100
Granite (King rosa)	Unknown	16	62	8	14	–	–	–	86
Granite (Rosa Porrino)	Porrino/ Spain	15	60	10	15	–	–	–	85
Granite (Kozak granite)	Bergama/ İzmir	32	12	33	15	8	–	–	84

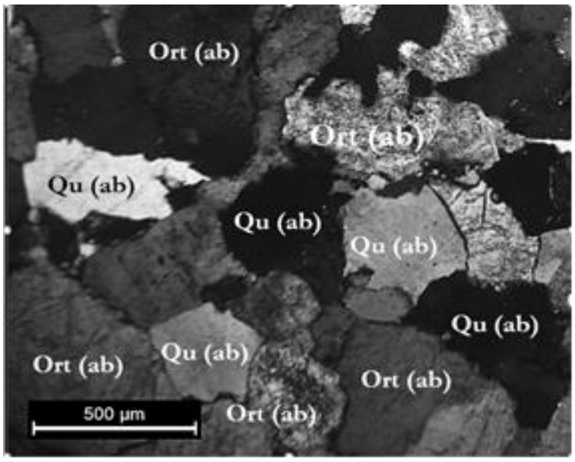

Figure 1. The rational mineral distribution of granite (Kaman rosa; Qu: quartz, Ort: orthoclase, ab: abrasive mineral).

4. Experimental studies

The physico-mechanical tests on the samples were carried out according to ISRM [17, 18] suggested methods. The average results of the tests are given in Table 2. The test methods are explained briefly in the following paragraphs.

4.1. Uniaxial Compressive Strength Test

NX-size core samples with length-to-diameter ratio of 2.5-3.0 were used in the uniaxial compressive strength tests. A stress rate of 0.5-1.0 MPa/s was performed in the tests. Five or more than five specimens were used for each rock type in the tests and the results were averaged.

4.2. Brazilian Tensile Strength Test

NX-size core samples with height to diameter ratio of about 0.5 were used in the Brazilian tensile strength tests. A constant stress rate was applied on the disc specimens in order to create a failure in 5 minutes of loading. Five to seven samples were used in the tests for each rock type and the average result were recorded as tensile strength.

4.3. Point Load Test

NX-size core samples with a length-to-diameter ratio of 1.2 were used in the diametral point load tests. The test results were corrected to the core diameter of 50 mm. The point load tests were performed at least seven times for each rock type and the average value of the results was inscribed as the point load strength

4.4. Schmidt Hammer Test

Table 2. The tested rocks and test results.

N-type Schmidt hammer tests were performed on the large blocks. The tests were conducted with the hammer held vertically downwards. During the tests, 20 rebound values from single impacts which were separated by at least a plunger diameter were recorded. Then, the upper 10 values were averaged. After repeating the tests three times for each rock type, the results were averaged as the Schmidt hammer value.

4.5. Density Test

The dry densities of the samples were determined using the smooth-cut core samples. After several calliper readings, the volumes of the specimens were calculated. The dry mass of the samples was weighed by a balance at an accuracy of 0.01g. Three specimens were used for each rock type in the tests and the results were averaged.

4.6. Porosity Test

The saturation and caliper techniques were used for the measurement of porosity of the smooth-cut core samples. Pore volumes of samples were determined from the difference between dry and saturated mass. The volumes of specimens were measured with a caliper. Three specimens were used for each rock type in the tests and the results were averaged.

4.7. Grinding Test

Crushed samples were prepared with a jaw crusher and sieved to gain 500 g materials in the size range of -2+1 mm for grinding tests. Then, the samples were charged into a stainless-steel ball mill and ground under dry conditions for 5 min. The dimension of the ball mill was 200×200 mm, and the mass of charged stainless steel balls was 5 kg. The diameters of the steel balls were 20, 30 and 40 mm, and their percentages were 30, 40 and 30, respectively. After grinding, the samples were sieved, and the size distribution graphs of the individual fractions were plotted and the d_{50} values were determined for each rock type (Table 2).

5. Evaluation of the results

5.1. Simple Regression Analysis

Each rock property was correlated to d_{50} values, respectively. There are no correlations between the d_{50} values and the rock properties (Figure 2). It looks as if the uniaxial compressive strength and density correlate inversely with the d_{50}. But, these inverse correlations between the mentioned rock properties and d_{50} are misleading. If there were some correlations between the d_{50} and the uniaxial compressive strength and density, they would be directly proportional.

Rock type	Uniaxial compressive strength (MPa)	Tensile strength (MPa)	Point load strength (MPa)	Schmidt hammer value	Density (g/cm^3)	Porosity (%)	d_{50} (mm)
Granite (Anadolu grey)	114.5±9.2*	9.0±1.5	7.2±2.2	56.0	2.60±0.05	0.62±0.04	0.34
Granite (Kaman rosa)	84.9±11.3	8.0±2.6	5.7±1.6	53.5	2.66±0.02	0.63±0.08	0.35
Granite (Kircicegi)	89.6 ±5.3	6.6±0 .7	4.4±1.1	56.4	2.52±0.03	0.98±0.02	0.38
Granite (King rosa)	120.3±4.8	14.8±1.8	14.4±3.2	50.8	2.62±0.04	0.36±0.10	0.36
Granite (Rosa Porrino)	90.2±6.9	7.5±2.3	6.7±1.6	46.1	2.59±0.02	0.90±0.09	0.46
Granite (Kozak granite)	121.8±8.4	11.6±3.1	11.1±2.4	45.8	2.69±0.06	0.70±0.03	0.24

* Standard deviations

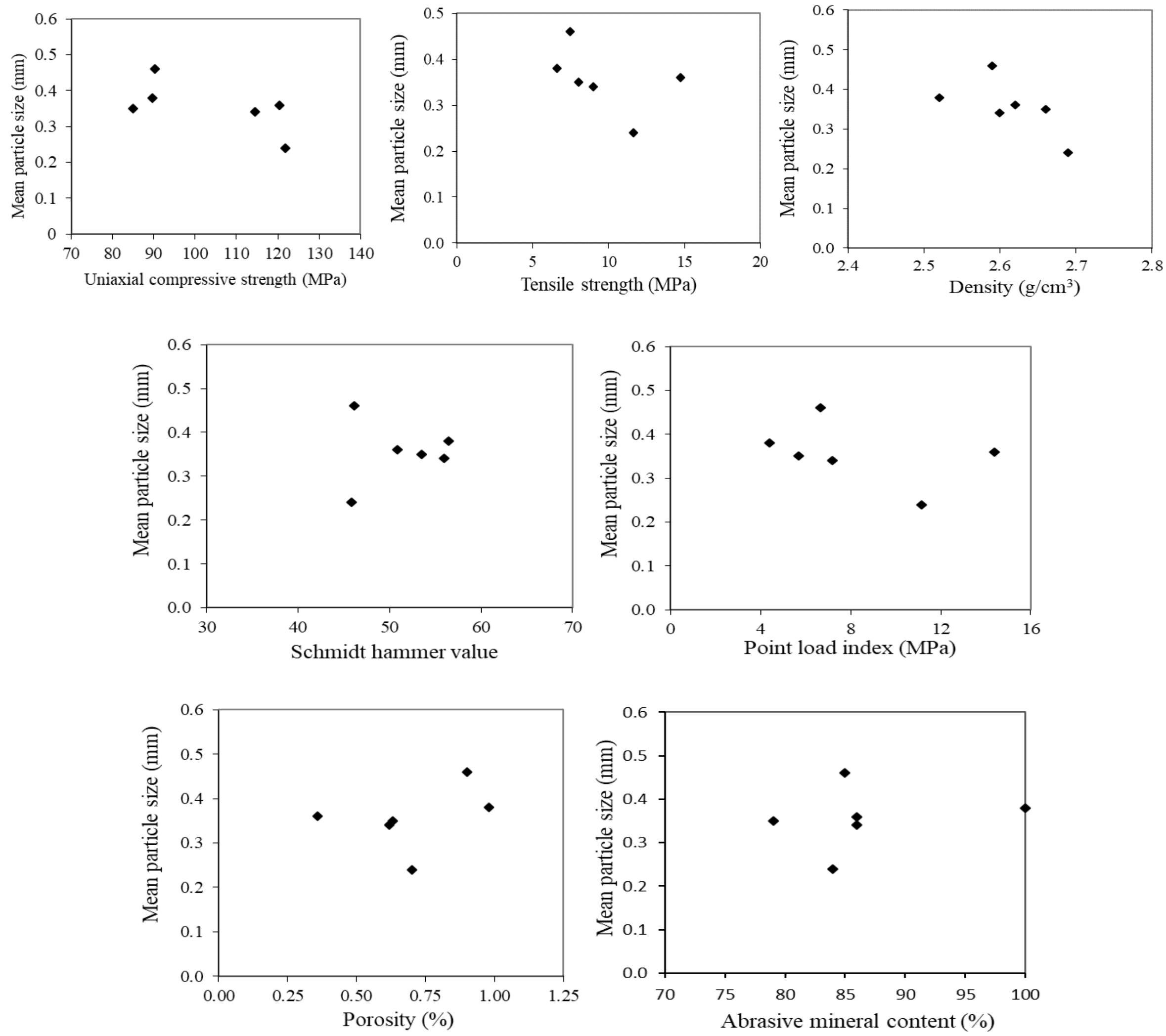

Figure 2. The correlations between the mean particle size (d_{50}) values and the physico-mechanical and mineralogical properties.

It is generally expected that strength and density increase with increasing the d_{50}. The cause behind the lack of correlations is very likely owing to the fact that grinding is a complex process and related to several properties of rock. Therefore, the evaluation of d_{50} should be carried out using multivariable regression.

5.2. Multiple Regression Analysis

Using the SPSS software, the stepwise multiple regression analysis was carried out for the derivation of the best model to predict d_{50}. The uniaxial compressive strength, the Brazilian tensile strength, Schmidt hammer value, density, and abrasive mineral content were automatically included to the best model by the software. The best model is given following:

$$d_{50} = 7.08 - 0.002\sigma_c + 0.007\sigma_t - 0.006SH - 2.06\gamma - 0.011AMC \quad (1)$$
r = 1.00

where d_{50} is the mean particle size (mm), σ_c is the uniaxial compressive strength (MPa), σ_t is the Brazilian tensile strength (MPa), SH is the Schmidt hammer value, γ is the density (g/cm^3), and AMC is the abrasive mineral content (%).

The best model has the highest possible correlation coefficient. However, it is not useful due to the complexity and impracticality. In order to derive simple and practical equations, multiple regression analysis including two and three variables was carried out. Two or three variables were manually added to the analysis and the regression analysis was carried out using SPSS software. The derived alternative models are given following:

$$d_{50} = 0.66 - 0.003\sigma_c - 0.02n \quad (2)$$
r = 0.64

$$d_{50} = 1.99 - 0.002\sigma_c - 0.56\gamma \quad (3)$$
r = 0.76

$$d_{50} = 0.52 - 0.003\sigma_c + 0.001AMC \quad (4)$$
r = 0.64

$$d_{50} = 0.49 - 0.01\sigma_t - 0.03n \quad (5)$$
r = 0.45

$$d_{50} = 2.15 - 0.004\sigma_t - 0.67\gamma \quad (6)$$
r = 0.66

$$d_{50} = 0.38 - 0.01\sigma_t + 0.001AMC \quad (7)$$
r = 0.46

$$d_{50} = 0.38 - 0.006I_s + 0.03n \quad (8)$$
r = 0.41

$$d_{50} = 2.23 - 0.002I_s - 0.7\gamma \quad (9)$$
r = 0.65

$$d_{50} = 0.33 - 0.007I_s + 0.001AMC \quad (10)$$
r = 0.41

$$d_{50} = 0.22 + 0.001SH + 0.11n \quad (11)$$
r = 0.36

$$d_{50} = 3.29 - 0.006SH - 1.01\gamma \quad (12)$$
r = 0.72

$$d_{50} = 0.18 - 0.0002SH + 0.002AMC \quad (13)$$
r = 0.20

$$d_{50} = 6.66 - 2.01\gamma - 0.01AMC \quad (14)$$
r = 0.91

Table 3. *t*- and *F*-test results.

$$d_{50} = 2.62 + 0.11n + 0.0002AMC \quad (15)$$
r = 0.35

$$d_{50} = 0.5 - 0.003\sigma_c - 0.07n + 0.002AMC \quad (16)$$
r = 0.66

$$d_{50} = 6.09 - 0.001\sigma_c - 1.8\gamma - 0.01AMC \quad (17)$$
r = 0.92

$$d_{50} = 0.41 - 0.01\sigma_t - 0.07n + 0.001AMC \quad (18)$$
r = 0.47

$$d_{50} = 6.74 - 0.001\sigma_t - 2.03\gamma - 0.01AMC \quad (19)$$
r = 0.92

$$d_{50} = 0.33 - 0.006I_s + 0.02n + 0.001AMC \quad (20)$$
r = 0.41

$$d_{50} = 6.91 + 0.002I_s - 2.1\gamma - 0.01AMC \quad (21)$$
r = 0.92

$$d_{50} = 0.23 + 0.001SH + 0.12n - 0.0004AMC \quad (22)$$
r = 0.36

$$d_{50} = 7.72 - 0.006SH - 2.28\gamma - 0.01AMC \quad (23)$$
r = 0.98

where d_{50} is the mean particle size (mm), σ_c is the uniaxial compressive strength (MPa), σ_t is the Brazilian tensile strength (MPa), Is is the point load index (MPa), SH is the Schmidt hammer value, γ is the density (g/cm^3), n is the porosity (%), and AMC is the abrasive mineral content (%).

6. Discussion

There are no correlations between the d_{50} and individual rock properties. As stated above, because the grinding a complex phenomenon, the d_{50} should be depends on two or more rock properties. That some strong models obtained by the multiple regression analysis indicates this reality.

Among the multiple regression models with two variables, Eq. (3) and (12) have acceptable correlation coefficients, but they are not strong. However, Eq. (14) has a very strong correlation coefficient. On the other hand, among the multiple regression models with three variables, Eq. (17), (19), (21), and (23) have very strong correlation coefficients.

An important point is that all strong estimation models include abrasive mineral content. This shows that the abrasive mineral content of rock is the dominant parameter in grinding. Before grinding a rock material, its abrasive mineral content should be determined and taken into consideration.

Among the strong estimation models, Eq. (14), (21), and (23) include density, point load index, Schmidt hammer value, and abrasive mineral content. The point load and the Schmidt hammer test are easy to carry out, economical and suitable for the field use. The determination of density and abrasive mineral content is also very easy. Therefore, these equations can be used easily and practically for the estimation of the d_{50}.

Model	Independent variables	*t*-value	Tabulated *t*-value	*F*-value	Tabulated *F*-ratio
Eq. 14	Constant	3.91			
	Density	-3.83	±2.13	7.73	7.71
	Abrasive mineral content	-2.78			
Eq. 21	Constant	3.05			
	Point load index	0.26	±2.35	3.57	9.55
	Density	-2.93			
	Abrasive mineral content	-2.30			
Eq. 23	Constant	6.25			
	Schmidt ham. value	-2.18	±2.35	13.18	9.55
	Density	-6.15			
	Abrasive mineral content	-4.24			

Although the correlation coefficients of the Eq. (14), (21), and (23) are strong, this do not necessarily identify the valid model. The significance of r-values can be determined by the t-test. In the t-test, it is assumed that both variables are normally distributed, and the observations are chosen randomly. The computed t-value is compared to the tabulated t-value using the null hypothesis. When the computed t-value is greater than tabulated t-value, the null hypothesis is rejected, indicating a relationship between the dependent and independent variables.

If the computed *t*-value is less than tabulated t-value, the null hypothesis is not rejected, and *r* is not significant. Because a 90 % confidence level was chosen in this test, a corresponding critical *t*-value ±2.13 for the equation 14 and ±2.35 for the Eq. (21) and (23) respectively, were found. As seen in Table 3, the computed *t*-values are greater than tabulated t-values for the Eq. (14) and (23). However, two of the t-values for the Eq. (21) is lower than tabulated t-values, indicating some doubt about the model.

Analysis of variance was also carried out to test the significance of the regressions. If the computed *F*-value is greater than tabulated F-value, the null hypothesis is rejected since there is a real relation between the dependent and independent variables. This test follows an F-distribution with degrees of freedom $\nu_1 = 1$ and $\nu_2 = 4$ for the equation 14 and $\nu_1 = 2$ and $\nu_2 = 3$ for the equation 21 and 23, so that the critical region will consist of values exceeding 7.71 and 9.55, respectively. In this test, a 90 % level of confidence was chosen. Since the computed F-values are greater than tabulated F-values the Eq. (14) and (23), these models are valid. However, F-value for the Eq. (21) is lower than tabulated F-value, showing some doubt about the model (Table 3).

Making an exact comparison between the results of this study and the previous studies is difficult, because the grindability criteria in this study are different from that of the prior studies. Just to clarify, while some researchers [10, 12, 14] used the Bond grindability index, others [15, 16] used Hardgrove grindability index for the grindability criterion. On the other hand, Bearman et al. [11] used the impact breakage parameters in the equation of the percentage passing 1/10th of the original feed size for the grindability criterion. In this study, the mean particle size was used for the evaluation of the grindability. Therefore, a general comparison can only be made between the results of this study and the previous studies. The Hardgrove grindability index, the Bond grindability index, and the impact breakage parameters used by Bearman et al. [11] inversely correlates to the rock strength. In other words, increasing the rock strength decreases the grindability of coals and rocks. However, if some simple correlations were established between the mean particle size used in this study and rock strength, they would be directly proportional.

7. Conclusions

Six different granitic rock types were tested in the laboratory and the relations between the d_{50} and the physico-mechanical properties were investigated. No correlations were found between the d_{50} and the physico-mechanical properties using the simple regression analysis. However, some strong models were derived by multiple regression analysis for the estimation of the d_{50}. The results show that the dominant parameter in grinding is the abrasive mineral content of rock.

It is concluded that the d_{50} of granitic rocks can easily be estimated from the models derived by the multiple regression analysis. Predicting the d_{50} from the physico-mechanical properties of rocks is easy, cheap and practical. The models are especially useful for the feasibility or preliminary studies of the projects for which the grindability test is expensive. If the project is feasible, before starting the project, the grindability tests should be carried out instead of using the estimation equations for a good planning. On the other hand, the derived models including index test values are essentially important for the practical use because the index test such as the point load and the Schmidt hammer test are easy to perform, cheap and suitable for the site use. It should be further checked if the derived equations are valid for the other granite or rock types.

8. Acknowledgement

This study has been supported by the Scientific Research Project Unit of Ömer Halisdemir University, under project number FEB 2008/10.

References

[1] P. Berry, E. M. Dantini, and P. Massacci, "Influence of mechanical characteristics of rock on size reduction processing," In Proceedings of Mineral Processing and Extractive Metallurgy., Beijing, IMM, pp. 15-26, 1984.

[2] R. A. Bearman, and R. W. Barley, A. Hitchcock, "Prediction of power consumption and product size in cone crushing," Minerals Engineering, vol. 4, pp. 1243-1256, 1991.

[3] P. Heikkila, "Improving the quality of crushed rock aggregate," Acta Polytechnica Scandinavica, Civil Engineering and Building Construction Series, vol. 96, pp. 1-169, 1991.

[4] C. A. Briggs, and R. A. Bearman, "An investigation of rock breakage and damage in comminution equipment," Minerals Engineering, vol. 9, pp. 489-497, 1996.

[5] C. M. Evertsson, "Cone crusher performance," Ph.D. Thesis, Chalmers University of Technology, Gotenburg, Sweden, 2000.

[6] M. Raisanen, and A. Torppa, "Quality assessment of a geologically heterogeneous rock quarry in Pirkanmaa county, southern Finland," Bulletin of Engineering Geology and the Environment, vol. 64, pp. 409-418, 2005.

[7] D. N. Whittles, S. Kingman, I. Lowndes, and K. Jackson, "Laboratory and numerical investigation into the characteristics of rock fragmentation," Minerals Engineering, vol. 19, pp. 1418-1429, 2006.

[8] B. Kekec, M. Unal, and C. Sensogut, "The effect of textural properties of rocks on their crushing and grinding features," Journal of University of Science and Technology Beijing, vol. 13 (5), pp. 385-392, 2006.

[9] O.Y. Toraman, S. Kahraman, and Cayirli, S., "Predicting the crushability of rocks from the impact strength index," Minerals Engineering, vol. 23, pp. 752–754, 2010.

[10] V. Deniz, G. Balta, and A. Yamik, "The interrelationships between bond grindability of coals impact strength index, point load index and friability index," In Proceedings of the 6th International Mineral Processing Symposium, Kusadasi, Turkey, pp.15-19, 1996.

[11] R.A. Bearman, C.A. Briggs, and T. Kojovic, "The application of rock mechanics parameters to the prediction of comminution behavior," Minerals Engineering, vol. 10, pp. 255-264, 1997.

[12] V. Deniz, and H. Ozdag, "A new approach to Bond grindability and work index: dynamic elastic parameters," Minerals Engineering, vol. 16, pp. 211-217, 2003.

[13] H.T. Ozkahraman, "A meaningful expression between Bond work index, grindability index and friability value," Minerals Engineering, vol. 18, pp. 1057-1059, 2005.

[14] N. Sengun, Y. Umucu, R. Altındag, V. Deniz, S. Çayırlı, and B. Oguz, "Kayaçların aşınma indeks değerlerinin fiziko-mekanik özelliklerle olan etkileşimlerinin değerlendirilmesi," VIII. Bölgesel Kaya Mekaniği Sempozyumu Kitapçığı, Istanbul, pp. 315-320, 2006. (In Turkish)

[15] O. Su, N.A. Akçın, and I. Toroğlu, "Kömürün öğütülebilirliği ile dayanım ve indeks özellikleri arasındaki ilişkiler," Türkiye 14. Kömür Kongresi Bildiriler Kitabı, pp. 77-86, 2004. (In Turkish)

[16] B. Tiryaki, "Practical assessment of the grindability of coal using its hardness characteristics," Rock Mechanics and Rock Engineering, vol. 38 (2), pp. 145-151, 2005.

[17] ISRM, The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974-2006. Ulusay R., Hudson J.A., Editors. Ankara: Kozan Ofset Press, 2007.

[18] ISRM, The ISRM Suggested Methods for Rock Characterization, Testing and Monitoring: 2007-2014, R. Ulusay, Ed., Springer International Publishing, Cham, Switzerland, 2015.