Predicting strength loss of igneous rocks treated with microwave energy

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ABSTRACT: This paper investigates the predictability of the strength loss of igneous rocks treated with microwave energy. First microwave treatment tests were performed at 6 kW power for the duration of 120s on the core samples of nine different igneous rocks such as granite, syenite and gabbro. Then uniaxial compressive strength (UCS) tests were carried out on the hot specimens. Mineralogical analysis, density and porosity tests were also performed on the samples. The data were evaluated using multiple regression analysis and an estimation equation with very high correlation coefficient was derived for the strength loss. The equation includes UCS, maximum surface temperature, quartz plus feldspar content and porosity values. The statistical test showed that the equation was valid. It was concluded that the derived equation could be used for the estimation of the strength loss of igneous rocks treated with microwave energy.

Keywords: Igneous rocks, Microwave treatment, Strength loss, Regression analysis.

1 INTRODUCTION

The mechanized excavation of rocks indicates a rapidly increasing trend in the world. But low advance rate and excessive tool wear are the important difficulties when excavating hard and abrasive rocks. Several studies have been carried out by several researchers to solve these problems. One of the recent studies is the microwave-assisted excavation of hard rocks. Some researchers have studied the effects of microwave irradiation on the mechanical properties of rocks for possible application in the microwave assisted rock excavation.

Basalt was subjected to studies by Satish (2005) and Satish et al. (2006) using low power microwaves (150W). Under the point load test, they saw that a long microwave treatment lead to samples spalling and local chipping. Additionally, several rock samples showed cracking and splitting at high exposure duration. With more exposure time, they noticed that the rock's strength decreased.

Motlagh (2009) looked into how microwave treatment affected the abrasivity and mechanical characteristics of several hard rocks. He demonstrated that after microwave treatment, the uniaxial compressive strength (UCS) values of almost all samples reduced by roughly 30%. Considerable decrease in Brazilian tensile strength (BTS) was seen in some samples. Nearly all samples exhibited a drop of roughly 30% in the Cerchar abrasivity index.

In a 3kW microwave oven operating at 2.45GHz, Peinsitt et al. (2010) examined the impact of microwave illumination on the UCS and sonic velocity of sandstone, granite, and basalt. Both dried and samples that had been drenched with water were used in the testing. They discovered that water saturation increased weakening, especially in sandstone, had a minimal impact on granite, and had no discernible impact on basalt.

Nejati et al. (2012) investigated microwaving effects on the basalt specimens' fracture toughness. According to the study, microwave illumination's power level and exposure time both cause a decrease in fracture toughness and an increment in crack density. Nevertheless, using stronger microwave powers for a shorter amount of time reduced fracture toughness and density significantly.

Hassani et al. (2016) and Hassani and Nekoovaght (2011) carried out detailed experimental studies to examine how microwave illumination effects temperature distribution and the loss of strength in hard rocks. They demonstrated that the UCS and BTS values decreased as treatment duration and power increased. It was discovered that the specimen size had an impact on the pace of heating: smaller disc-shaped specimens heated faster than larger cylindrical samples.

Kahraman et al. (2020) examined the influence of microwave exposure on UCS and BTS of nine igneous rock specimens. The evaluation of the results showed that the temperature and strength loss after microwave exposure were different for each rock type. Sample temperature and strength loss generally increase as microwave power and treatment duration increase.

Lu et al. (2019) investigated the heating degrees and strength changes of basalt rock samples under microwave energy at 5 kW power. They indicated that the strength values decreased depending on the microwave application time, some samples broken down and some samples melted.

Deyab et al. (2021) examined how microwave radiation influence the strength of kimberlite and granite rocks by applying microwave radiation between 2 kW and 15 kW. They showed that the strength values decreased significantly as a result of microwave radiation.

Lu et al. (2021) studied the CT values, acoustic emission values, and the UCS values of hard rocks exposed to microwaves. They revealed that CT and sonic velocity values decreased with increasing exposure time. Compressive strength and acoustic emission values also decreased gradually with increasing exposure time.

Gao et al. (2022) carried out laboratory and numerical studies on the effect of microwave energy on hard granite. The test results showed that the samples reached temperatures as high as 550ºC; some cracks and meltings were observed. They revealed that microwave power of 1 kW should be applied power for minimum of 3 min. to granite sample subjected to the test in order to cause irreversible deformations.

This paper investigates the predictability of the strength loss of igneous rocks treated with microwave energy. The microwave treatment tests were performed at 6 kW power for the duration of 120s on the core samples of nine different igneous rocks such as granite, syenite and gabbro.

2 PHYSICO-MECHANICAL TESTS

Six granites, two syenites and one gabbro types were selected for testing in this study. The types and locations of the samples are given in Table 1. The selected granite and syenite types have different mineralogical constitutes and grain sizes.

NQ (47.6 mm) size core samples were prepared from the blocks of rocks for the laboratory studies. Density, porosity, and the uniaxial compressive strength (UCS) tests were conducted according to ASTM (2014) standards and ISRM (2007) suggested methods. The averages of the test results are listed in Table 1.

Table 1. The rock types used in the tests and physico-mechanical tests results.

Code	Rock type	Location	Density (g/cm^3)	Porosity (%)	UCS (MPa)
1	Granite (Rosa Well)	Spain	2.57±0.02	1.35±0.5	115.01±9.2
2	Granite (Rosa Minho)	Spain	2.58±0.02	1.06±0.3	129.13±3.5
3	Granite (Steppe Yellow)	Egypt	2.49±0.08	1.21±0.5	152.70±5.6
4	Granite (Nublado)	Spain	2.65±0.02	1.19± 0.5	131.46±6.2
5	Granite (Kaman Rosa)	Türkiye	2.50±0.02	2.17±0.2	95.51±14.7
6	Granite(Kozak Granit)	Türkiye	2.62±0.02	1.27±0.4	141.32±9.6
7	Syenite (Volga Blue)	Ukraine	2.64±0.02	1.97±0.4	116.32±13.6
8	Syenite (Jungle Green)	Egypt	2.63±0.03	1.24±0.2	204.89±24.4
9	Gabbro (Nero Turka)	Türkiye	3.00±0.02	0.51±0.1	197.70±7.7

3 MICROWAVE TREATMENT TESTS

A 6 kW industrial microwave oven at the frequency of 2.45 GHz was used for the irradiation of the air dried samples (Figure 1). The specimens were exposed to microwaves at 6 kW power for the duration of 120s. The surface temperature of each specimen was measured with an infrared gun before the microwave irradiation and immediately after removing the sample from the oven. The strength tests were carried out on the samples right after being treated with microwave energy. Three samples were tested for each case.

Figure 1. The microwave oven used in the study.

4 MINERALOGY

Thin sections were prepared from each rock type to determine the mineral types and percentages under the polarizing microscope. For the rock types with coarse grain size, two thin sections were prepared, and the counted mineral percentages were averaged. Table 2 presents the mineral types and percentages of the tested rock types.

Table 2. The mineral contents and the percentages of the specimens.

Mineral type	Rock codes and mineral contents (%)								
	1	2	3	4	5	6	7	8	9
Quartz	15	27	23	19	28	12	-	-	-
Orthoclase	45	26	36	28	41	25	70	35	13
Plagioclase	11	12	18	15	18	32	-	8	27
Microcline	4	3	-	15	-	-	-	-	-
Biotite	9	12	8	11	9	16	12	8	7
Hydrobiotie	5	-	-	-	-	-	3	-	-
Muscovite	-	-	-	8	-	-	-	-	-
Amphibole	-	-	3	-	-	13	-	-	4
Sericite	4	9	-	4	-	-	4	3	-
Chlorite	4	8	2	-	4	2	-	2	4
Titanite	2	-	-	-	-	-	-	-	-
Pyroxene	1	-	4	-	-	-	6	-	42
Epidote	-	3	4	-	-	-	-	-	3
Nepheline	-	-	-	-	-	-	-	32	-
Tourmaline	-	-	-	-	-	-	-	6	-
Garnet	-	-	-	-	-	-	-	6	-
Calcite	-	-	2	-	-	-	-	-	-
Pyrite	-	-	-	-	-	-	3	-	-
Magnetite	-	-	-	-	-	-	2	-	-

5 RESULTS AND EVALUATION

Table 3 lists the maximum surface temperatures and the UCS losses of the specimens after the microwave treatment. Granite/Rosa Well (Code 1) has the lowest surface temperature and the lowest UCS loss. This is due to the fact that Granite/Rosa Well has high content of quartz and feldspar minerals absorbing microwave energy less. On the other hand, Syenite/Volga Blue (Code 7) has the highest surface temperature and the highest UCS loss. Since Syenite/Volga Blue has pyrite and magnetite minerals absorbing microwave energy too much, its surface temperature reached high value and its UCS loss was too high.

Table 3. The surface temperatures of the specimens before and after the microwave treatment.

Code	Max. temperature after microwave treatment (°C)	UCS loss (%)
1	**174.3**	**6.8**
2	430.2	16.5
3	288.1	26.3
4	227.2	7.8
5	192.3	23.0
6	295.2	26.5
7	**522.3**	**38.9**
8	195.6	25.0
9	503.1	22.3

Since several parameters affect the microwave heating of rocks, the strength loss cannot be evaluated using simple regression analysis. Therefore, multiple regression analysis was performed including maximum surface temperature, the UCS, the percentage of quartz plus feldspar (orthoclase and plagioclase), and porosity values for the estimation of the strength loss. A very strong model with the correlation coefficient (r) of 0.97 was developed. The equation of the model is as follows:

$$L_{UCS} = 0.05T_{max} + 0.37UCS + 0.52(Q + F) + 19.55n - 109.14 \quad (1)$$

where, L_{UCS} is the UCS loss (%), T_{max} is the maximum surface temperature (ºC), UCS is the uniaxial compressive strength (MPa), (Q+F) is the percentage of quartz plus feldspar (Orthoclase and plagioclase), and n is porosity (%).

Eq. (1) has strong correlation coefficients. However, a strong correlation coefficient does not always show a valid model. Student test (t-test) and F–test are the common methods used for the validation of the regression equation. For performing the t-test, the variables should indicate normal distribution. The histogram analysis shows that the variables have non-normal distribution. Therefore, t-test was not carried out. The analysis of variance can be used for checking the significance of regressions. The confidence levels were selected as 95 % in the analysis. In the F–test, when the test values of F-ratios are higher than the critical F-ratio found in the standard table, the null hypothesis is rejected, suggesting an actual correlation is found between the two variables. The test value of the F-ratio is 18.41 and the critical F-ratio is 4.74. Because the test F-ratio is higher than the critical F-ratio, Eq. (1) is valid.

The scatter plot of the measured and predicted UCS losses was also used to show the reliability of Eq. (1). The data points should ideally be scattered around a 1:1 diagonal straight line on the plot of measured versus predicted values. As shown in Figure 2, the data points are scattered around 1:1 line, indicating that the estimation capability of Eq. (1) is very high.

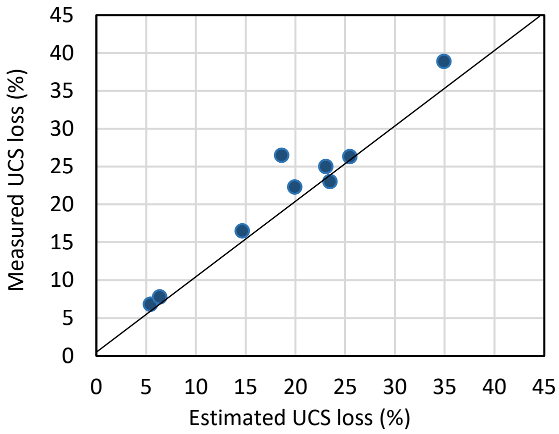

Figure 2. The scatter plot of the measured and predicted UCS losses.

Eq. (1) is valid for the microwave irradiation at 2.45 GHz with 6 kW of power for 120 s on air-dried igneous rocks. Its estimation may not be valid in other circumstances.

It is difficult to make an exact comparison between this study and previous studies since rock types tested, applied microwave power and exposure duration are different in this study and previous studies. Nevertheless, it can be said that there is a general consistency between this study and previous studies.

6 CONCLUSIONS

The predictability of the strength loss of igneous rocks treated with microwave energy was investigated. The UCS loss was evaluated considering the mineralogical contents. The surface temperatures of the tested rocks with similar UCS values reached very different values and their UCS losses were very different. This shows that other factors such as mineralogy and porosity are effective on the strength loss due to microwave energy.

The derived estimation equation for the UCS loss is reliable and can be used for the prediction of the strength loss of igneous rocks due to microwave treatment under the same test conditions. The validity of the derived equation should be further investigated for other igneous rocks.

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