THE EFFECT OF MICROWAVE IRRADIATION ON THE MECHANICAL PROPERTIES OF KIMBERLITE AND LIMESTONE

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Abstract

In underground excavation, rock fragmentation can be achieved by blasting with explosive materials or using continuous excavation machinery. The significant challenges with the explosives include noise, vibration, pollution, and potential issues such as damage to nearby structures. A less disruptive method for breaking rocks is using machines such as tunnel boring machine and road header those have the capability of continuous operation and are suitable for autonomous mining. In hard rock applications, the excavation machinery is associated with high equipment wear rates, low penetration rates and consequently high operating costs. This paper investigates the work being undertaken at McGill University on the effect of microwave (MW) irradiation on hard rocks to facilitate continuous mining and improve the production rate while reducing costs. Tuffistic Kimberlite (TK) and limestone rocks were studied in this research. Physical properties of untreated samples were measured, and the rock samples were treated for various exposure times in a multi-mode MW unit at power levels ranging from 2 to 10 kW. The results indicate that MW irradiation reduced the strength of TK and limestone rocks. It was concluded that Brazilian Tensile Strength (BTS) and Uniaxial Compressive Strength (UCS) of samples decayed proportionally with exposure time and power level.

Keywords: Kimberlite, Microwave Irradiation, Fragmentation, Mechanical Strength, Rock Excavation

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1. Introduction

Hard rock breakage is one of the considerable challenges in mining and civil applications. In underground and surface applications, rock excavation is still mainly revolving around drilling and blasting. But this method has negative consequences on the surrounding natural environment [1]. Over the past decades, mechanical excavation technologies for surface mining and underground mining such as Narrow Reef Miner, Oscillating Disc Cutter, Tunnel Boring Machine (TBM) and Road header have been developed to ensure the future continuous mining, continuous advancement and avoiding unwanted effects due to explosion. Unfortunately, in hard rock applications, the field trials proved that these technologies may face some of the challenges and limitations including a high amount of wear on cutting tools, high cost of tool replacement and low production rates [2, 3]. To address these limitations, various thermal and non-thermal assisted rock breakage methods have been proposed, including laser, water jet, torching, electric pulse, ultrasonic, and microwave (MW) irradiation. These techniques have been addressed in an extensive literature review by McGill Geomechanics Group with contributions from the South African Council for Scientific and Industrial Research (CSIR), The Colorado School of Mines, and Natural Resources Canada [3]. Among these techniques, MW irradiation appears to be an efficient method to reduce hard rock strength before the excavator cutters engage with the rock face because MW irradiation heats materials based on their dielectric properties, thus the energy is not wasted heating the entire host rock, it transfers energy (not heat) rapidly and indirectly (without contact), it is safe when appropriate precautions are taken, it can create the micro-cracks and reduce the strength, reduce the disk cutter wear, improve the performance of the TBM and reduce the cost of Crushing, Grinding and the wear of the equipment.

Electromagnetic (EM) waves were discovered in the mid-1800s and in 1945, the application of MWs for heating was developed. Since the 1990s, applications of MW technology to mining excavation and mineral processing have been studied. MW irradiation heats brittle material based on the principle of orientation-polarization. Rock is a heterogeneous material comprising several mineral components with differing physical and electrical properties. The mineral components receive inductive heat and therefore expand at different rates. Under MW irradiation, cyclical expansions and contractions of minerals create cracks between grain boundaries. The degree to which a rock sample is weakened by MW treatment depends on the crack density [4, 5].

In recent years, researchers have studied how MW irradiation can be used to break hard rocks. In one of the studies performed by Satch et al. examined how low-power microwave irradiation (2450 MHz) impacted basalt samples. In these experiments, the sample height measured 40 mm, diameter measured 38.1 mm, the highest average temperature was 101 °C, and exposure time for the microwave irradiation ranged between 60 seconds and 360 seconds. At exposure time of 360 seconds, there were visible cracks detected, along with a reduction of compressive strength (118.25 MPa to 78.55 MPa) and point load index (5.62 MN/m² to 3.73 MN/m²) [6]. In other studies, Benvie carried out a series of mineralogical imaging tests on kimberlite ore with a dispersive spectrometer (EDS) and a scanning electron microscope (SEM). The ore's inhomogeneity caused numerous challenges for the researcher, in addition to the particle size differences and the fine-grained quality of the silicate [7]. In a related study, Prokopenko discovered that the prevalence of fractures in kimberlite rock was caused by water vapor pressure in rock pores. When wet, kimberlite can hold up to 8% of its overall water content that has been trapped in the rock's pores. The presence of the water was a major factor in the samples' disintegration. However, the study also found that dry specimen destruction resulted in enhanced diamond content recovery [8]. Didenko et al. studied the fracture temperature and heat rate of the samples. The kimberlite was placed in a circular cavity TE 111 mode, with the magnetron supplying the resonator with 600 W of power at a 2.45 GHz frequency. The results indicated that microwave heating to 150 ℃ at a 40 deg/sec rise in temperature rate caused the destruction of the kimberlite samples, with pressure in the rock pores topping out at 5-105 Pa. Based on these results, the researcher then performed fractional analysis experiments to determine the kimberlite samples' technological parameters for the fracture process[9]. In a numerical study, Toifl et al. investigated a 3D numerical simulation of microwave-induced stress on hard rocks. They used open-ended microwave power of 25kW at a 2.45 GH frequency and applied two time intervals of 15 and 25 seconds. They then performed a comparative analysis of these results with those from a heterogeneities model to determine how the microstructure was affected by the microwave-induced stress. They also performed microwave irradiation experiments on some granite samples to compare the simulation and experimental results. The outcomes of these comparisons revealed that the stresses which occurred during microwave irradiation sessions which lasted longer than 15 seconds exceeded the tested rock material's strength [10].

There are a limited number of researches assessing the behavior of Kimberlite rocks exposed to microwave irradiation. Therefore, and extensive investigation on the effect of microwave treatment on the mechanical properties of Kimberlite and its associated rocks is being conducted at McGill University. Part of the results achieved in this research area is discussed in the present article.

2. Microwave-Assisted Drilling and Rock Excavation Systems

The concept of using MW irradiation is to reduce rock strength before excavation was first proposed by Maurer, who designed a MW with a maximum power of 4.8 kW to treat blocks of rocks. Depending on MW exposure time and block size, spallation began on the rock surface, then fractures began to develop. However, MW treatment did not cause a complete fracture of some types of rocks. Mechanical forces were still needed, thus [11] proposed MW-assisted drilling to drill hard rocks—combining mechanical and MW methods. In 1991, MW-assisted hard rock cutting was first patented by a group of researchers in the United States. With this invention, rock was first pre-weakened with MWs and then a cutting member was advanced to cut the strata [12]. A conceptual design of the MW assisted drilling machine, patented by McGill University is shown in Figure 1. According to this design, the MW antenna is placed at the bit face to emit MWs at the rock surface when the bit is rotating [13, 14].

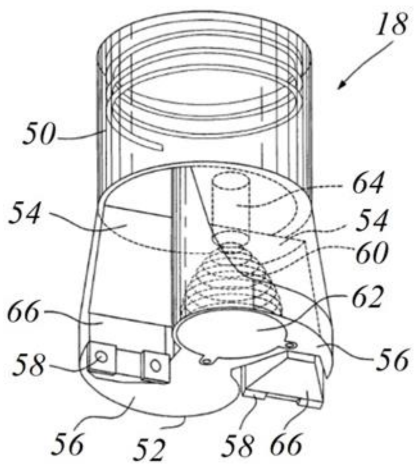

Figure 1. Conceptual design of a drag bit at McGill University equipped with microwave antenna. 18- Excavation bit; 50- Base body; 52- Cutting surface; 54- Sections; 56- Two wings; 58- Cutting tool; 60- Housing; 62- Cover plate; 64- Opening; 66- cutting tool holders [13, 14].

Jerby et al. designed a MW drill system based on generating a hot spot on the surface of an object. In their design, MW irradiation from a rectangular waveguide was transmitted to a coaxial waveguide. The central electrode (central antenna), which also functioned as a drill bit, concentrated the MWs to a point. The hot spot weakened the object's strength before drilling was done. Later work expanded the basic design to create a system capable of drilling a 26cm deep × 12mm diameter hole in concrete silently and without vibration [15]. In other studies, Nekoovaght and Hassani studied the temperature distribution in basalt slabs when tested at various depths from a microwave's horn antenna. The slabs, which measured 40 cm in length, 40 cm in width, and 2 cm in height, were subjected to 3kW microwave power at a frequency of 2.45 for exposure durations of 60 and 120 seconds. The results indicated that rock surface temperatures in closest proximity to the horn antenna were the highest, rock temperatures rose with increases in exposure time, and surface macrocrack density increased with rises in temperature [16]. Hassani et al. studied the effects of MW treatment on the strength of three hard rocks: norite, granite, and basalt. Norite responded the most to MW treatment. The power density, time exposure, and sample size and distance from the MW antenna influenced the magnitude of the treatment effect. Higher power and longer exposure times caused more strength reduction. The heating rate of rocks decreased as the distance from the antenna increased regardless of power and exposure time [5]. In a related study, Hassani and Nekoovaght determined that high-power, single-mode microwaving of rocks can reduce rock strength significantly. The researchers discovered that the UCS of basalt samples and the BTS of norite samples reduced after the treatment at high power and exposure time. They proposed single-mode MW-assisted drilling or cutting as an effective way for rock breakage or tunneling [14]. For example, the performance of TBM is calculated by the USC and BTS of the rock as given in equations 1 and 2. Noting that in this context, the performance corresponds to the rate of penetration.

$$\mathrm{P_{Rev}} = 3940 \frac{F_n}{UCS} \qquad (1)$$

$$\mathrm{P_{Rev}} = 624 \frac{F_n}{\sigma_{BTS}} \qquad (2)$$

where *Fn* is the load applied to the disc cutter (N), σ_{UCS} is the UCS of rock (MPa) and σ_{BTS} is the BTS of rock (MPa) [3, 5]. Figure 2 shows the penetration mechanism of TBM into the rock surface.

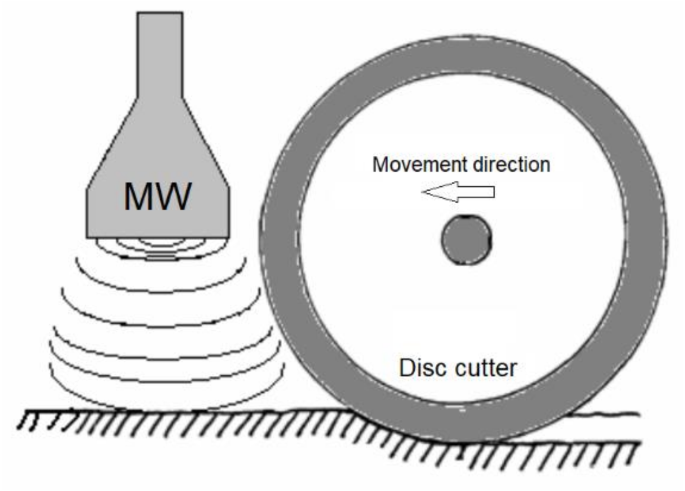

Figure 2. The schematic illustration of a microwave-assisted disc cutter [5, 14, 16]

In different studies aiming to better understand how granite forms cracks when subjected to high-power microwave irradiation and how the overall process of mechanical cutting of granite is affected through this process.

3. Experimental Procedures and Study Material and Samples Preparation

Kimberlite rocks are igneous rocks and because of hosting diamonds, they are a field of interest in the mining industry. The main types of Kimberlite are RVK (Resedimented volcaniclastic kimberlite), HK (Hypabyssal kimberlite), PK (pyroclastic kimberlite), VK (Volcaniclastic kimberlite) [17] [18]. The present work investigates TK kimberlite and limestone rocks. The rock samples were provided from Gahcho Kue mine in the Northwest Territories of Canada. By using a wet diamond saw and applying standard cutting procedures, the discs were made from the cylindrical samples to provide standard sample sizes for BTS and UCS tests. BTS samples were subjected to 3 kW MW power, and the BTS was measured using a "Wykeham Farrance 100 kN" test rig. The UCS samples were exposed to 6 kW and 10 kW MW powers, and the UCS was measured by a "MTS 250 MN" compression machine. The UCS and BTS of the treated and untreated specimens were measured according to ISRM standards [19, 20]. The physical properties of TK and limestone rocks were determined according to the ASTM standards, which includes the specific gravity, the rock quality designation (RQD), porosity and specific heat capacity as presented in Table 1. The XRD test results showing the mineral composition of TK are provided in Table2.

Table 1. Physical properties of TK and Limestone rocks

Rock Types	**Porosity**	**RQD (%)**	**Specific heat capacity (J/gr c)**	**Specific Gravity**
TK	0.68	71	0.82	2.51
Limestone	6.11	75	0.81	2.56

Table 2. XRD results of TK samples

Mineral	**Composition**
Microcline	$KAISi_3O_8$
Albite	$Na(ALSi_3O_8)$
Magnetite	Fe_3O_4
Calcite	$CaMg(CO_3)_2$
Quartz	Fe_3O_4
Clinochrysotile	$CaCO_3$
Clinochlore	$Mg_3 (Si_2O_5(OH)_4)$
Illite(phlogopite)	$KMg_3(Si_3Al)O_{10}(OH)_2$

4. Microwave treatment

TK and limestone rock samples were treated using an industrial multi-mode MW system (frequency: 2.45 GHz, power: 1kW - 15kW). The MW system consists of the following units as shown in Figure 3.

1. Control system
2. Power generator
3. Magnetron
4. Waveguide
5. Cooling system
6. Multi-mode cavity

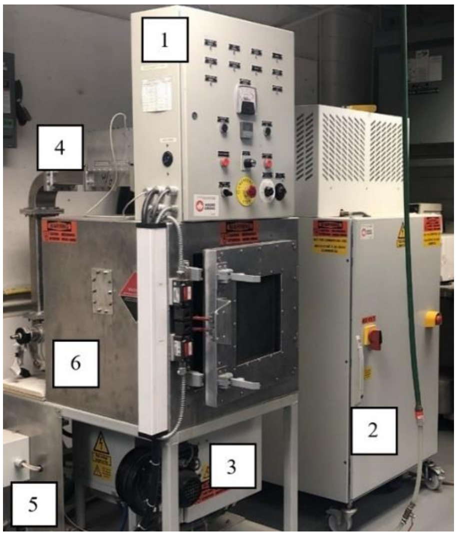

Figure 3. Multi-mode MW system components

5. Experimental results and discussion

The mean UCS values for untreated TK and limestone were measured equal to 58 and 68 MPa respectively. The UCS of TK and limestone decreased with the increase of the MW power and the exposure time. The UCS of TK decreased by 59% at 6kW MW power and 45 sec of exposure time. While at 10 kW and the same time of exposure, the UCS reduction was 66%, as plotted in Figure 4. Similar behavior was observed for limestone (Figure 5). The UCS of limestone samples reduced by 62% at 6kW MW power and 45 sec of exposure time. Whereas at 10kW MW power and the same exposure time, the UCS reduction was recorded as 68%.

The mean BTS values of untreated TK and limestone were measured equal to 7 and 4.90 MPa, respectively. The BTS reduced with the increase of exposure time Figures 6-7. The BTS of TK decreased by 51% after 90 sec of exposure. Whereas the BTS of limestone rocks reduced by 28% after 90 sec of exposure time.

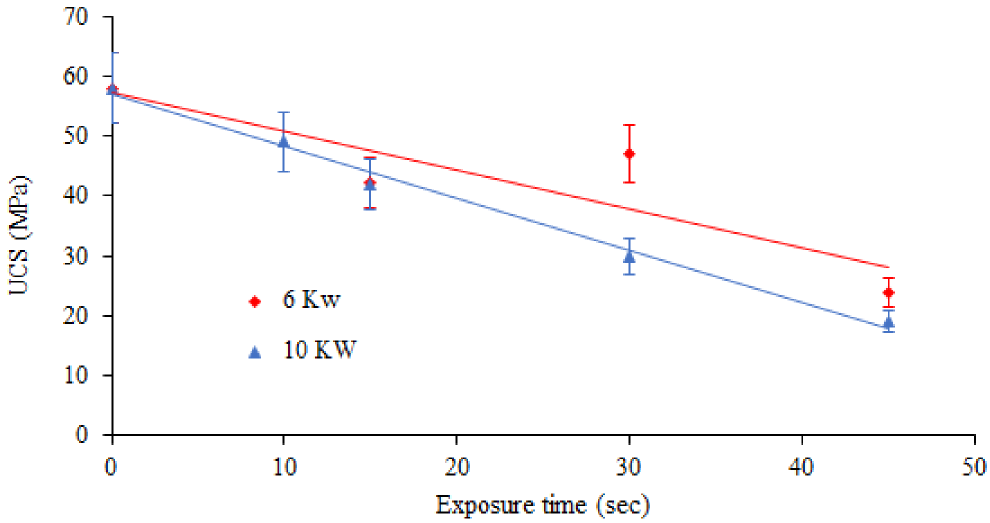

Figure 4. Unconfined Compressive Strength vs. exposure time at two MW power levels for TK

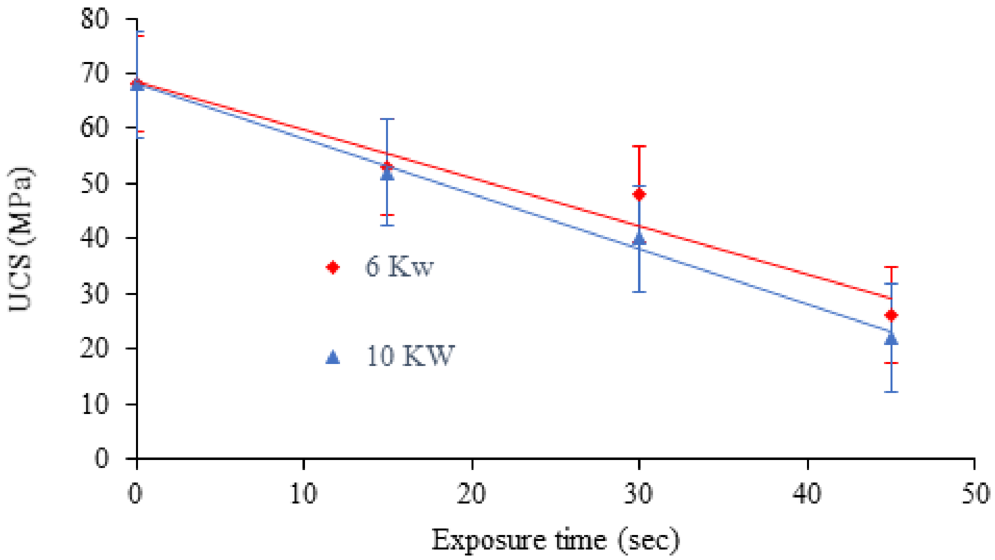

Figure 5. Unconfined Compressive Strength vs. exposure time at two MW power levels for limestone

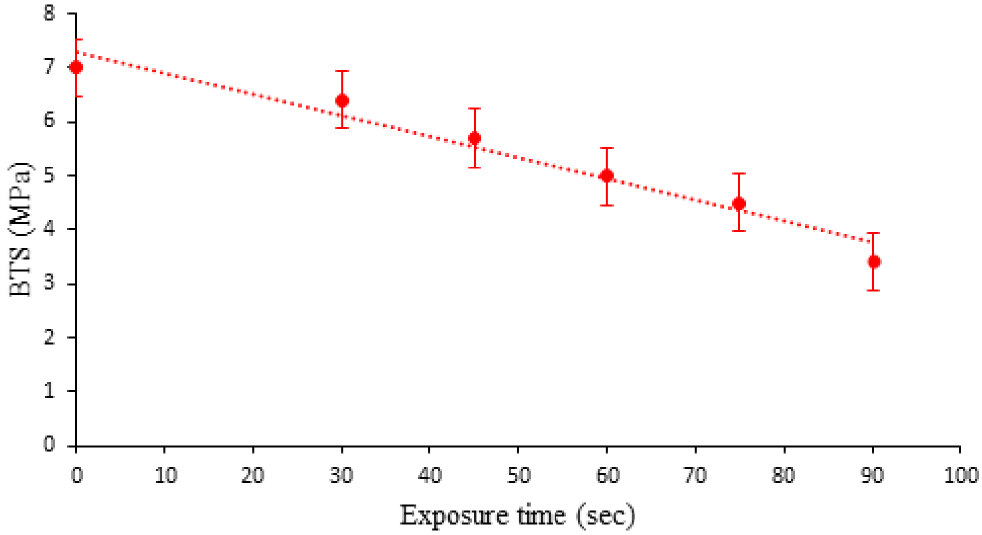

Figure 6. Brazilian Tensile Strength vs. exposure time at 3 kW MW power for TK

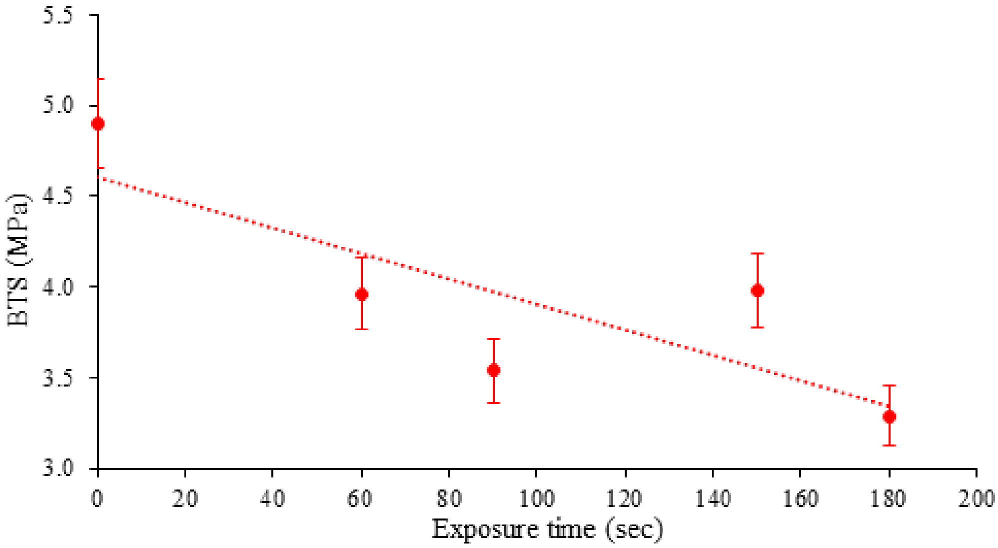

Figure 7. Brazilian Tensile Strength vs. exposure time at 3 kW microwave power for limestone

6. Conclusions

This research work demonstrates that microwave irradiation has a significant effect on the mechanical properties (BTS and UCS) of TK and limestone rocks. It was observed that the longer the samples were exposed, and the higher the MW power was, the higher reduction of UCS and BTS was achieved. For TK, 59% and 66% reduction in UCS was measured after 45 sec. of MW exposure at 6 kW and 10 kW power levels, respectively. While the reduction of UCS was 62% and 68% at 6 kW and 10 kW power levels and at the same duration of exposure for limestone rock.

BTS also showed a decremental trend as a result of MW treatment. Approximately 51% and 28% reduction after 90 sec. of treatment at 3kW power was measured for TK and limestone, respectively. According to the results, MW irradiation has a high potential for assisting the mechanical rock breakage machines.

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