An investigation on the influence of microwave energy on basic mechanical properties of hard rocks

Pejman Nekoovaght Motlagh

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Drilling and blasting is one of the most commonly used and convenient method for many mining and civil applications to break rocks, especially hard rocks. Because of many environmental, safety and productivity issues (i.e. Cycle time), the industry and contractors are looking for an alternative system of breaking of rocks. In underground rock breakage applications such as tunneling, continuous mechanical excavation method, normally with tunnel boring machines (TBMs) or road headers is becoming more popular and commonly used by contractors. One of the main disadvantages of such system is that, it cannot handle very hard rocks and uneconomical major disc or bit wear takes place. Today, novel explosive free rock breaking technologies (thermal, electrical, nuclear energy and microwave) are available and could be used on their own or assist mechanical conventional machines to be able to break harder rock material. This is possible because it is hoped that the microwave will reduce the strength of the rock prior to the impact of mechanical device.

Three main mechanical parameters of rocks such as compressive strength, tensile strength and abrasivity index value were used to highlight the influence of microwave on to the mechanical properties of rocks. Seven different rock types were prepared and tested.

Each individual specimen was exposed to the microwave energy in three power levels 800, 1250 and 3000 watts, within 0, 15, 30, 60, 120 and 240 seconds time of exposure. Different rocks due to their mineralogy behave differently when exposed to microwave energy. CERCHAR abrasivity index value of almost all samples shows reduction of about 30% as the power level of exposure increases. The tensile strength of certain samples reduces significantly as in basalt reduces of up to 80%. The unconfined compressive strength value of almost all samples reduces about 30% as well. The reduction of the strength and abrasivity of hard rock cause the penetration rate and the life time of cutter tools of a TBM to be increased by combining the microwave energy to the cutter head of the mechanical excavator.

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I would like to respectfully dedicate this thesis to my dear parents who gave me their pure love and supports all along my life.

Nomenclatures

E = Electric Field intensity (V/m)
H = Magnetic field intensity (A/m)
j = Conduction electric current density (A/m^2)
ε= Permittivity (F/m)
ε□ = Dielectric constant
ε□ = Dielectric loss factor
κ_r = Relative permittivity
ε_0 = Constant permittivity of free space (F/m)
κ□ = Relative dielectric constant
κ□ = Imaginary loss factor
$\tan\delta$ = Loss tangent
P_d = Microwave power dissipation density (W/m^3)
f = Microwave frequency (Hz)
λ = Wave length (m)
t = Microwave exposure time (seconds)
T = Temperature (Celsius)
ρ = Density (Kg/m^3)
ω = Angular frequency of the electromagnetic wave (Hz)
μ□ = Relative magnetic loss factor
μ_0 = Permeability of free space (1.257 x 10-6 H/m)
D_p = Penetration depth (m)
L = Length of the distance that a disc cutter can roll on hard rock (m)
CAI = Stands for CERCHAR abrasivity Index value
σ_C = Compressive strength value of the rock (MPa)
σ_{PLT} = Point load test value of rock (MPa)
F = Load applied to the cutter (N)
D = Diameter of the disc cutter (m)
w = Width of the edge of the disc cutter (m)
θ = Angle between the two faces making the edge of the disc cutter (°)
P_{Rev} = Penetration per revolution
σ_{tB} = Brazilian tensile strength (MPa)
F_n = Normal force applied to the cutter (kN)
F_r = Shear force applied to the cutter (kN)
UCS = Stands for unconfined compressive strength
BTS = Stands for Brazilian tensile strength
st = short tonne
P = Load applied on specimen by the machine (kN)
eV = electron volt
hr = hour
BWI = Stands for bond work index
ρ = Density (kg/m^3)
l = high of specimen (m)
W = Watt of power (W)
A = Area of the cross section (m^2)

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CHAPTER ONE

1. Introduction

1.1 Introduction

The first human beings were challenged with rocks in nature to built or create a safe place to live such as caves. Later in the Bronze Age, at the time of the creation of metallic tools and followed to the Iron Age era, breakage of rocks was a great challenging application for human beings. For a very long time, nails and hammers were used for breaking rocks. Heating the surface of the rock to be broken was an advancement at that time. In fact, the surface of the rock was heated by placing it in a big fire then cooling it very quickly by throwing water on the rock, so the rock is then weakened and it is easier to break with primary tools. That procedure was used in many kinds of rock breakage applications such sculpturing, mining and tunneling for a very long time (Stack, 1982).

Tunneling applications have developed rapidly since the creation of Quanaates by ancient Persians (Bybordi, 1974). Since then, tunneling has been done for many purposes and uses such as hydro-power tunnels, mining, ventilations, traffic, and transportation purposes. The needs and development of technology led us to today's way of tunneling. Various techniques of rock breakage in tunneling applications are available such as drill and blast methods by using explosives and mechanically without using explosives by using mechanical excavators such as tunnel boring machines (TBM) or road headers. This thesis introduces an alternative way of improving the efficiency of mechanical excavators by combining microwave technology with a mechanical excavator such as TBM.

To date, there are various types of TBMs on the market being able to be operational in different types of natural geological formations. In hard rock formations, the performance of TBMs is limited also the consumption of consumable parts is very high. This thesis will mainly discuss about the combination of a conventional mechanical tunneling machine (TBM) with a novel energy as microwave energy, so the technique will be categorized as a novel technology to be developed.

Microwave energy, being a part of the electromagnetic spectrum, has different uses such as communication, remote sensing and heating purposes. Using microwave energy for heating materials has been recognized to have some advantages over traditional and conditional heating method (convective heating), which has been discussed within the literature review.

The literature review shows that the application of microwave energy on natural materials such as rock has a significant impact on reducing the material's strength. Mostly, researchers have investigated on examining and evaluating the influence of microwave energy on rock comminution in mineral processing plants. Few investigations have been conducted on the assistance of microwave energy with drilling applications in rocks. According to the literature review done for this research, it has been concluded that since microwave energy has a significant impact on certain materials' strength reduction, therefore, the combination of microwave energy with a TBM machine can possibly have an impact on the machine's performance. In order to evaluate the influence of the microwave energy on the performance of a TBM operation, important parameters influencing the performance of TBM will be specified first and the effect of microwave energy will be investigated on those parameters.

1.2 Motivation and organization of the thesis

This research is a part of larger project recently started at McGill University in the Department of Mining, Metal and Metallurgy Engineering. The start up of the research at McGill

University was the investigation on the combination of both mechanical and novel energy (such as laser, microwave and nuclear energy) for special drilling applications. The advancement of the research led to the realization that the actual technology can possibly be operational within both mining and civil applications such as tunneling techniques as well (the current research).

Since most works done in the area of microwave application are mainly on metallic ore bodies, more investigations need to be done on those rocks that are commonly found in tunneling applications. However, there are unlimited rocks forming the crust of the earth. For this thesis, seven different rocks have been selected to be exposed to microwaves and then tested to evaluate the effective parameters on performance.

The combination of both microwave energy with TBMs research has been split in two major phases. The first phase, which is the current thesis topic, is the investigation of the influence of microwave energy on hard rock's mechanical properties. The second phase is to simulating the operation of a TBM by implementing the microwave energy into a small predesigned cutter head and study the influence of microwave energy on rocks while the head is rotating, which will be performed in the future.

1.3 Thesis Objectives

The main objective of this thesis is to introduce the possibility of microwave assisted mechanical excavator as TBM and to investigate and highlight the influence of microwave energy on basic physical and mechanical properties of rocks. The basic mechanical and physical parameters of rocks investigated are the tensile strength and compressive strength values of rocks which influence the penetration rate of a TBM chosen as an alternative mechanical excavator in this thesis. The third mechanical parameter is the abrasivity value of rock which influences the life time of a disc cutter.

1.4 Outline of the thesis

The present thesis is divided in six chapters, which are outlines as the following:

Chapter one gives a general introduction and a perspective view to the project and its related application, the research motivation and organization followed by its objectives as well as the thesis outline.

Chapter two briefly explains about the microwave technology itself and introduces the parameters related to rock materials and how microwave energy can affect rocks. It also briefly introduces the types of tunnel boring machines with their various types of cutter tools being designed and in operation for various types of natural geological formation. This chapter also consists of the introduction of the fields where microwave energy can be suitable to be used including the introduction of the possible implementation and the combination of both conventional mechanical tunnel boring machines with a novel energy as microwave energy.

Chapter three presents a literature review identifying the research performed to date with regards to the influence of microwave energy on rocks and what can be done within the present research.

Chapter four explains about the materials that are used in this thesis and the experimental methodology. This chapter also includes the introduction and pictures of all materials and apparatus used for measuring and calculating the mechanical parameters of selected rocks.

Chapter five discusses the results obtained and the evaluation of the results with the works done to date.

Chapter six, the final chapter, includes a conclusion and recommendation.

CHAPTER TWO

2. Microwave assisted a tunnel boring machine

2.1 Definition of microwave energy

During the Second World War, serious research was done into high-definition radar which led researchers to develop microwave frequencies of 500 MHz to 100 GHz. During the post-war years, further development continued, including using microwaves for heating purposes in the mining industry, as well as for domestic usage. Microwave energy is an electromagnetic wave consisting two electronic & magnetic waves traveling perpendicular to each other and transporting energy with the speed of light (Figure 2-1).

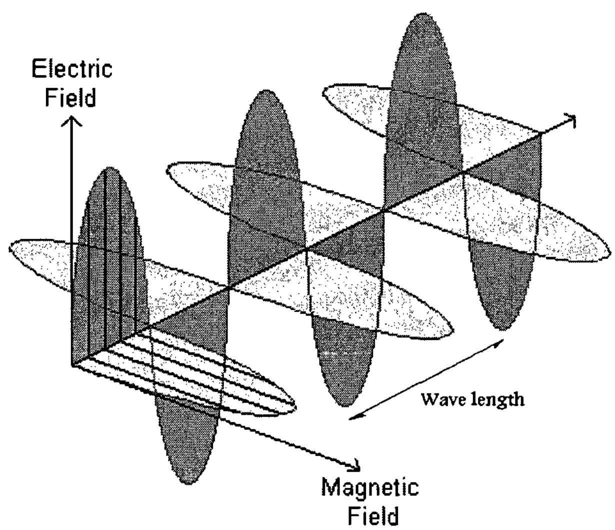


Figure 2-1 An electromagnetic wave (Scott, 2006).

Microwaves occupy a part of the electromagnetic spectrum where wavelength varies between 1mm and 1m and a frequency of 0.3 - 300 GHz (Figure 2-2). Within that range, a frequency of

2.45GHz of microwave energy is the most popular and most commonly used (Metaxas et al., 1983). Generally, domestic and industrial use microwave energy at a frequency of 2.45 GHz corresponding to a wavelength of 12.2cm and energy of 1.02 x 10^{-5} eV (Jacob et al., 1995). The amount of energy transmitted relates to increasing the frequency and shortening the wavelength, respectively.

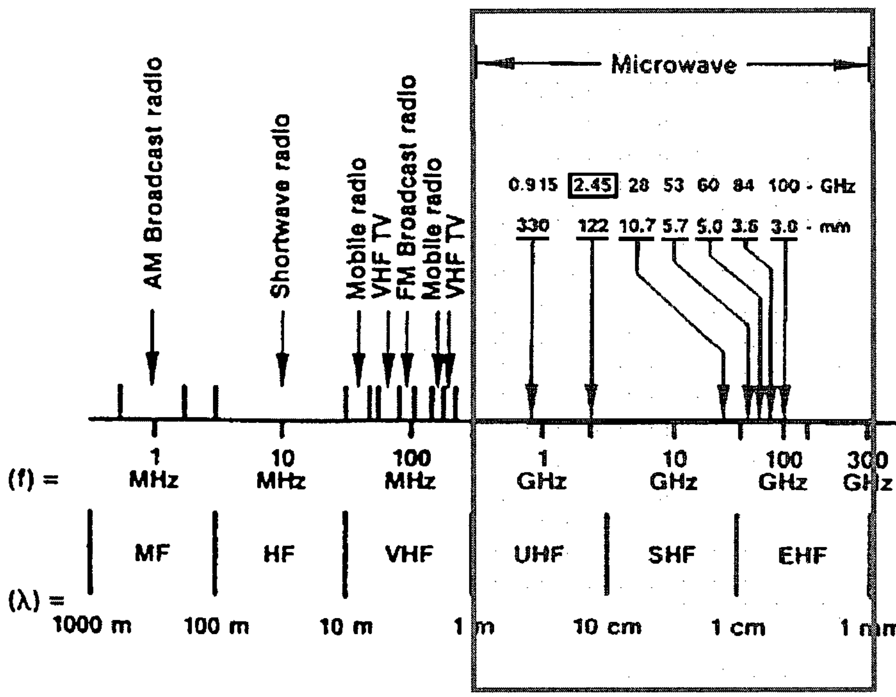


Figure 2-2 Representation of the electromagnetic spectrum (National Research Council U.S., 1994).

Microwaves carry less energy than the other waves within the electromagnetic spectrum, however, other properties such as large penetration depth into materials relative to its large amount of energy dissipation, make it a prime candidate for producing heat in materials (Oespchuck, 1984). In general, all materials can be classified in three main groups (Figure 2-3).

- Conductors, which reflect microwaves
- Insulators, through which microwave passes with no effect
- Absorbers, which absorb a part of the microwaves and produce heat

All the materials which absorb microwave radiation are called dielectrics. Dielectrics have two main important properties (Oespchuck, 1984):

1- They have the ability to allow the electricity to pass through. Each material has its own value of electricity carriage when electricity is applied from an external source.
2- Normally, heat is generated in them due to the dipole rotation mechanism.

Basically, heating is generated within a material which is exposed to microwave irradiation. The energy emitted to the material is normally dissipated as heat through the material. Heat is generally generated within the material, due of being exposed to the microwave energy, by two basic mechanisms (Pickles, 2008):

(1) Dipolar rotation, and

(2) Ionic conductance.

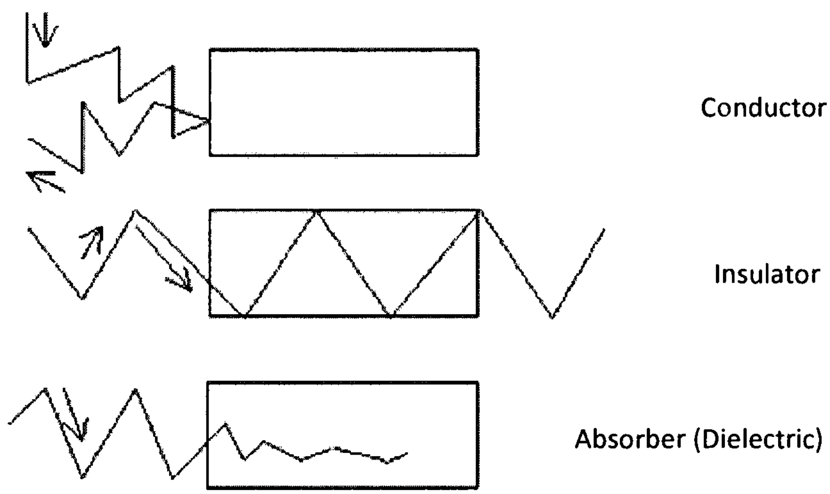


Figure 2-3 Classification of behavior of materials exposed to microwaves (D.A. Jones, 2001).

In materials with molecular and atomic structures having two positive and negative concentration of electricity, such as water molecules, heat is generated by dipolar rotation when exposed to microwave energy. In the case of rotation of molecules or atoms, heat is generated due to like and dislike of the two positive and negative electricity concentrations by the two magnetic poles, which causes the molecules to rotate.

However, in those materials that have ionic structure, such as electrolyte solvents, heat is generated by ionic conductance while being exposed to microwave irradiation. Thus, by like and dislike action of ions by the electricity provided from the electric field within the material, ions tend to move back and forth which that movement causes the ionic conductance heat generation.

Since the electromagnetic energy consists of two perpendicular waves, electric and magnetic, they are also able to influence the material independently. In the dipole rotation mechanism, where molecules have two poles of positive and negative electricity concentration, the polar charges reverse because of the electric wave. However, the magnetic wave oscillates molecules in their own place back and forth due to absorption and distraction of polar charges. As a result of that procedure, internal friction between molecules (Figure 2-4) causes the generation of heat within the dielectric material (Meredith, 1998; Pickles, 2008).

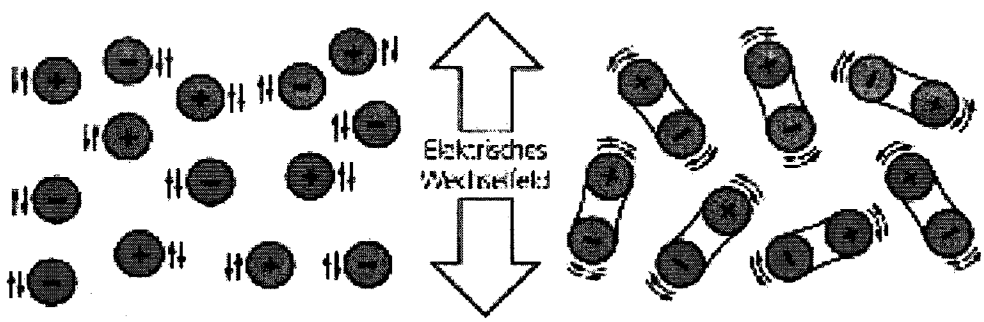


Figure 2-4 Heat generating mechanism by microwave irradiation into a dielectric (Anton-paar.com, 2009)

There are some advantages that microwave energy has over conventional heating methods, which are (Haque, 1999):

- Non-contact heating;
- Energy transfer, not heat transfer;
- Rapid heating;
- Material selective heating;
- Volumetric heating;
- Quick start-up and stopping;

- Heating starts from interior of the material body toward exterior;
- Can be transported from the source through a hollow nonmagnetic metal tube like waveguide;
- Higher level of safety and automation;

2.2 Dielectric properties

A non-metal, non-conductive and insulating material which does not allow electricity to pass through is called a dielectric material. The complex permittivity of a material defines the interaction between the material and the electromagnetic energy (Santamarina, 1989).

$$\varepsilon = \varepsilon' + j\varepsilon'' \qquad (2\text{-}1)$$

When the complex permittivity is modified with the constant permittivity of vacuum ($\varepsilon_0 = 8.854 \times 10^{-12}$ f/m), it is then called the complex relative permittivity measured in farad per meter (f/m), as:

$$\kappa_r = \kappa' + j\kappa'' \qquad (2\text{-}2)$$

$$\tan\delta = \kappa''/\kappa' \qquad (2\text{-}3)$$

Where: κ_r is the complex relative permittivity

κ' is the dielectric constant (real loss factor)

κ'' is the imaginary loss factor

$\tan\delta$ is the tangent loss factor

Microwave energy emitted into the material dissipates through the dielectric material and turns to heat. In fact, the energy dissipated in the material has been lost within the material which is measured as loss factor. Generally, materials can be categorized in two main groups as (Santamarina, 1989):

1) Low loss materials $\tan\delta \ll 1$
2) High loss materials $\tan\delta \gg 1$

2.3 Dielectric properties of rocks

The range for the dielectric constant of rocks containing minerals (Table 2-1) is between 3 and about 200 Farads/meter, however most values are between 4 and 15 Farads/meter. In addition, their loss factor range is between 10^{-3} and 50 Farads/meter (Santamarina, 1989).

The permittivity of any rock type forming mineral is totally dependent to its mineralogy and petrography characteristics. Each mineral has its own dielectric properties, whereas the complex of several minerals together results in completely new dielectric properties. Some other parameters, such as the grain size, the mixture percentage and the type of minerals forming rocks reflect the final dielectric properties of the rock. Moreover, if the permittivity of the rock changes the dielectric properties of the rock will change significantly.

2.4 Energy transmission of microwave and penetration depth

As microwave energy is emitted to a dielectric material, it penetrates into the material, into a certain depth until it losses its strength. As shown in Figure 2-5, the loss of attenuation strength of wave penetration as is passes through the material is shown (Scott, 2006).

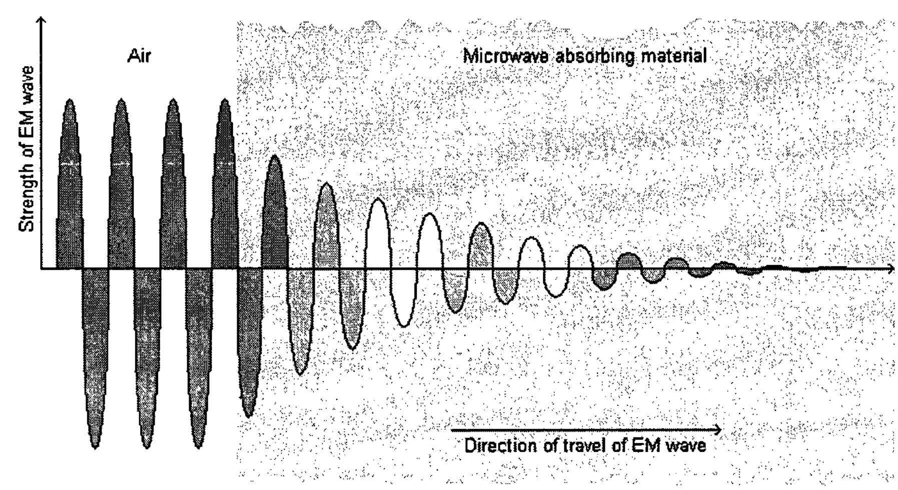


Figure 2-5 Attenuation of microwave energy as load absorbs power (Scott, 2006).

Once the power attenuation of an electromagnetic energy penetrates into a dielectric material reaches the value of 1/e of the power at the surface, that level of depth is defined as the effective penetration depth, specified as D_p, of the electromagnetic wave through the dielectric material. Assuming that the attenuation has an exponential decrease as it penetrates into the material; the penetration depth is computed as Equation 2-4 (Metaxas et al., 1983).

$$D_p = \frac{1}{2\omega} \frac{\sqrt{\dfrac{2}{\mu'' \mu_o \kappa_o \kappa'}}}{\sqrt{\sqrt{1+\left(\dfrac{\kappa''}{\kappa'}\right)^2} - 1}} \qquad (2\text{-}4)$$

Where: ω, is the angular frequency of the electromagnetic wave

μ□, is the relative magnetic loss factor

μ_0, is the permeability of free space (1.257 x 10^{-6} H/m)

D_p, is the penetration depth

However, the above equation can be rewritten as the following simple equation in the case of low-loss and high-loss dielectric materials (Santamarina, 1989).

(a) Low-loss dielectric materials (κ"/ κ' << 1): $$D_p = \frac{\lambda \varepsilon^{1/2}}{2\pi\kappa''} \qquad (2\text{-}5)$$

(b) High-loss dielectric materials (κ"/ κ' >> 1): $$D_p = \frac{\lambda}{2\pi\kappa''^{1/2}} \qquad (2\text{-}6)$$

Where, "λ" is the appropriate electromagnetic wavelength in meters.

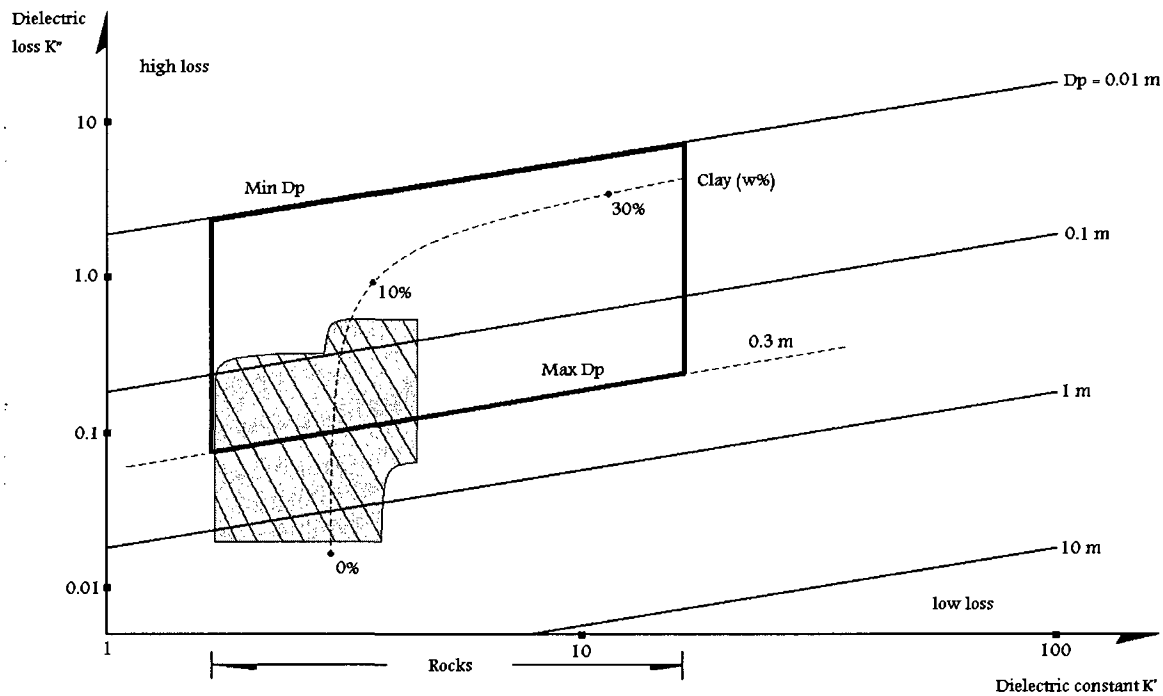


Figure 2-6 Penetration depth region for rocks and soil at λ=100mm (Santamarina, 1989).

Santamarina (1989) calculated and predicted the penetration depth of geotechnical material at λ=100mm as a function of the material dielectric properties (Figure 2-6). The dashed line for clay gives data at different water contents. It is very important to consider the water content in the material in the calculation of the penetration depth of electromagnetic energy through the material in addition to other factors mentioned earlier in this chapter; as the dielectric loss of clay in Figure 2-6 increases with water content, the penetration depth of the electromagnetic energy decreases.

2.5 Tunnel boring machines for hard rocks

Recorded history shows that from a certain period in the past, since people started to live in the cities, providing fresh water to the city was a problem. In 1200 B.C., during the period of Roman Empire, canal systems were very common for centuries (Bickel et al., 1982). The water was driven to the city through some canals dug out from rivers or water sources. In order to avoid the water evaporation and the loss of significant amounts of water at the destination, ancient Persians built miles of Quanaats, tunneling between closely spaced shafts, which many of them are still operational today (Bybordi, 1974).

As time passed and the cities' populations increased, more requirements are needed for different reasons. When the population grows in a city, more power, larger transportation systems and other infrastructure is needed. Modern type of tunnels include rail road and underground mining and other uses within both civil and mining applications such as transportation, traffic, and hydro-power tunnels.

As the technology grows, tunneling techniques develops. In the ancient times, tunneling in various earth conditions was done by the simplest tools such as nail and hammer. Since the invention of dynamite, tunneling has been done by blasting the mass of earthen structure by placing the explosion deep in a predrilled hole, which is still in common use today, known as the drill and blast method. In parallel to the drill and blast method, continuous tunneling technology has been developed, which leads to today's tunnel boring machines. Although drill and blasting technique in most applications is still an economical method, tunneling continuously with tunnel boring machines has some advantages with regards to excavation rate, safety and technical impact (Stack, 1982).

This chapter will briefly introduce the tunnel boring machines specifically designed for tunneling in hard rocks including various types of cutter tools. The rock cutting mechanism will be studied in accordance to different rock cutting tools applied on the tunnel boring machine cutter head. Fracture characteristics and mechanisms in medium to very hard rock will also be reviewed in a sense to understand what are the basic parameters influencing the performance of a tunnel boring machine.

A tunnel boring machine is a device to excavate a tunnel continuously through a mass of natural material within the crust of the earth. Such a device consists of several parts assisting one another to excavate smoothly and simultaneously. The body of such a device remains always stationary while the head rotates against the rock face. On the cutter head groups of cutting tools are installed, with which the material is mainly cut. All the cutting tools installed on the cutter head are positioned in a certain order and arrangement that they overlap the fracture zone of each other. The cutter head including its group of cutting tools is designed in order to be suitable for excavation and rotating against the rock face under a large thrust provided by the body of the machine (Figures 2-7 and 2-8).

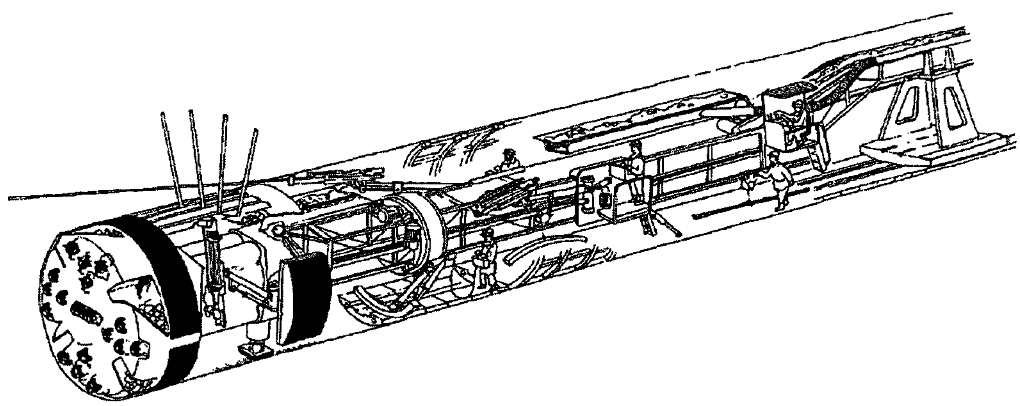


Figure 2-7 A schematic view of a tunnel boring machine and its components in the body (Wijk, 1992).

Generally, fragmented rock, water and other waste (muck) is removed from the excavated face by a number of buckets designed on the cutting head leading the muck onto a conveyor belt installed in the back of the cutting head. The muck is then conveyed to a transportation system to be carried out of the tunnel. The transportation system operates totally independent of the tunnel boring machine (TBM). This system allows to tunneling continuously.

Continuous mechanical underground rock cutting machines have been and still are gaining use because of their efficiency and economy compared to conventional drill and blasting methods. Moreover, TBMs are more viable than conventional drill and blasting method because of the reduced the cost of production (Wang et al., 1979). Tunnel boring machine performance in medium to very hard rock boring application is still limited due to the interaction with hard material. However, continued improvements in the design and operation of the machine allow the TBM to become more feasible today than before.

Mechanical tunnel boring machines have some advantages compare to the conventional drill and blasting methods. Some of the advantages are as follows (Friant et al., 1993):

Excavation rate:

TBMs tunnel continuously in a way that the buckets, pre-installed on the cutter head, remove all muck from the excavation face to the back of the head simultaneously. The transportation system, the conveyor and the train, move the muck out of the tunnel. Therefore, cutter tools are always interacting with fresh rock to be excavated. As a result of that continuous procedure, the cycle of excavation from the conventional drilling and blasting method (drilling, explosion, ventilation and haulage) is eliminated, so the excavation rate increases.

Safety:

Generally, most hazardous accidents in underground openings are due to rock falls. The conventional tunneling methods mostly destabilize potential stresses among the rock mass to be released due to explosion vibrations. Rock falls in underground are common, particularly while installing supports. TBMs, because of their operational procedure and design, reduce those risks in two ways: (1) By not possibly disturbing the stresses stored among rock masses to be released, and (2) installs supports, either automatically or manually, as needed while excavation is underway such that worker rarely even see the rock.

Technical:

Technically, TBMs excavate by producing less vibration in order not to disturb any sensitive remaining structures. TBMs also create a much smoother wall, so the lining and grouting would be much easier in addition to consuming less grout.

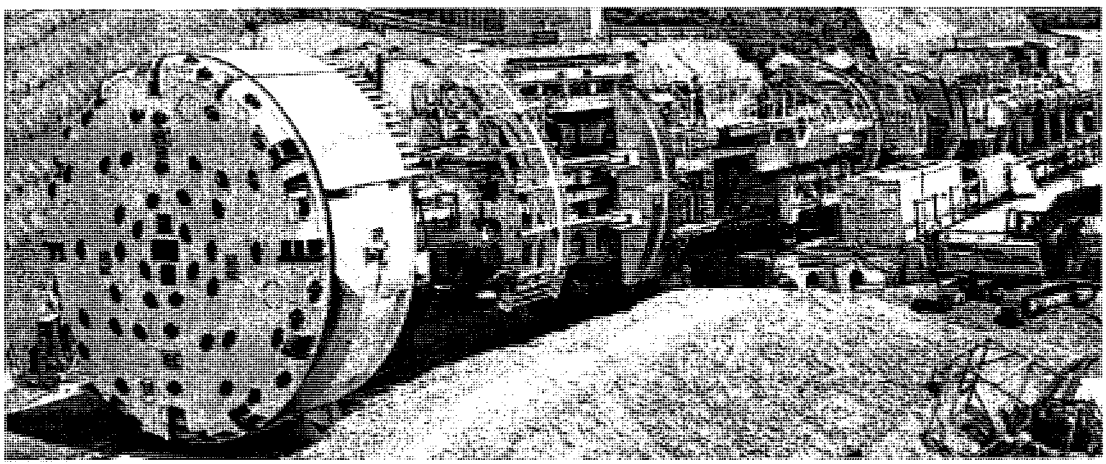


Figure 2-8 An actual hard rock TBM in site (Herrenknecht, year).

2.6 Cutter and cutter heads

The characteristics and personalities of a tunnel boring machine are typically defined depending on the geologic formation in which they are designed to operate. Various types of formations exist within the crust of the earth as soft ground, soft rock, medium hard and hard rock formations (Bickel et al., 1982).

Table 2-1 classifies the total formation of the crust of the earth in a few categories which TBM manufacturers use commonly often in their design (Bickel et al., 1982). A tunnel boring machine is designed to work in various rock formation and conditions as it tunnels through the mass rock. Normally, operational characteristics of a tunnel boring machine depend on the type of the cutter tools that should be used on the cutter head. The cutter type designed for a type of a geologic formation in which it is suppose to operate, is specified in order to cut , groove and fracture the rock in the most efficient and economical way. Figures 2-9 and 2-10 demonstrate cutter types that are designed to have fixed picks for operating in soft rocks. Those types of cutters, chisel the rock as it grooves through it. For harder rock types, normally single or multiple disc cutters, toothed cutters, roller cutters or cutters with tungsten carbide inserted buttons are used (Kennedy, 1990).

A tunnel boring machine is selected depending on the rock formation along the path that the machine intends to excavate (Maild et al., 2008). The efficiency of the machine is related to the inherent and basic properties of the rock, principally to strength, the extent of jointing, strain modulus and abrasion (Friant et al., 1993). The main objective by selecting the right machine and cutting tool for a project is to cut the rock by reducing cutting work and generate bigger cuttings caused by brittle fractures. Principally, the cutter action generates a high local difference in principal stresses and high tensile stresses to create cracking (Zhang, 2004).

Table 2-1 Classification of formations on the bases of the characteristics for tunneling (Bickel et al., 1982).

Classification	Unconfined compressive strength (psi)	Typical formation
Soft ground		Uncemented deposit of clay, silt, sand and gravel, possibly saturated; marl
Soft rock	Less than 8,000	Shale, tuff, claystone, siltstone, sandstone
Medium hard rock	8,000 to 25,000	Some basalt, granite, and andesite; average sandstone and limestone, dolomite, chalk, rhyolite, gneiss, schist.
Hard rock	Over 25,000	Some basalt, granite and andesite; well-cemented sandstone and limestone; marble, chert, diorite, quartzite, argillite.

Each type of cutter with all kinds of pattern is designed to operate in different conditions (Figures 2-9 and 2-10). Each design is considered being able to work in a certain range of rock formation from soft to very hard rock. (Heinio, 1999) gave some reasons which can cause difficulties in performance:

- Hard rock which is cut by grooving instead of being fractured causes significant wear of cutting tools.
- Inappropriate cutter tool selection in plastic rock causes reduction in fragmentation efficiency.
- Silica, the most abrasive mineral, is the most important cause of sear due to overheating.
- Rock variability causes the bearing load to increase.
- If the mass of rock is heavily jointed or fractured, it may fall on the machine or its head and cause the head to jam at the face.

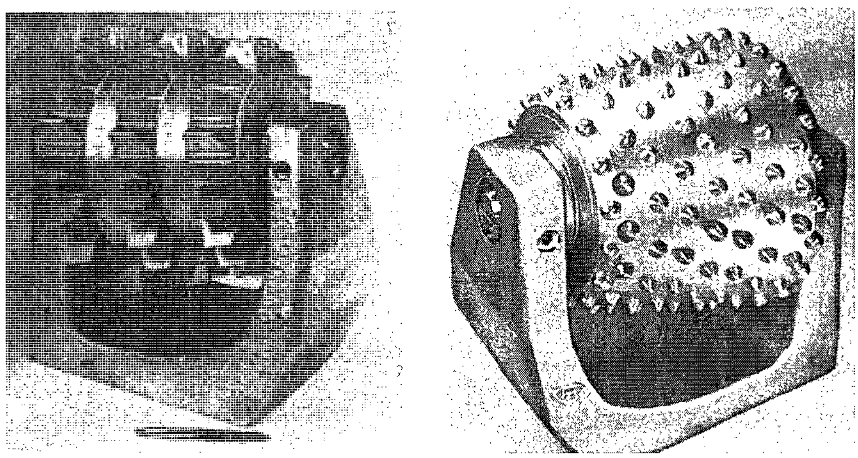


Figure 2-9 Tooth cutter (left) and ballistic TC button cutter (right) (Heinio, 1999).

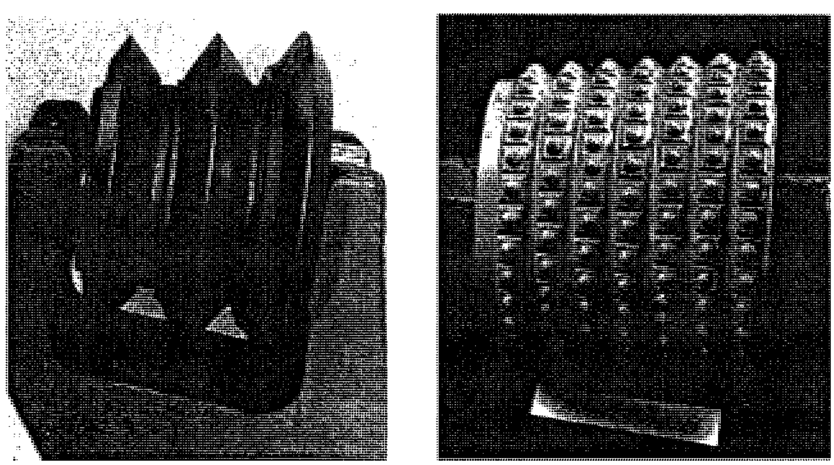


Figure 2-10 Multidisc cutter (left) and spherical TC button cutter (right) (Bickel et al., 1982).

Generally, the main criterion of cost estimation of a project using TBM, concerns the cost of repairing and replacing cutter tools of the machine. Normally, cutter tools of a tunnel boring machine are nearly the only consumable part of the machine. In soft rock, the cost of cutter consumption is also relevant to other cost of an application but not with a significant increase as of consumption. However, in hardest rock, the cost consumption of cutter tools increases significantly due to rapid wearing. Moreover, it causes the machine to stop frequently as well, which stoppage of the machine for cutter replacement (Kolymbas, 2005).

2.7 Combining microwave energy with mechanical excavators

Although tools operate on different scales, penetration and fragmentation occur by applying energy through similar mechanisms to break rock. To date, it is well known that parameters, such as compressive, shear and tensile strength of rock resist failure caused by the applied loads. In drilling, cutting, breaking, boring or any other similar applications, the penetration rate is directly proportional to the amount of energy applied to the process (Kennedy, 1990).

The combination of microwave energy with a tunnel-boring machine operation, as an alternative method of rock breakage, raises the total energy applied to the rock. Figure 2-11 demonstrates the basic possible design of microwaving rocks while operating. Thus, it can be assumed that the penetration rate of microwave-assisted tunnel-boring machine will be increased respectively. It is obvious that this assumption needs some laboratory or field test investigation. To date, microwave drilling introduced in 1960s led to the exploration of different novel techniques and the issues of the usage of microwave energy in the mining environment such as microwave assisted drilling, the usage of the energy in mineral processing industry, space drilling applications, impact on cutting tool wear and tunneling.

Microwaves underground

Microwave radiation, which is a part of the electromagnetic energy, is eventually harmful for human beings. According to the standard for safety level with respect to human exposure to radio frequency electromagnetic fields, 3kHz to 300GHz, IEEE (2005) microwave energy exposure can lead to serious injury and death to human body. The usage of microwave energy requires shielding to avoid any leakage. In underground hard rock mining or tunneling applications, the rock surrounding the excavation face simplifies the shielding issues. Moreover, in mining applications remote control of underground techniques is developing, so it creates a safer environment that the workers would not be exposed to the irradiation. These facts would lead to a possible conclusion that underground would be a suitable and ideal environment to securely work with microwave energy (Radziszewski et al., 2008).

Impact cutting tool wear

Rocks consist of one or several minerals, which each mineral has its own characteristics such as abrasivity and hardness. Essentially, the more abrasive the mineral, the more the cutting tool interacting with it is worn. Wear is also proportional to the amount of energy applied on the tool to cut the rock (Deketh, 1995). Since by using microwave energy is expected to decrease the resistance of rock, it would be possible to have an influence on the abrasivity as well. It is therefore why CERCHAR test is performed in the present research, which has been explained in detail in chapter five, to calculate the influence of microwave energy on the abrasivity of rocks. This test is a standard and common test used for estimating the wear ratio of cutter tools in a TBM application, thus, estimating the cutter tool life time. Although the life time of a cutter tool is affected by other parameters, the abrasivity index of rock is a basic parameter.

Mineral processing

More investigation on microwave-assisted energy has been conducted in the mineral processing industry than on assisting mechanical excavators. The influence of the energy has also been studied on both crushing and liberation of valuable minerals from gangue minerals within the mineral processing industry. According to Walkiewicz et al., (1991) about 50 to 70% of the amount of energy of mineral extraction is used in comminution, where the efficiency of conventional grinding is only 1%. Walkiewicz (1991) showed 10 to 24% reduction in Bond Work Index (is a standard test to calculate the grindability of the material) of iron ores by irradiating samples to the microwave energy before the grinding procedure.

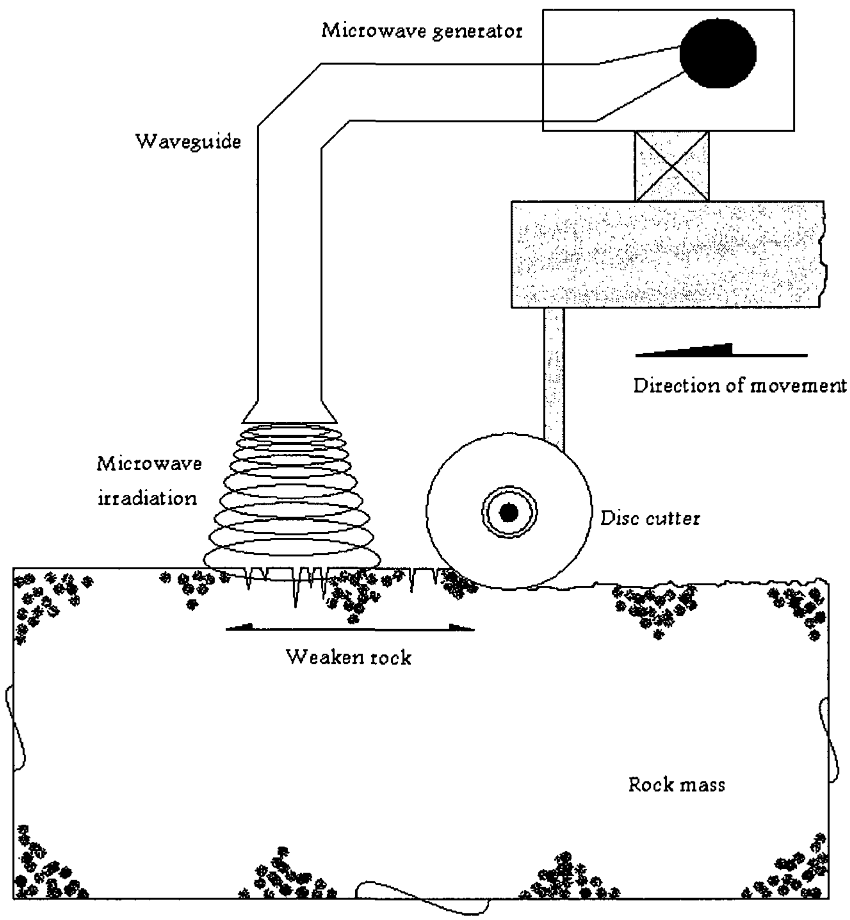


Figure 2-11 Conceptual combination of microwave energy and a single disc cutter of a TBM as pre-conditioning the surface of the rock by microwave irradiation (Lindroth et al., 1991).

Space drilling applications

In space applications, drilling, excavation and core sampling are done by different methods than on the earth. Drilling and coring applications are mostly performed for mineral analysis and water exploration, such as drilling through the Martian polar ice cap (Radziszewski et al., 2008) in order to explore life. Normally, Lunar and Martial materials are most likely similar to terrestrial coarse sand and plutonic basalt, respectively. Moreover, transportation of heavy equipment into the space is enormously expensive. Therefore, equipment designed should have enough power efficiency and performance as well as being as light as possible to ease the transportation. According to Satish (2005), microwave-assisted drilling reduces the resistance of terrestrial basalt which it has been estimated and increase in drilling penetration rates.

2.8 Microwave-assisted tunnel boring machine

Figure 2-12 shows the actual face of rock excavated by a TBM. The white lines are the grooves and traces left by the disc cutter tools. Figure 2-13 demonstrates a possible design of a microwave-assisted tunnel boring machine by placing rectangular microwave antennas (shown as black areas in the Figure) in a way to cover the whole face of the tunnel. The design includes a bit of overlap on the edges of the antennas in order to irradiate the full face of the tunnel. However, the area at the center of the cutter head is not irradiated, which should be taken in consideration to be designed in a way that the center would be exposed to the microwave irradiation as well. Evidently, all the criteria and circumstances of the combination of microwave energy to the head of a tunnel boring machine should be taken into consideration. Further lab and field tests should be done in order to determine the ultimate power and time of exposure with regards to the microwave energy.

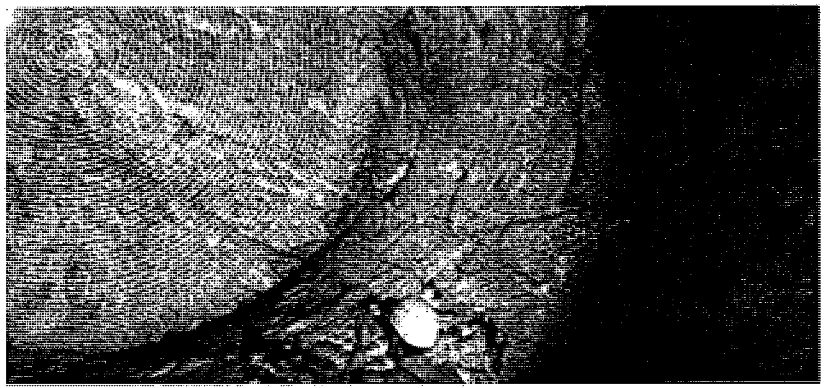


Figure 2-12 Grooves of disc cutter on hard rock tunnel face by a TBM machine (Herrenknecht, 2008).

Generally, the concept is to irradiate the face of the tunnel with microwave energy while boring the tunnel. This function allows the rocks to be exposed to the microwave irradiation first, so the possible decrease in strength to a certain amount within a specific depth depending on the type of rock and microwave conditions. As it is mentioned later on in this chapter, the amounts of shearing and normal forces are mainly effective on the tunnel boring machine penetration rate (Sanio, 1985). Therefore, by possible weakening of the rock by exposing it to microwave irradiation, the penetration rate should be increased.

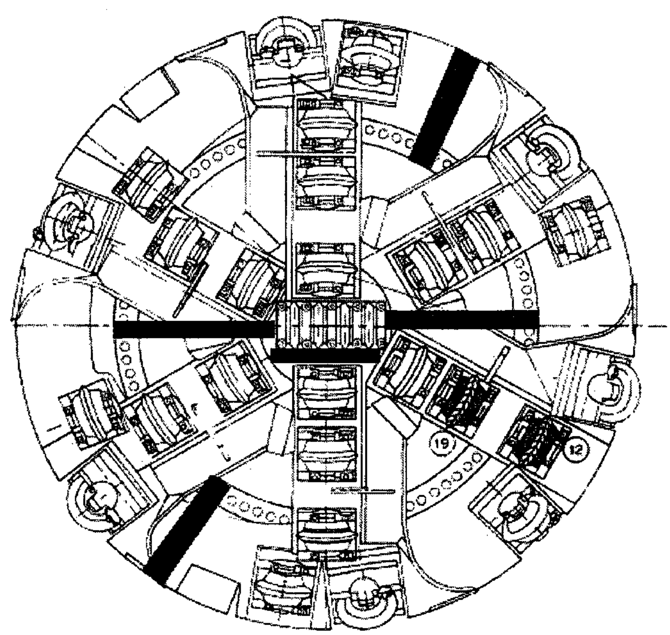


Figure 2-13 A possible design of a microwave assisted TBM

2.9 Mechanism of rock cutting by mechanical tools and TBMs

Mechanical tools generate mechanical stresses in different ways as impact, abrasion and erosion (Hood et al., 2000). "Brittle fracture can be created if the generated stress exceeds the strength of the rock" (Hood et al., 2000) (Figure 2-14). Fracture is a planar discontinuity generated in brittle rock materials, normally in hard rocks, in the form of cracks, joints or faults (Roberts, 1981).

Percussion tools, explosion and electrical discharges are different ways to generate impact. Those techniques produce a zone of crushed rock underneath the area of impact caused by the technique. "If the impact energy is large enough, it can create fractures in the area of crushed rock zone" (Chaiai, 2001).

"Abrasion tools are made of hard materials, such as diamond or tungsten carbide, to be able to abrade the surface of the rock" (Kennedy, 1990). Abrasion tools are designed to move parallel to the surface of the rock in a way to erode the surface of the material on which it is operating. The procedure of erosion creates fine crushed particles from the surface eroded (Kennedy, 1990).

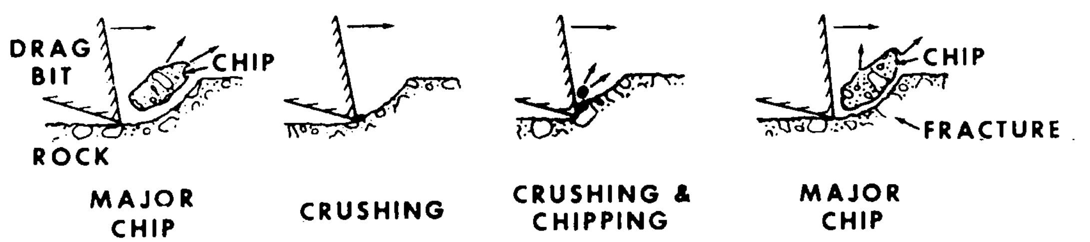


Figure 2-14 Cutting sequence of a rotary drag bit (Kennedy, 1990).

Mechanical responses of rocks being subjected to a certain stress field is scientifically called the mechanical properties of that rock. Generally, rocks have physical and chemical characteristics of their own, which are functions of their origins of creation (Prasad, 2000). The response of rocks to variations of tensile stresses is mainly dependent on the mechanical properties of the rock material and the number and nature of geological discontinuities present throughout the rock.

Tunnel boring machines are designed to operate in various rock types with different properties. Parameters such as strength, hardness or abrasion resistance, geological structures such as jointing, bedding and schistosity of the formation have a significant role influencing the penetration rate of a TBM (Figure 3-9) (Sanio, 1985). In homogenous and isotropic rocks, several predictor equations have been introduced, which it is also used by tunnel contractors as well, to estimate the performance of a TBM machine. On the other hand, for anisotropic or discontinuous rocks there is still no reliable formula to evaluate and predict the performance of a TBM due to the wide variety of changes in geological characteristics (Figure 2-15).

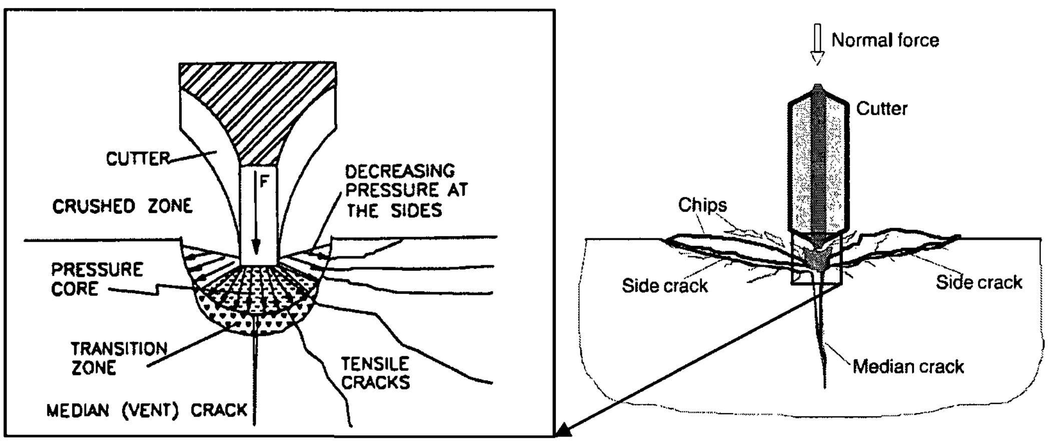


Figure 2-15 The crushed zone or pressure bulb under disc a cutter (Rostami et al., 1993).

In a hard rock tunneling application, working with a tunnel boring machine, many criteria are considered in the cost estimation of the project. The major part of the project cost is related to the disc cutters. In fact, disc cutters in TBMs are the most consumable part of the machine. Depending on the rock characteristics and mineralogical descriptions, by having abrasive minerals, the disc cutters can wear rapidly. Using the formula below, the lifetime of a disc cutter of a tunnel-boring machine can be computed (Wijk, 1992):

$$L = \sum dw^3 \frac{\cot(\theta)}{F\sqrt{\sigma_c \sigma_{PLT}}(CAI)^2} \tag{2-7}$$

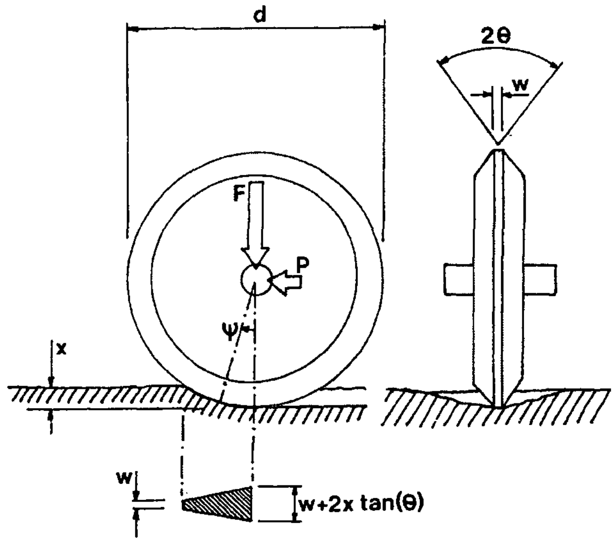


Figure 2-16 One disc cutter of a TBM showing the force distribution (Wijk, 1992).

Where:

"L" is the length of the distance that a disc cutter can roll on hard rock in meters

"CAI" indicates the CERCHAR test value which specifies the abrasion value of the surface of the rock

"σ_C" is the compressive strength value of the rock

"σ_{PLT}" is the point load test value of rock

"F" is the load applied to the cutter

"d" is the diameter of the disc cutter

"w" is the width of the edge of the disc cutter

"θ" is the angle between the two faces making the edge of the disc cutter

From the formula above, it is concluded that the lifetime of the disc cutters are inversely proportional to the compressive strength (Figure 2-16) and CERCHAR index values. Thus, as those two parameters decrease, the life time of the disc cutters increases (Salehi, 2007). In Figure 2-17 the horizontal axes, Fr and Fn, are the shear and normal forces respectively, influencing the penetration rate depending on the hardness of rock, which are applied to the rock face provided by the machine.

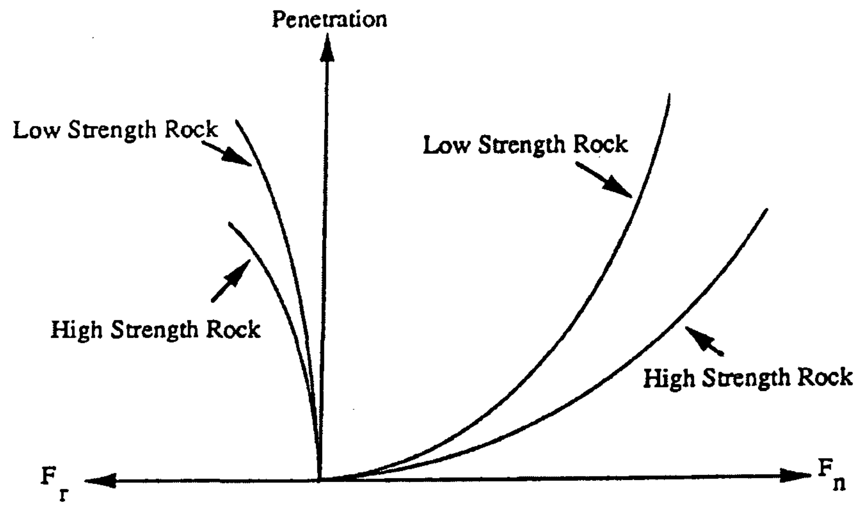


Figure 2-17 Penetration rate of a tunnel boring machine by applying shear and normal forces to high and low strength rocks (Wijk, 1992).

There are a few methods and techniques to predict penetration rate of a TBM machine in hard rock. A common applied penetration correlation equation of TBMs in various rocks suggested by (Farmer et al., 1980), using Brazilian tensile strength of the rock, can be defined as:

$$P_{Rev} = 624\frac{F_n}{\sigma_{tB}} \qquad (2\text{-}8)$$

Where: "P_{Rev}" is the penetration per revolution

"σ_{tB}" is the Brazilian tensile strength in mega pascal (MPa)

"F_n" is the normal force applied to the cutter in kilo-newton (kN).

Graham (1976) has suggested a similar equation calculating the penetration from the unconfined compressive strength of rock instead of Brazilian tensile strength (for rocks having UCS from 140 to 200 MPa) as the following equation:

$$P_{Rev} = 3940\frac{F_n}{UCS} \qquad (2\text{-}9)$$

Where: "F_n" is the normal load in kN

"UCS" is the unconfined compressive strength in MPa.

2.10 Summary

1) Dielectric materials absorb microwave energy and dissipate the energy to heat.
2) Permittivity of materials, which is directly frequency dependent, has a key role to determine the dielectric properties of that material.
3) Dielectric properties of rocks play a very important role in determining the depth level at which the electromagnetic energy penetrates.
4) Permittivity, moisture content, loss factor and the microwave frequency influence each other in defining the penetration depth into the material.
5) Due to its very high dielectric value, water content has a significant influence on the penetration depth level. As the water content of rock is higher, the penetration depth is lower.
6) As each individual mineral behaves differently against the electromagnetic energy, the combination of some forming rocks creates a much more complex behavior and characteristics.
7) Tunnel boring machines are more commonly used in both civil and mining applications creating underground openings for different reasons.
8) According to the variety of rock properties and their correlation with cutting tools, TBM machines have certain limitations regarding efficient performance in hard rock tunneling applications: high erosion and abrasion of cutting tools leads to short cycles of cutting, as a result of frequent cutter tool replacement. The advancement rate of the machine lowers,

so the capital cost of the project could be increased due to the very high consumption of cutter tools within the project.

9) Some parameters are in direct relation and proportional to the advancement rate of the TBM. Each of these parameters changes, the performance of the machine changes. These parameters are:
    - rock properties as strength, brittleness, abrasiveness
    - geological structures as fractures, joint, bedding and schistosity
    - mechanical characteristics of the machine as thrust, RPM.

10) By affecting rock properties due to microwave energy, advancement rate of TBMs would be increased.

11) Since the microwave energy could have an impact on rock strength or abrasiveness, it will be a great opportunity to assist TBMs to increase the machine performance in terms of advancement also increasing the cutter tools lifetime.

CHAPTER THREE

3. Review of the influence of microwave energy on rocks

3.1 Background of microwaving rocks

Serious studies on microwaves, which are a part of the electromagnetic spectrum, have been done from the time of World War II. Microwave energy possesses a vast range of uses that can be categorized in communication and non-communication applications. Communication applications of microwave power include telecommunication and satellite data transmission applications (Osepchuk, 1984). Non-communication applications of microwave power are widely used for industrial applications in which the power corresponds to that of heating. Other uses exist in the medical field, but will not be discussed further. Since the beginning of 1960's, microwave ovens for home use became available. Not long after, some industries began using microwave power in industrial applications such as rubber extrusion, plastic manufacture and the treatment of foundry core ceramics (Kingman et al., 1998). Gwarek et al., 2004, categorizes the typical areas of microwave power application as below:

- Food processing (heating, thawing, biological deactivation, quality control)
- Industrial material drying (paper, wood, explosive wood drying)
- Chemical reaction enhancement (micro-reaction control, fluidized beds)
- Melting of industrial materials (glass, rubber, sludge)
- Sintering (ceramics, metal powders)
- Plasma generation
- Mineral processing (rock crushing, comminution)

- Waste treatment and recycling

In the mid-1960's (Gray, 1965) described the influence of heat on the mineral spallation process utilizing a conductive surface heating device. By increasing the temperature of the surface of materials with a heat source, a stress distribution is created within the area heated. The stress field generated through the surface of the specimen subjected to the heat source causes cracks to grow and propagate rapidly, so the surface starts to fall apart in the form of very thin disc shapes (Figure 3-1).

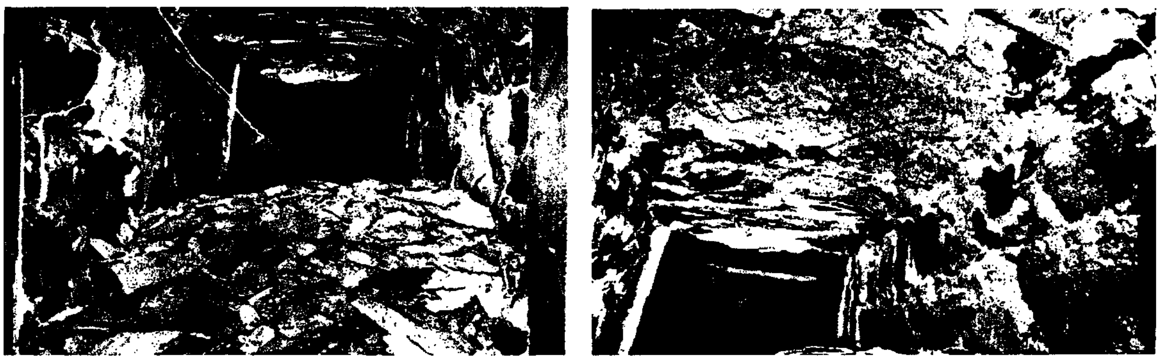


Figure 3-1 Thermal spallation of an underground tunnel to expand the passage. (Gray, 1965)

Applying heat in order to thermally fracture rock came to the interest of scientists and soon other alternatives were evaluated; such as heating with microwave power energy. (Maurer, 1968) categorized all kinds of possible novel drilling systems or technologies and evaluated their performance. The author designed and introduced different possible novel drills based on various methods of rock breakage, such as: mechanically induced stresses, thermally induced stresses, fusion and vaporization and chemical methods (Maurer, 1968).

Lauriello (1974) performed a vast investigation on the issue of thermal weakening of hard rocks by applying a conductive heat source. The author chose two types of hard rocks: granite as a spallable specimen and basalt as a non-spallable rock. Both rocks were subjected to a conductive heat source such as a flame torch, and their thermal characteristics were analyzed. According to the results from spallable and non-spallable rocks, the author predicted an increase in penetration rate of drilling in a limestone from Indiana by applying a convective heat source to the drill system after performing some experimental tests (Figure 3-2). In other words, the author's research specifies that by applying a convective source, the surface of rock can be fracture and spall off due to the rise of temperature.

Lauriello et al. (1974) describe the dielectrical heating effects in rocks due to microwave energy. As in-depth heating happens upon being exposed to the microwave irradiation, internal rock fracturing occurs, so the rock strength can be reduced. The authors' research includes a cost comparison of enhancing rock excavation with different methods of applying heat to the rock such as laser, electron beams, microwaves, radiant heaters and torches.

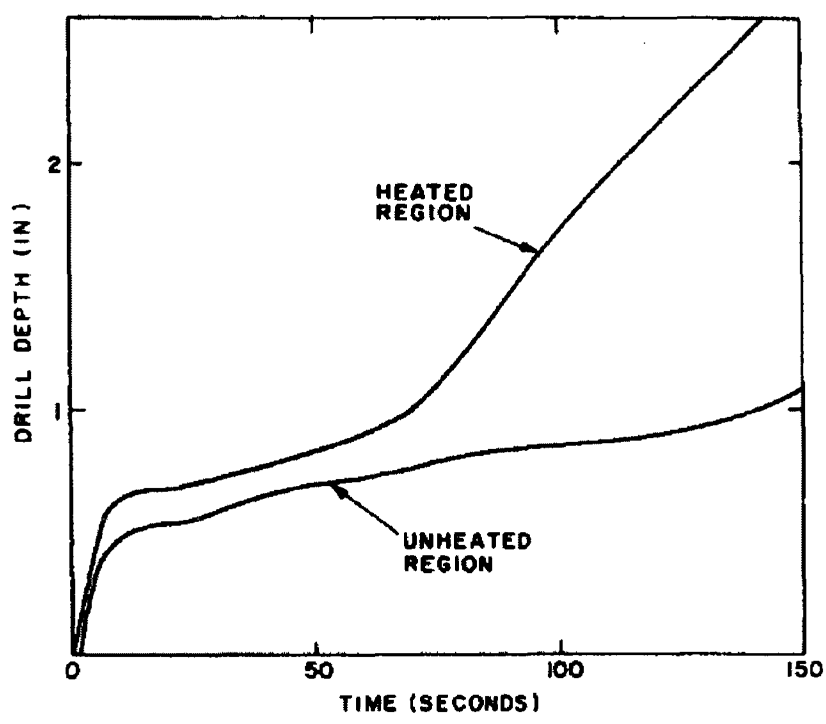


Figure 3-2 Estimated penetration rate of 0.25 inch diameter of tungsten carbide drill bit in Indiana limestone (Lauriello, 1974).

Table 3-1 Summary of various types of rock excavation methods cost comparison. (Lauriello et al., 1974)

Thermal source	Status	Specific energy kW-hr/ft^3 (Btu/in^3)	Transfer efficiency (%)	Fuel cost ($/kW-hr)	Specific Cost ($/ft^3)	Equipment ($)	Limitations
Electron beam	Lab	>4.5 (9.0)	50	0.03	0.27	50,000 ?	X-ray emission - requires heavy shielding
Microwaves	Comm		10	0.03		40,000	Severly restricted to rocks with high attenuation
Jet torches	Comm	1.0 (2.0)	1.8	0.0032	0.18	1,500	Hazard around gas pipes
Flame torches	Comm	1.0 (2.0)	1	0.13	13	300	Hazard around gas pipes
Laser	Lab	1.0 (2.0)	9	0.03	0.33	60,000 ?	Very large equipment for forming beam
Electrical radiant heater	Lab	1.0 (2.0)	22	0.03	0.14	2,000 ?	Maintaining clear reflectors and windows
Gas radiant heater	Idea	1.0 (2.0)	6	0.13	2.3	2,000 ?	A serious problem
Mechanical excavation as a comparison standard		3 (6)			2 to 5.5	2,500	Labor intensive activity, noisy, costs saor in very hard rock

However, most of the heat source candidates were eliminated because of the very high equipment cost (i.e. laser, microwave and electron beam) (Lauriello et al., 1974). The cost comparison table is shown in Table 3-1. Although, the preceding author suggests the microwave energy might come at a high cost, (Roberts, 1981) indicates that the higher the power of attenuation of microwave energy, the more the rock could be fractured more efficiently.

The relative transparency of minerals to microwave energy which specifies the behavior of minerals against microwave radiation was determined by (Chen et al., 1984). The authors exposed forty different pure minerals to microwave irradiation and measured the minerals' temperatures at certain applied energy (power) and time of irradiation. Purified (99% pure) samples, weighing 0.5-1g, were exposed to microwave irradiation at a frequency of 2450MHz and 150W of power for 3-5 minutes. In that study, the affect of microwave energy was examined on the purified ore samples. The study concluded that most silicates, carbonates and sulphates, some oxides and some sulphides were transparent to microwave radiation and let the radiation pass through themselves without producing any reaction and being heated (Table 3-2), however, most sulphides arsenides, sulphosalts and sulphoarsenides heated strongly, emitting fumes and fusing (Tables 3-3 and 3-4).

Table 3-2 Minerals transparent to microwave irradiation (Chen et al., 1984).

Mineral Class	Minerals/Compounds
Carbomates	Aragonite, Calcite, Dolomite, Siderite
Jerosite-Type compounds	Argentojarosite,Synthetic Natrojarosite (Zinc plant residue, Kidd Creek Mines Ltd), Synthetic Plumbojarosite (Zinc plant residue, Cominco Ltd)
Silicates	Almandine, Allanite, Anorthite, Gadolinite, Muscovite, Potassum Feldspar, Quartz, Titanite, Zircon
Sulfates	Barite, Gypsum
Others	Fergusonite, Monazite, Sphalerite (low Fe), Stibnite

Typically, ores contain minerals with different mechanical and heat properties which can lead to different behaviors of rock. Due to different thermal expansion coefficients existing between mineralogical species, some stresses will be created upon heating. According to Kingman et al. (1998) it is concluded that stresses produced can lead to inter-granular or trans-granular fractures. Indeed, microwave exposure dissipates energy through heat into the rock. Since different minerals act and behave differently against microwave irradiation, some minerals will heat up and some will not. At this point, microwaves create a strong thermal gradient and thermal stresses within different mineral phases and causes inter-granular cracks (Passchier et al., 2005).

Table 3-3 Results of microwave heating on oxides and uranium minerals; microwave frequency 2450 MHz; exposure time 3-5 min (Chen et al., 1984).

Mineral	Power (W)	Heating response	Product examination
Allanite	> 150	Does not heat	No change; allanite
Cassiterite	40	Heats rapidly	No change; cassiterite
Columbite (40 vol.%) pyrochlore in silicates (almandine 40%)	60	Difficult to heat when cold	Niobium minerals fused; most silicates unchanged
Fergusonite	>150	Does not heat	No change; fergusonite
Hematite	50	Heats readily; arcing at high temperature	No change; hematite
Magnetite	30	Heats readily	No change; magnetite
Monazite	>150	Does not heat	No change; monazite
Pitchblende (90 vol. %); contains chlorite, galena, calcite	50	Heats readily	Some fused to UO2, U3O8, ThO2 and Fe-Al-Ca-SiO2 glass; others unchanged

Since Chen et al. (1984)'s results on the influence of microwave energy on more than 40 different minerals, microwave energy has gained popularity among geoscientists to study its effect on materials for various purposes such as mineral processing. In the 1990's, thermally-assisted liberation of minerals from ore using microwave energy to provide heat was introduced by Fitzgibbon et al. (1990) and Veasey et al. (1991). Both researchers introduced thermal application on minerals in order to ease the grindability and liberation of minerals from their host material due to influence of microwave energy on minerals. In addition, Veasey et al. (1991)

mentioned the use of microwave energy as a useful potential alternative to generate heat into the material within mineral processing.

Each type of cutter with all kinds of pattern is designed to operate in different conditions (Figures 2-9 and 2-10). Each design is considered being able to work in a certain range of rock formation from soft to very hard rock. Heinio (1999) gave some reasons which can cause difficulties in performance:

- Hard rock which is cut by grooving instead of being fractured causes significant wear of cutting tools.
- Inappropriate cutter tool selection in plastic rock causes reduction in fragmentation efficiency.
- Silica, the most abrasive mineral, is the most important cause of sear due to overheating.
- Rock variability causes the bearing load to increase.
- If the mass of rock is heavily jointed or fractured, it may fall on the machine or its head and cause the head to jam at the face.

The range of permittivity for each category includes the variety of mineral component forming rocks, which changes the physical and chemical properties of rocks from one to another. The authors concluded that the permittivity of all kinds of rocks is affected by the frequency of the microwave energy depending on the mineralogy of the rock. As a result of treating the selected rock samples with microwave energy, the permittivity of all kind rocks in mentioned categories decreases as the frequency of the microwave energy increases.

Table 3-4 Results of microwave heating experiments on ore minerals; microwave frequency 2450 MHz; Exposure time 3-5 min (Chen et al., 1984).

Mineral	Power (W)	Heating response	Product examination
Arsenopyrite	80	Heats, some sparking	S and as fumes; some fusion. Pyrrhotite, As, Fe-arsenide and arsenopyrite
Bonite	20	Heats readily	Some changed to bornite-chalcopyrite-digenite; some unchanged
Chalcopyrite	15	Heats readily with emission of sulfur fumes	Two Cu-Fe-Sulfides or pyrite and Cu-Fe-Sulfide
Covellite/anilite (60% vol. %)	100	Difficult to heat; sulfur fumes emitted	Sintered to single composition of (Cu,Fe)9S5
Galena	30	Heats readily with much arcing	Sintered mass of galena
Nikeline/cobaltite (3vol. %)	100	Difficult to heat	Some fused; most unaffected
Pyrite	30	Heats readily; emission of sulfur fumes	Pyrrhotite and S fumes
Pyrrhotite	50	Heats readily with arcing at high temperature	Some fumes; most unaffected
Sphalerite (high Fe; Zn 58.9, Fe 7.4, S 33.7%)	100	Difficult to heat when cold	Converted to wurtzite
Sphalerite (low Fe; Zn67.1, Fe 0.2, S 32.7 %)	>100	Does not heat	No change, sphalerite
Stibnite	>100	Does not heat	No change; stibnite
Tennantite (Cu 42.8, Ag 0.1, Fe 4.8, Zn 1.7,As 12.5, Sb 10.6, S 27.5 %) (90 vol% tennantite, 6% chalcopyrite, 4 % quartz)	100	Difficult to heat when cold	Fused mass of tennantite-chalcopyrite; arsenic fumes emitted
Tetrahedrite (Cu 24.9, Ag 18.0, Fe 1.9, Zn 4.8, Sb 25.6, As 1.3, S 23.4 %) (85 vol.% tetrahedrite, 10% quartz, 5% pyragyrite, galena, chalcopyrite)	35	Heats readily	Fused mass of Ag-Sb alloy, PbS, tetrahedrite, Cu-Fe-Zn sulfide and Cu-Fe-Pb sulfide

Church et al. (1988) selected a group of minerals that can be commonly found in natural ores. They are grouped by their chemical composition within six major classes as: (1) oxides, (2) carbonates, (3) silicates, (4) phosphates and sulfates, (5) haloids and (6) tungstates (Church et al., 1988). As a result of being a weak absorbent of microwave energy, those minerals are known as low loss minerals in nature because low microwave energy is lost within the material. Powdered minerals were exposed to microwave irradiation of frequency ranging from 300 MHz to 1 GHz and the dielectric properties of individual samples were measured.

Table 3-5 Effect of microwave heating on the temperature of reagent grade elements and compounds (Walkiwicz et al.,

Chemical	Temp., °C	Time, min	Chemical	Temp., °C	Time, min
Al	577	6	Mo	660	4
$AlCl_3$	41	4	MoS_3	1106	7
C	1283	1	NaCl	83	7
$CaCl_2$	32	1.75	Nb	358	6
Co	697	3	NH_4Cl	31	3.5
Co_2O_3	1290	3	Ni	384	1
CoS	158	7	$NiCl_2$	51	2.75
Cu	228	7	NiO	1305	6.25
CuCl	619	13	NiS	251	7
$CuCl_2 \cdot 2H_2O$	171	2.75	Pb	277	7
CuO	1012	6.25	$PbCl_2$	51	2
CuS	440	4.76	S	163	6
Fe	768	7	Sb	390	1
$FeCl_2$	33	1.5	$SbCl_3$	224	1.75
$FeCl_3$	41	4	Sn	297	6
$FeCl_3 \cdot 6H_2O$	220	4.5	$SnCl_2$	476	2
Fe_2O_3	134	7	$SnCl_4$	49	8
$Fe_2(SO_4)_3 \cdot 9H_2O$	154	6	Ta	177	7
Hg	40	6	$TiCl_4$	31	4
$HgCl_2$	112	7	V	557	1
HgS	105	7	YCl_3	40	1.75
KCl	31	1	W	690	6.25
Mg	120	7	WO_3	1270	6
$MgCl_2 \cdot 6H_2O$	254	4	Zn	581	3
$MnCl_2$	53	1.75	$ZnCl_2$	609	7
MnO_2	1287	6	Zr	462	6
$MnSO_4 \cdot H_2O$	47	5			

[a]Maximum temperature recorded in indicated time.

Walkiewicz et al. (1988) did a vast investigation on the microwave heating characteristics of a number of minerals commonly in the nature and compounds. The authors exposed different types of powdered minerals into the microwave irradiation of 1 kW of power level and 2.45 GHz of frequency. All samples size were 25gr or a constant volume of 18ml for low density materials. All the test results of heating selected minerals versus time are given in the Table 3-5 for chemical compounds and Table 3-6 for common minerals. The authors also exposed chalcopyrite ore samples from Bingham Canyon, UT, to a 3 kW power level of microwave energy. Micro-cracks were observed within the microwaved ore mineral (Walkiewicz et al., 1988).

Table 3-6 Effect of microwave heating on the temperature of natural minerals (Walkiwicz et al., 1988).

Mineral	Chemical composition	Temp., °C	Time, min
Albite	$NaAlSi_3O_8$	82	7
Arizonite	$Fe_2O_3 \cdot 3TiO_2$	290	10
Chalcocite	Cu_2S	746	7
Chalcopyrite	$CuFeS_2$	920	1
Chromite	$FeCr_2O_4$	155	7
Cinnabar	HgS	144	8
Galena	PbS	956	7
Hematite	Fe_2O_3	182	7
Magnetite	Fe_3O_4	1258	2.75
Marble	$CaCO_3$	74	4.25
Molybdenite	MoS_2	192	7
Orpiment	As_2S_3	92	4.5
Orthoclase	$KAlSi_3O_8$	67	7
Pyrite	FeS_2	1019	6.76
Pyrrhotite	$Fe_{1-x}S$	886	1.75
Quartz	SiO_2	79	7
Sphalerite	ZnS	87	7
Tetrahedrite	$Cu_{12}Sb_4S_{13}$	151	7
Zircon	$ZrSiO_4$	52	7

[a] Maximum temp. recorded in the indicated time.

After Santamarina's (1989) research on rock characteristics against microwave energy, Lindroth et al., 1992 and 1993, equipped a drag bit with a high power microwave energy device in order to examine the penetration rate of drilling by treating the sample with microwave energy

(Figure 3-3). Two different rock types were chosen for this test: St. Cloud gray granodiorite and Dresser basalt. All physical, mechanical and electrical properties of the samples were calculated prior to testing to be able to compare them before and after microwave treatment. The samples were exposed to variable microwave power of up to 25kW and time of irradiation to reach the wanted temperature. This concept of microwave-assisted hard rock cutting was also patented by (Lindroth et al., 1992) (US Patent 5,003,144) (Lindroth et al., 1991).

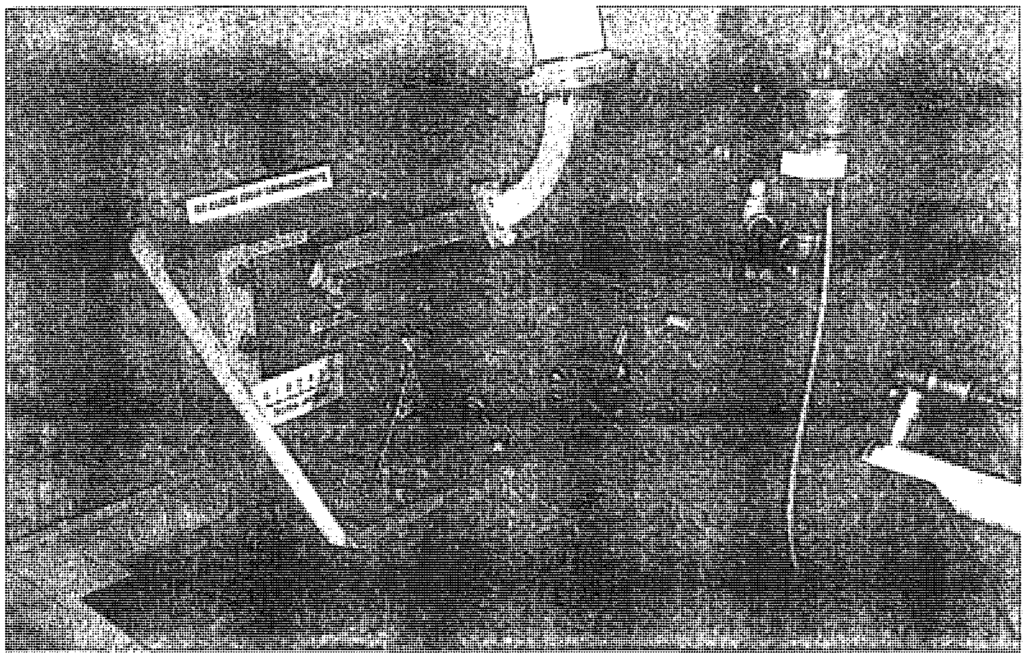


Figure 3-3 Microwave-assisted drilling in hard rock (Lindroth et al., 1992).

The drill bit was chosen for the purpose of being effective, a Kennametal tungsten carbide spade bit. The microwave conditions which the combination of conventional drilling and microwave energy works against the rock samples are as follows:

- Microwave
    - Single mode cavity
    - Adjustable power of 0-25kW
    - Frequency of 2.45 GHz
    - One minute exposure time

- Drilling parameters
    - Drill thrust 401 kg
    - Torque speed 36 rpm
    - One minute drilling time

The drilling apparatus was designed in a way that a drag bit is drilling the rock specimen with a rotary method and the microwave energy is simultaneously released near the drill bit by a wave guide (Figure 3-3).

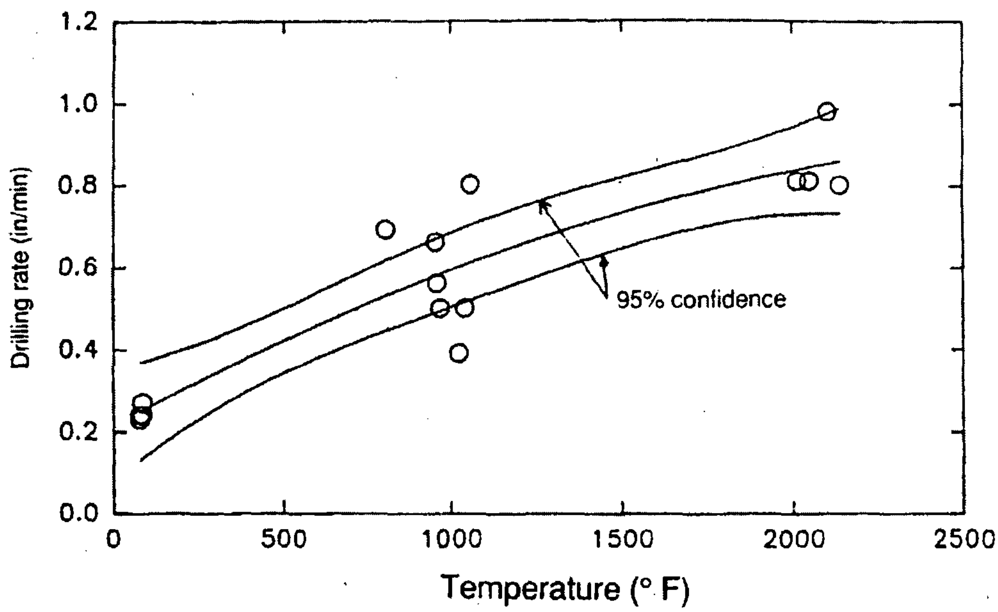


Figure 3-4 Drilling penetration rate as a function of temperature of St-Cloud gray granodiorite (Lindroth et al., 1991).

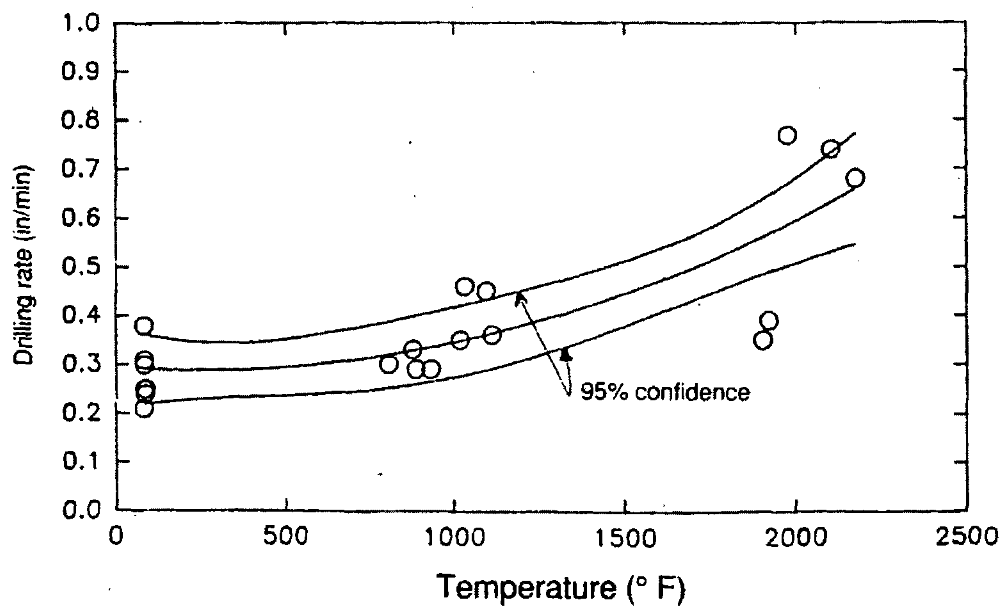


Figure 3-5 Drilling penetration rate as a function of temperature of Dresser basalt (Lindroth et al., 1991).

Figures 3-4 and 3-5 show the drilling rates as a function of temperature. It was concluded that the drilling penetration rate is increased by a rise in temperature. In addition, negligible wear on the bit was observed. Since bit temperatures remain low, no destruction of the carbide-to-steel brazing occurred, and the entire bit remained in good condition (Lindroth et al., 1993). The industrial application of this technology includes: continuous miners, road-headers and tunnel-boring machines (Hartman, 1992). Lindroth et al. (1993) also performed a theoretical comparison of the operating costs of conventional drilling and microwave-assisted drilling which evidently showed that generating microwave energy is costly but the overall cost of operation is reduced as shown in Table 3-7.

Table 3-7 Direct cutting cost, conventional vs. microwave-assisted (Lindroth et al., 1993).

	Conventional (cost/shift)	Microwave-assisted (cost/shift)
Capital costs		
Base excavator (500kW):		
$500,000/2,500 shifts	$200	$200
Microwave generator (250 kW):		
$500,000/2,500 shifts	NA*	$200
Operating costs		
Excavator power:		
500 kW x $0.05/kWh x 4 hr	$100	$100
Microwave power:		
250 kW x 1.11 x $0.05/kWh x 4 hr	NA*	$56
Bits: $5.00/bit	$500 (1 bit/st of prod.)	$500 (1 bit/2 st of prod.)
Total	$800/shift or $8.00/st (100 st/shift)	$1056/shift or $5.28/st (200 st/shift)
NA* : not applicable		

3.2 Influence of Microwave Radiation on Material Strength Properties

Two types of microwave cavities have been suggested for irradiation, multi-mode cavity and single-mode cavity. "A mode is a defined pattern of distribution of the electric and magnetic field components of an electromagnetic wave excited in a closed cavity" (Kingman et al., 2004). "They are mechanically simple, closed metal boxes, consisting of two dimensions of several wavelengths long which support many modes" (Kingman, 2005). Kingman et al. (2004) indicates that the heat generated into the dielectric in a multi-mode cavity can be affected by several parameters as the shape, dimension, configuration of microwave feeds, the microwave characteristics irradiated and material properties itself.

"A single-mode cavity is a metallic enclosure which supports only a single mode to localize the microwave radiation into a small volume and generate a high electric field" (Kingman, 2005).

In single mode cavity the volume of energy absorbed by the dielectric directly depends on the electric field, provided by the electromagnetic energy, which can lead to rapid heating (Kingman, 2005).

Znamenáckovά et al. (2003) investigated the influence of microwave radiation on andesite rock samples from the locality of Ruskov, Romania. The authors exposed and melted three core samples of andesite using microwave radiation. Samples were completely melted after being exposed to 1350W of power at a frequency of 2.45GHz for 10 minutes in a multi-mode cavity, followed by 30 minutes at 2700W of power and the same frequency. X-ray diffraction analyses were performed on the samples before and after irradiation. The result of this experiment showed that the basic chemical composition of andesite remained the same without any losses in weight, but the structure of andesite turned amorphous after melting (Znamenáckovά et al., 2003).

Whittles et al. (2003) and Jones et al. (2007), used numerical modeling to investigate the influence of the power density on the strength of the material. Both authors simulated a 30x15mm pyrite-hosted calcite sample in FLAC simulator software and examined the effect of microwave radiation on the strength of the numerically designed sample. Whittles et al. (2003) used the simulated sample to model irradiation to the normal constant microwave energy in various conditions, such as different times of exposure and power levels of microwave energy. Whereas, Jones et al. (2007) studied the influence of pulsed microwave energy on the strength of the same simulated pyrite hosted calcite sample. Jones et al. (2007) modeled sample exposure for five times from 0.1 to 10 seconds. Both researchers evaluated the influence of the energy on the unconfined compressive strength of the rock sample and showed a significant reduction either by exposing the simulated sample to constant or pulsed microwave energy.

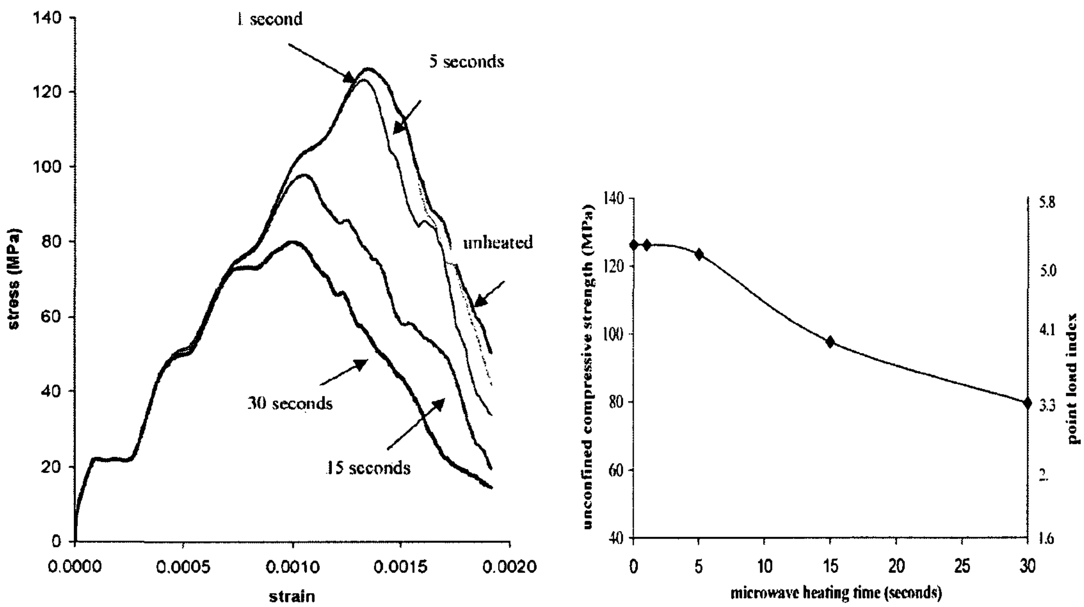


Figure 3-6 Theoretical comparative results of numerically modeled effect of microwave heat treatment on pyrite particles hosted calcite in microwave condition 1 (Whittles et al, 2003).

For Whittles research, small pyrite particles were distributed randomly throughout the calcite host model. Both multi-mode and single-mode microwave applicators were used. Pyrite is absorbent and calcite transparent to the microwave radiation. In this numerical simulation, where no physical experiment has been subjected to be tested, two different microwave conditions were used with the same frequency of 2.45GHz. In the first condition, the sample was exposed to 2.6kW of power in a multi-mode cavity producing power density between 3x109 W/m3 at 300°K and 9x109 W/m3 at 600°K. The time of exposure in the first condition was 1, 5, 10, 15 and 30 seconds (Whittles et al., 2003). After heat treatment, uni-axial compressive strength (UCS) and point load test (PLT) were performed in order to compare the strength of sample irradiated by microwaves. Figure 3-6 evidently shows that the strength of the simulated material drops fairly smooth as the time of exposure increases.

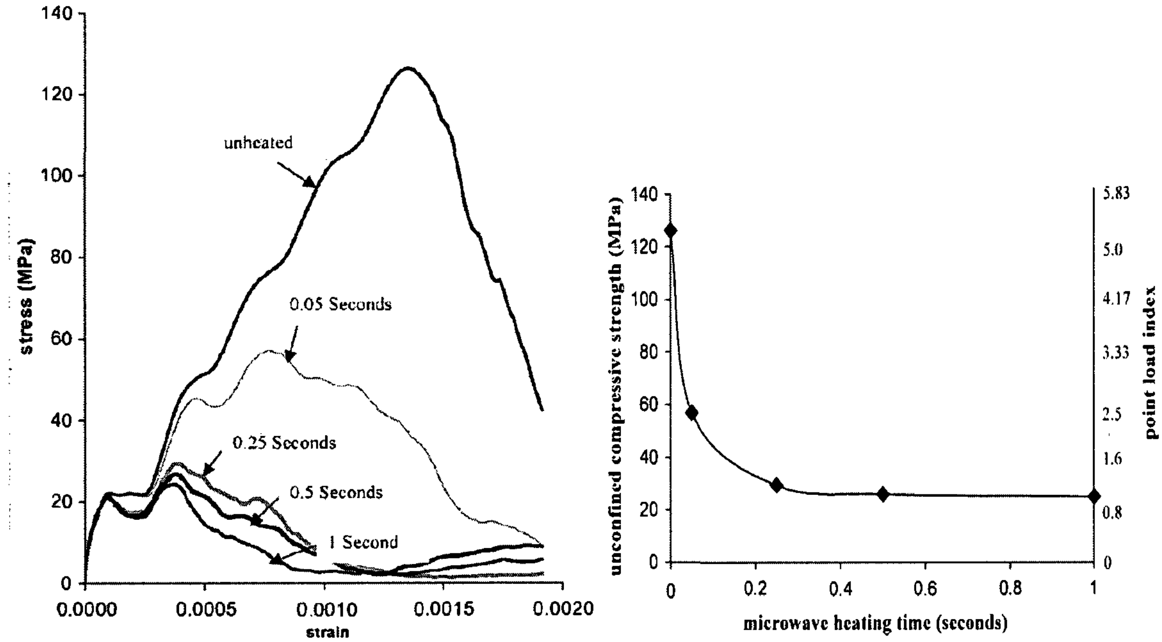


Figure 3-7 Theoretical comparative results of numerically modeled effect of microwave heat treatment on pyrite particles hosted calcite in microwave condition 2 (Whittles et al., 2003).

In the second microwave condition, a single-mode cavity with 15kW of power was used to illustrate a power density of 1011 W/m3. The samples were treated for 0.05, 0.25, 0.5, and 1 seconds. The power density in this condition is almost 10 to 15 times greater than the power density generated in a multi-mode cavity (Whittles et al., 2003). Since the power density is directly proportional to the magnitude of the electric field, specimens heat up quicker than in a multi-mode cavity, therefore rapid heating in single mode cavity is much effective for shorter times of exposure. Although in multi-mode cavity calcite is heated by pyrite particles conducting heat, in the single-mode cavity, the time of heat treatment exposure is reduced due to higher power density created (Whittles et al., 2003). The comparative results of UCS and PLT analysis after treatment in a single-mode cavity are shown in Figure 3-7, which it shows a sharp reduction of strength in simulated material as the time of exposure increases. Thus, it is clear that the single mode cavity is much powerful and effective on strength reduction of material than the multi-mode cavity.

Due to lower power density in the multi-mode cavity than single-mode, the time of exposure increases the generation of heat, thus the calcite host will heat by conductance with pyrite particle. Therefore, little change in strength appears or in other words the strength is reduced smoothly by the time of exposure increases (Figure 3-6). In the single-mode cavity, heat is generated rapidly, so the pyrite particles will heat before the calcite host. As a result of heat expansion of pyrite particles, some stresses will be released in the form of shear planes. Hence, the strength is significantly and rapidly reduced.

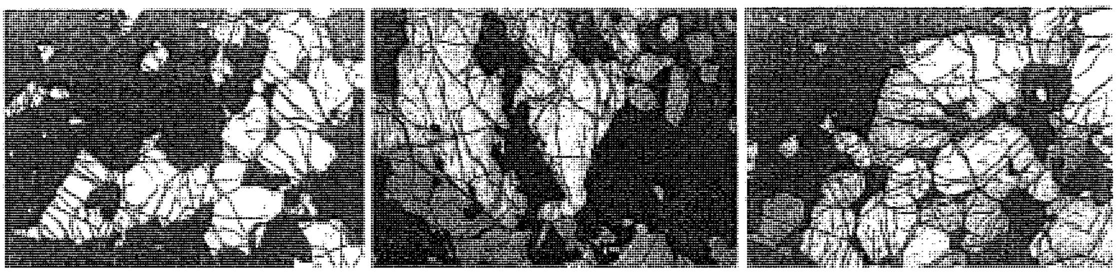


Figure 3-8 Digitized monochrome reflected photomicrograph photos of massive Norwegian Ilmenite ore treated with microwave radiation of 2.6kW power, 2.45GHz and exposure time of 0, 30 and 60 sec respectively from left to right (Kingman et al., 1998).

The nature of the grain boundaries between minerals is not well understood, but it is suggested that it is an area of disorder between two ordered species, which can be a potential area of weakness within the rock (Passchier et al., 2005). Previous research done by Chen et al. (1984), Haque (1999) and Jones et al. (2002) determined that different minerals have different reactions to microwave radiation. Some absorb the radiation and some are transparent. With respect to different mechanical properties, minerals heat in different rates in an applied microwave field. Different heating rates will necessarily increase the level of volumetric expansion at the grain boundaries (Res et al., 2003).

It is assumed that this rise in the volumetric expansion will hence create potential stress in the grain boundaries which can lead to weakening of the material due to inter-granular and trans-granular cracks through the material. The investigation of the effect of microwave on massive Norwegian Ilmenite ore performed by Kingman et al. (1998, 2000) validates the inter-granular and trans-granular cracks created within the minerals (Figure 3-8). Another investigation also showed reduction in Bond Work Index (BWI) of up to 90% (Figure 3-9) (Kingman et al., 2004).

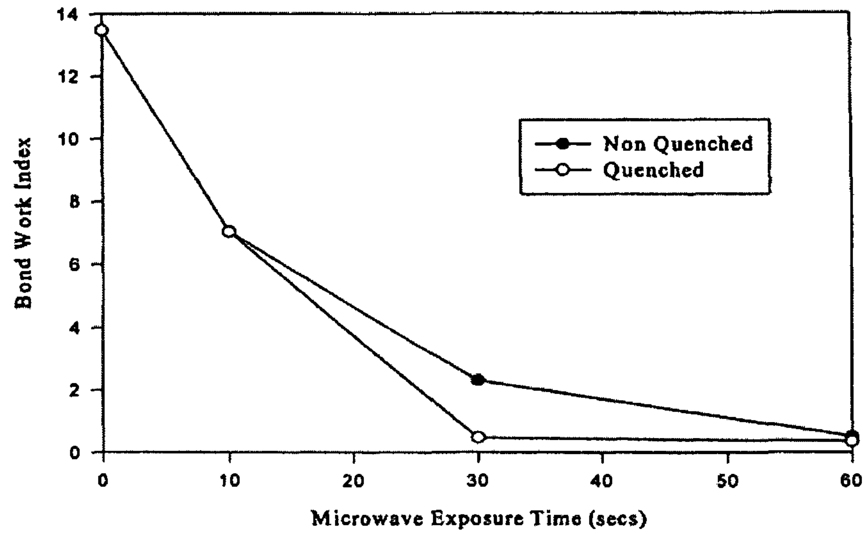


Figure 3-9 Effect of microwave radiation on the Bond Work Index of massive Norwegian ilmenite ore, quenched or non-quenched in water after irradiation (Kingman et al., 2004?).

Vorster et al. (2001) determined the influence of microwave energy on the Bond Work Index reduction of two kinds of copper ore from Neves Corvo, Southern Portugal. The samples were massive copper ore (MC) and massive copper-zinc ore (MCZ). The authors exposed the samples being irradiated for 90s by microwave energy of 2.6 kW of power level and 2.45 GHz of frequency in a multimode cavity. The results of treated tests compared to the untreated samples shows almost 70% reductions in Bond Work Index (Figure 3-10). Moreover, the authors experienced an increase of 15% reduction of BWI by quenching the treated samples in water. This is due to the high temperature gradient of treated hot samples and water at ambient temperature which causes a shock of expansion ratio of grains that leads to the micro-fracturing procedure within particles (Vorster et al., 2001).

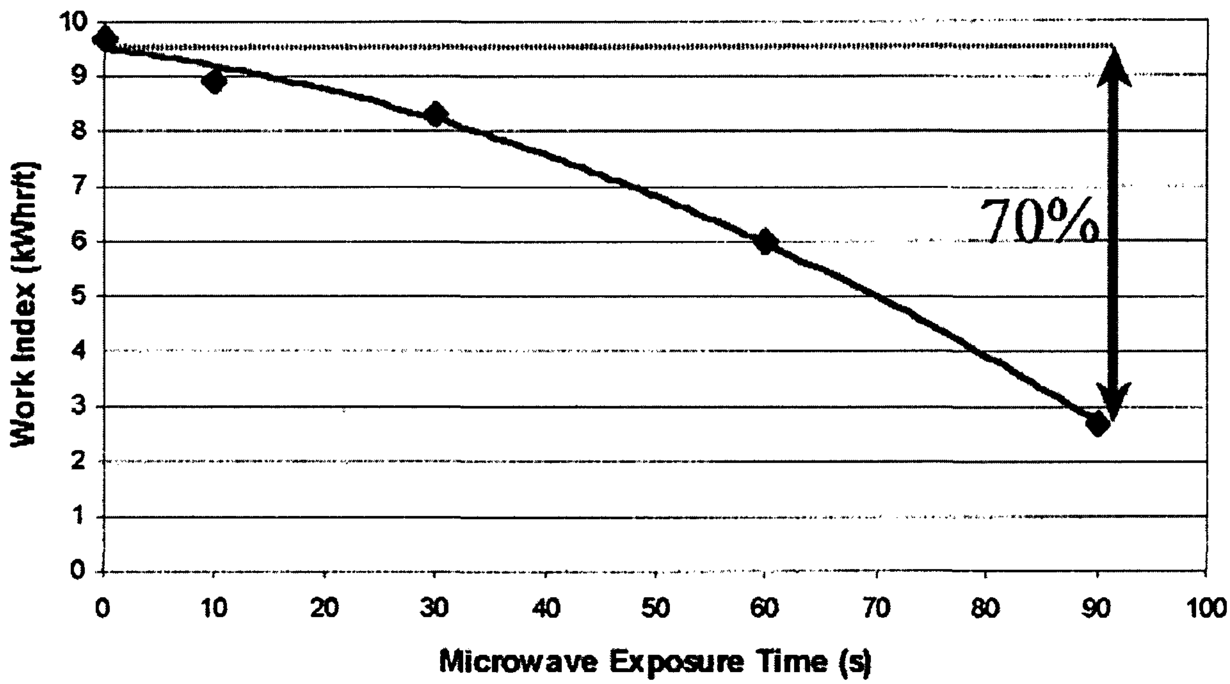


Figure 3-10 A plot of work index reduction versus microwave exposure time for MC-ore after quenching (Vorster et al., 2001).

Jerby et al. (2002) designed an apparatus which drives the microwave energy from a magnetron to the material through a waveguide in a way that the microwave irradiation is localized into a predesigned spot location on the material. The subjected material will be exposed to the microwave irradiation as much as the microwaved area on the material is melted, so the moveable electrode will be inserted and penetrated into the hot zone melted material (Jerby et al., 2004). As the electrode is pushed into the molten material, a hole is shaped by taking the form of the inserted nail (Figure 3-11).

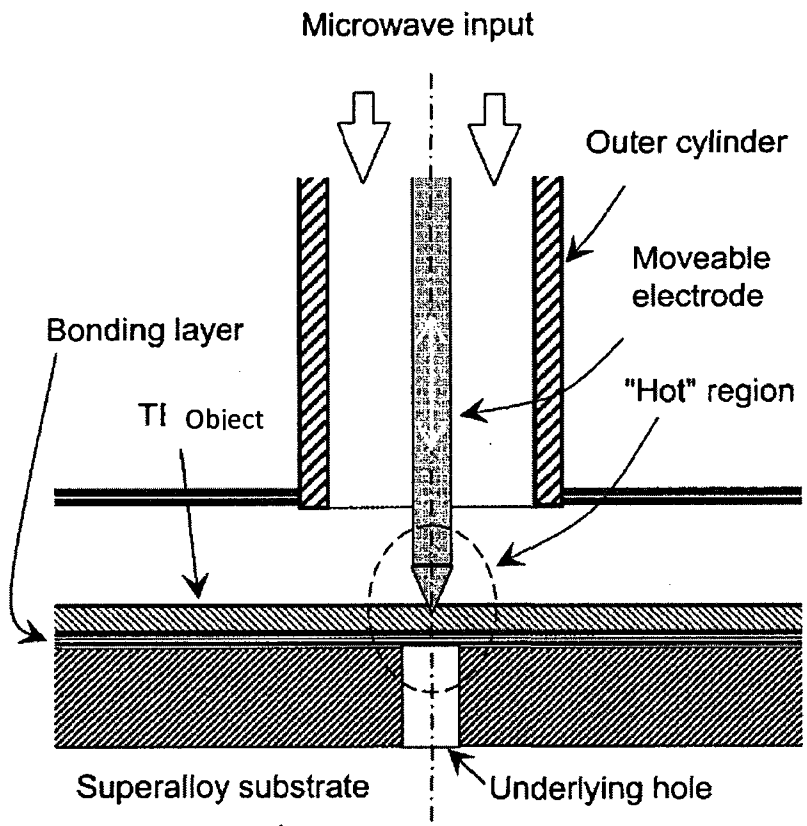


Figure 3-11 A schematic view of the microwave-drill device (Jerby et al.,2002).

This device consists of a 1 kW power magnetron generating microwaves of 2.45 GHz frequency. The electrode used in the device is made by tungsten rod resistant enough to heat and erosion criteria as it will be inserted into melted material of over 1500°C (Jerby et al., 2002;. 2004). This study is still at the laboratory scale and has been successfully performed on a variety of materials such as: glass, basalt, concrete, ceramics and silicon (Jerby et al., 2002; 2003; 2004). A hole of two millimeters in diameter and two centimeters in depth has been drilled in the materials mentioned above within less than a minute (Jerby et al., 2000; 2002).

Kingman et al. (2004) investigated the influence of microwave irradiation on ore comminution within a processing plant. The author used actual lead and zinc ore obtained from a mine in Sweden. One kilogram samples were exposed to microwave radiation in two different conditions.

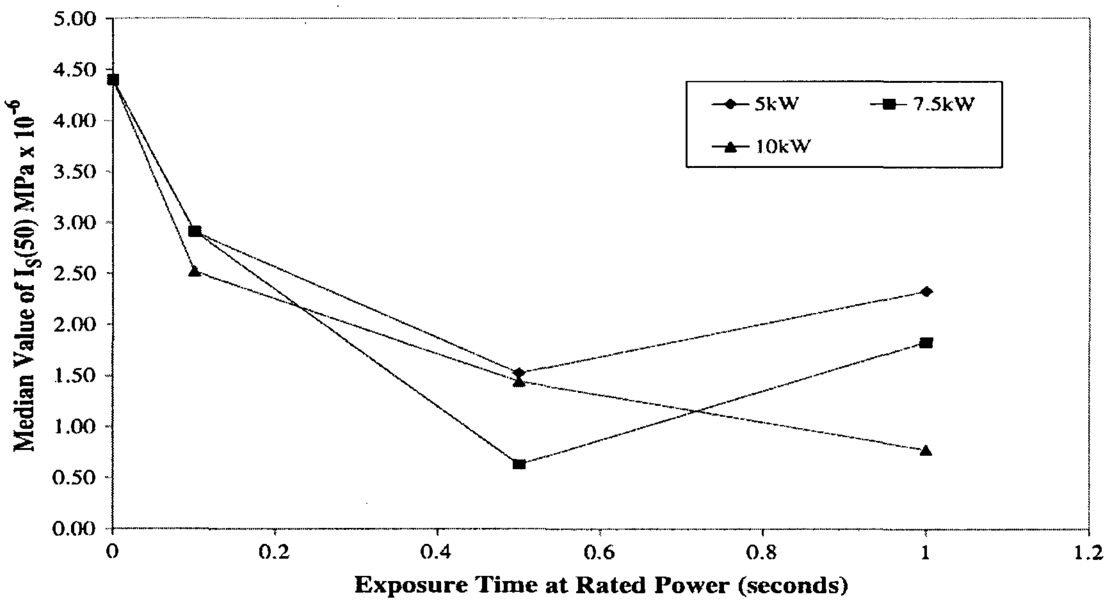


Figure 3-13 Point load test results from single-mode cavity (Kingman et al., 1998).

Scott (2006) investigated on the impact of microwave energy on copper ore liberation from South Africa. The author exposed 1kg batches of crushed samples into 10.5 kW power level of microwave irradiation of 2.45 GHz frequency for 0.5sec. The result shows a significant strength reduction through mills within the processing plant and also increase in the potential of copper liberation from its host during flotation (Scott et al., 2008). However, this study also specifies that the most efficiency of treated liberation of copper mineral is within coarse particle grain size range of 106 to 300 μm (Scott et al., 2008).

Recently, some detailed investigation specifically regarding the influence of microwave energy on rock strength has been conducted at McGill University. Satish (2005) and Satish et al. (2006) exposed basalt core samples to the microwave irradiation of 750 watts for 60, 120, 180 and 320 seconds in a multi mode cavity. In addition to observing a reduction in the strength of the rock with increasing time exposure, they also found that longer exposure (180 and 320 sec) causes the sample to spall and chip off locally under point load test (Figure 3-14).

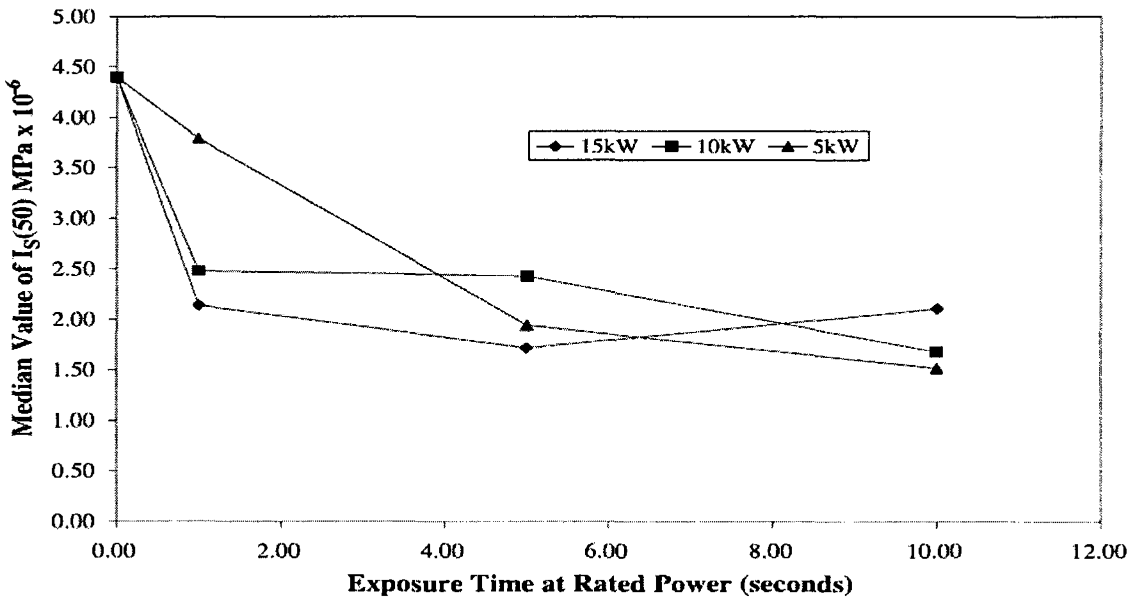


Figure 3-12 Point load test results from multi-mode cavity (Kingman et al., 1998).

In both multi-mode and single-mode cavity conditions, the frequency of microwave is 2.45GHz. Samples were irradiated with 5, 10 and 15kW power for 1, 5 and 10 seconds each in multi-mode cavity; and 5, 7.5 and 10kW power for 0.1, 0.5 and 1 second in single-mode cavity. Ore samples were not exposed to the radiation of 15kW in single-mode cavity because of melting of the sample. The strength of samples was determined by the point load test before and after heat treatment of microwave radiation. The comparative strength results of microwave treated samples within both multi-mode and single mode cavity are shown in Figures 3-12 and 3-13.

It has been concluded from this investigation that rapid and significant failure can happen in single-mode applicators due to high electric field strength. In other words, the higher the power level of the microwave, the more the strength of the sample is reduced (Kingman et al., 2004). Hence, this experiment on actual rock samples proves numerical experiments (Whittles et al., 2003; Jones et al., 2007).

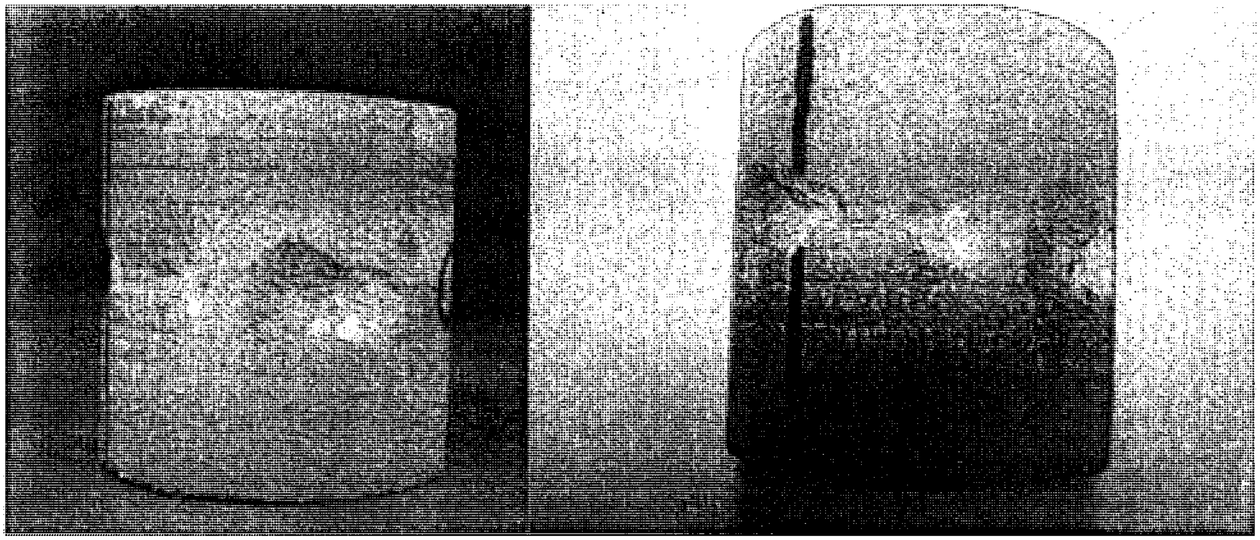


Figure 3-14 Chipping and spallation of sample under point load test after being exposed to the microwave energy for 180 and 320 seconds (Satish, 2005).

In order to understand the mechanism of strength reduction of rock caused by being exposed to the microwave energy, Satish (2005) has refined Whittles et al. (2003) simulations using finite element method (FEM) in modeling the energy density of the microwave field in the cavity instead of assuming a power density as done by Whittles et al. (2003). In his simulations, he also used the same material as Whittles et al. (2003) but in a different shape, a single pyrite particle hosted calcite in a shape of a sphere, to show the generation of stress within the grain boundaries. Because of the axes of symmetry of the model, the FEM model could be reduced to the two dimensional quadrant illustrated in Figure 3-15. Because of the transparency difference of minerals, a large amount of potential stress can be generated in the boundary of the particles, which leads to strength reduction (Figure 3-15).

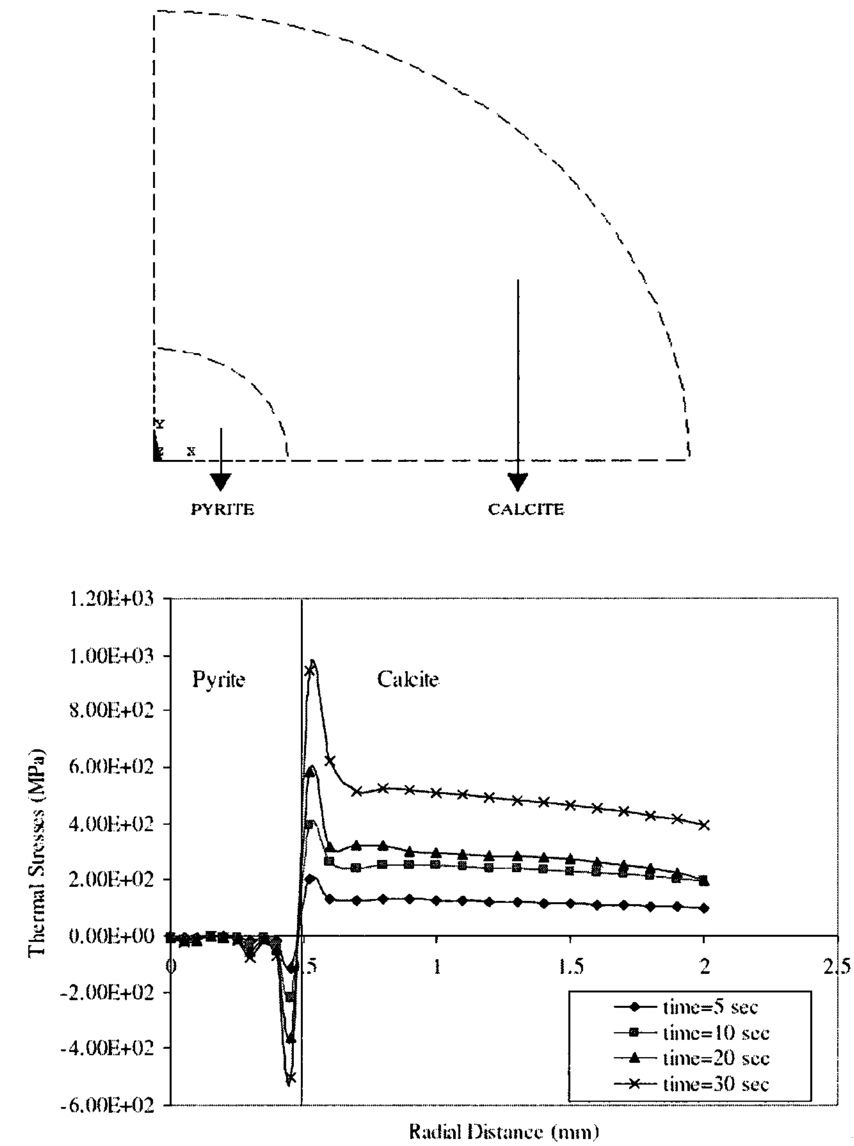


Figure 3-15 Stress vs. radial distance simulated (lower diagram) in the boundary of a pyrite hosted calcite (upper diagram) (Satish, 2005).

Furthermore, to be able to better understand how rapid heating generates stresses among particles due to differential volumetric expansion, Wang et al. (2005) performed a numerical modeling investigation on the mechanism of microwave assisted rock breakage. By using the discrete element method (DEM), they developed a model showing the breakage density produced in the boundary of a single pyrite particle hosted by calcite (Figure 3-16). Wang et al. (2005) used two different power levels to conduct his experiment. They realized that by increasing the power level also the time of exposure respectively, the density of breakage increases in the area of the particles boundaries.

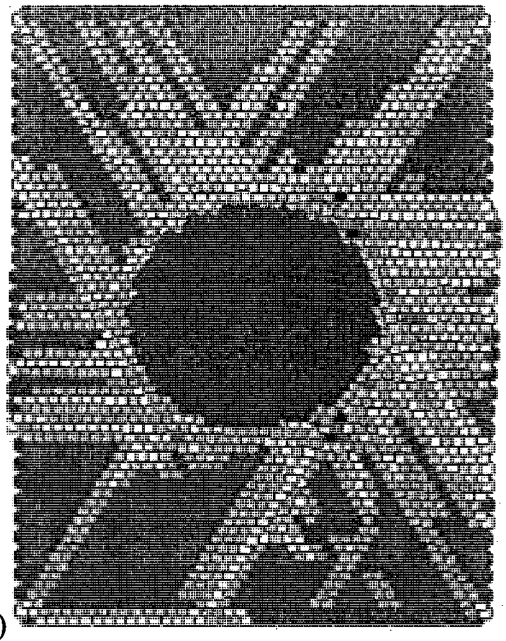
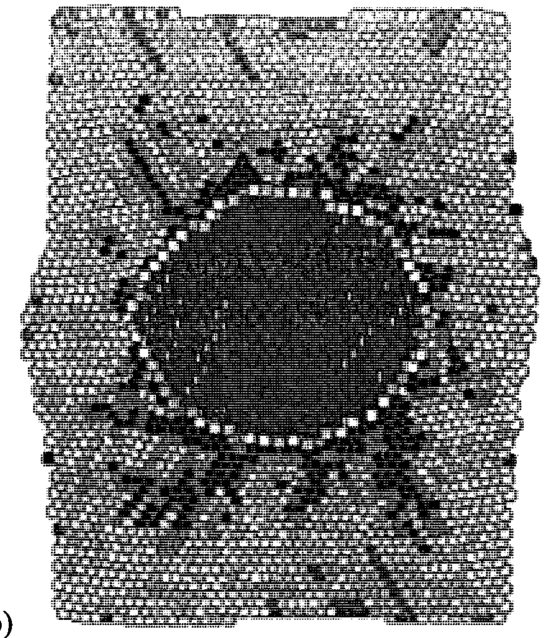
a)  b) 

Figure 3-16 Simulated micro-fractures using a discrete element model. The amount of black dots indicates the fracture density from a) before to b) after being microwaved (Wang et al., 2005).

3.3 Summary

Since the 1960's, when microwave energy has been proposed as an alternative novel technology for rock breakage within different applications, many studies have been conducted on the influence of microwave on rocks. In fact, all research performed was regarding the breakage of rocks only using direct emission of microwave energy until Lindroth et al. (1991) introduced and proposed the assistance of the electromagnetic energy with mechanical rock excavation tools. Those authors obtained positive results of drilling penetration rate by first irradiating blocks of hard rocks with a high power microwave energy (up to 25kW power) then drilling rotary method using a normal drag bit within a short period of time. Since the 1990's, researchers have been more interested to use microwave energy in mineral processing industries in order to reduce the amount of energy consumption rather than implementation in rock excavation methods.

Part of the purpose of this literature review was to determine suitable microwave conditions to expose different rocks. The difficulty in thoroughly assessing the previous literature was that researchers have exposed various types of rocks to microwave irradiation under several different conditions such as type of cavity used, time of exposure and energy power level (Table 3-8) introducing a large number of variables without data on all combinations.

Microwave energy, which induces inter-granular and trans-granular cracks into rock in order to reduce the strength of the material or even increase liberation of minerals, may be a very good candidate for use in rock comminution techniques. In addition, in order to have a significantly rapid result, the power level of the microwave energy needs to be increased, increasing the power absorption density of materials. Only the single-mode applicators are able to create such a powerful electric field and a high power level absorption density.

Since microwaves are a good source of heat treatment with significant penetration rates, a combination of microwave and more traditional mechanical methods of rock breakage is suggested. Microwave technology could be combined with a mechanical drilling method in order to first reduce the strength of the rock, followed by drilling in a conventional way. Since different materials have different reactions, mechanical properties and heat parameters when applied to a heat source, each should be investigated to influence the impact of microwave irradiation on their individual composition.

Table 3-8 Summary of microwave condition used by different researcher.

Sample	Cavity Mode	Frequency (Hz)	Power (kW)	Exposure time (s)	Effect	Authors
40 minerals	Single	2.45	0.8			Chen et al., 1984
Concrete	Single	2.45	1	60	Melting	Jerby et al., 2004
Ilmenite	Multi	2.45	1.3	30	Fracture	Kingman et al., 1998 & 2000
Andesit	Multi	2.45	1.35	600		Znamenackova et al., 2003
Ilmenite	Multi	2.45	2.6	60	More Frature	Kingman et al., 1998 & 2000
Pyrite & Calcite	Multi	2.45	2.6	1, 5, 15, 30		Whittles et al., 2003
Andesit	Multi	2.45	2.7	1800	Melting	Znamenackova et al., 2003
Sand Stone	Single	2.45	2x 2.5	20-120	Spallation	Maurer, 1968
				180-600	micro-fractures	Maurer, 1968
Lead & Zinc	Multi	2.45	5	1,5,10		Kingman et al., 2004
			10	1,5,10		Kingman et al., 2004
			15	1,5,10		Kingman et al., 2004
Pyrite & Calcite	Single	2.45	5	0.1, 0.5, 1		Whittles et al., 2003; Jones et al., 2007
(computer			7.5	0.1, 0.5, 1		Whittles et al., 2003; Jones et al., 2007
simulation)			10	0.1, 0.5, 1		Whittles et al., 2003; Jones et al., 2007
	Single	2.45	15	0.05, 0.25, 0.5, 1		Whittles et al., 2003; Jones et al., 2007
Basalt	Multi	2.45	0.75	60, 120, 180, 320	Spallation	Satish, 2005
Copper carbonatite	Single	2.45	5,10,15	From 0.1 to 1	Weaken	Kingman et al., 2004

The present research will introduce the combination of conventional mechanical rock brakage machines with microwave energy, such as TBM and road header. In that sense the research studied more on the operation of tunnel boring machines (TBM), as an alternative rock breakage method, in hard rock due to their limited performance in instances with very high strength rocks. However, TBMs are able to provide the power needed to generate sufficient high power microwave energy emission. Although the assistance of microwave energy necessitates more initial investment and expenses within tunnelling projects, it can also have a remarkable economical and technical impact. In this research, five exposure times and three power levels have been chosen for the laboratory experiments.

CHAPTER FOUR

4. Materials and methodology

4.1 Materials

Seven rock types have been chosen to be investigated in the current research to study some mechanical and structural effects of microwave energy on them. Those seven rock samples are:

A. Light Granophyre, from Vale Inco underground nickel mine in Sudbury, Ontario;

B. Dark Granophyre, from Vale Inco underground nickel mine in Sudbury, Ontario;

C. Barre gray granite, from Barre Granite Association quarries in Vermont;

D. Gabbro, available in the laboratory;

E. Gneiss, in other words recrystalized sandstone, available in the laboratory;

F. Limestone, ore body, from Lafarge Incorporation cement plant in Montreal, Quebec;

G. Basalt, from IAMGold Corporation underground Mouska gold mines in Quebec.

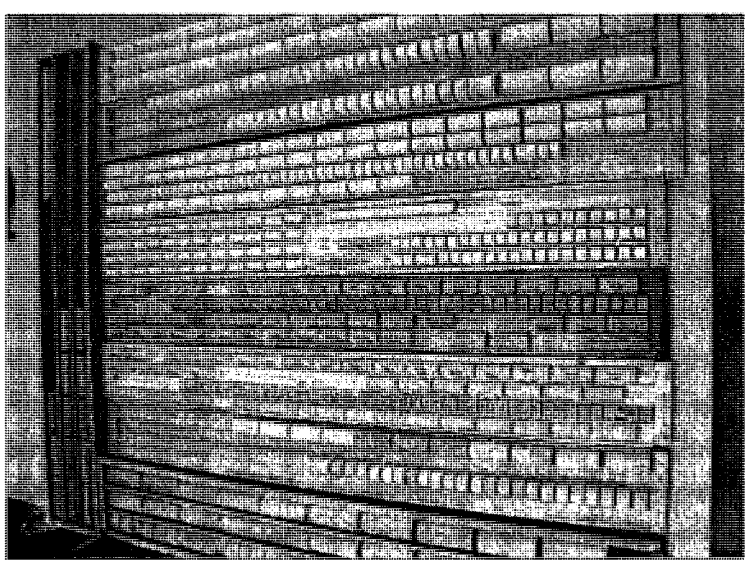


Figure 4-1 Rock samples prepared for experiments.

However, the amounts of samples were limited to be able to have enough replicates (or variables) in order to perform different tests without any worries. Five types of samples were ordered and received from their actual mine sites, except two of them which were available in the laboratory, which will be introduced later (Figure 4-1). All samples chosen are classified as hard to very hard rocks commonly found in the crust of the earth. Five samples utilized in this research are categorized as igneous rocks, one metamorphic and one sedimentary rock. Thin sections have been prepared out of the above mentioned rock samples, which their petrography description follows. The rock samples are identified and analysed with the assistance of Professor B. Martin, the geologist at McGill University in the geology department that examined the samples.

Granophyre is a type of igneous rock in which graphically intergrown quartz and perthitic alkali feldspar surround plagioclase [$(Na,Ca)(Si,Al)_4O_8$]. Miner epidote, biotite, and amphibole crystals are found in this type of rock in various portions. Accessory minerals within the granophyres are apatite, calcite and chlorite (Therriault et al., 2002). Samples A and B are granophyres belonging to the Sudbury igneous complex rock, collected from one of the mines of Vale Inco company. One has light color and the other darker because of a lighter proportion of mafic minerals (Figure 4-2). Those rocks have about 60 to 70% quartz and alkali feldspar, 20 to 30% plagioclase, less than 10% biotite [$K_2(Fe,Mg,Al,Ti)_6(Si,Al)_8O_{20}(OH,F)_4$] and amphibole [$AX_2Y_5Z_8O_{22}(OH,F)_2$] (in which A: Na, K or vacancy; X: Na, Ca, Fe, Mg, Mn; Y: Fe, Mg, Al; and Z: Si, Al). The darker rock contains up to 30% of mafic minerals and proportionally less of the lighter minerals.

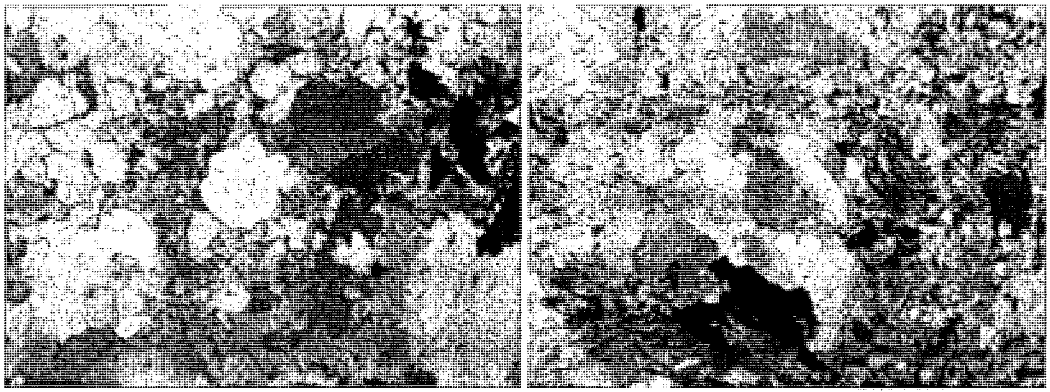


Figure 4-2 Light Granophyre (left) and dark Granophyre (right) from Vale Inco petrography thin sections.

Granite is a plutonic rock, one of the most common types of igneous rock in the crust of the Earth and is typically medium to coarse grained. It usually comes in variety of colors from pink to light gray. Granite primarily contains orthoclase or microcline [$(K,Na)AlSi_3O_8$] and sodic plagioclase, quartz [SiO_2], muscovite (white mica) [$K_2Al_4(Si,Al)_8O_{20}(OH,F)_4$] and biotite (dark mica), amphibole, with minor accessory minerals such as magnetite [Fe_3O_4], garnet [$X_3Y_2(SiO_4)_3$], zircon [$ZrSiO_4$], titanite [$CaTiSiO_5$] and apatite [$Ca_5(PO_4)_3(F,Cl,OH)$] (Best et al., 2001). Very rarely, the iron-rich olivine fayalite [$(Fe,Mg)_2SiO_4$], occurs. Gray granite from Barre in Vermont, chosen for the present research, consists 60 – 70% of the two kinds of feldspar, 20 – 30% of quartz [SiO2], 5 – 7% of biotite and 1 – 2% titanite and muscovite (Figure 4-3).

Figure 4-3 Barre Granite petrography thin section from Vermont.

Gabbro is also an igneous rock, typically coarse grained, mainly comprised of pyroxene [$XY(Si,Al)_2O_6$], calcic plagioclase, amphibole and olivine [$(Mg,Fe)_2SiO_4$]. It is a dense rock that is mostly dark gray (Best et al., 2001). The sample used in this research consists of 60% plagioclase and about 40% hornblende, of which 5% has been replaced by biotite [$K(Fe,Mg)_3AlSi_3O_{10}(OH,F)_2$] (Figure 4-4). In addition, 1 – 2% metallic oxides and sulfides are present. Gabbro is commercially important as a dimension stone and maybe associated with ultramafic rocks. It also may be associated with ores of nickel (Ni), chromium (Cr), and platinum-group elements. Gabbroic complexes may be associated with primary magnetite [Fe_3O_4] and ilmenite [$FeTiO_3$] deposits as well.

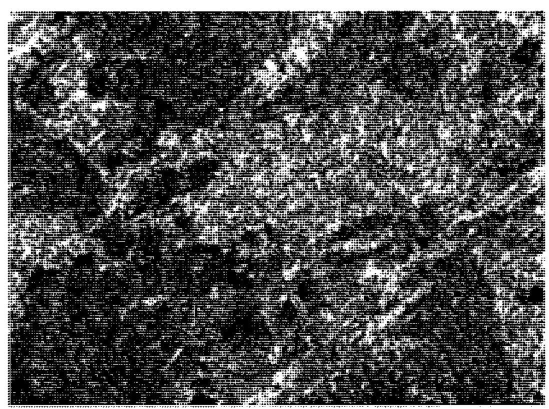


Figure 4-4 Gabbro petrography thin section.

Gneiss is commonly a product of high-grade regional metamorphism of igneous or sedimentary rocks. Gneiss derived from igneous rocks is labeled orthogneiss and that from sedimentary rocks, paragneiss. As a result of recrystallization of minerals while being subjected to high temperature, pressure and deformation, the resulting rock could be fine-grained (Boggs, 2009). Parallel banding because of recrystallization phenomena forms a texture by which gneiss is normally defined. In an orthogneiss, a mineral assemblage typically of granite is found in the light-colored bands, dominated by quartz and feldspars. The darker bands are rich in mafic minerals. The sample chosen for this research comprises 70 – 75% of quartz [SiO_2], about 10% calcite [$CaCO_3$], 5 – 10% sulfides and oxides, and the remaining 5 – 15% of the rock is biotite (Figure 4-5). As such, it most likely represents a metasedimentary rock (i.e., paragneiss), possibly a quartzite.

Limestone consists of calcite (calcium carbonate: $CaCO_3$) with traces of Mg, Mn, Fe and Zn. Dolomite [$CaMg(CO_3)_2$] may also be present. This type of rock is commonly used in as roadbed material, in construction and cement manufacturing. The presence of impurities, such as clay, sand, organic remains, iron oxide [Fe_2O_3], magnesium carbonate, silica [SiO_2], alumina [Al_2O_3] and other materials, gives the rock a darker color, especially on weathered surfaces (Boggs, 2009). The limestone from Lafarge Ltd. has about 75 – 85% calcite and 15 – 25% dolomite, iron oxide and clay minerals (aluminum-rich).

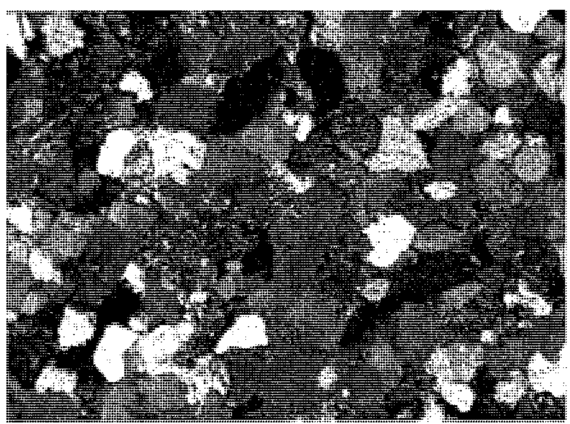


Figure 4-5 Gneiss (recrystalized sandstone) petrography thin section.

Basalt is a volcanic rock equivalent in composition to gabbro. It is fine-grained because of rapid cooling as the lava comes out on the surface. It is normally gray. This type of rock typically contains calcic plagioclase and pyroxene; olivine [$(Mg, Fe)_2SiO_4$] can also be present as well. Basalt can also contain an iron oxide (Fe_3O_4) and an iron-titanium oxide [$FeTiO_3$]. The basalt from Mouska gold mine has been highly modified and mineralized. It now contains up to 75% sulphides, mostly pyrite [FeS_2] with some chalcopyrite [$CuFeS_2$], with quartz, dolomite

$[CaMg(CO_3)_2]$, and calcite as the main gangue minerals; chlorite and rutile $[TiO_2]$ occur as trace constituents.

4.2 Methodology

In the present research, some mechanical properties of rock samples chosen are the main parameters to be investigated. According to the previous chapters, the importance of strength and abrasivity of hard rock within the advancement rate of tunnel boring machines has been explained. Generally, Ozdemir, (1999) has specifically specified all types of rock tests required to be performed for any TBM projects. Since some basic rock tests specified by Ozdemir, (1999) are investigated in the present research, all available standards, suggested methods and descriptions for rock testing in any TBM projects are given in Table 4-1.

From previous chapters, it has been concluded that the more the strength and abrasivity of hard rock is reduced, the higher the penetration rate of TBMs and the longer life of cutting tools. Therefore, some laboratory tests should be performed on rock samples in order to determine the influence of microwave energy on the mentioned mechanical parameters. Precisely three main laboratory tests will be performed on rock samples within different microwave conditions. Unconfined compressive strength and Brazilian tensile strength test for strength parameters of rocks and CERCHAR (Centre d'Études et Recherches des Charbonnages de France) test for the abrasivity of rock samples has been chosen to be done.

Table 4-1 Available standards, suggested methods and descriptions for rock testing for TBM projects (Ozdemir, 1999).

Test / Investigation	ISRM suggested methods	ASTM standards	Other descriptions
Petrographic description	ISRM (1978)		
Hardness			
Moh's hardness	ISRM (1978)	-	
Vickers hardness	ISRM (1978)	-	
Siever's J-value	-	-	NTH (1990)
Toughness / Brittleness			
Punch penetration	-	-	CSM (1987)
Fracture thoughness	ISRM (1988, 1995)	-	
S20 (NTNU)	-	-	NTH (1990)
Mechanical Strength			
Unconfined compressive strength	ISRM (1979)	ASTM D 7012-04	
Tri-axial compressive strength	ISRM (1983)	ASTM D 4406-93	
Brazilian tensile strength	ISRM (1978)	ASTM D 3967-05	
Point load	ISRM (1985)	ASTM D 5731-95	
Abrassiveness			
Cerchar	-	-	CSM (1987)
AVS (NTNU)	-	-	NTH (1990)
Various physical and mechanical properties			
Elasticity	ISRM (1979a)	ASTM D 3148-96	
Sound velocity	ISRM (1978d)	ASTM D 2845-95	
Density	ISRM (1979b)	-	
Porosity	ISRM (1979b)	-	
Cutting tests			
Linear	-	-	CSM (1985)
Rotary	-	-	CSM (1986)

TBM machines will evidently be equipped to microwave facilities in a way to be able to irradiate against the tunnel face. The type and kind of microwave facilities to be used on TBMs are not yet defined and require further more research and design, which are not included in the outline of the present research. In order to have a good understanding on the effect of microwave irradiation on rock mechanical properties, samples will be exposed to the electromagnetic energy at three different power levels and five durations each in a multi-mode cavity. According to the previous research studies done with regard to the current research topic, it has been chosen to expose rock samples to the microwave energy for 15, 30, 60, 120 and 240 seconds in three power levels of 800, 1250 and 3000 Watts.

Table 4-2 Selected rock sample mechanical properties

Rock sample	Diameter (mm)	High of disc shape specimen (mm)	High of cylindrical specimen (mm)	Density (kg/m3)	Brazilian tensile strength (MPa)	Unconfined compressive strength (MPa)	CERCHAR abrasivity index value
Granophyre	36.22	20.64	76.49	2621.38	11.04	211.54	4.63
Mafic Granophyre	36.16	20.64	75.50	2815.31	12.23	139.68	4.05
Barre Granite	26.64	23.41	51.19	2634	10.34	91.96	4.48
Gabbro	41.73	25.47	86.33	2881.4	14.4	65	3.07
Gneiss	63.45	36.39	129.74	2615.59	8.94	133.82	4.11
Limestone	37.67	21.45	75.90	2689.92	8.98	84.37	1.43
Basalt	37.67	21.40	74.28	3019.23	15.41	128.99	3.92

Core samples were prepared and cut in two sizes of cylindrical shape. For unconfined compressive strength (UCS) tests, samples have been prepared in a cylindrical shape respecting the ratio of 2:1 for the sample length depending on core diameter prior to be treated in microwave irradiation. Disc shape specimens have been prepared for Brazilian tensile strength (BTS) test respecting to have the length between 0.5D < L < D (Figure 4-6). CERCHAR abrasiveness index (CAI) test has been performed on the flatten face of disc shape specimen prepared for Brazilian tensile strength test. General properties of selected rock samples are given in Table 4-2.

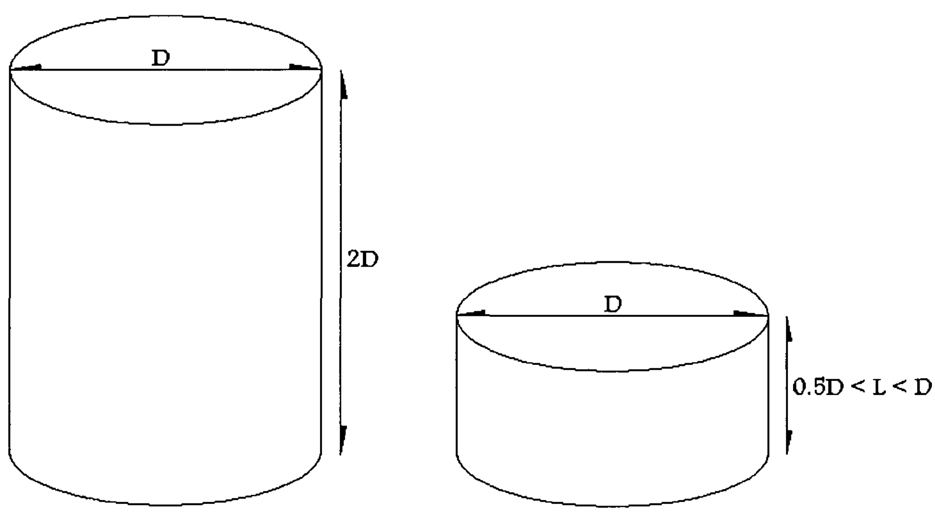


Figure 4-6 Dimension of specimen prepared for experiment

All tests (UCS, BTS and CAI) were performed on untreated specimens in order to calculate the actual strength parameter of the rock sample used in this study also to be able to compare the results of treated samples strength values. Each specimen is treated in the appropriate time of exposure and power level preplanned then cooled to ambient temperature. The surface temperature of each specimen is measured by an infrared gun before and right after being treated with the microwave energy. For each test consisting of a time of exposure within a certain power level, three replicate specimens have been used in order to have a better evaluation of results. After treating the samples to different microwave conditions and being cooled to ambient temperature, all predefined mechanical tests are performed on each specimen. In other words, unconfined compressive strength test on cylindrical cores, CERCHAR test first then Brazilian tensile strength test on the disc shaped samples prepared.

The analytical study of the results obtained from the tests performed should show the influence of microwave energy on the mechanical properties of rock samples used in the current research. Strength and abrasivity index versus time of exposure graphs will show the effect of microwave energy on the behavior of mechanical properties of rock samples.

4.3 Tests and equipment

Some equipment has been used within the process of the research in order to obtain proper results, which they will be introduced as following:

Core drill machine

Some samples were sent directly from the actual mine site and some of them have been received in the form of a chunk rock. The samples received from the actual mine site were core samples collected for geological purposes where as the chunk rock masses were been cored in the laboratory. The gray granite, limestone and the Basalt were in the form of chunks. The Basalt sample was the remaining chunks collected from an already blasted bench in IAMGold quarry.

Therefore, in addition to the weathering phenomena the chunks are completely fractured (Figure 4-7 right).

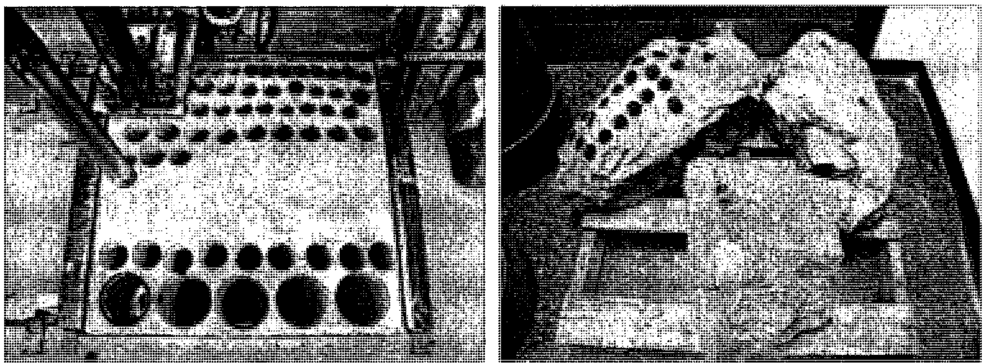


Figure 4-7 Drilling process of a block of barre granite (left) and basalt (right)

A Diteq core drill machine with a Shibuya automatic feeder installed was used to core the chunks of rock mass received from the mine sites. The core drill machine is a low range equipment to supposedly be working in small scale of rock masonry. Unfortunately, the power transmission system of the drill machine is not strong enough to avoid any jamming within the rock. Since the Basalt sample was a blasted product, they were completely fractured that the drill bit of the core drill machine jams totally. Because of that weakness of equipment, only one set of samples has been prepared in order to evaluate the behavior in 1250 watts of power level. Samples have been cored out with a 4.45 millimeters core bit diameter, except the granite, which is cored out with a 2.54 millimeters core bit diameter, and Gneiss, which has already been existed in 5.6 millimeters core bit diameter.

Saw machine

Core samples either prepared from the core drill machine or received from the mine site were cut to the appropriate shape in order to perform the tests for the present research. In order to cut the samples in the appropriate shape needed for the right tests, a diamond product 4 inch wet diamond saw was used to prepare rock specimens. The geometry shape of the samples have a great impact on the test results, therefore, samples were cut precisely to the shape needed in unconfined compressive strength and Brazilian tensile strength tests, described earlier in this chapter.

Infrared gun

This device was used to measure the surface temperature of the specimen before and after being treated with microwave energy. Materials have different infrared emissivity values. Emissivity is a measure of the ability of an object emitting infrared energy. Emitted energy from the object specifies the temperature of the object. Emissivity can have a value from zero (shiny mirror surface) to 1.0 (dark body). Most organic, painted, or oxidized surfaces have emissivity values close to 0.95 (Raytec, 1999). All materials are categorized into two main groups as metallic and non-metallic materials. Since rocks are known as non-metallic material, the emissivity has been chosen to be set on relevant emissivity value from the table of emissivity of non-metals in Appendix 1.

The surface temperature of each specimen is measured by a Raytec Raynger MX4+ high performance infrared gun (Figure 4-8) before and right after being treated with microwave energy. The infrared gun is able to measure the minimum, maximum and average temperature emitted from the specimen, which has been set to measure and show the average temperature. This device emits the infrared exposure to the surface of the specimen within 20 dots from 0.5 to 1 meter distance to the specimen and calculates the average temperature obtained from those points.

As reviewed in chapter three, the most consumable part of a TBM machine is its disc cutter tools. Therefore, the length of life of TBMs' disc cutter tools plays a significant role in predicting the tunnel boring performance as well as the quantity of disc consumption for the whole project (Plinninger et al., 2004). CERCHAR is a practical and the most common test used to measure and predict the wearing rate of cutter tools by examining the abrasivity of the rock, which is recently validated by (Plinninger et al., 2008) among other tests. In the current study, the modified West apparatus of CERCHAR test (Figure 4-9left) has been used to performed abrasion tests (West, 1987).

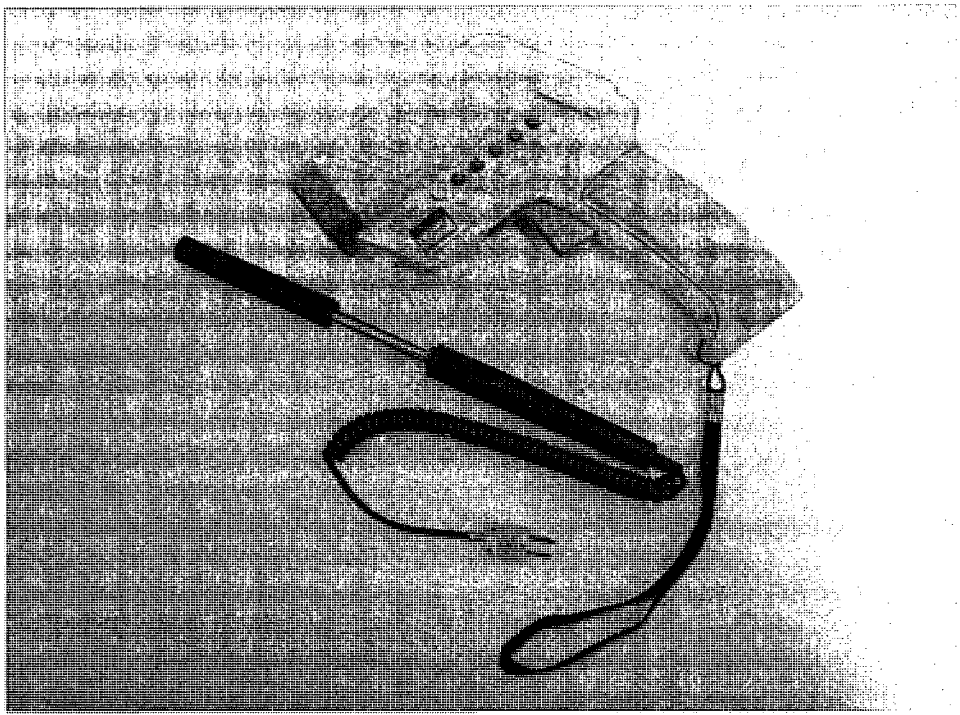


Figure 4-8 Raytec Raynger MX4+ high performance infrared gun

CERCHAR apparatus, microscopes and grinder

The mineralogy and petrography of the rock forming minerals have a significant influence on the CERCHAR abrasivity index of rocks (Suana et al., 1982). According Suana et al. (1982), there is a good relationship between the amount of silica (SiO2), the most abrasive mineral, and the abrasivity index value of the rock containing silica (Table 4-3). The CERCAHR apparatuse has been designed and built for this current research experiments at McGill University from scratch with the assistance of technicians from mechanical engineering department.

Table 4-3 Reletive cerchar abrasivity index of rocks in relation to quartz amount (Suana et al., 1982).

Minerals	Quartz equivalence
Quartz	100%
Feldspar	70 - 80%
Olivine	57 - 60%
Pyroxenes	50 - 53%
Amphiboles	47 - 53%
Serpentinites	23 - 30%
Carbonates	17 - 34%
Claystone	up to 41%

Basically, by scratching a heat treated hardened metal tool on the surface of the rock, for at least 10 mm long under a constant load of 70 Newton, gives us the estimation of wearing rate of cutter tools on TBMs (Plinninger et al., 2004 & 2008). The scratching metal tools are a heat treated hardened metal rods with one centimeter diameter and length at least 7.5 mm. The rods have one flat end and a precise sharp 90° cone at the other. According to West (1989) the most suitable and representative steel type to be used in the test is EN24 which is heat treated to the Rockwell hardness of HRC 40. In addition, that the type of heat treated steel has the least deviation among other types of steel (West, 1989), Michalakopoulos et al. (2006) has also validated that situation.

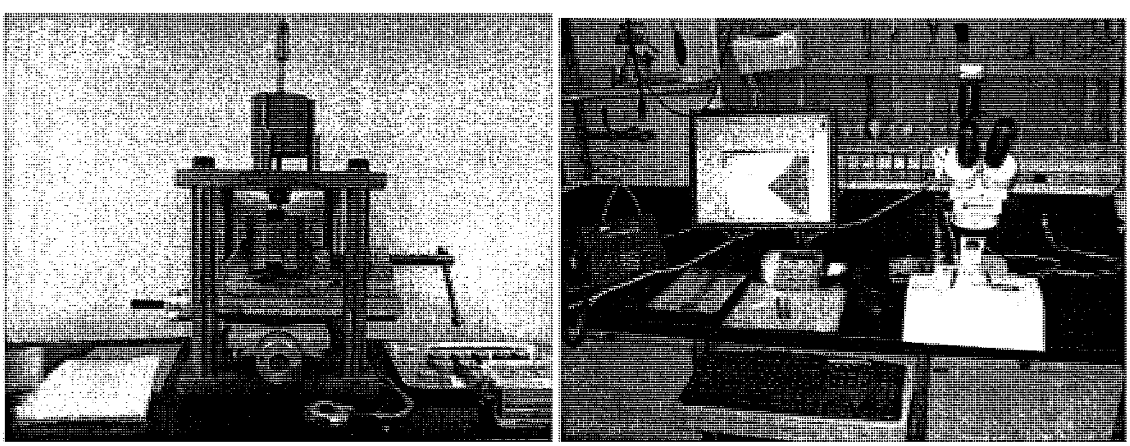


Figure 4-9 CERCHAR apparatus set up at in the geo mechanics lab McGill University (left), stereo-master zoom microscope set up in the materials lab at Concordia University (right)

With respect to the condition required to perform the test (Plinninger et al., 2003) the tools should be scratched on a fresh surface of the rock then the worn area of the tool is determined under a microscope (Figure 4-9right). For better and much more accurate results, each specimen was subjected to three to six scratches, with a new fresh sharp tool used for each scratch. The value of 0.1 mm worn area on the tool represents 1 CAI value of CERCHAR abrasivity index. After each use, the tools are sharpened with a cutter grinder machine. In order to be sure about the accuracy of the sharp end of the tools, a 10x Zeiss microscope has been used to verify the work done by the grinder (Figure 4-10).

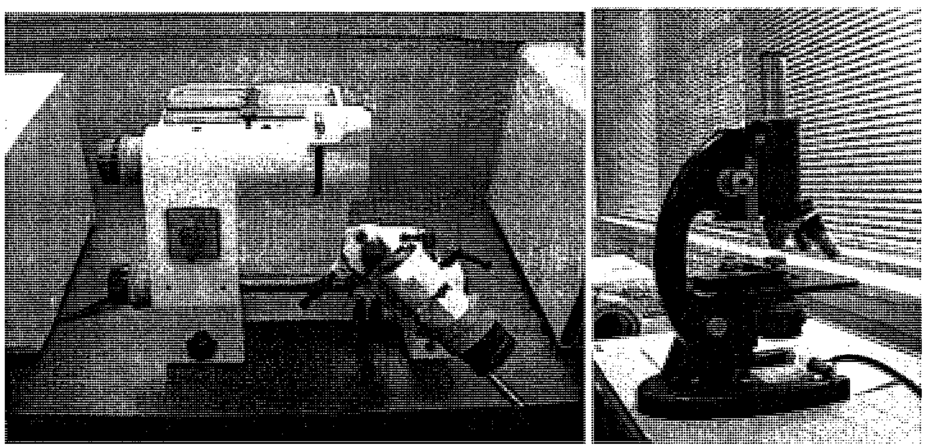


Figure 4-10 Cutter grinder machine (left), Zeiss microscope 10x (right)

All the disc shape specimens exposed to the microwave irradiation have been cooled down to the ambient temperature. CERCHAR test has been performed on each individual disc shape specimens, repeated three times on the surface of rock samples on three different locations and directions. Each scratch on each specimen should be made with a fresh tool tip.

Unconfined compressive strength apparatus

As it is obvious from chapter three, the unconfined compressive strength parameter is a very important parameter influencing all TBMs penetration calculations. Generally, the unconfined compressive strength (UCS) test is the most important and commonly used by tunneling application contractors. Basically, according to ASTM D7012-04 and ISRM 1979 suggested method, the UCS procedure is to subject a cylindrical cored specimen with a diameter of D and length of L, which should be at least equal to 2D, to a vertical load, longitudinal to the specimen, until failure.

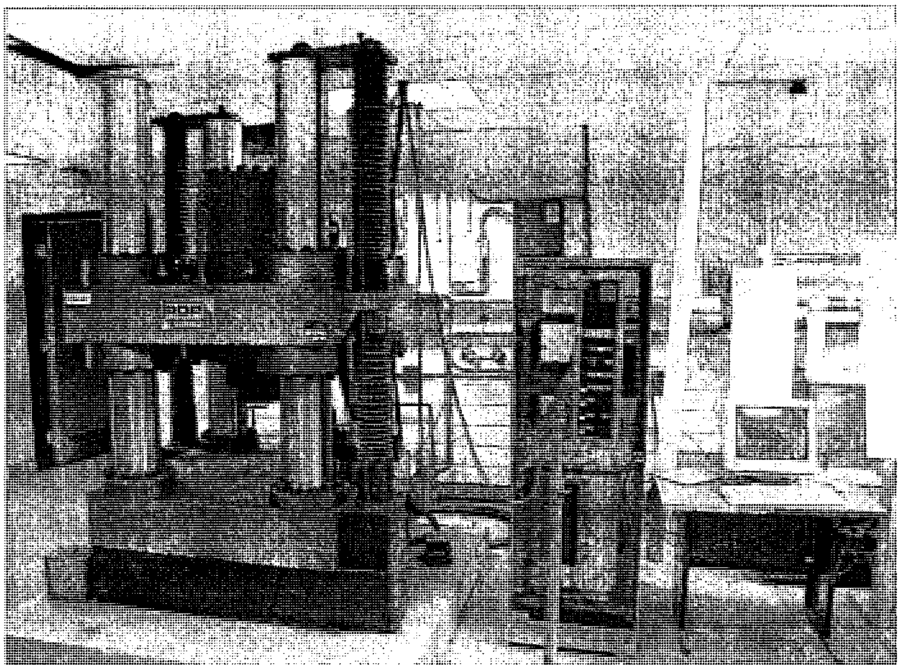


Figure 4-11 Computerized MTS unconfined compression strength apparatus in the geomechanics laboratory at McGill University

Figure 4-11 shows the actual UCS measurement apparatus used in the current study. The UCS value is calculated as equation (4-1).

$$\sigma_C = \frac{P}{A} \qquad (4\text{-}1)$$

Where "P" is the load applied by the machine (kN).

"A" is the cross section area of the specimen (m^2)

"σ_c" is the unconfined compressive strength value of rock specimen (MPa)

Brazilian tensile strength apparatus

After unconfined compression strength of rock, Brazilian tensile strength test became one of the most common and useful tests for estimation and prediction the performance of tunnel boring machines. The Brazilian tensile strength (BTS) test is measuring the tensile strength of rocks indirectly. The simplicity and the ease of sample preparation have made this test commonly used by many tunnelling application contractors.

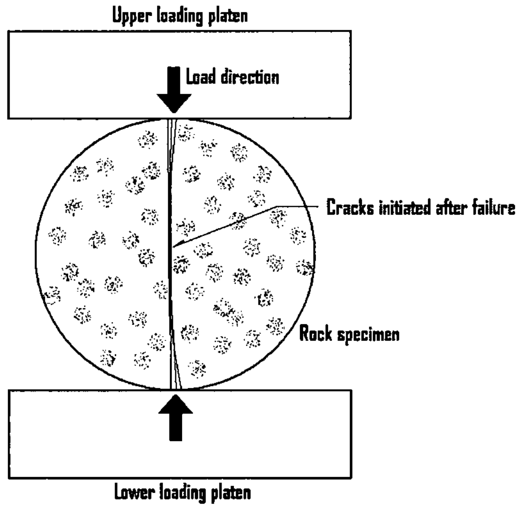


Figure 4-12 Sketch of Brazilian tensile strength test mechanism

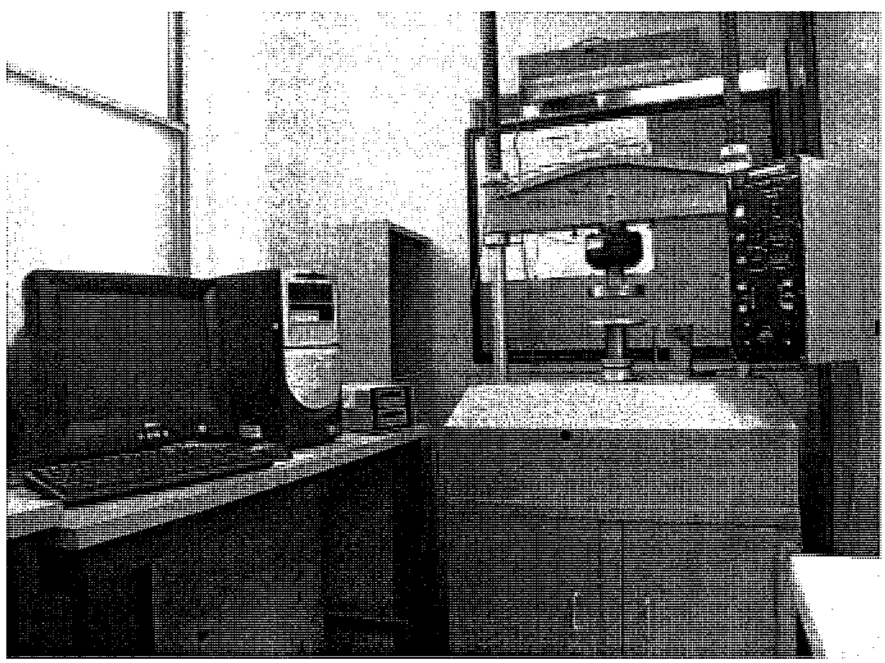


Figure 4-13 Schematic view of Brazilian tensile strength apparatus in the geo mechanics laboratory at Mcgill University.

Basically, as it is demonstrated in the Figure 4-12 the rock sample, in the form of a disc, having a diameter of D and thickness of L are subjected to a vertical load, provided by two upper and lower loading platen until failure vertical to the platens. ASTM D3967-05 and ISRM 1978 suggested method are the two standards describing the procedure and the setups of Brazilian tensile strength test which the experiments of the present research are based and referenced to those standards. Figure 4-13 demonstrates the actual Brazilian tensile strength measurement apparatus used within the current study.

The Brazilian tensile strength value of the specimen is then calculated from the equation (4-2).

$$\sigma_T = \frac{2P}{\pi DL} \qquad (4\text{-}2)$$

Where "P" is the load applied from the machine causing failure (kN)

"D" is the diameter of the specimen (mm)

"L" is the length or the thickness of the specimen (mm)

"σ_T" is the Brazilian tensile value of the specimen (MPa)

Microwave facilities

Within the present research, microwave facilities used for the study to treat the samples are simply normal kitchen microwave ovens. Kitchen microwave ovens have multi-mode cavity. The difference between multi-mode and single mode cavity has been described earlier in chapter two. Based on the literature review in chapter two, several authors have used various microwave conditions prepared for treating rock samples. They mostly exposed rock samples to the microwave irradiation in a single mode cavity and evaluating the influence of microwave energy on rock comminution in mineral processing industries. To evaluate and conclude that the microwave energy has a great impact on rock materials in order to be able to use it in assistance of TBM machines, first, the examination of the influence of microwave energy on rock materials is necessary. Obviously, the microwave energy emitting to the face of the tunnel by TBM is categorized in single mode cavity but first in laboratory scale the present research experiments the influence of microwave energy on rocks using commercial microwave ovens providing multi-mode cavity.

Basically, within this research, samples are planned to be exposed to three different microwave power levels and five different time durations of exposure for each power. In other words, samples are treated to the energy within the microwave ovens for 15, 30, 60,120 and 240 seconds in three power levels used as 800, 1250 and 3000 watts individually.

Three commercial microwave ovens are used in this experiment providing the three power level required. A Panasonic NNS335W microwave oven with maximum output power of 800 watts, a Litton MG0873 with maximum output power of 1250 watts and an Amana RC30S2 with maximum output power of 3000 watts have been chosen and treat the rock samples. The Panasonic microwave oven has a turn table but the other two ovens do not have turn tables but rotatable microwave antenna instead. All three microwave ovens were set to emit their maximum output power during the tests procedure in order to avoid microwave pulsation.

In order to have a constant irradiation on all specimens, three individual specimens have been decided to be irradiated in each time of exposure within all three power levels. Respectively, disc and cylindrical shape specimens have been exposed to the microwave energy for a same time of exposure. Once the specimen has been irradiated to the microwave energy for the amount of time wanted for the experiment, its surface temperature has been measured with the infrared gun right after being exposed to the energy.

CHAPTER FIVE

5. Results and discussion

5.1 Experiment results and discussion

In this chapter, the results of the experiments performed on different sedimentary, metamorphic and igneous rocks are shown in the form of graphs based on the average value of each test. The standard deviation is calculated in order to specify the error range of the results in each test, or in other words, for each time of exposure. The slope of the trend drawn based the average value shows the amount of the microwave influence along the experiment. Generally, slope of the trend up to 15% positive or negative is assumed to be normal changes within the range of rock properties due to anisotropy and inhomogeneity of samples in addition to the experimental errors. Slope over 15% is counted as the influence of the microwave energy on rock samples. In this research the percentages of slopes given in graphs or figures is based on the comparison of values at zero seconds and the longest time of microwave exposure.

As described in the previous chapter, Brazilian tensile strength, unconfined compressive strength and CERCHAR abrasiveness tests were performed on microwave treated and untreated specimens. Due to limited amount of samples in some cases, some of the rock types were subjected to only one or two power levels of irradiation instead of three. The basalt andesitic was only treated at 1250 watts of power level of microwave irradiation, the gabbro at 3000 watts and the gneiss to both 1250 and 3000 watts of power levels.

Figures 5-1 and 5-2 demonstrate the temperature behaviour of disc and cylindrical shape specimens of light granophyre exposed to the microwave energy as the time of exposure increases. A slight increase in temperature with exposure time was observed. For the cylinders, increase in temperature was significant for 3000W, which according to Pickles (2008) can be due to the high power level and power density absorbed by the dielectric, since the cylinders are bigger than disc shape specimens. At the lower two powers, the temperature also increased at a lesser rate. Generally, the slight increase in temperature specifies that the heat is generated very slowly within the rock sample as the mineral content are not a very good absorbent according to Chen et al., 1984, in other words the sample is most likely transparent to the microwave energy.

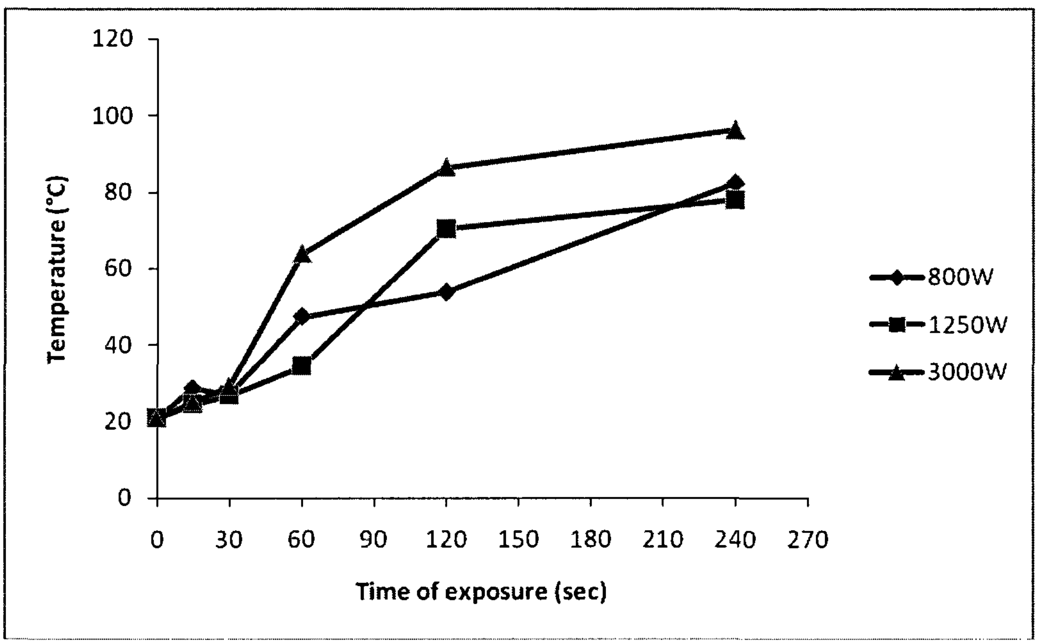


Figure 5-1 Temperature of disc shape specimens of light Granophyre versus time of exposure in different power levels of microwave.

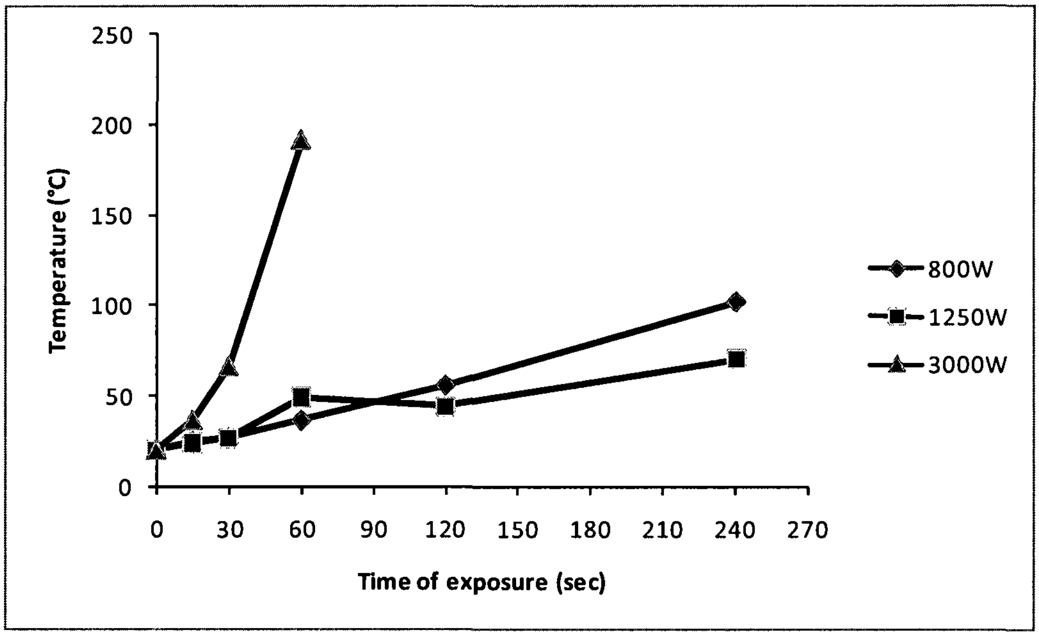


Figure 5-2 Temperature of cylindrical shape specimens of light Granophyre versus time of exposure in different power levels of microwave.

Figure 5-3 demonstrates the results of Brazilian tensile strength tests on the granophyre rock samples at three different power levels of 800, 1250 and 3000 watts. Some specimens of this type of rock, such as 240s for the disc shape and 120 and 240s for cylindrical shape specimens, could not be treated in the microwave ovens of 3000W due to some sparks within the cavity. As is shown in Figures 5-3, 5-4 and 5-5, the Brazilian tensile strength and unconfined compressive strength properties of the rock sample remains relatively unchanged, as well as the CERCHAR abrasivity index value in lower power levels. However, the CERCHAR abrasivity index value at high power level shows about 30% reduction after 120 seconds of microwave exposure (Figure 5-4c). The disc shape specimens have not been exposed to the energy for more than 120s and the cylindrical shape specimen not more than 60s in high range power level irradiation due to sparking within the oven cavity.

a) b) c)

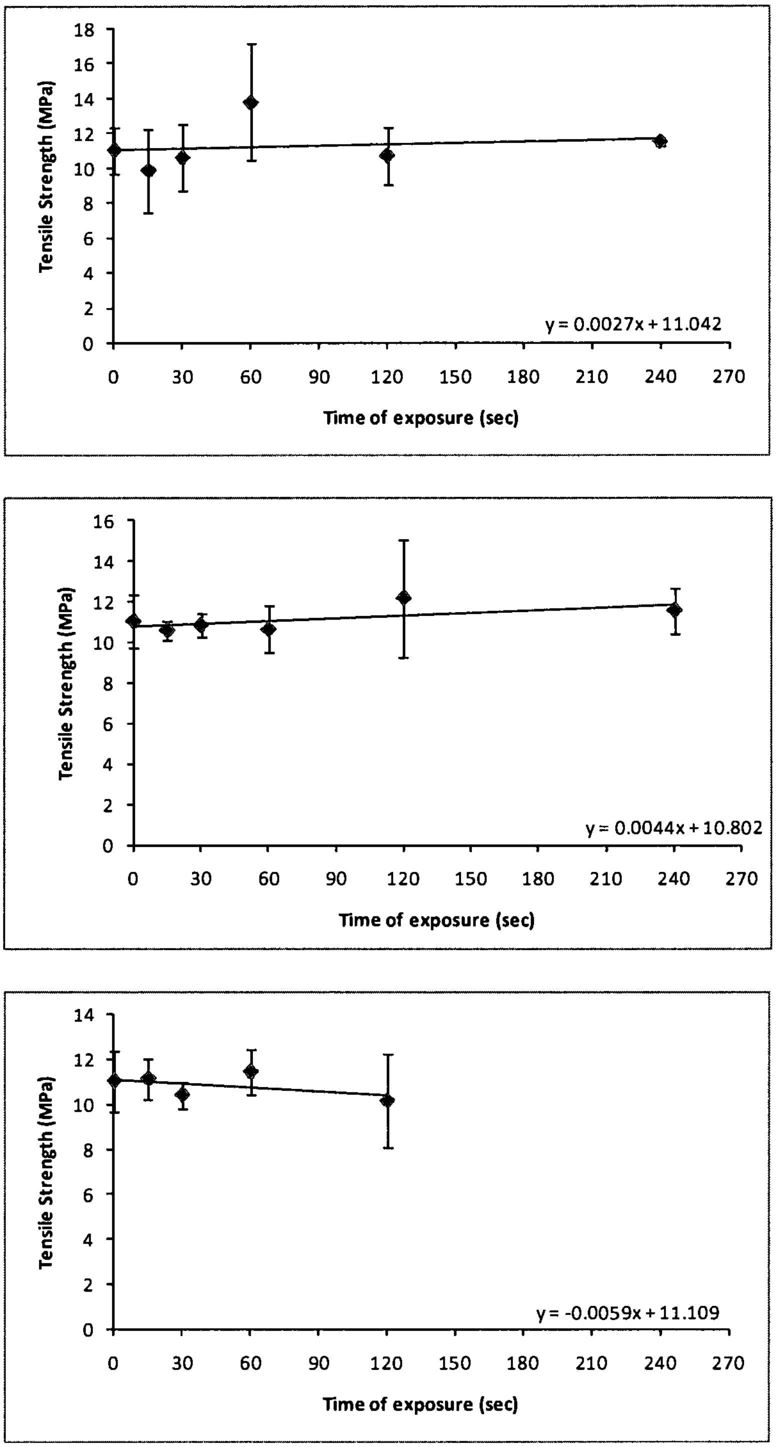


Figure 5-3 Results of Brazilian tensile strength tests for Light Granophyre in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

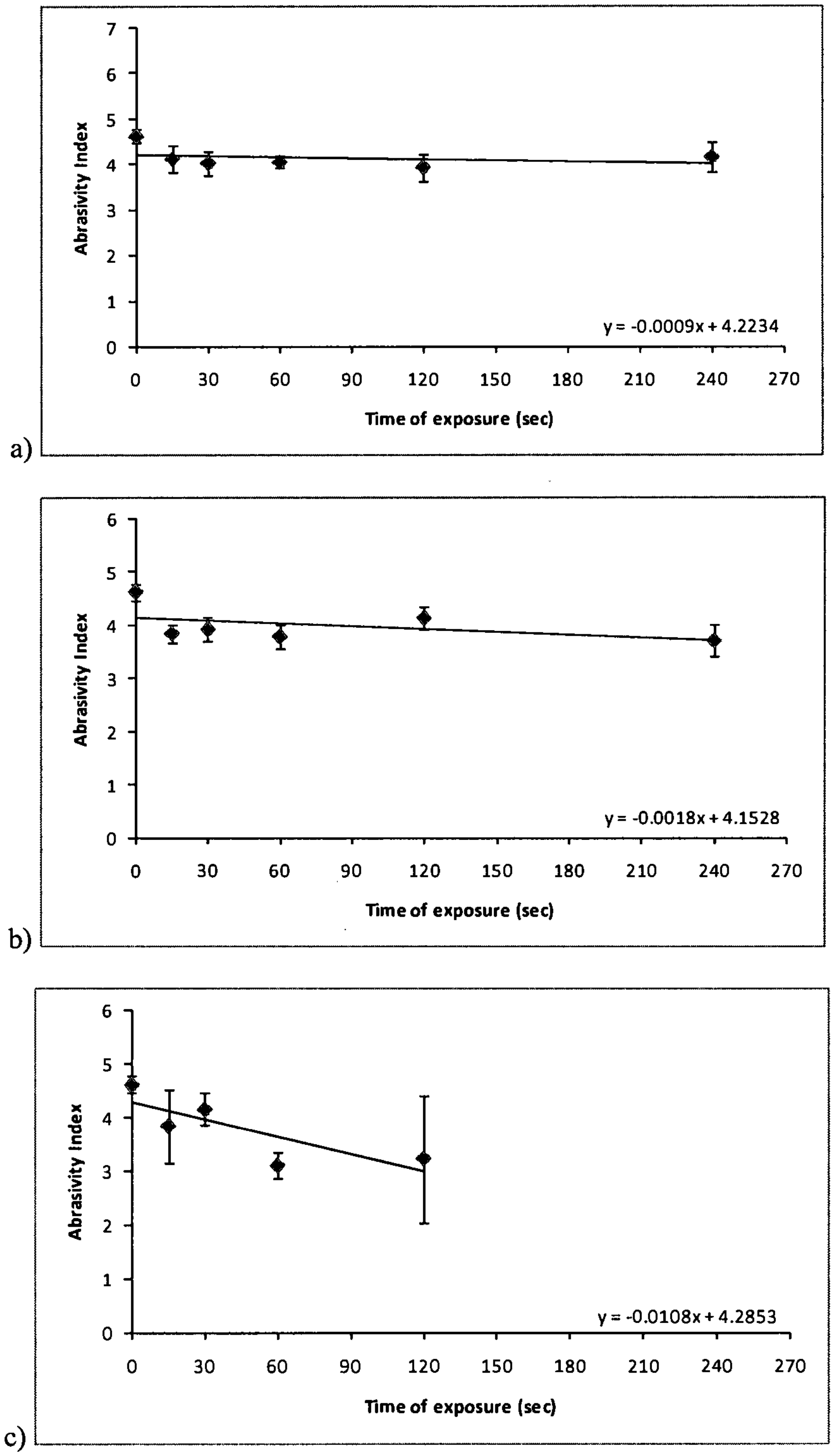
a)
b)
c)


Figure 5-4 Results of CERCHAR abrasiveness tests for Light Granophyre in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

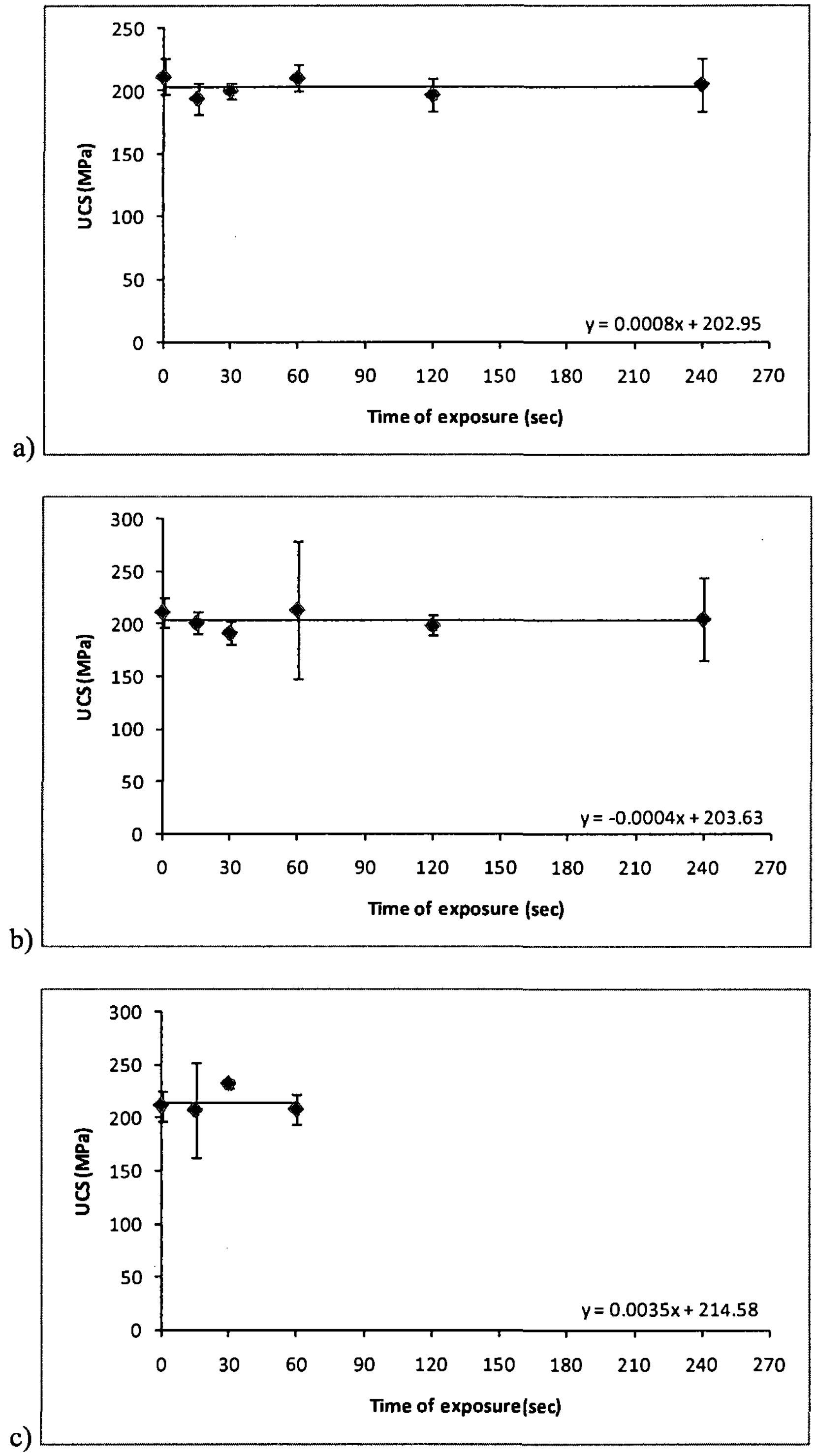


Figure 5-5 Results of unconfined compressive strength tests for Light Granophyre in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

Figures 5-6 and 5-7 demonstrate similar temperature behavior in mafic granophyre as the light granophyre. Heat is generated in the rock samples slowly and slightly as the power level increases. In other words, it can be concluded that conductive heat should be generated in between the mineral grains.

Figures 5-8, 5-9 and 5-10 demonstrate the results of tests performed on the mafic granophyre. This type of rock has also an orientation of about 45 degree longitudinal of mafic minerals mainly biotite, which is 30% of the rock minerals. Due to some sparks within the cavity, the cylindrical specimens of this type of sample could not be treated in the microwave oven on high power level for 120 and 240 seconds of microwave exposure (Figure 5-6c). The results shows that the mechanical properties of this rock sample remains unchanged except its tensile strength at high power level which shows about 30% reduction due to the presence of a large amount of biotite (Figure 5-8c). That amount of biotite also causes the CERCHAR abrasivity index value of the rock to be reduced about 30% in high power level as well (Figure 5-9c). The cylindrical shape specimens have not been exposed to the energy for more than 60s in high range power level irradiation due to sparking within the oven cavity

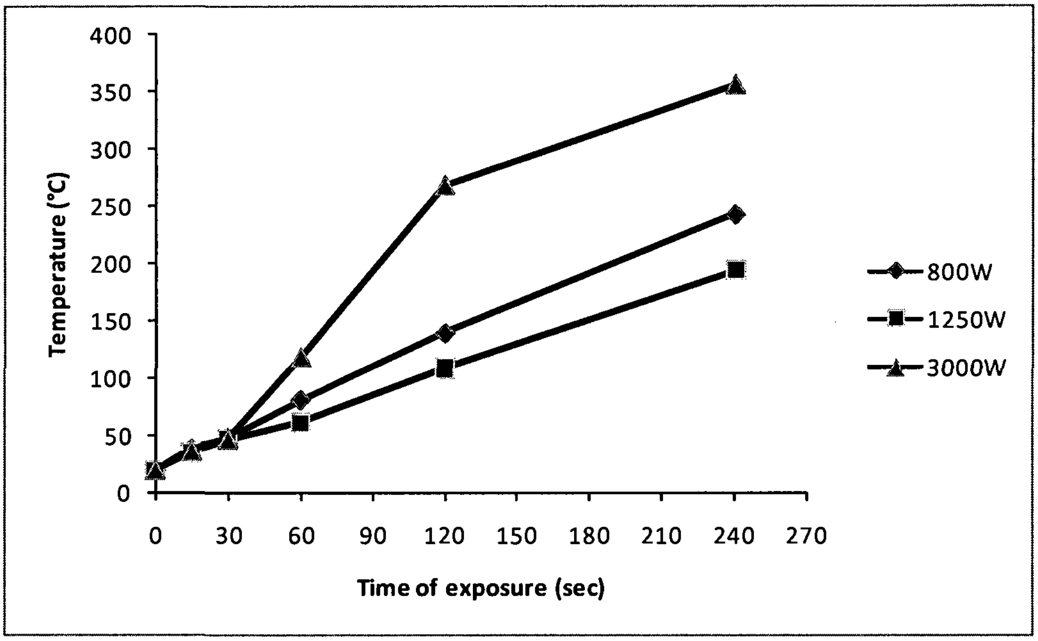


Figure 5-6 Temperature of disc shape specimens of mafic granophyre versus time of exposure in different power levels of microwave.

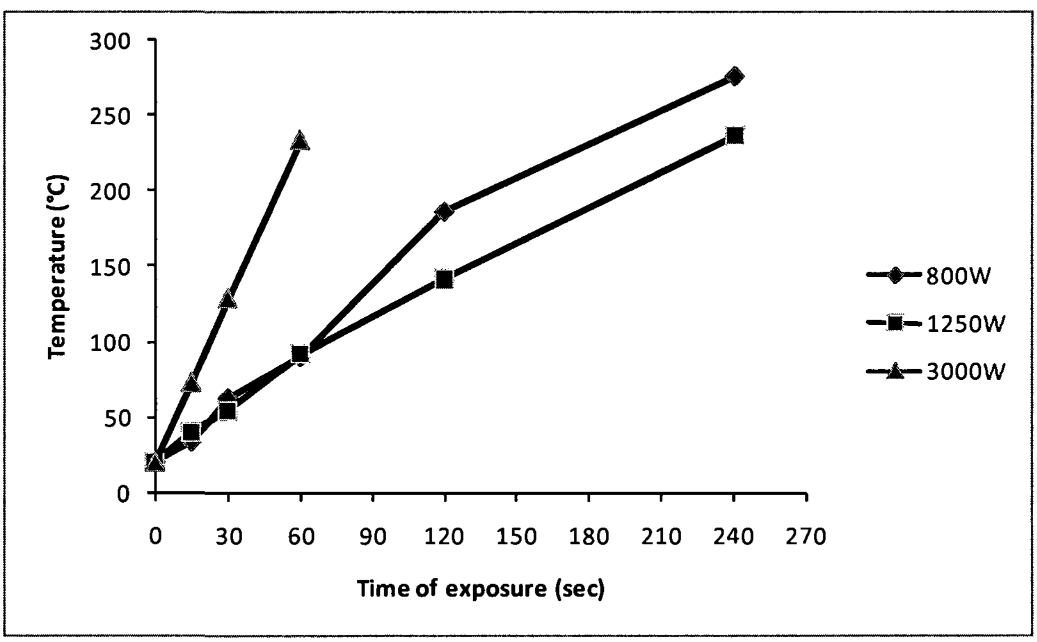


Figure 5-7 Temperature of cylindrical shape specimens of mafic granophyre versus time of exposure in different power levels of microwave.

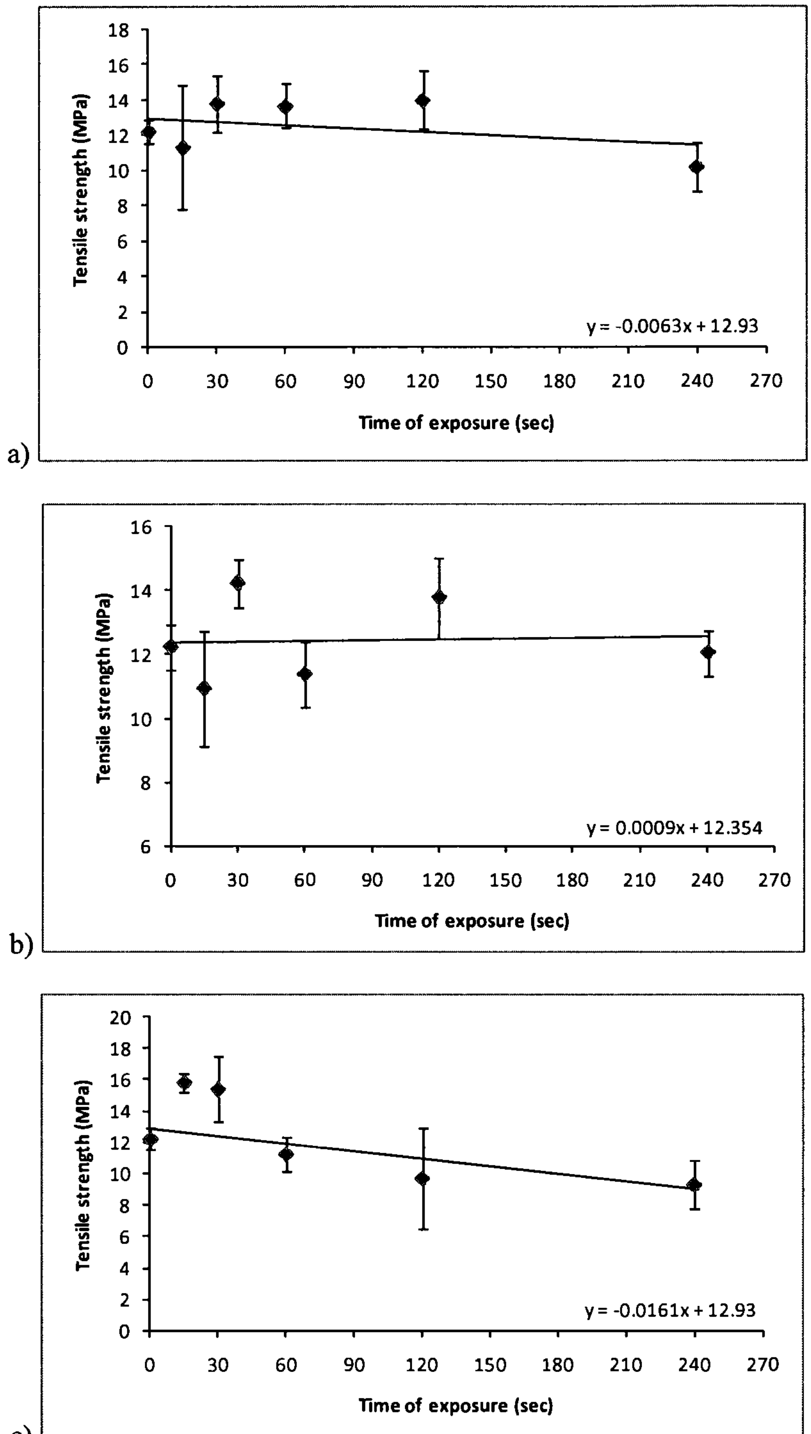


Figure 5-8 Results of Brazilian tensile strength tests for mafic granophyre in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

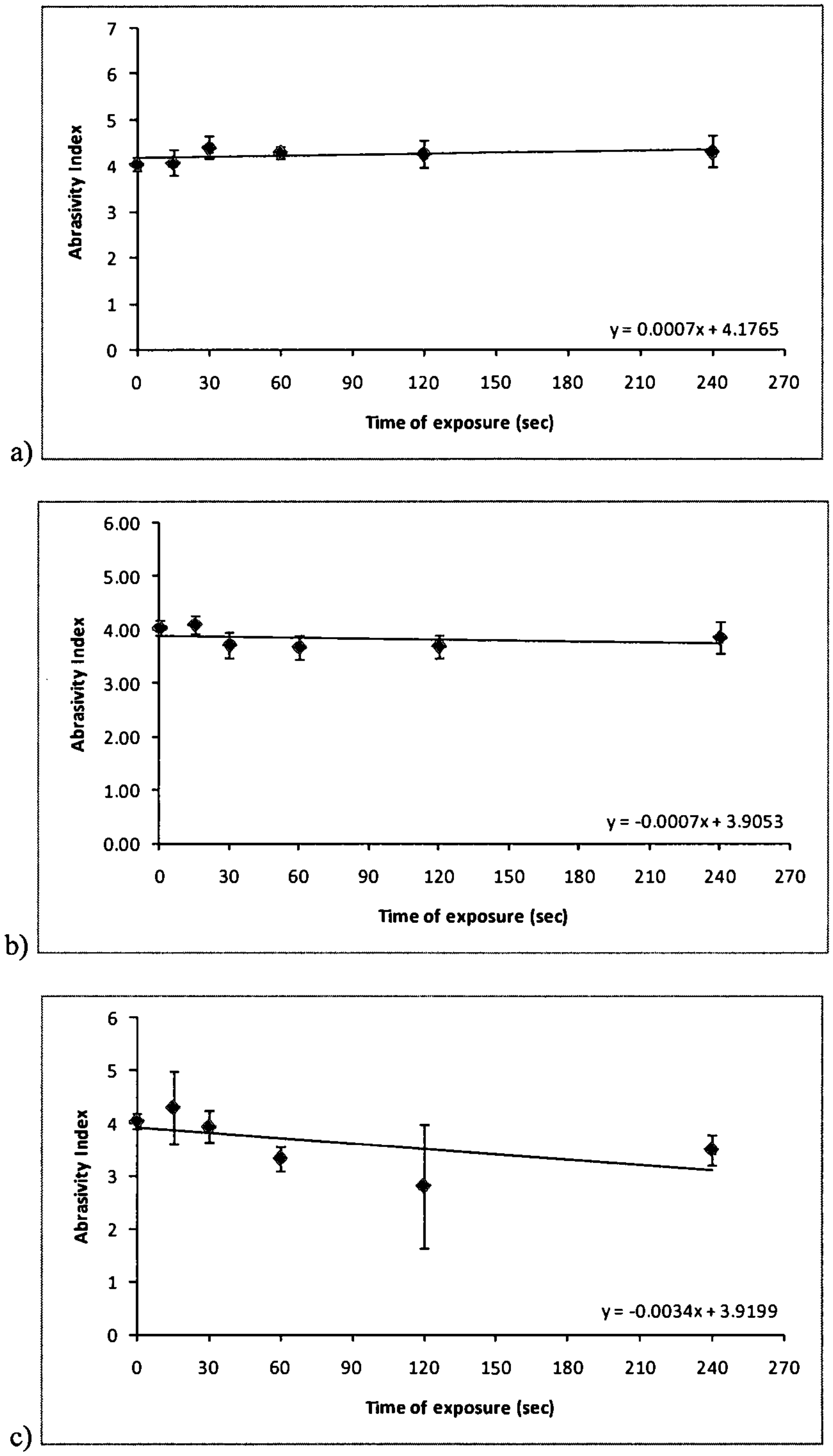


Figure 5-9 Results of CERCHAR abrasiveness tests for mafic granophyre in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

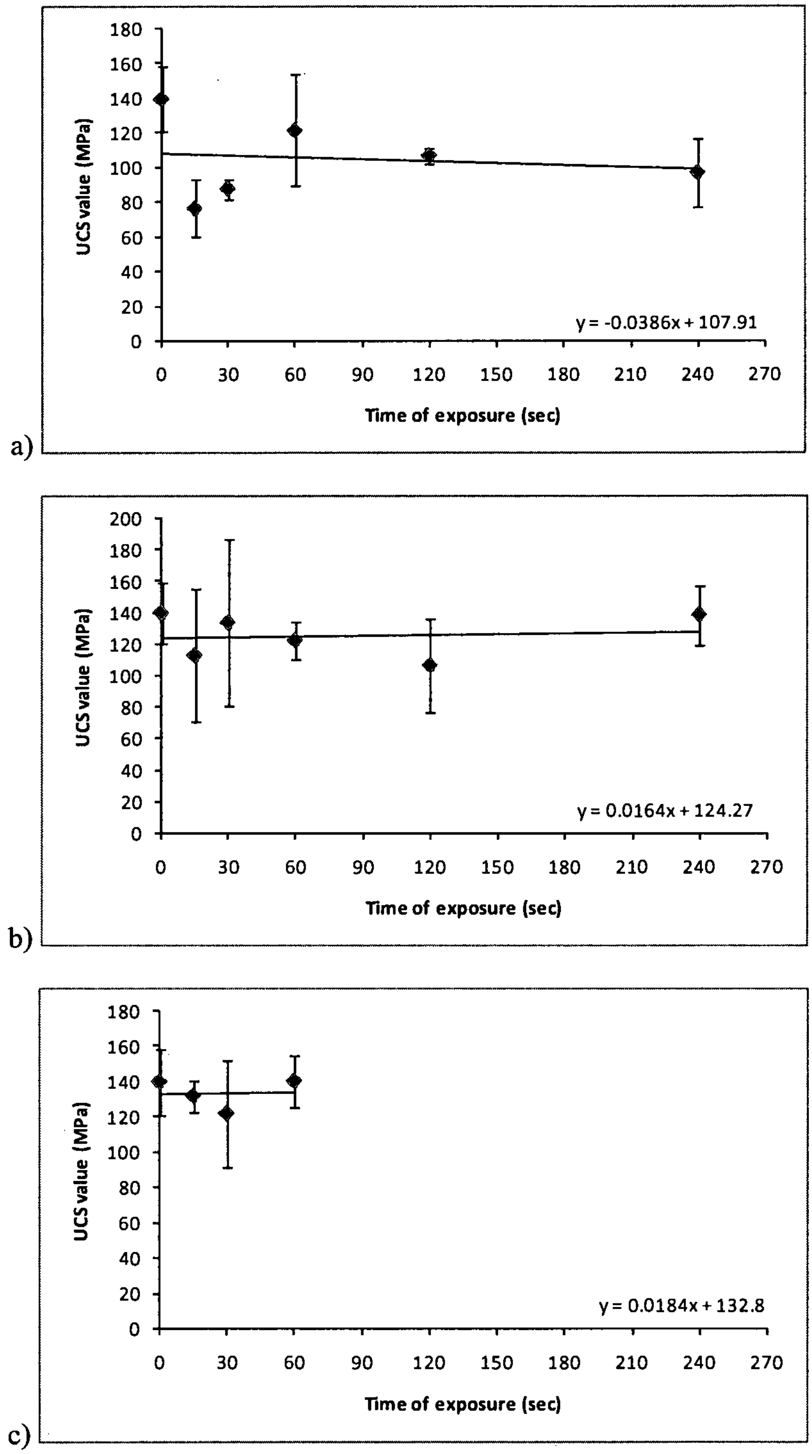


Figure 5-10 Results of unconfined compressive strength tests for mafic granophyre in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

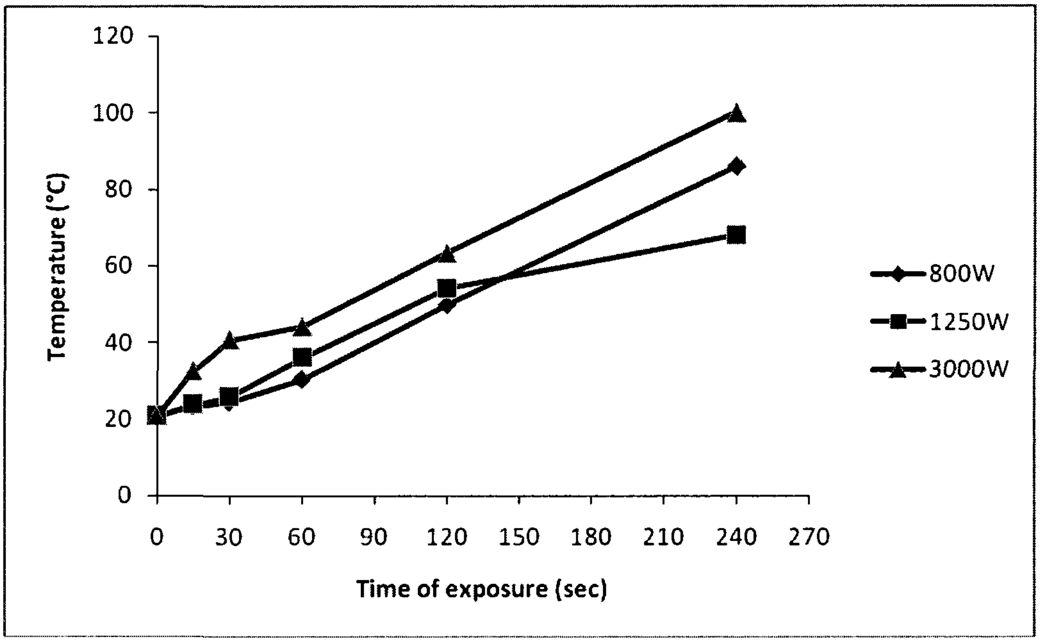


Figure 5-11 Temperature of disc shape specimens of Barre granite versus time of exposure in different power levels of microwave.

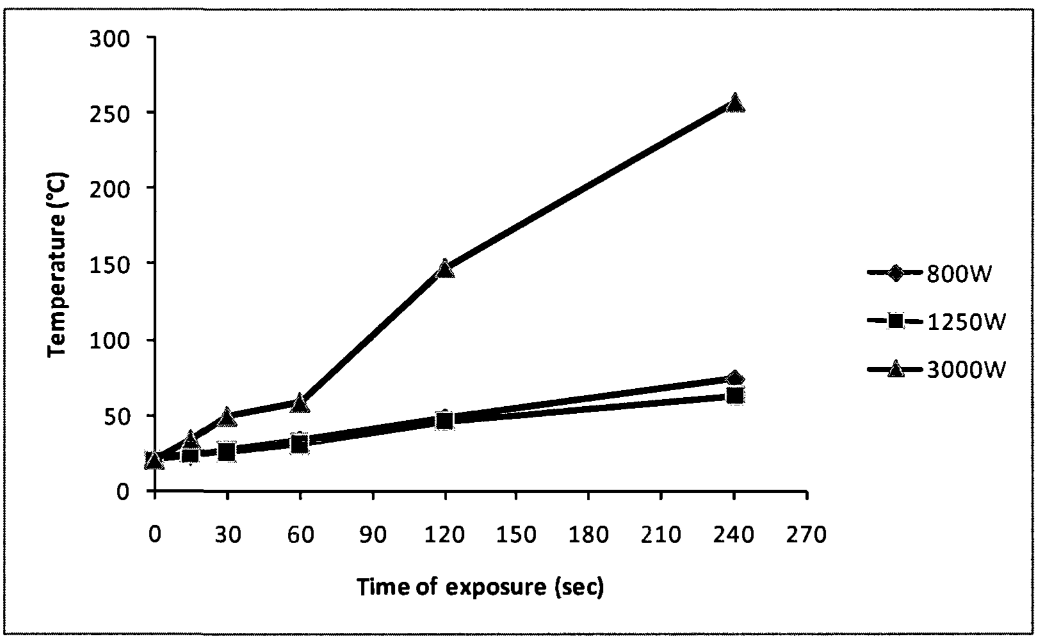
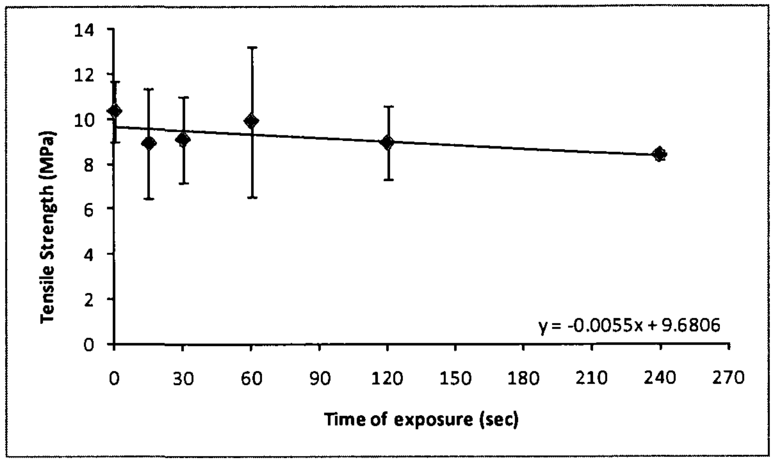


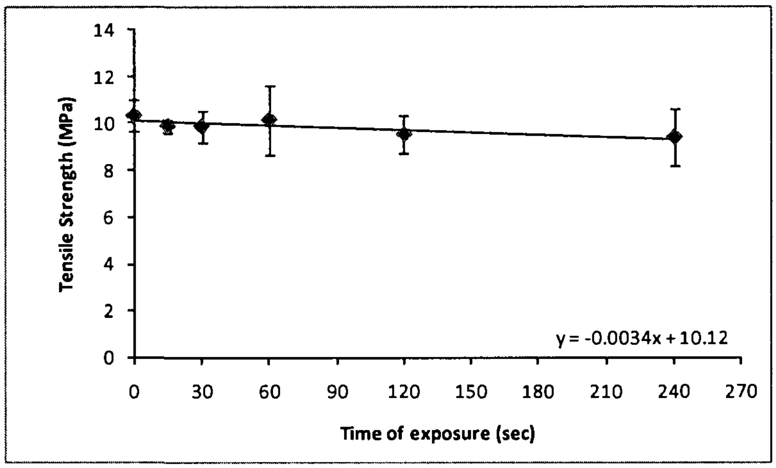
Figure 5-12 Temperature of cylindrical shape specimens of Barre granite versus time of exposure in different power levels of microwave.

Figures 5-11 and 5-12 show the temperature behavior of the Barre granite rock sample as the power level increases. There is a similarity between the three igneous rock types as the granophyres and granite. Conductive heat is generated in all of these rock samples slowly and smoothly.

The Barre granite has larger grain size than the two granophyres. Figures 5-13, 5-14 and 5-15 demonstrate the results of Barre granite tests performed. As it is evident from the figures, all mechanical properties of the Barre granite remain unchanged. However, the CERCHAR abrasivity index value and the unconfined compressive strength of Barre granite is reduced about 30% at the high level power microwave irradiation after 240s of microwave exposure for CAI and 120s for the UCS value (Figure 5-14c and 5-15c).

Although granophyres and Barre granites are almost transparent to the microwave energy because of their constituents, high power level of microwave energy shows reduction in strength of mafic granophyre, due to the large amount of biotite present, and the Barre granite due to having larger grain size than the granophyres. The cylindrical shape specimens have not been exposed to the energy for more than 120s in high range power level irradiation due to sparking within the oven cavity.

a)


b)


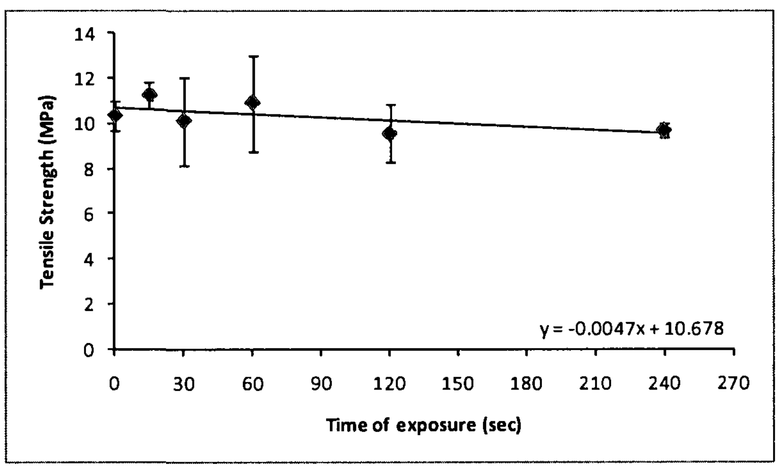
c)


Figure 5-13 Results of Brazilian tensile strength tests for Barre granite in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

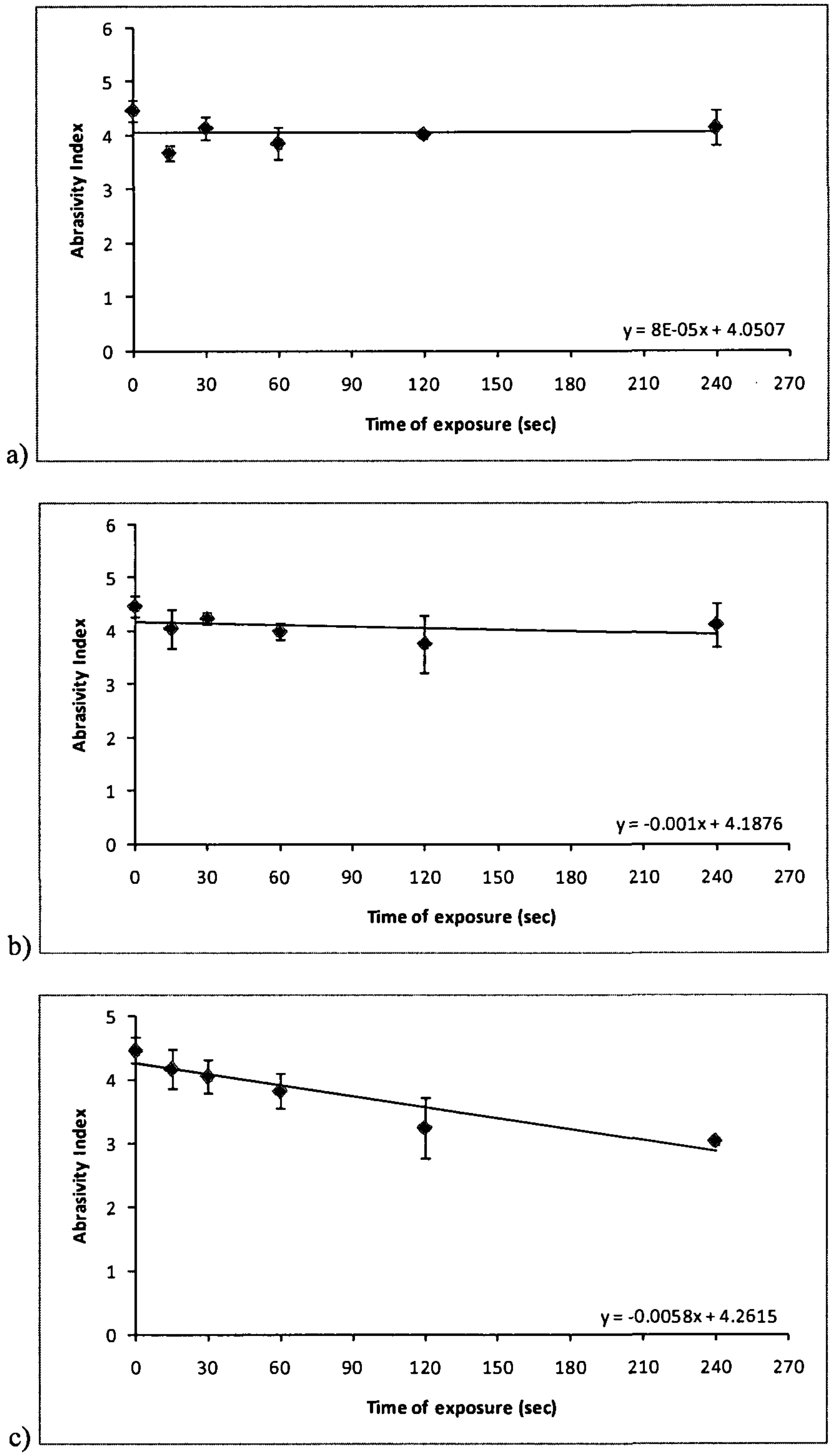


Figure 5-14 Results of CERCHAR abressiveness tests for Barre granite in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

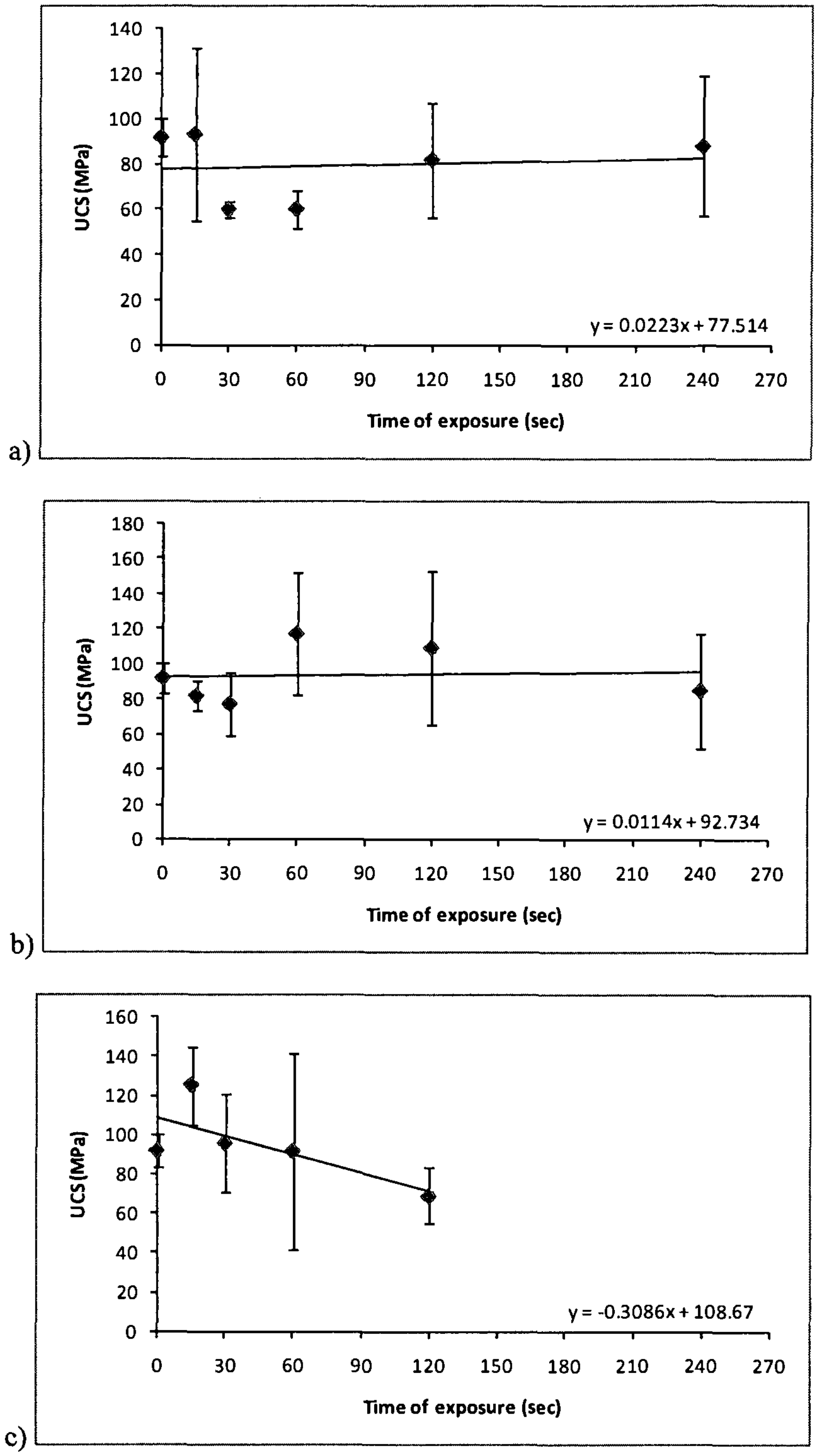


Figure 5-15 Results of unconfined compressive strength tests for Barre granite in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

Due to limited amount of rock samples, the gabbro was subjected to only the high level power energy of microwave exposure. Figures 5-16 and 5-17 show the temperature of disc and cylindrical shapes, respectively, of gabbro type of rock. Since there are some metallic oxides and sulfides present in the gabbro, the trend of temperature shows a rapid increase as the time of exposure increases. As it is evident from Figure 5-18, the mechanical properties of gabbro have remained unchanged. However, since there are still a few metallic oxides or sulfides such as pyrite or ilmenite present in the rock sample, about five cylindrical specimens cracked inside of the microwave cavity as they were exposed to the microwave irradiation for 30 to 120s. Specimens were not exposed to the microwave irradiation for 240s of exposure in high power level due to some sparks within the cavity of the oven.

The cracks were due to the presence of some metallic minerals which absorb the microwave energy and create potential stresses within the boundary of minerals, so they create cracks. UCS tests were not performed on those cracked specimens. As a result of cracks initiated within the specimens, the results of those limited tests and specimen show about 30% reduction in strength (Figure 5-18c). The other tests of that type of rock sample remained unchanged. The cylindrical shape specimens have not been exposed to the energy for more than 120s in high range power level irradiation due to sparking within the oven cavity.

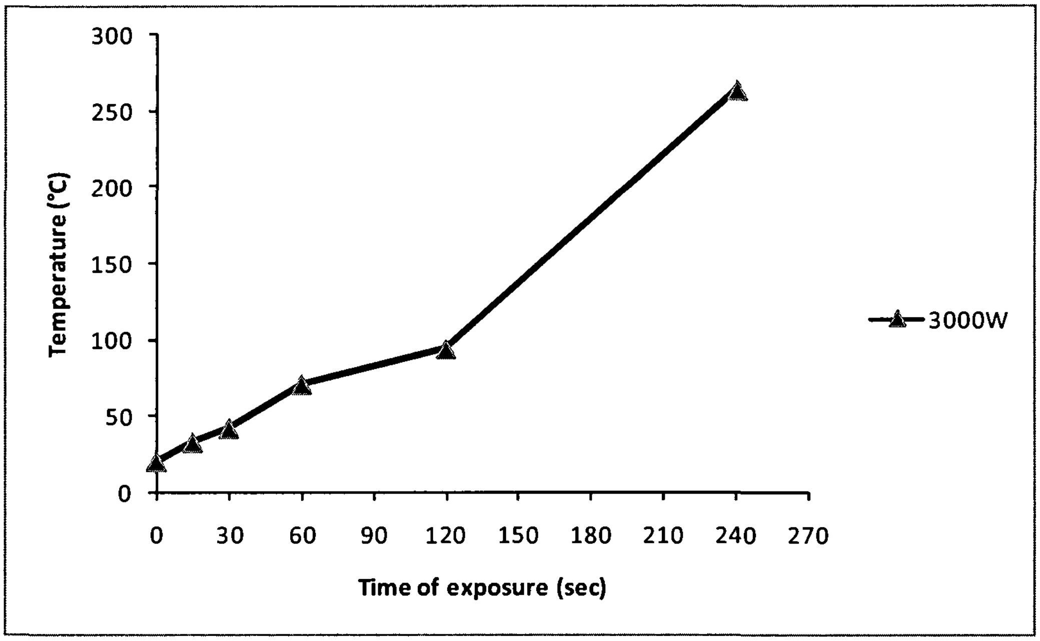


Figure 5-16 Temperature of disc shape specimens of gabbro versus time of exposure in 3000W power level of microwave.

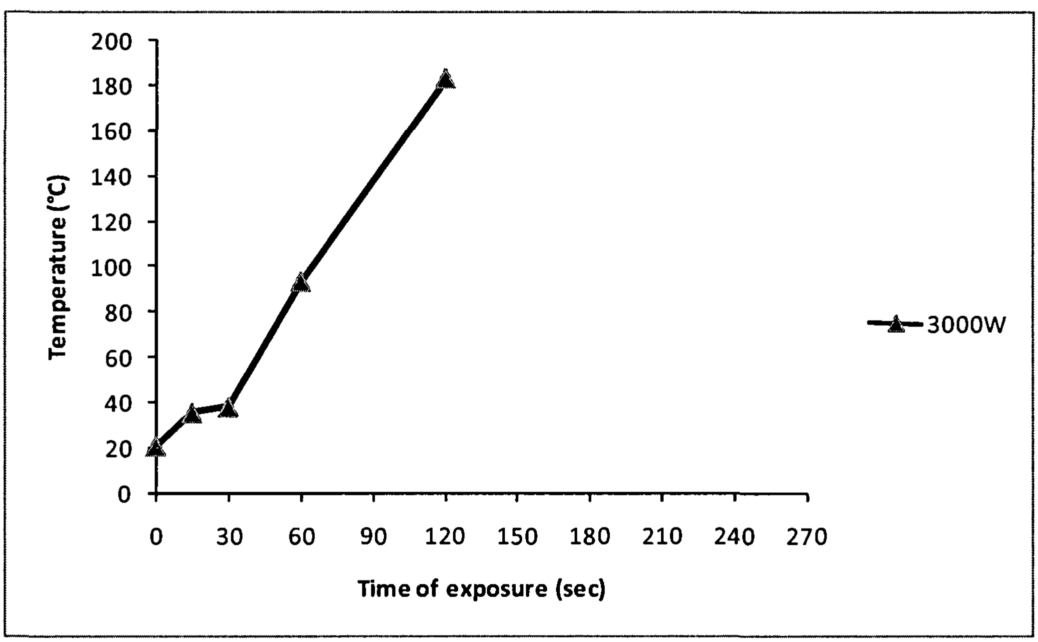


Figure 5-17 Temperature of cylindrical shape specimens of gabbro versus time of exposure in 3000W power level of microwave.

a)

b)

c)

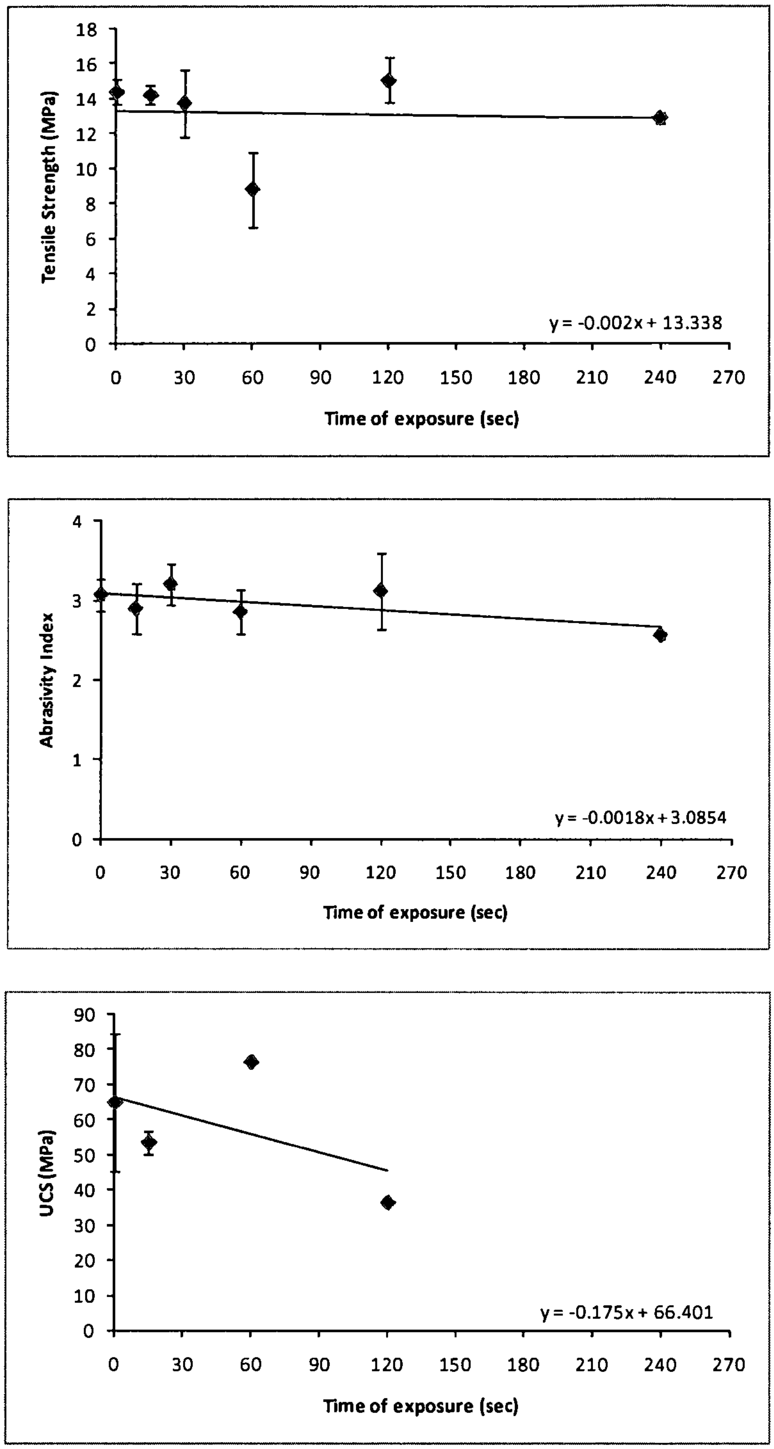


Figure 5-18 Results of Brazilian tensile strength, CERCHAR abrasiveness and unconfined compressive strength tests for gabbro in 3000 watts of power level versus the time of exposure in seconds.

Figures 5-19 and 5-20 are showing the temperature behaviour of disc and cylindrical shaped specimens of the gneiss rock sample as the time of exposure increases. The temperature of gneiss grows rapidly up to 400 degree Celsius at the high power level of microwave energy as the time of exposure increases. The rapid growth in temperature shows the absorption ability of the rock sample. As it was discussed in the previous chapter, this type of rock is fine grained re-crystallized sandstone which makes that rock a metamorphic rock. The presence of up to 5-10% metallic oxide and sulfide mineral in this rock cause the rapid growth of temperature as it is exposed to the microwave energy, reduction of about 35% of the surface abrasivity and even more reduction in the tensile strength value (Figure 5-21).

The specimens of this rock type burst from inside toward outside in the microwave oven when exposed to the energy for about 60 seconds and over. However, one cylindrical specimen burst also after 240 seconds of microwave exposure and the other two specimens in the same time of exposure cracked both longitudinal and cross sectional. Since the cracks initiate within the cylindrical specimens mostly cross sectional, therefore, the load applied on the specimen from the UCS test apparatus is spent to close the cracks first then cause the specimen to fail. Hence, the cracks initiated did not reduce the unconfined compressive strength value that much, so the Figure 5-21c demonstrates no changes in UCS value. The disc shape specimen of gneiss bursts after being exposed to the energy for 60s of exposure time.

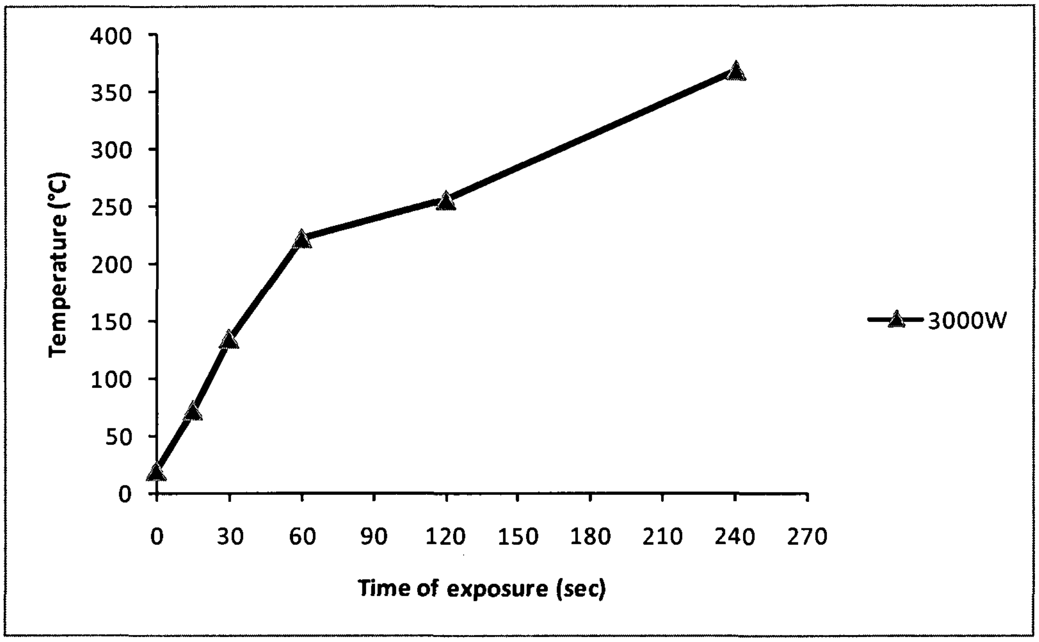


Figure 5-19 Temperature of disc shape specimens of gneiss versus time of exposure in 3000W power level of microwave.

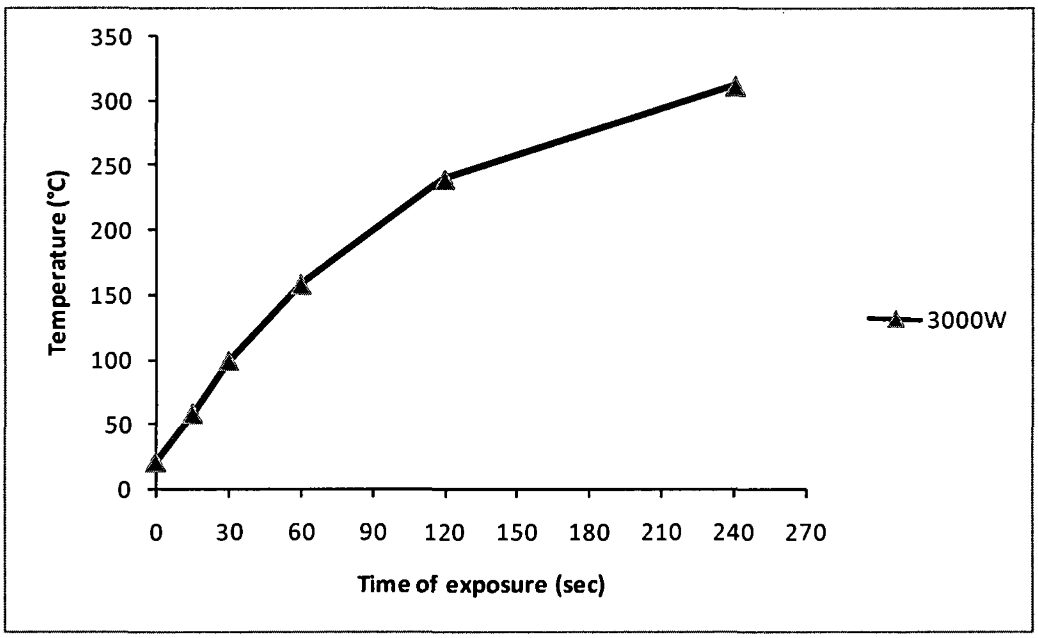


Figure 5-20 Temperature of cylindrical shape specimens of gneiss versus time of exposure in 3000W power level of microwave.

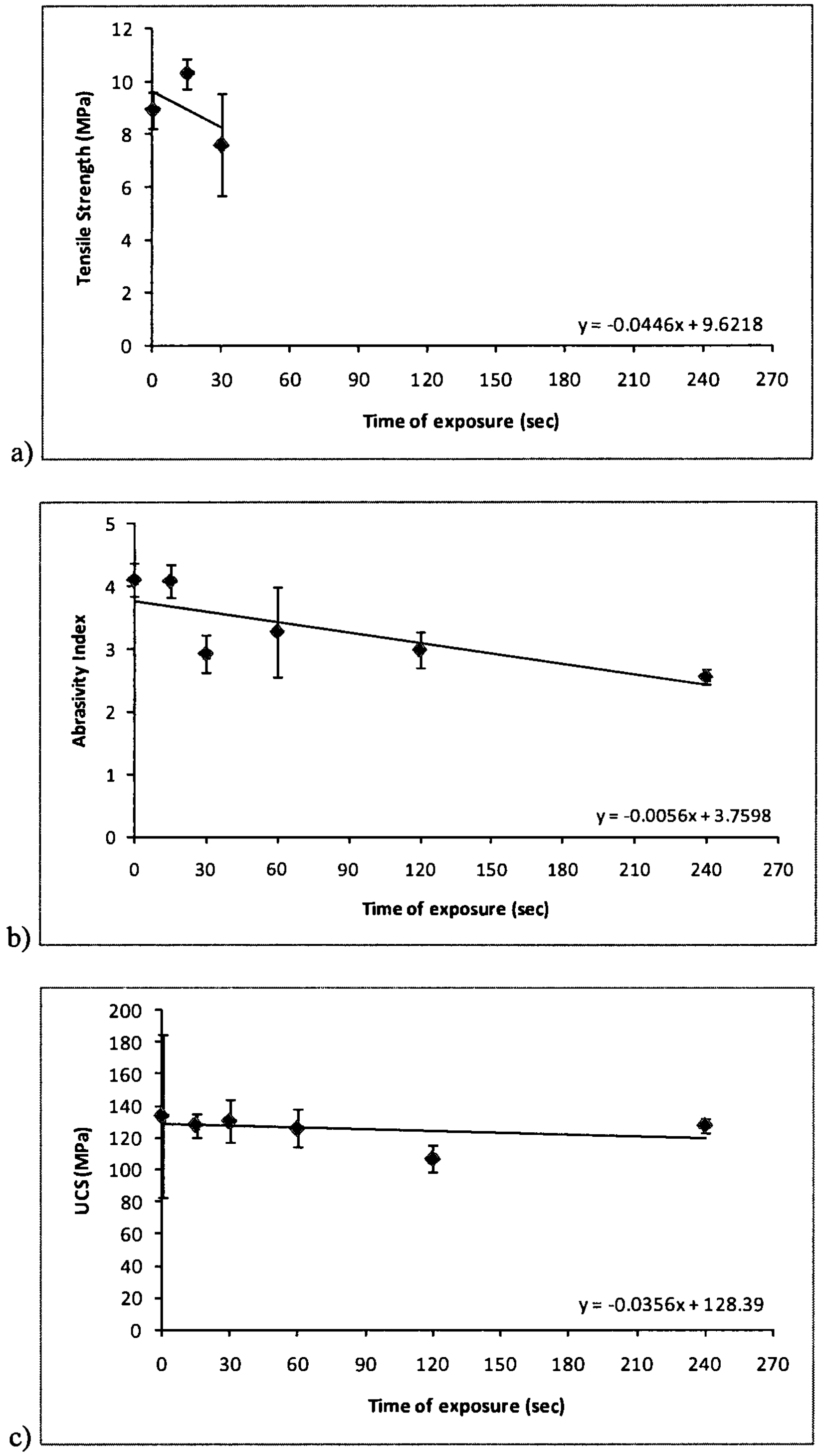


Figure 5-21 Results of Brazilian tensile strength, CERCHAR abrasiveness and unconfined compressive strength tests for gneiss in 3000 watts of power level versus the time of exposure in seconds.

Figures 5-22 and 5-23 demonstrate the temperature behaviour of disc and cylindrical shapes of limestone at different power levels as the time of microwave exposure increases. As Figures 5-22 and 5-23 show the temperature of specimens in low and medium power levels (800 and 1250 watts) increases slightly and slowly up to 200 degree Celsius. Indeed, at the high power level, the temperature increases rapidly and significantly.

Since limestone consists of about 15-20% metallic oxide and sulfide minerals, which are microwave energy absorbent, the temperature of treated specimen in high power level raised rapidly. As those metallic oxide and sulfide minerals absorb the energy and heat up within the rock, their expansion caused the initiation of cracks on the treated minerals. Most of the specimens being treated in the microwave oven cracked due to the heat generated by the microwave energy. Cracks on the specimens initiated after 60 seconds of exposure and over in low and medium power levels of microwave. However, in high power level, cracks started to be initiated on the specimens after 30 seconds of exposure. Normally, cracks were along the mud vein of the specimen.

Figures 5-24, 5-25 and 5-26 show the results of tests performed on limestone specimens at different power levels and time of exposure. It is evident that the mechanical properties of limestone are reduced about 30% as the power level and the time of exposure increases. However, the surface abrasiveness reduces in medium power level. The disc and cylindrical shape specimens have not been exposed to the energy for more than 120s in high range power level irradiation due to sparking within the oven cavity.

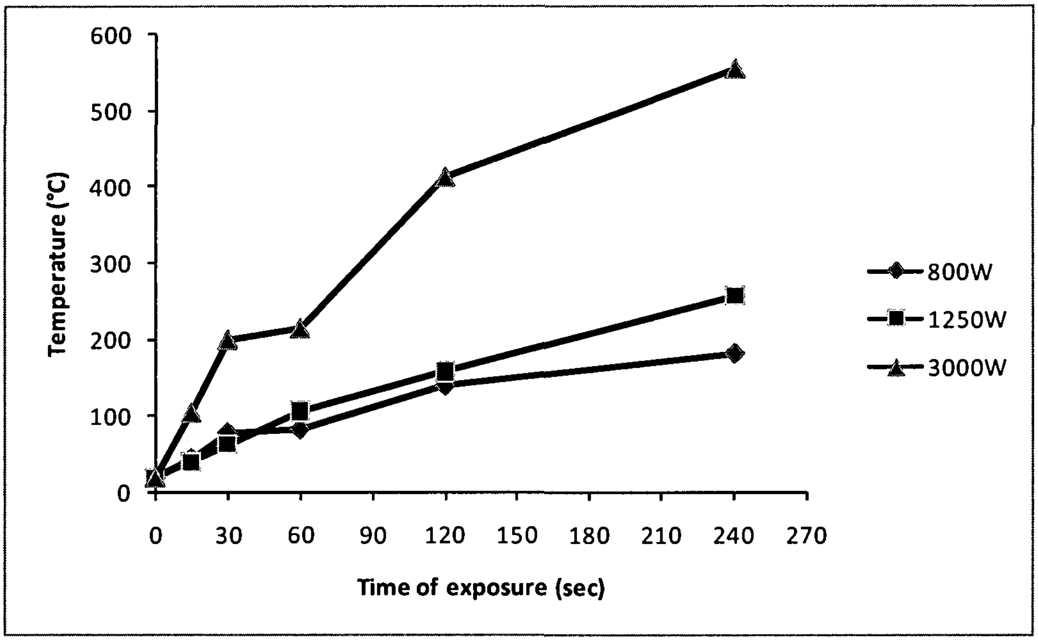


Figure 5-22 Temperature of disc shape specimens of Limestone versus time of exposure in different power levels of microwave.

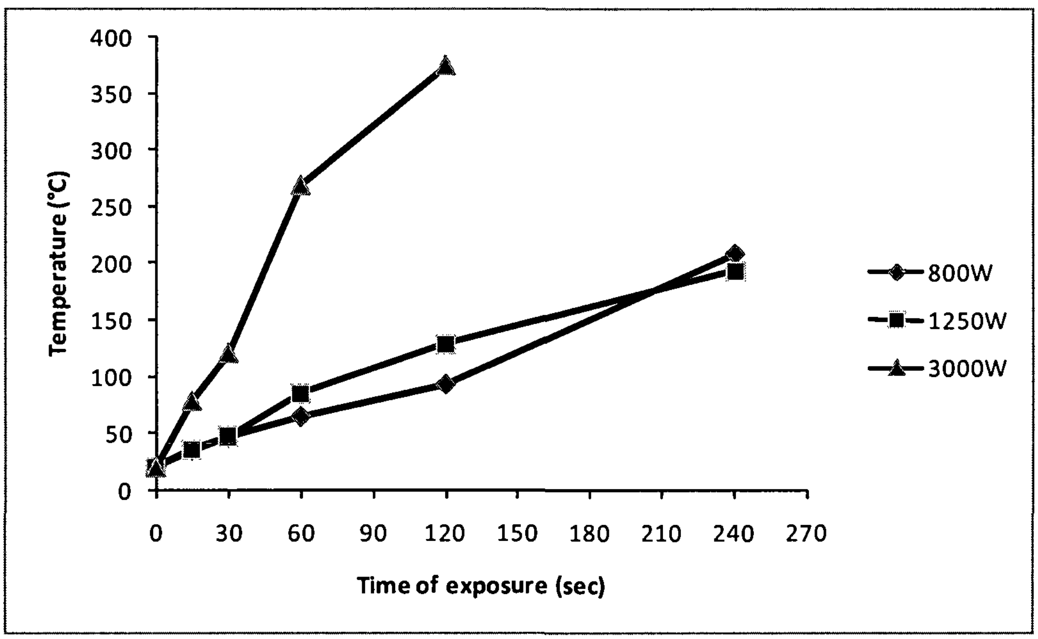
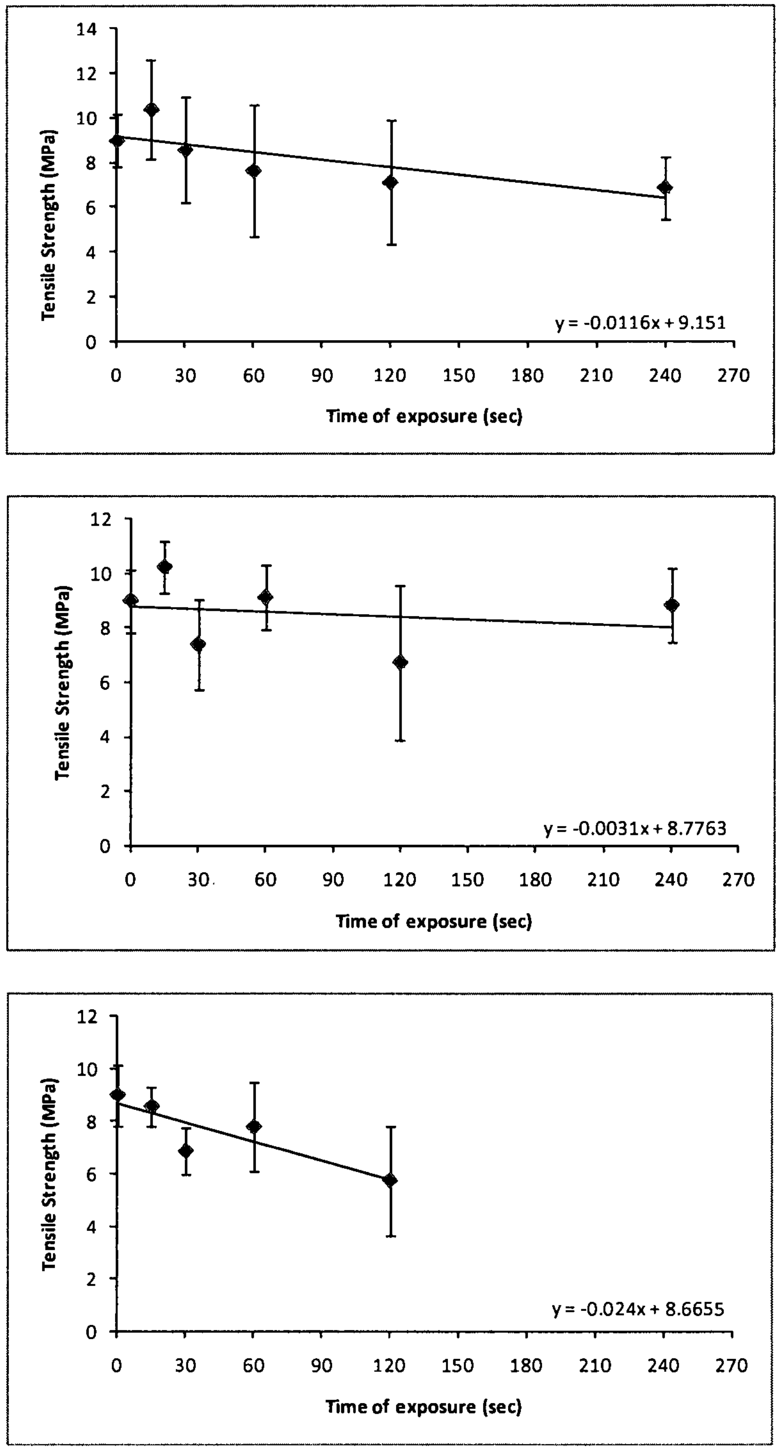


Figure 5-23 Temperature of cylindrical shape specimens of Limestone versus time of exposure in different power levels of microwave.



a) b) c)

Figure 5-24 Results of Brazilian tensile strength tests for limestone in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

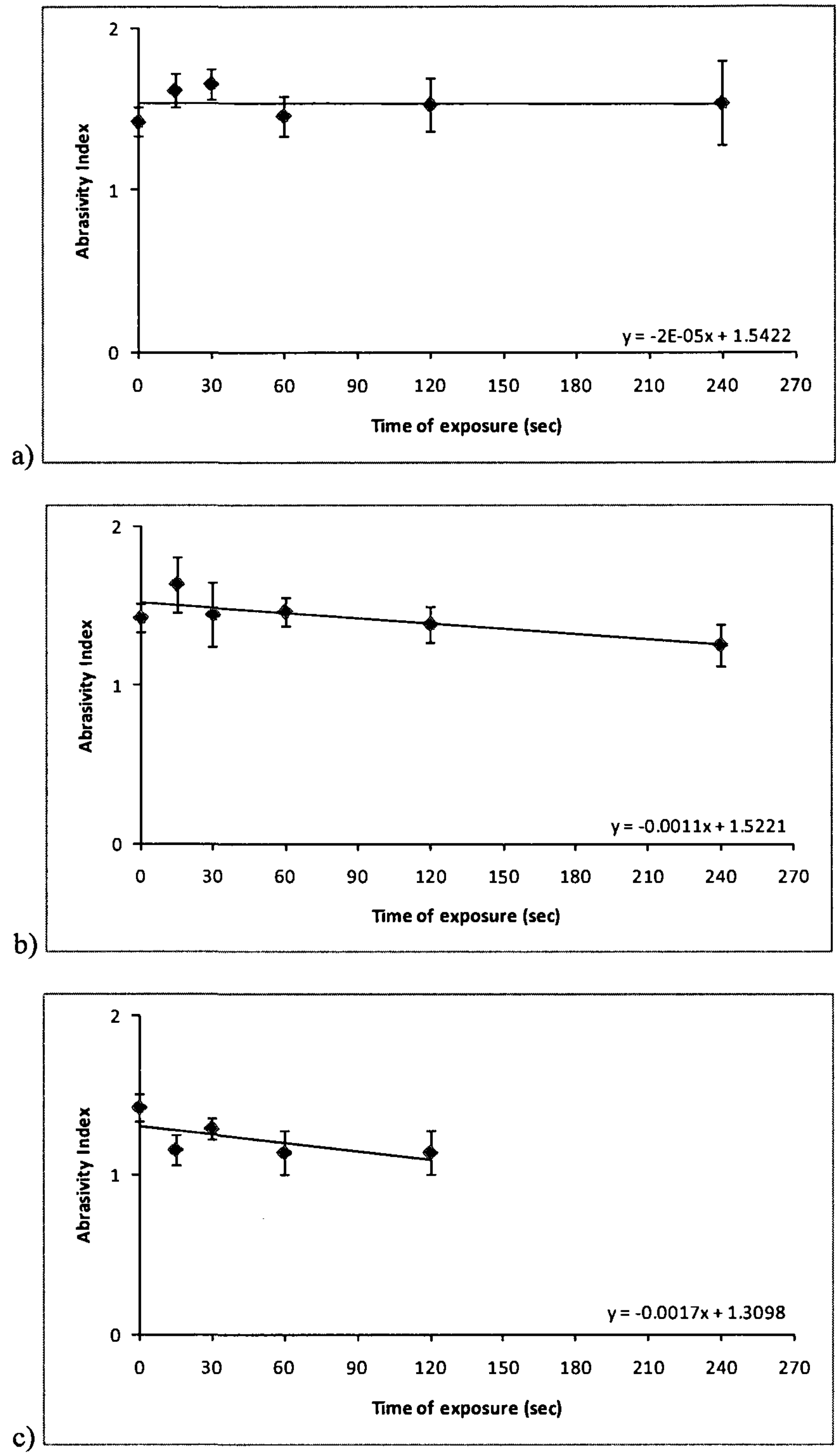
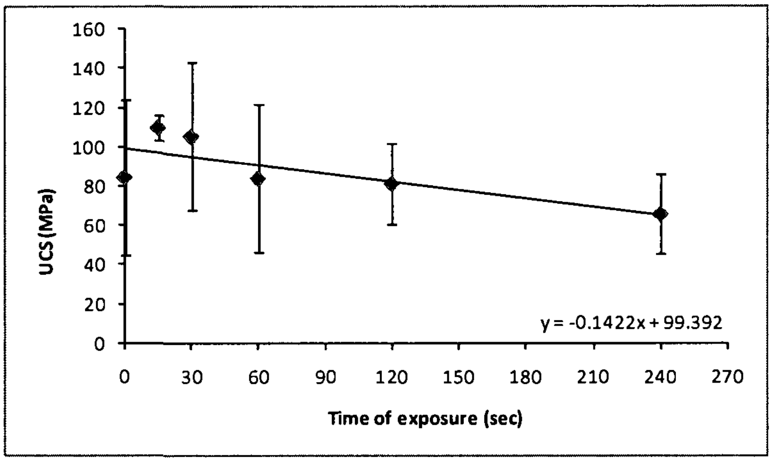
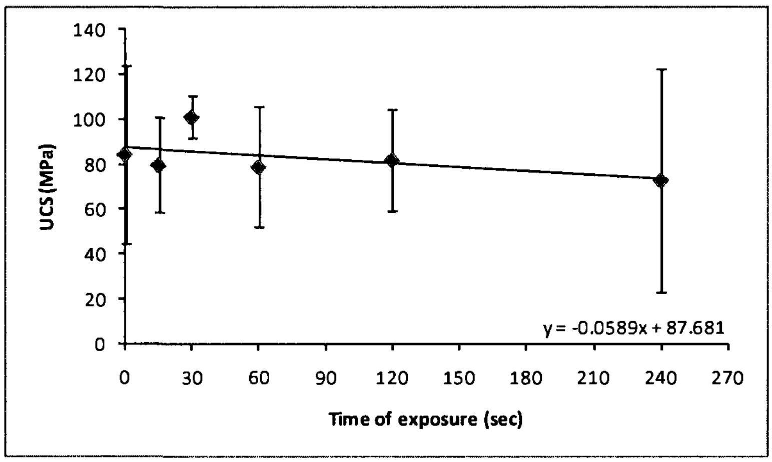


Figure 5-25 Results of CERCHAR abrasiveness tests for limestone in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

a)


b)


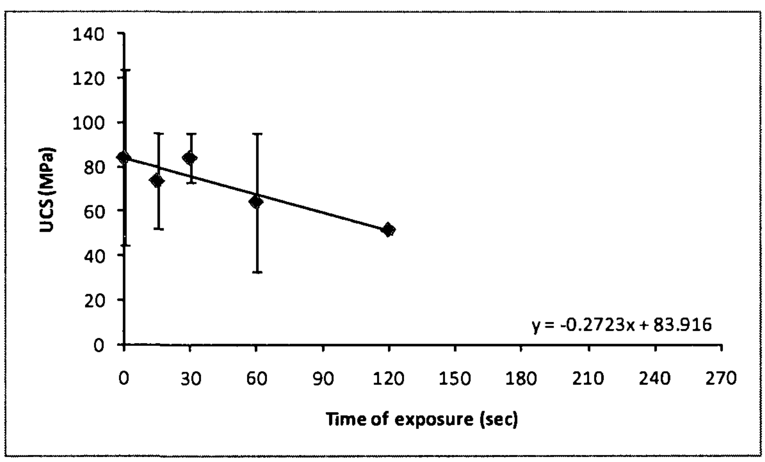
c)


Figure 5-26 Results of unconfined compressive strength tests for limestone in a)800, b)1250 and c)3000 watts of power levels versus the time of exposure in seconds.

Similar to gabbro and gneiss, due to lack of sample basalt andesitic rock type has been only subjected to 1250 watts of power level. Since this rock type contains about 70-75% pyrite it was not suitable to be irradiated to high level microwave energy due to high amount of sparks which could have been generated within the cavity of the microwave oven. The basal andesitic rock sample was received as chunks of rocks collected from the bench of the mine after being blasted. Hence, the boulders were fully cracked such that core sampling from them was difficult, so enough samples were able to be collected for only one power level.

Figures 5-27 and 5-28 show the temperature behaviour of disc and cylindrical shapes of basalt in different power level and time of exposure. Because of the high amount of pyrite present in the rock sample, the temperature raises very rapidly and high. Since the pyrite is a very good absorbent of microwave energy, it starts to expand when heated. The expansion phenomena causes large potential stresses in the grain boundaries and initiates cracks within the rock sample. Almost all the rock specimens were cracked due to the expansion of pyrite after 60 seconds of microwave exposure and over. The pyrite stats to burn and change color from 60 seconds of microwave exposure with the fusion of sulfur. When the pyrite burns, its sulfur fuses and the remaining iron starts to burn with the oxygen of the air and make a bigger volume of iron oxide, which this change of volume also is a plus to fail the rock sample apart after 240 seconds of microwave exposure. The results show about 40% reduction in compressive strength and up to 80% reduction in tensile strength (Figure 5-29).

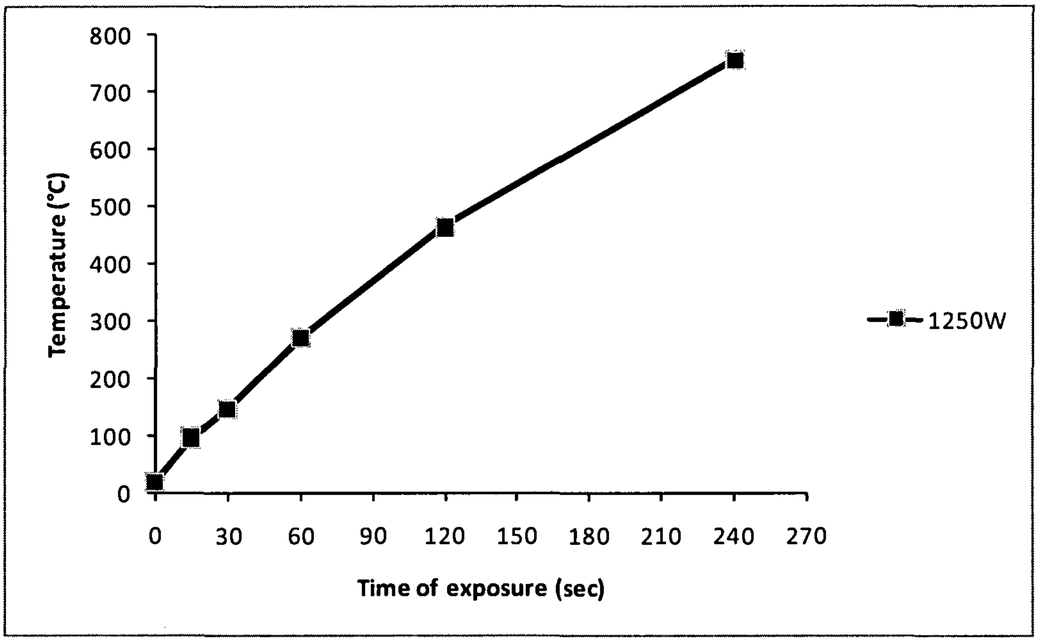


Figure 5-27 Temperature of disc shape specimens of basalt versus time of exposure in 1250W power level of microwave.

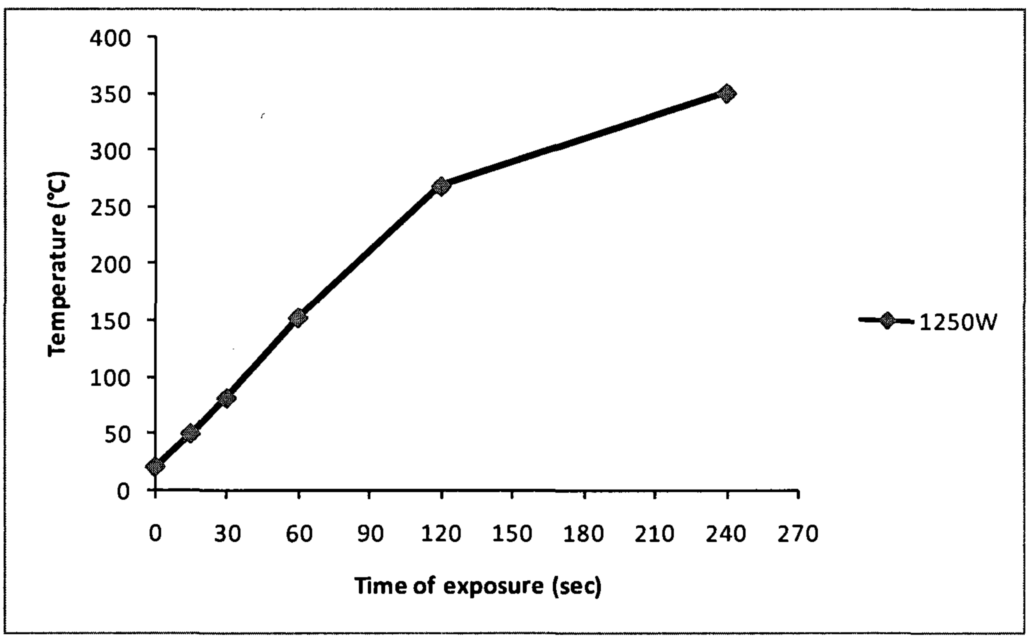
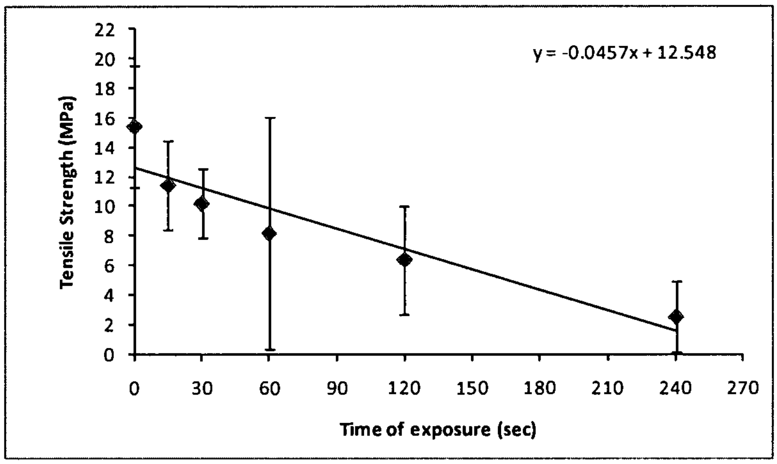
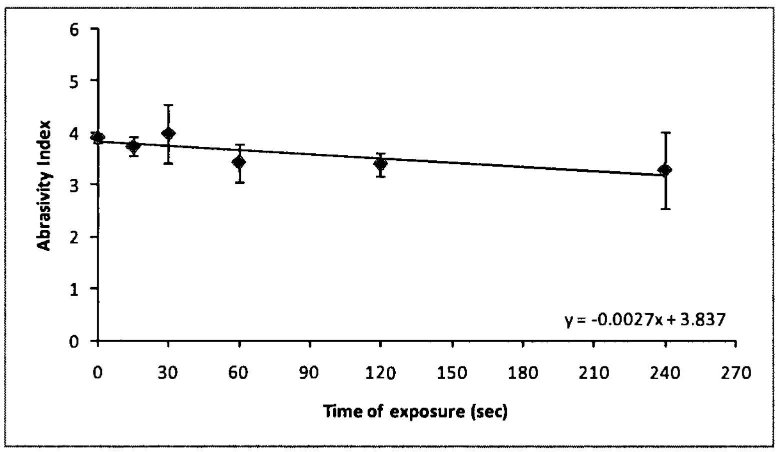


Figure 5-28 Temperature of cylindrical shape specimens of basalt versus time of exposure in 1250W power level of microwave.

a)


b)


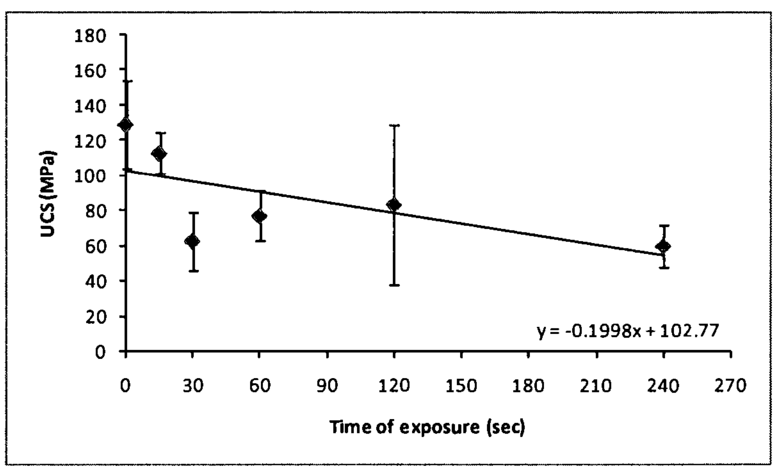
c)


Figure 5-29 Results of Brazilian tensile strength, CERCHAR abrasiveness and unconfined compressive strength tests for basalt in 1250 watts of power level versus the time of exposure in seconds.

The results obtained are validated from previous researchers according to relative and similar experiments performed. Chen et al. (1984) validates the transparency of certain minerals among the selected rock samples being subjected to the current thesis experiments. Table 5-1 shows the amount of minerals percentage of constituent of selected rocks. It is therefore, realized that the only minerals being affected by the microwave energy are the metallic oxides and sulfides existing in the rock samples.

Table 5-1 Mineral compositions of the selected rocks.

<table>
<tr><th>Minerals</th><th>Granophyre</th><th>Mafic Granophyre</th><th>Barre Granite</th><th>Gabbro</th><th>Gneiss</th><th>Limestone</th><th>Basalt</th><th></th></tr>
<tr><td>Quartz</td><td rowspan="2">60 - 70</td><td rowspan="2">60 - 70</td><td>20 - 30</td><td></td><td>70 - 75</td><td></td><td></td><td>Transparent</td></tr>
<tr><td>K-Feldspar</td><td rowspan="2">60 - 70*</td><td></td><td></td><td></td><td></td><td>Transparent</td></tr>
<tr><td>Plagioclase</td><td>20 - 30</td><td>20 - 30</td><td>60</td><td></td><td></td><td></td><td>Transparent</td></tr>
<tr><td>Biotite</td><td>10</td><td>30</td><td>5 - 7</td><td>5</td><td>5 - 15</td><td></td><td></td><td>Transparent</td></tr>
<tr><td>Titanite</td><td></td><td></td><td>1 - 2</td><td></td><td></td><td></td><td></td><td>Transparent</td></tr>
<tr><td>Metalic oxides an sulfides:
Pyrite, Chalcopyrite, Magnetite, Ilmenite</td><td></td><td></td><td></td><td>1 - 2</td><td>5 - 10</td><td>15 - 25</td><td>25</td><td>Absorbant</td></tr>
<tr><td>Hornblende</td><td></td><td></td><td></td><td>30 - 35</td><td></td><td></td><td></td><td>Transparent</td></tr>
<tr><td>Calcite</td><td></td><td></td><td></td><td></td><td>10</td><td>75 - 85**</td><td></td><td>Transparent</td></tr>
</table>

* Sodic plagioclase in granite. ** Dolomite is also part of the percentage in limestone.

Chen (1984) and Fitzgibbon (1990) validated the thermal effects on minerals when exposed to the microwave energy. Within the granophyres and the barre granite samples, biotite is the only mineral among all other transparent minerals, which is sensitive to heat that it fails rapidly after being treated with microwave energy.

According to Kingman (2000-5), Jones (2007) and Whittles (2003) the statement of presence of metallic oxide and sulfide minerals being affected by microwave energy can be validated. Since those authors investigated the influence of the microwave energy on rocks, hence, the grain size effect, expansion of pyrite and generating potential stresses in between the grain boundaries to initiate cracks within rocks can be validated.

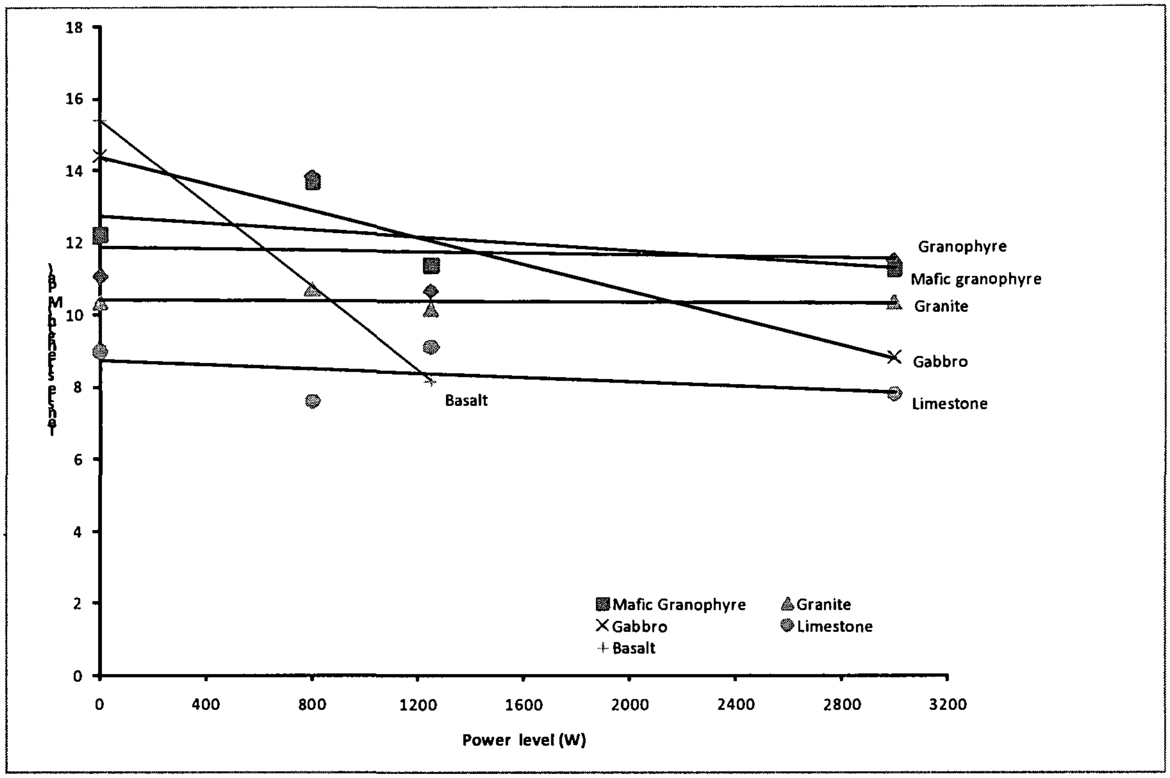


Figure 5-30 Influence of power level on the tensile strength of selected rocks based on highest change in each power level.

In order to have a perspective evaluation on the influence of the power level, the highest change in each power level at 60 seconds of exposure time has been taken in consideration. Figure 5-30 demonstrates the influence of the power level of microwave irradiation on the tensile strength of selected rocks at 60 seconds of energy exposure. A slight reduction of about 10% is observed in tensile strength of mafic granophyre and limestone as the power level increases. However, the gabbro and basalt shows about 40% reduction in tensile strength as the power level increases.Tensile strength reduction of basalt is due to the presence of large amount of metallic oxide and sulfide minerals. The gneiss sample burst after being exposed to 60s of exposure time. The other types of selected rocks, light granophyres and granite remain almost unchanged.

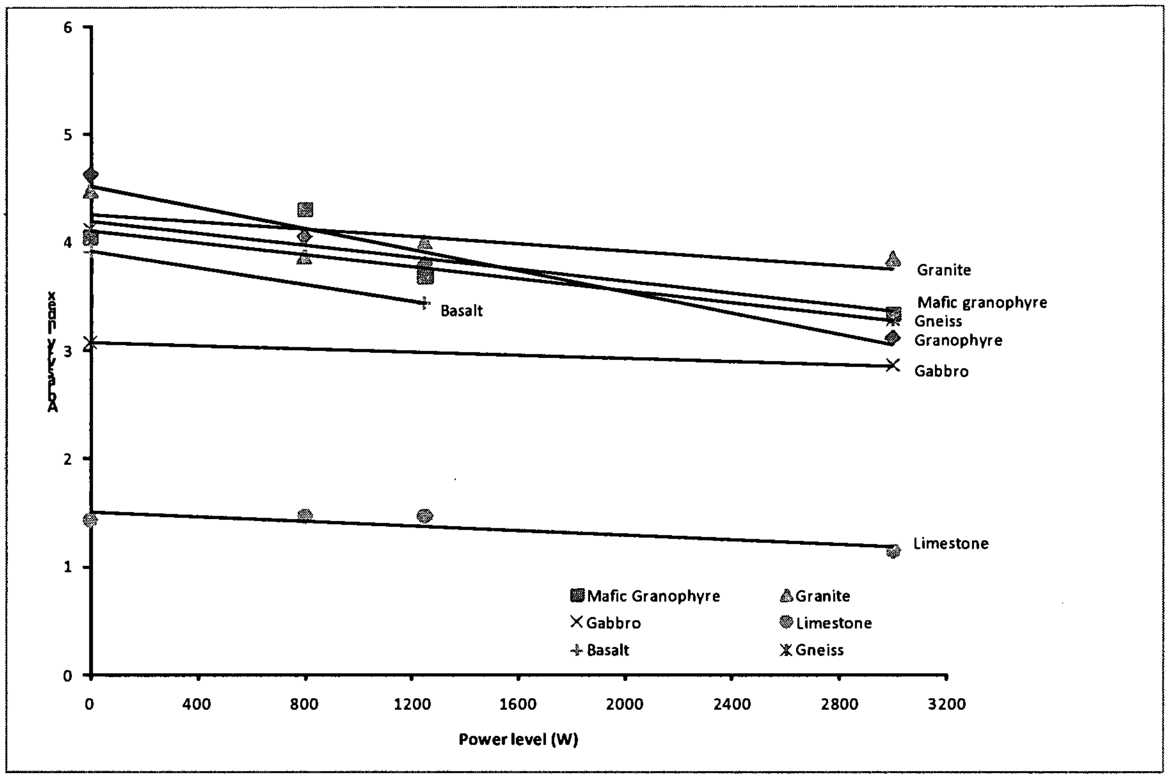


Figure 5-31 Influence of power level on the abrasivity index of selected rocks based on highest change in each power level.

Figure 5-31 demonstrates the influence of power level on the abrasivity index of selected rocks based on the highest change in each power level at 60 seconds of exposure time. Gabbro and limestone remain unchanged as the power level of microwave energy increases. However, almost all other rock samples demonstrate up to 30% reduction of abrasivity as the power level increases at 60s of exposure time. Although granophyres and granite mainly consist of silicates and feldspars which are transparent to microwave energy, they also show a significant reduction of surface abrasivity index due to mafic minerals present on the surface of rock.

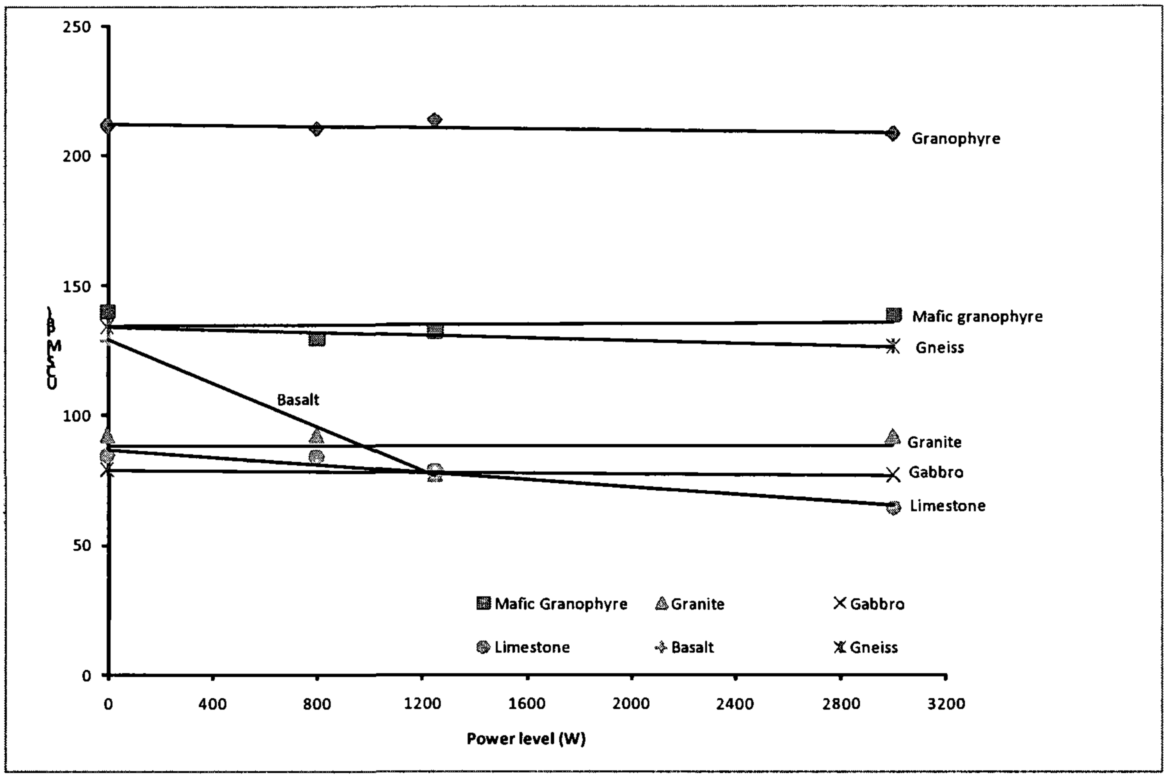


Figure 5-32 Influence of power level on the unconfined compressive strength of selected rocks based on highest change in each power level.

Figure 5-32 demonstrates the influence of power level of microwave energy on compressive strength of selected rocks based on the highest change in each power level at 60 seconds of exposure time. It is shown that the compressive strength of almost all rock samples at that time of exposure remain unchanged. However, limestone and granite show 25% and 40% reduction as the power level increases, respectively. The significant reduction of compressive strength in basalt can be due to the high volume of metallic oxide and sulfide minerals present within the rock sample. It is then concluded that the higher the power level of microwave energy, the more influence the energy has on the mechanical parameters of hard rocks.

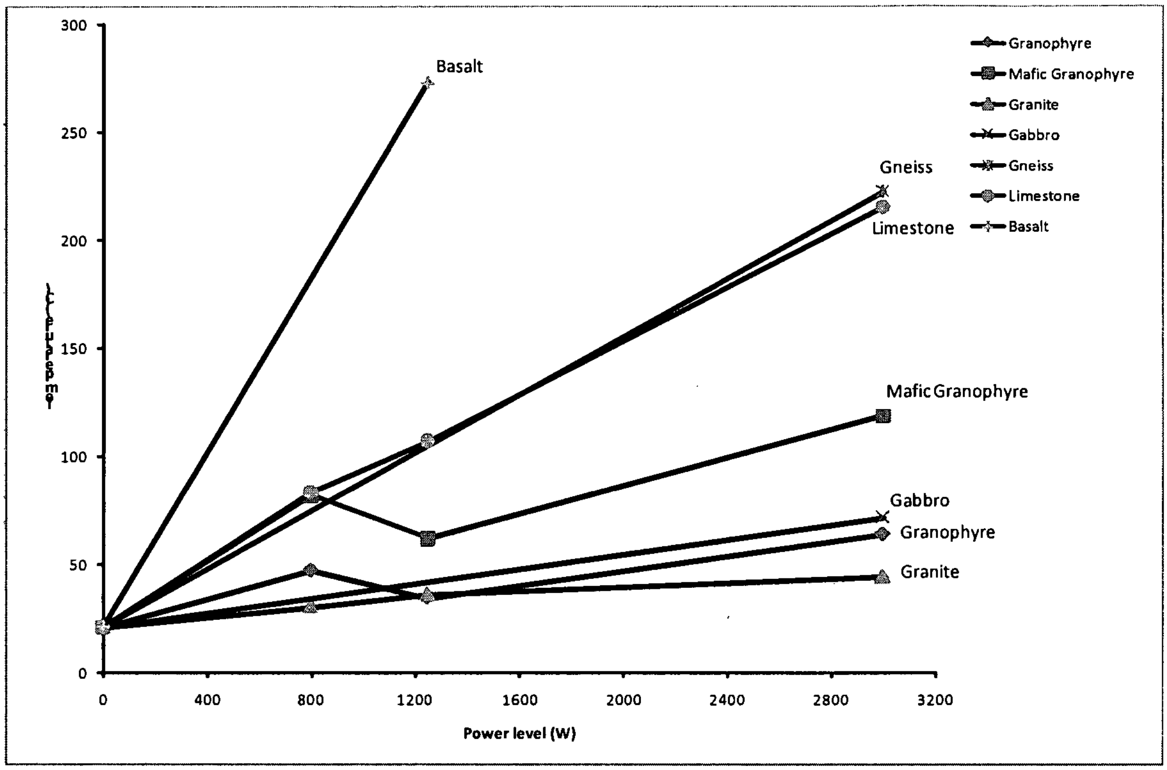


Figure 5-33 Temperature of disc shape specimen of selected rocks versus power level of microwave exposure based on the highest value in each power level.

The temperature of each individual specimen is calculated immediately after being exposed to the microwave energy. Figures 5-33 and 5-34 demonstrate the comparison of the temperature of disc and cylindrical shape specimens, respectively, of selected rocks at zero (ambient temperature) and the highest value obtained after being exposed to 60 seconds of microwave energy exposure. Figure 5-33 shows the temperature behaviour of disc shape specimens versus the power level of microwave energy. It is shown that each individual rock sample behave differently and heat differently as the power level increases due to the variability of the rock sample mineralogy and composition. The granophyres shows a slight drop down of temperature at 1250 watts of power which the reason need further investigation. It might be because of the difference in the equipment as the oven used for that power level is older than the other two brand new ovens. Also another possible reason could be because of the rotatable table in the cavity which the oven exposing 1250 watts of energy does not have a rotatable table in its cavity.

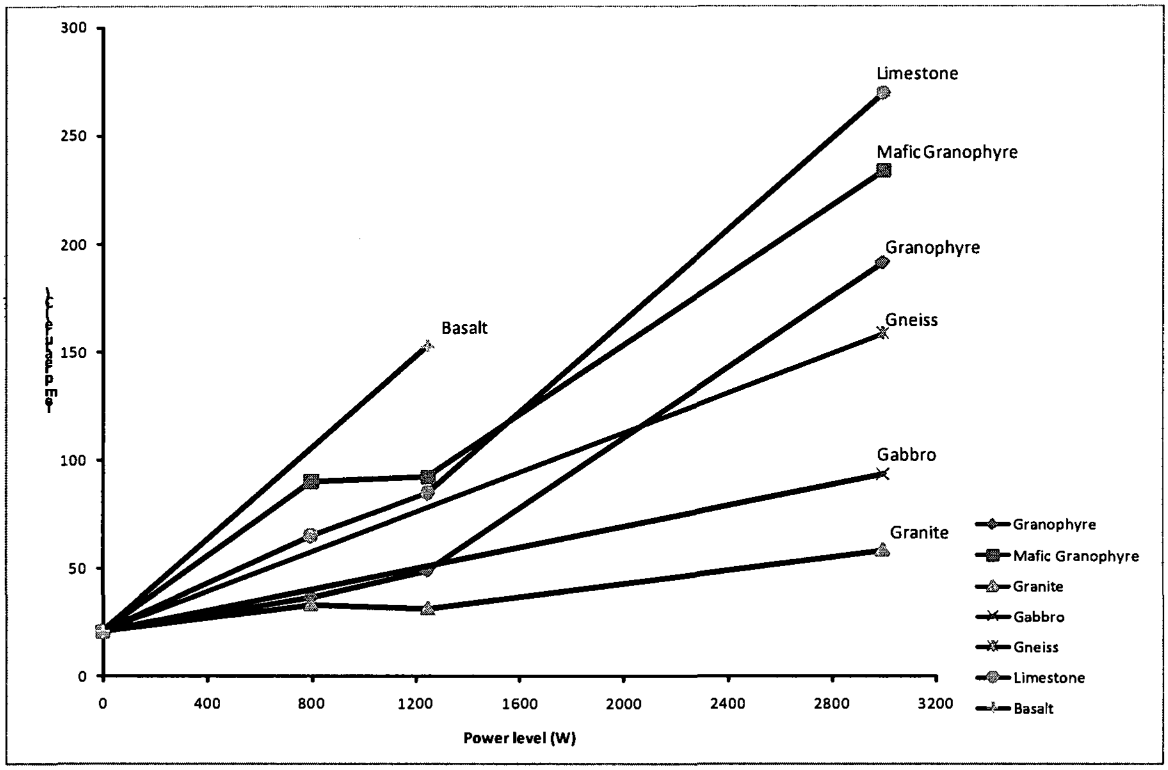


Figure 5-34 Temperature of cylindrical shape specimen of selected rocks versus power level of microwave exposure based on the highest value in each power level.

Figure 5-34 demonstrates the temperature behaviour of cylindrical shape specimens of selected rocks as they are exposed to different power level of microwave energy at 60 seconds of exposure time. Mafic granophyre shows a constant temperature in both low-range and mid-range power level of microwave energy. Another slight drop down of temperature is observed in granite at 1250 watts of power level. Basalt rock sample has not been exposed to high-range power level due to having a large amount of metallic oxides and sulphides which causes sparking in the cavity of high-range power level.

CHAPTER SIX

6. Conclusion & future works

6.1 Conclusion

Granophyres and granite are mainly acting transparent to microwave energy because of their mineral constituents. Quartz and plagioclase are the main consistent minerals of those rocks and according to the literature review they are transparent to the microwave energy. In other words, they are made from transparent or light minerals which they let the microwave energy pass through. Although Barre granite is almost transparent to the microwave energy similar to the granophyres, its compressive strength shows slight reduction after being exposed to the energy. Barre granite has larger grains than the granophyres. Larger grains in granite cause more potential stress in between the grains due to the difference in expansion ratio of minerals. The large amounts of biotite present in the mafic granophyre cause strength reduction in Brazilian tensile strength tests. This reduction is in addition to the longitudinal 45 degree foliation of biotite within the rock sample. Mafic minerals show sensitivity to heat as they lose their strength when heated. The heat can either be generated within the mineral through conduction with other absorber minerals or by absorbing the microwave energy. Various amount of biotite present within the granophyres and granite rock samples has different effect on the mechanical behaviour of rock samples as being exposed to the microwave energy.

Generally, metallic oxide and sulfide minerals in rocks are the main microwave energy absorbent and heat rapidly validated according to the literature review. Their expansion rate within the rock due to heat cause the generation of great potential stresses, hence, the reduction of strength of hard rocks. Metalic oxides and sulfides cause sparks in high range of microwave energy. The electric field created due to the high power electromagnetic energy emitted causes an electric discharge in the form of spark. Besides the size of absorbent grain minerals, the amount of those absorbent minerals also plays a significant role in strength reduction or failure of rocks. In the selected metamorphic rock, the amount of fine metallic oxide and sulfide grains causes spallation from inside the specimen toward outside as they burst. It is concluded that higher power level of microwave energy can have more influence on mechanical properties of rock in shorter time than lower power level. By exposing hard rock materials to microwave energy, depending on its mineral characteristics, the rock's mechanical parameter as tensile strength, compressive strength and surface abrasiveness can be reduced up to 40% in most cases. Changes in basalt sample is unexpectedly significant which may not be representative for all basalt and needs further investigation.

As mentioned in previous chapters, the penetration rate of a tunnel boring machine is mainly affected by basic mechanical parameters of rock masses in which is operating. Three basic mechanical parameters of hard rock which have been investigated within the current research are mainly influencing the advancement rate of a TBM. Two of those parameters as tensile and compressive strength indicate the penetration rate of a TBM and the CERCHAR abrasivity index value which indicated the lifetime of the cutter tool of a TBM. In order to study the effect of microwave energy on the performance of a TBM, the influence of microwave has been investigated on those three mentioned mechanical parameters of rocks. It is concluded that rocks consisting metallic oxides and sulfides are mostly the ones that will be affected by microwave energy. Depending on the amount of metallic oxides and sulfides within the composition of rock, the strength is reduced by being exposed to microwave irradiation. In addition to the reduction of strength, mafic minerals also which lose their strength as they heat by being exposed to microwave energy can increases the life time of the cutter tool.

6.2 Recommended future work

Respective to the present research, some future work is recommended.

1. It is evident that more investigation is needed to optimize the power level and the time of exposure in order to obtain a better result in reduction of the strength and abrasiveness value of hard rocks.
2. The specimens used in the current research were treated with the microwave energy first then left to be cooled down in the ambient temperature prior to testing. In order to obtain an evaluative result from the influence of heat itself, it is recommended to perform mechanical tests on rock samples right after being treated with microwave energy and is still heated.
3. It is also necessary to do more mineralogical and petrographical investigation on rock samples to determine and predict the influence of microwave energy on rocks.
4. It is recommended to perform a finite element method or discrete element method analysis on the behavior on grain minerals as they are exposed to microwave energy in order to predict the influence of the energy.
5. In the current research, rock samples were irradiated to microwave energy within a multi-mode cavity of a kitchen microwave oven. Since the energy is emitted to the excavation face through a single mode cavity, it is then recommended to expose rock samples to a single mode cavity microwave in order to obtain a practical evaluation of the influence of the energy on rocks.
6. According to the standard for safety level with respect to human exposure to radio frequency electromagnetic fields, 3kHz to 300GHz (IEEE) C95.1. Oct 2005, an investigation on better shielding of the area from which the electromagnetic energy is emitted is recommended in order to better protection against any health injuries.

7. In order to have a functional evaluation of the influence of the microwave energy assisting a mechanical equipment it is recommended to drill rocks while emitting microwave energy on the excavation surface of rock using the apparatus designed and proposed by Hassani et al., (2008), and presented by Nekoovaght et al., (2008). That apparatus is a rotary drilling machine with which drilling rocks and microwaving at the same time can be studied.

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Appendix 1

Emissivity Table for Non-Metals and Metals

These emissivities values are approximate and may vary depending on the actual material surface and conditions.

n.r. = not recommended

Non- Metallic Material	Emissivity			
	1.0 µm	5.0 µm	7.9 µm	8-14 µm
Asbestos	0.9	0.9	0.95	0.95
Assphalt	n.r.	0.9	0.95	0.95
Basalt	n.r.	0.7	0.7	0.7
Carbon				
Unoxidized	0.8-0.95	0.8-0.9	0.8-0.9	0.8-0.9
Graphite	0.8-0.9	0.7-0.9	0.7-0.8	0.7-0.8
Carborundum	n.r.	0.9	0.9	0.9
Ceramic	0.4	0.85-0.95	0.95	0.95
Clay	n.r.	0.85-0.95	0.95	0.95
Concrete	0.65	0.9	0.95	0.95
Cloth	n.r.	0.95	0.95	0.95
Glass				
Plate	n.r.	0.98	0.85	0.85
Gob	n.r.	0.9	n.r.	n.r.
Gravel	n.r.	0.95	0.95	0.95
Gypsum	n.r.	0.4-0.97	0.8-0.95	0.8-0.95
Ice	n.r.		0.98	0.98
Limestone	n.r.	0.4-0.98	0.98	0.98
Paint (non-Al.)		0.9-0.95	0.9-0.95	
Paper (any color)	n.r.	0.95	0.95	0.95
Plastic				
Opaque	n.r.	0.95	0.95	0.95
Over 20 mils	n.r.			
Rubber	n.r.	0.9	0.95	0.95
Sand	n.r.	0.9	0.9	0.9
Snow	n.r.		0.9	0.9
Soil	n.r.	< td>	0.9-0.98	0.9-0.98
Water	n.r.		0.93	0.93
Wood, (natural)	n.r.	0.9-0.95	0.9-0.95	0.9-0.95

Metalic Material	Emissivity		
	1.0µm	1.6µm	8-14µm
Aluminum			
Unoxidized	0.1-0.2	0.02-0.2	n.r.
Oxidized	0.4	0.4	0.2-0.4
Alloy A3003			
Oxidized	n.r.	0.4	0.3
Roughened	0.2-0.8	0.2-0.6	0.1-0.3
Polished	0.1-0.2	0.02-0.1	n.r.
Brass			
Polished	0.8-0.95	0.01-0.05	n.r.
Burnished	n.r.	n.r.	0.3
Oxidized	0.6	0.6	0.5
Chromium	0.4	0.4	n.r.
Copper			
Polished	n.r.	0.03	n.r.
Roughened	n.r.	0.05-0.2	n.r.
Oxidized	0.2-0.8	0.2-0.9	0.4-0.8
Electrical Terminal Blocks	n.r.	n.r.	0.6
Gold	0.3	0.01-0.1	n.r.
Haynes			
Alloy	0.5-0.9	0.6-0.9	0.3-0.8
Inconel			
Oxidized	0.4-0.9	0.6-0.9	0.7-.95
Sandblasted	0.3-0.4	0.3-0.6	0.3-0.6
Electoropolished	0.2-0.5	0.25	0.15
Iron			
Oxidized	0.4-0.8	0.5-0.9	0.5-0.9
Unoxidized	0.35	0.1-0.3	n.r.
Rusted	n.r.	0.6-0.9	0.5-0.7
Molten	0.35	0.4-0.6	n.r.
Iron, Cast			
Oxidized	0.7-0.9	0.7-0.9	0.6-0.95
Unoxidized	0.35	0.3	0.2
Molten	0.035	0.3-0.4	0.2-0.3
Iron, Wrought			
Dull	0.9	0.9	0.9
Lead			
Polished	0.35	0.05-0.2	n.r.
Rough	0.65	0.6	0.4
Oxidized	n.r.	0.3-0.7	0.2-0.6
Magnesium	0.3-0.8	0.05-0.3	n.r.
Mercury	n.r.	0.05-0.15	n.r.
Molybdenum			
Oxidized	0.5-0.9	0.4-0.9	0.2-0.6
Unoxidized	0.25-0.35	0.1-0.35	
Nickel			
Oxidized	0.8-0.9	0.4-0.7	0.2-0.5
Electrolytic	0.2-0.04	0.1-0.3	n.r.
Platinum			
Black	n.r.	0.95	0.9
Silver	n.r.	0.02	.n.r
Steel			
Cold-Rolled	0.8-0.9	0.8-0.9	0.7-0.9
ground Sheet	n.r.	n.r.	0.4-0.6
Polished Sheet	0.35	0.25	0.1
Molten	0.35	0.25-0.4	n.r.
Oxidized	0.8-0.9	0.8-0.9	0.7-0.9
Stainless	0.35	0.2-0.9	0.1-0.8
Tin(Unoxidized)	0.25	0.1-0.3	n.r.
Titanium			
Polished	0.5-0.75	0.3-0.5	n.r.
Oxidized	n.r.	0.6-0.8	0.5-0.6
Tungsten	n.r.	0.1-0.6	n.r.
Polished	0.35-0.4	0.1-0.3	n.r.
Zinc			
Oxidized	0.6	0.15	0.1
Polished	0.5	0.05	n.r.