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*RESEARCH ARTICLE / ARAŞTIRMA MAKALESI*

# Statistical Investigation of the Mineralogical Effect on Blastability in Granitic Rocks

# Granitik Kayaçlarda Patlatılabilirlik Üzerindeki Mineralojik Etkinin İstatistiksel İncelenmesi

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## Abstract

In this study, the effect of physico-mechanical and mineralogical properties of core samples taken from granite rocks obtained from different locations on blastability was statistically analyzed. The relationship between the mineral content of the rocks and rock mechanics parameters was evaluated. The best regression equations with strong relationships ($R^2>0.700$) involving the parameters used in the blastability formulas were then obtained. These equations were analyzed for five different blastability indices and the results of the forecasting accuracy analyses (RMSE= 0.000-0.085 and MAPE= 0.06-1.82) showed that the models were quite successful. According to the results of the best forecasting accuracy analysis, the parameters to be considered in the specific charge calculation were mineral content, uniaxial compressive strength, tensile strength, apparent porosity, density and ultrasonic P-wave velocity. As a result of the studies, it was concluded that the mineralogical composition of the rocks had a significant effect on the blastability parameters and lower specific charge values were achieved if the minerals are taken into account.

***Keywords:*** *Blastability, Rock Mechanics, Mineralogy, Statistics, MAPE, RMSE*

## Öz

Bu çalışmada farklı lokasyonlardan temin edilen granit kayaçlarından alınan karot numunelerinin fiziko-mekanik ve mineralojik özelliklerinin patlatılabilirliğe etkisi istatistiksel olarak incelenmiştir. Kayaçların mineral içeriklerinin ve kaya mekaniği parametrelerinin birbirleriyle olan ilişkisi değerlendirilmiştir. Sonrasında patlatılabilirlik formüllerinde kullanılan parametreleri içeren güçlü ilişkilere ($R^2>0,700$) sahip en iyi regresyon eşitlikleri elde edilmiştir. Bu eşitlikler beş farklı patlatılabilirlik indeksine göre incelenmiş ve yapılan tahmin doğruluğu analizlerinin sonuçları (RMSE= 0,000-0,085 ve MAPE= 0,06-1,82) modellerin oldukça başarılı olduğunu göstermiştir. En iyi uyum analiz sonuçlarına göre özgül şarj hesabında dikkate alınacak olan parametreler; Mineral içeriği, tek eksenli basınç dayanımı, çekme dayanımı, görünür porozite, yoğunluk ve ultrasonik P-dalga hızıdır. Çalışmalar sonucunda, kayaçların mineralojik bileşimlerinin patlatılabilirlik parametrelerine önemli etkisinin olduğu ve minerallerin dikkate alınması durumunda daha düşük özgül şarj değerlerine ulaşılmaktadır.

***Anahtar Kelimeler:*** *Patlatılabilirlik, Kaya Mekaniği, Mineraloji, İstatistik, MAPE, RMSE*

## 1. Introduction

As a source of raw materials, mining has always been an essential engineering area for humanity. Blasting, which is used in the excavation process and where each step involves significant costs, has become a sensitive area in this sector. Recently, blasting has played an important part in both the mining and construction sectors, particularly with regard to tunneling and transport projects. The results of the blasting have a direct impact on all subsequent process.

In addition to the direct impact on the loading and transportation operations in mining, it also has a significant impact on the ore processing in terms of cost and efficiency through its size reduction. For this reason, the issue of blastability is of great importance in order to fully understand blasting, an important and attention-consuming application. Blastability indicates the sensitivity of the rock mass to explosions and is closely related to the specific charge [1]. To date, numerous investigations into blastability have been carried out and these investigations used experimental blasting under field conditions.

According to Fraenkel [2], there was an empirical relationship between maximum burden, hole depth, charge diameter and charge height [3]. According to Hino [4], blastability coefficient was the ratio of compressive strength to tensile strength. Hansen [5] gave a formula for estimating the amount of explosives for the corresponding fragmentation required for the Marrow Point dam and power plant project. Sassa and Ito [6], in a study primarily concerned with tunneling applications, proposed the RBFI (rock breakage field index) by conducting regression analyzes between crack frequency values and values from laboratory experiments on rock mechanics. Heinen and Dimock [7] defined blastability based on field studies in a copper mine in Nevada (USA) and showed a relationship between specific charge and seismic propagation [3]. Langefors [8] proposed a factor (rock constant)

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that indicates the influence of rock. Praillet [9] defined the burden value as a function of bench height, charge density, detonation velocity, setting height, uniaxial compressive strength, and type of loading equipment [10]. Borquez [11] calculated the blastability factor (Kv) by correcting the drilling equation for the burden using RQD (Rock Quality Designation) with the alteration coefficient [1,10]. Ashby [12] empirically determined the specific charge required for blasting in the Bougainville copper mine (Papua New Guinea) based on the effective internal friction angle, which represent the strength of the rock mass and the crack frequency, which represent the crack density. Leighton et al. [13] developed an equation using the RQI (Rock Quality Index) value proposed by Mathis and a rotary drill [10,14]. Rakishev [15] defined blastability as the resistance to cracking by blasting. Lopez and Jimeno [16] proposed the drilling index for rock character, taking into account the limitations of the RQI [10]. The blasting index developed by Lilly [17] was derived from rock mass properties such as crack density and orientation, specific gravity and hardness. Ghose [18] suggested a geomechanical rock mass classification system and correlated specific charge with blastability under coal mine conditions [1,10]. Gupta et al. [19] attempted to estimate specific charge (kg/m$^3$) values for different rock strengths based on field data [1,3]. JKMRC [20] conducted blastability analysis of the coal layer and classified rock mass properties affecting blast performance [21].

Han et al. [22] used artificial neural networks (ANN) to define the blastability of a rock mass. They designed a back propagation network with 6 input, 5 hidden and 1 output processing elements. The concept of blastability was defined in the study by Rustan et al. [23] as the ability of rock to be fragmented by blasting. The most important physical and mechanical rock properties for blastability; Gokhale [3] explained the blastability index specified by the Norwegian University of Science and Technology (NTNU) about sample blastability in his book. Sawmliana and Pal Roy [24] suggested blastability for the French coal production technique of gallery fan-shaped blasting where roof management is difficult.

In the literature, the effect of mineralogy on the mechanical and physical properties of rocks examined [25], however no study on the mineralogical effect on blastability was found. Within the scope of this study, the parameters that may have an effect on blastability other than the parameters mentioned in the literature were tried to be statistically revealed as a result of petrographic analysis and rock mechanics experiments, and to express the extent of their effects through Mean Absolute Percentage Error (MAPE), Root Mean Square Error (RMSE) and R$^2$.

## 2. Materials and Methods

### 2.1. Material

Rock mechanics tests, mineralogical investigations and statistical studies were carried out on granite samples taken from five different regions in the Eastern Black Sea Region. The granite samples used in the study were obtained from Doğankent (Harşit) district of Giresun (1 piece), Of district of Trabzon (2 pieces) and İkizdere district of Rize (2 pieces). Mineralogical investigations of the samples were carried out at General Directorate of Mineral Research and Exploration (MTA, TÜRKİYE), and rock mechanics tests were carried out at Karadeniz Technical University, Department of Mining Engineering [26].

### 2.2. Methods

Core samples were prepared according to standards. Uniaxial compressive strength test (UCS), determination of elastic modulus (Young's modulus; E) and Poisson's ratio ($\nu$), triaxial compressive strength test (TCS; c, $\phi$), indirect tensile test (ITS; $\sigma_t$), density ($\rho$), unit volume weight (UVW), apparent porosity test (n) were performed according to ISRM [27] and ultrasonic P-wave velocity test (Vp) was performed according to ASTM-D2845 [28].

Based on the data obtained, a statistical analysis was carried out. In our study, the package program SPSS 17.0 was used to statistically evaluate the results. In rock engineering, researchers use multiple regression analyses to create a predictive model among relevant rock properties. Multiple regression analysis showed better predictive performance than simple regression analysis on rock mechanics properties.

After determining that the data were normally distributed, correlation analysis was performed to determine the degree of relationship between the variables. Upon identification of the correlated parameters, the relationship between these parameters was expressed mathematically using multiple regression analysis. In the analysis carried out using the ENTER method, the effects of the independent variables with correlation between them were observed. Therefore, the STEPWISE method was preferred in the multiple regression analysis. Whether the mathematical model formed as a result of the analysis is significant or not is determined by F and Sig. value in the output of the ANOVA analysis. As Sig. < 0.05, the model is significant. The aim of the stepwise method is to find a solution to the multicollinearity problem. The problem of multicollinearity is that the mathematical expression becomes meaningless due to the correlation between the independent variables that we add to increase the explanation rate of the dependent variable. Hence, selecting stepwise will determine the strongest model by eliminating the models that are correlated with each other. The relationship between the rock properties was determined by the Pearson correlation coefficient, and the degree of linear relationship between them was calculated by regression analysis.

Regression analysis provides an equation that mathematically expresses the degree of relationship between a dependent variable and one or more independent variables [29]. In regression analysis, the value of the coefficient of determination (R$^2$) indicates the rate at which a change in the dependent variable is expressed by the independent variables added to the independent model [30]. In addition, the “F-statistic”, which shows the significance of the mathematical models obtained as a result of regression analysis, and the “Sig. value” are important for the interpretation of regression models. If Sig. Value (p)< 0.05, it is concluded that this model is a significant model [31].

Beside the correlation coefficient, analysis of forecasting accuracy analyses (RMSE and MAPE) were calculated to verify the predicted performance of the models with the estimated and measured data, and the prediction performance both models were compared.

The percent prediction error (Eq. 1) was calculated to determine how close the prediction values were to the measured values. Although the values for MAPE (Eq. 2) and RMSE (Eq. 3) always take positive values, the ideal value is close to zero (Table 2.1.) [32].

$$Prediction\ Error\ (\%) = \frac{y - y'}{y}\ 100 \tag{1}$$

$$MAPE\ (\%) = \left[\frac{1}{N}\sum_{i=1}^{N}\frac{y-y'}{y}\right]100 \tag{2}$$

$$RMSE\ (\%) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(y - y')^2} \qquad (3)$$

y is the measured value and y′ is the predicted values and N is the number of data.

**Table 2.1.** Classification of MAPE values [32,33]

| MAPE (%) | Evaluation |
|---|---|
| $MAPE\ \leq \%10$ | Very good prediction |
| $\%\ 10 < MAPE\ < \%\ 20$ | Good prediction |
| $\%\ 20 < MAPE\ < \%\ 50$ | Acceptable prediction |
| $MAPE\ > \%\ 50$ | False prediction |

Data from rock mechanics experiments and petrographic studies of granites were applied to blastability formulas to calculate direct blastability values. The parameters that directly and indirectly affect the blastability were then tested by replacing the relevant parameters with mathematical models resulting from a regression analysis. The results were evaluated using the RMSE and MAPE values.

When determining the parameters used in the studies, a few principles were first established. These principles are: 1. When more than one parameter was present, only one parameter at a time and other parameters affecting it indirectly were applied in the regression analysis to understand their individual effects. 2. Average values representative of the granites were used for the analysis. 3. Since the formation of minerals was a natural process, they were taken into account directly in model identification and were not considered dependent variables and were not replaced by any model.

According to the above principles, the relationships were studied, and the success of the models was demonstrated by analysis of forecasting accuracy between the directly obtained and the calculated results. The aim of the calculations carried out in this study was to demonstrate the need to investigate the parameters that influence blastability not only alone, but in a variety of ways. It was statistically proven that the neglected parameters also have an influence.

## 3. Results and Dicussion

### 3.1. Physical and Mechanical Properties of Rocks

The mineralogical composition of Harşit (H), Hayrat Gray (HG), Hayrat Yellow (HS), İkizdere Yellow (İS) and İkizdere Blue (İM) samples were given in the table (Table 3.1). The results of the rock mechanical tests, which indicate the physical and mechanical properties of the rocks, were shown in Table 3.2. Of the rock mechanical data, only the parameters that influence blastability were analyzed in comparison to the literature.

**Table 3.1** Mineralogical composition of Granitic rocks

| | Mineral Percentages (%) | | | | |
|---|---|---|---|---|---|
| **Samples** | **İM** | **İS** | **HS** | **HG** | **H** |
| Quartz | 25 | 45 | 35 | 35 | 25 |
| Alkali feldspar | 30 | 35 | 40 | 40 | 30 |
| Plagioclase | 40 | 15 | 15 | 10 | 35 |
| Mafic Minerals | 4 | 4 | 5 | 5 | 8 |
| Others | 1 | 1 | 5 | 10 | 2 |

**Table 3.2.** Physical and mechanical properties of granites

| Granite Group | ρ (g/cm³) | UCS (MPa) | ITS (MPa) | Vp (km/sn) | n (%) | c (MPa) | ϕ (o) | E (GPa) | ν |
|---|---|---|---|---|---|---|---|---|---|
| **İM** | 2.639 | 181.28 | 12.50 | 4.682 | 0.60 | 17.84 | 63 | 67.05 | 0.21 |
| **İS** | 2.613 | 112.39 | 11.46 | 3.658 | 0.85 | 13.55 | 60 | 47.21 | 0.25 |
| **HS** | 2.619 | 148.39 | 10.83 | 4.131 | 0.98 | 19.81 | 57 | 45.97 | 0.25 |
| **HG** | 2.621 | 153.23 | 10.78 | 4.243 | 0.86 | 19.56 | 59 | 60.03 | 0.22 |
| **H** | 2.699 | 206.89 | 14.66 | 4.695 | 0.56 | 23.72 | 60 | 69.14 | 0.20 |

ρ: Density, UCS: Uniaxial Compressive Strength, ITS: Indirect Tensile Strength, Vp: Ultrasonic P-Wave Velocity, n: Apparent Porosity, c: Cohesion, ϕ: Internal Friction Angle, E: Modulus of Elasticity, ν: Poisson's Ratio

### 3.2. Statistical Analysis

### 3.2.1. Simple and multiple regression tests

In studies on blastability, the most effective parameters from the physical and mechanical properties of rocks were density ($\rho$), modulus of elasticity (E), ultrasonic P-wave velocity (Vp), uniaxial compressive strength (UCS), indirect tensile strength (ITS), internal friction angle (ϕ) values. In the statistical analysis tests, simple and multiple regression tests were performed and only the models with R² values above 0.700 (Table 3.3.) within the significant values of the resulting data were used in the explosibility calculation.

**Table 3.3.** Statistical analysis of dependent variables affecting blastability

| Dependent Variable | Equation No | Regression | Compliance Test | Anova Test | |
|---|---|---|---|---|---|
| $\boldsymbol{\rho}$ | D1 | $\rho = 2.634 + 0.015 * Maf - 0.093 * n$ | $R^2 = 0.889$ | F: 87.982 | Sig.: 0.000 |
| $\boldsymbol{E}$ | D2 | $E = 35.665 + 15.675 * Vp - 197.636 * v$ | $R^2 = 0.758$ | F: 34.434 | Sig.: 0.000 |
| | D3 | $E = -58.546 + 31.119 * Vp - 215.472 * v + 0.974 * K$ | $R^2 = 0.807$ | F: 29.360 | Sig.: 0.000 |
| $\boldsymbol{Vp}$ | D4 | $Vp = 2.385 + 0.012 * UCS$ | $R^2 = 0.902$ | F: 212.166 | Sig.: 0.000 |
| | D5 | $Vp = 5.977 - 0.051 * K$ | $R^2 = 0.853$ | F: 133.200 | Sig.: 0.000 |
| | D6 | $Vp = 2{,}421 + 0.014 * UCS - 0.087 * Maf$ | $R^2 = 0.953$ | F: 222.198 | Sig.: 0.000 |
| $\boldsymbol{UCS}$ | D7 | $UCS = -166.242 + 76.295 * Vp$ | $R^2 = 0.902$ | F: 212.166 | Sig.: 0.000 |
| | D8 | $UCS = 296.391 - 4.120 * K$ | $R^2 = 0.851$ | F: 130.897 | Sig.: 0.000 |
| | D9 | $UCS = -152.806 + 65.151 * Vp + 6.592 * Maf$ | $R^2 = 0.967$ | F: 321.773 | Sig.: 0.000 |
| | D10 | $UCS = -533.214 + 61.533 * Vp + 4.098 * Maf + 154.981 * \rho$ | $R^2 = 0.973$ | F: 250.992 | Sig.: 0.000 |
| $\boldsymbol{ITS}$ | D11 | $ITS = -54.472 + 27.127 * \rho - 0.144 * AF$ | $R^2 = 0.784$ | F: 39.863 | Sig.: 0.000 |
| $\boldsymbol{\phi}$ | D12 | $\phi = 77.643 - 0.414 * AF - 0.643 * Maf$ | $R^2 = 0.867$ | F: 71.720 | Sig.: 0.000 |
| | D13 | $\phi = 73.728 - 0.359 * AF - 0.730 * Maf + 0.042 * E$ | $R^2 = 0.915$ | F: 75.043 | Sig.: 0.000 |
| | D14 | $\phi = 73.453 - 0.243 * AF - 0.799 * Maf + 0.035 * E - 3.937 * n$ | $R^2 = 0.942$ | F: 81.840 | Sig.: 0.000 |

### 3.2.2. Blastability Analysis

#### 3.2.2.1. Blastability According to Hino

In the study by Hino [4], compressive and tensile strengths were used as rock mechanical parameters. The aim here was to demonstrate how close the coefficient value calculated with the values of the existing parameters taking into account the equation from Hino [4] was and the coefficient value calculated with the parameters determined from the regression model. For this reason, in this study, the direct effect of the strength parameters on the blastability was evaluated by replacing the strength parameters and then the indirect effect parameters were evaluated using high $R^2$ regression models expressing the compressive strength (Table 3.4). The parameters, that directly affect the Hino [4] equation, were UCS and ITS. According to the forecasting accuracy analysis, the best results were obtained with equations D10 and D9 (ITS constant) and D11 (UCS constant), respectively. Consequently, Vp, mafic mineral content and density were the primary parameters, beside quartz content and alkali feldspar content also influence the blastability.

**Table 3.4.** Direct and indirect calculation of blastability with rock mechanics parameters according to Hino [4].

| Blastability Formula | | Direct Account | Indirect Account | | | | |
|---|---|---|---|---|---|---|---|
| | | | ITS (constant)<br>UCS | | | | UCS (constant)<br>ITS |
| | Equation / Sample name | | D8 | D7 | D9 | D10 | D11 |
| $Blastability\ coefficient = \frac{UCS}{ITS}$ | İM | 14.502 | 15.471 | 15.278 | 14.288 | 14.422 | 14.163 |
| | İS | 9.807 | 9.685 | 9.847 | 9.763 | 9.88 | 9.885 |
| | HS | 13.702 | 14.053 | 13.752 | 13.785 | 13.607 | 13.727 |
| | HG | 14.214 | 14.118 | 14.609 | 14.526 | 14.339 | 14.097 |
| | H | 14.113 | 13.192 | 13.094 | 14.039 | 14.104 | 14.347 |
| | RMSE | | 0.622 | 0.6 | 0.177 | 0.085 | 0.195 |
| | MAPE | | 3.54 | 3.22 | 1.04 | 0.58 | 1.16 |

#### 3.2.2.2. Blastability According to Ashby

The Ashby [12] equation differs from the Hino [4] equation in that it calculates the specific charge directly. Considering the blastability equation presented in his study, he used density, internal friction angle, and crack frequency. In this equation, Ashby [12] attempted to explain blastability by considering the intrinsic parameters between discontinuities and grains. Density and angle of internal friction were parameters that are directly substituted and the other parts were assumed to be constant (Table 3.5). The roughness angle was considered within the internal friction angle, while the crack frequency was taken to be 10, which corresponds to the bedrock transition zone reported in his study. By direct calculation, it was calculated that the blastability of the granites in the study varies between 1.0 and 1.3 kg/m³. When evaluated with regression models, the calculated specific charge was between 1.0 and 1.3 kg/m³, as in the direct calculation, and was above the specific charge value given by Dyno Nobel (0.7 to 0.8 kg/m³) [34].

**Table 3.5.** Direct and indirect calculation of blastability with rock mechanics parameters according to Ashby [12].

| Blastability Formula | | Direct Account | Indirect Account | | | |
|---|---|---|---|---|---|---|
| | | | Internal Friction Angle (constant)<br>Density | Density (kg/m³) (constant)<br>Internal Friction Angle | | |
| | Equation / Sample name | | D1 | D12 | D13 | D14 |
| $Specific\ Charge = \frac{0,56.\rho.\tan(\phi+i)}{\sqrt[3]{crack/meter}}$ | İM | 1.347 | 1.346 | 1.326 | 1.338 | 1.344 |
| | İS | 1.177 | 1.178 | 1.205 | 1.188 | 1.179 |
| | HS | 1.049 | 1.048 | 1.084 | 1.075 | 1.068 |
| | HG | 1.134 | 1.137 | 1.085 | 1.101 | 1.110 |
| | H | 1.215 | 1.217 | 1.219 | 1.216 | 1.215 |
| | RMSE | | 0.000 | 0.032 | 0.020 | 0.014 |
| | MAPE | | 0.14 | 2.38 | 1.42 | 0.86 |

As can be seen from the values in Table 3.5, the RMSE and MAPE values obtained when the regression models were substituted for the density and internal friction angle values used in Ashby's [12] study were close to perfect. Furthermore, ρ and ϕ directly affected the angle, while Maf, n, AF and E indirectly affected the blastability. Alkaline Feldspar content, Mafic Mineral content, Modulus of Elasticity and Apparent Porosity values had a strong effect on blastability when MAPE and RMSE values in multiple regression were analyzed. This was seen in the analysis calculated according to equations D1, D14 and D13.

#### 3.2.2.3. Blastability According to Rakishev

Rakishev's [15] examined the influence of the mechanical properties of many rocks on blastability and attempted to calculate a critical velocity required for cracking. He tried to explain the blastability of the rock based on the calculated speed.

Rakishev [15] used compressive strength, tensile strength, density and ultrasonic P-wave velocity in his formula. In the study conducted by Rakishev [15], the average k was 0.964, the g was 9.807 m/s² and the average dn was 0.51 m, which were found from the values given for granodiorite rocks. RMSE and MAPE values were calculated between the predicted and actual values and RMSE and MAPE, the best value, were performed (Table 3.6a,b).

**Table 3.6a.** Direct and indirect calculation of blastability with rock mechanics parameters according to Rakishev [15].

| Blastability Formula | | Direct Account (km/s) | Indirect Account (km/s) | | | | |
|---|---|---|---|---|---|---|---|
| | | | UCS, Vp, ITS (constant) | ρ, Vp, ITS(constant) | | | |
| | | | Density | UCS | | | |
| | Equation / Sample name | | D1 | D8 | D7 | D9 | D10 |
| Critical Crack Velocity $= k\sqrt{g.d_n + \frac{0{,}1\,UCS+ITS}{\rho.V_p}}$ | İM | 4.635 | 4.636 | 4.733 | 4.713 | 4.613 | 4.627 |
| | İS | 4.531 | 4.529 | 4.516 | 4.536 | 4.525 | 4.540 |
| | HS | 4.529 | 4.530 | 4.564 | 4.534 | 4.537 | 4.519 |
| | HG | 4.503 | 4.496 | 4.494 | 4.541 | 4.533 | 4.515 |
| | H | 4.946 | 4.943 | 4.839 | 4.828 | 4.937 | 4.945 |
| | RMSE | | 0.000 | 0.068 | 0.066 | 0.020 | 0.000 |
| | MAPE | | 0.06 | 1.12 | 1.02 | 0.32 | 0.18 |

**Table 3.6b.** Direct and indirect calculation of blastability with rock mechanics parameters according to Rakishev [15].

| Blastability Formula | | Direct Account (km/s) | Indirect Account (km/s) | | | |
|---|---|---|---|---|---|---|
| | | | UCS, ITS, ρ (constant) Vp | | | ρ, Vp, UCS (constant) ITS |
| | Equation / Sample name | | D5 | D4 | D6 | D11 |
| Critical Crack Velocity $= k\sqrt{g.d_n + \frac{0{,}1\,UCS+ITS}{\rho.V_p}}$ | İM | 4.635 | 4.624 | 4.701 | 4.673 | 4.659 |
| | İS | 4.531 | 4.515 | 4.483 | 4.539 | 4.521 |
| | HS | 4.529 | 4.494 | 4.509 | 4.570 | 4.527 |
| | HG | 4.503 | 4.531 | 4.513 | 4.567 | 4.511 |
| | H | 4.946 | 4.943 | 4.845 | 4.991 | 4.927 |
| | RMSE | | 0.020 | 0.058 | 0.042 | 0.014 |
| | MAPE | | 0.40 | 1.04 | 0.84 | 0.26 |

When calculated directly, the resulting velocity values were between 4.5-4.9 km/s. These results were consistent with the values given by Rakishev [15] for igneous rocks in his study in the range of 3.65–4.88 km/s. When analyzing Table 3.6b, it becomes clear that the indirect calculation based on density produces almost perfect results. In the same way, another good result was obtained from the indirect calculation according to equation D10 (MAPE: 0.18, RMSE: 0.000) for ITS and UCS. According to Rakishev [15], the granites used in the study were considered difficult to blast (Table 3.7).

**Table 3.7.** Correlation between critical crack velocity and blastability [15]

| Critical crack velocity (m/s) | Blastability |
|---|---|
| $3{,}6 > V_{cr}$ | Easy to blast |
| $3{,}6 < V_c < 4{,}5$ | Partially easy to blast |
| $4{,}5 < V_{cr} < 5{,}4$ | Difficult to blast |
| $5{,}4 < V_{cr} < 6{,}3$ | Very difficult to blast |
| $6{,}3 < V_{cr}$ | Extremely difficult to blast |

When Table 3.6 was examined; It was statistically shown that in addition to the directly influencing parameters (density, ITS, UCS and Vp), the quartz content, the mafic mineral content, the alkali feldspar and the apparent porosity also had an influence on the blastability. Taking MAPE and RMSE into account, the results were at a very good level of prediction. The best results were obtained with equations D1, D10 and D11, respectively.

#### 3.2.2.4. Blastability According to Lilly

Lilly [17] proposed a method that is easier to use. According to this method, the condition of the joints (openness and alignment) was important. The calculated index value was then designated from Figure 3.1 which the number in relation to the specific charge and the required amount of ANFO was determined. In the study by Lilly [17], the rock mechanical parameters that contribute to the equation include; Given the values considered in this study, only the density parameter was used. The blast index developed by Lilly [17] was derived from rock mass properties such as crack density and orientation, specific gravity and hardness. The constant values were taken from his table (RMD:50, JPS:10, JPO:30, H:7) (Table 3.8.). The results of the density substituted regression model are shown in the following table (Table 3.9).

**Table 3.8.** Blastability index parameters according to Lilly [17].

| | | |
|---|---|---|
| RMD<br>(Rock mass definition) | Crumbly/Fragmentable rock mass | 10 |
| | Blocky rock mass | 20 |
| | Completely massive rock mass | 50 |
| JPS<br>(Distance between planes) | Close range (<0.1m) | 10 |
| | Moderate (0.1-1.0 m) | 20 |
| | Wide range (>1.0 m) | 30 |
| JPO<br>(Joint plane orientation) | Horizontal | 10 |
| | Branching out of the slope | 20 |
| | Normal sheet orientation with slope | 30 |
| | Inwardly branched from the slope | 40 |

By analyzing the results in Table 3.9, it was found that the density in indirect calculation had excellent MAPE and RMSE values. It was also found that mafic mineral content and apparent porosity could be used as parameters instead of density. Therefore, taking into account the study of Lilly [17], it was statistically proven that mafic mineral content and apparent porosity had an influence on blastability.

**Table 3.9.** Direct and indirect calculation of blastability with rock mechanics parameters according to Lilly [17].

| Blastability Formula | Equation / Sample name | Direct Account | Indirect Account<br>ρ<br>D1 |
|---|---|---|---|
| Blasting index = $0,5\ (RMD + JPS + SGI + M)$ | İM | 56.488 | 56.475 |
| | İS | 56.163 | 56.188 |
| | HS | 56.238 | 56.225 |
| | HG | 56.263 | 56.363 |
| | H | 57.238 | 57.275 |
| | RMSE | | 0.049 |
| | MAPE | | 0.06 |

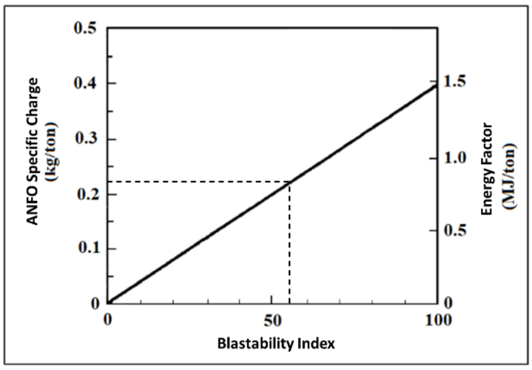

**Figure 3.1.** Blastability index-specific charge relationship [17].

Considering Figure 3.1, the calculated values for the rocks used in this study varied by approximately 0.23 kg/ton (0.62 kg/m³) and the specific charge values were below and close to the specific charge value (0.7– 0.8 kg/m³) given by Dyno Nobel [34]. According to the result of the MAPE and RMSE analysis, the process had very good predictive values based on the only available variables (Eq. D1).

### 3.2.2.5. Blastability According to Gupta

In the study conducted by Gupta [19], the parameters specified in the blastability formula included UCS and modulus of elasticity, which are the rock mechanics parameters used in this study, and the rest were considered constant, and the results were given in Table 3.10. The constant burden in Gupta's equation was accepted as 1.2 m considering the field applications [19]. Table 3.10 showed that the best results were obtained with equations D9 and D10 based on UCS. Gupta [19] directly calculates the specific charge (kg/m³) and this value varied between 0.49-0.82 kg/m³ for the rocks studied. As can be seen from the figure below; in Grupta's [19] research, it was statistically revealed that Vp, density and mafic mineral content, quartz content and Poisson's ratio also affect the specific charge. In the calculations made with the models, the specific charge value varies between 0.49-0.84 kg/m³ and was in accordance with the specific charge (0.7-0.8 kg/m³) value range specified by Dyno Nobel [34]. According to the prediction accuracy analysis, the best results are obtained with equations D9, D10 and D3, respectively.

**Table 3.10.** Direct and indirect calculation of blastability with rock mechanics parameters according to Gupta [19].

| Blastability Formula | Equation / Sample name | Direct Account (kg/m³) | Indirect Account (kg/m³)<br>UCS (constant)<br>E<br>D2 | <br><br><br>D3 | <br>E (constant)<br>UCS<br>D8 | <br><br><br>D7 | <br><br><br>D9 | <br><br><br>D10 |
|---|---|---|---|---|---|---|---|---|
| Specific Charge = $0,278\ B^{-0,407}\ F^{0,6}$ | İM | 0.722 | 0.722 | 0.731 | 0.786 | 0.774 | 0.712 | 0.720 |
| | İS | 0.490 | 0.524 | 0.512 | 0.491 | 0.501 | 0.496 | 0.503 |
| | HS | 0.722 | 0.670 | 0.677 | 0.738 | 0.718 | 0.720 | 0.709 |
| | HG | 0.619 | 0.640 | 0.630 | 0.625 | 0.652 | 0.648 | 0.637 |
| | H | 0.826 | 0.834 | 0.841 | 0.771 | 0.764 | 0.833 | 0.838 |
| | RMSE | | 0.028 | 0.024 | 0.037 | 0.040 | 0.014 | 0.014 |
| | MAPE | | 3.70 | 3.12 | 3.78 | 4.56 | 1.68 | 1.82 |

## 4. Conclusions

Within the scope of this study, rock mechanics experiments, mineralogical investigation and statistical studies were carried out on granite samples taken from five different regions in the Eastern Black Sea Region ("H" Harşit region, "HG and HS" Of region and "IM and IS" İkizdere region). The findings obtained as a result of the studies were given below.

- As a result of the study, a strong correlation was found between blastability and mineral distribution.

- Considering the study of Hino [4], the best result was obtained from equation D10. The analysis of forecasting accuracy (MAPE and RMSE) results of this equation containing Vp - Mafic Mineral - ρ were 0.085 of RMSE and 0.58 of MAPE.

- Considering the Ashby [12] study, the best analysis of forecasting accuracy result was obtained with regression equation D14 containing Alkali Feldspar - Mafic Mineral - E - n (RMSE: 0,014, MAPE: 0,86).

- Considering the formula of Rakishev [15], the best result was obtained with equation D1 containing Mafic Mineral-n, where UCS, ITS, Vp were constant (RMSE: 0,000 MAPE: 0,06).

- When the study of Lilly [17] was analyzed, the model was in a very good prediction range. While other parameters were constant, the best analysis of forecasting accuracy were obtained with equation D1 (Mafic Mineral-n) (RMSE: 0.014, MAPE: 0.26).

- Gupta [19] concluded that when E was constant, the model with equation D9 with Mafic Mineral - n was the best analysis of forecasting accuracy (RMSE 0.014, MAPE 1.82).

As a result of the evaluations made by statistical analysis, it was revealed that mineralogy had an effect on the parameters used in the calculation of blastability and the specific charge value decreased even more when minerals were taken into account. The values given were all in terms of specific charge except Hino [4] and Rakishev [15]. When the calculated values were examined, the parameters to be taken into account in the specific charge calculation according to the best analysis of forecasting accuracy results were mineral content, uniaxial compressive strength, indirect tensile strength, apparent porosity, density and ultrasonic P-wave velocity. In future studies, it is recommended to create a new blastability index including the mineral structure and the mentioned parameters with detailed field and laboratory model blasting studies.

## Ethics committee approval and conflict of interest statement

There is no need to obtain permission from the Ethics Committee or the article prepared.

There are no conflicts of interest with any individual or institution in this article.

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