# The Impact of Water on Heat Distribution and Mechanical Properties of Basalt after Microwave Treatment

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## Abstract

Every underground excavation technique has shortcomings (e.g., low productivity, high cost). Heating rocks with microwave energy before excavation can change their mechanical properties and reduce rock strength. Microwave-assisted rock fragmentation not only reduces equipment maintenance costs, but increases drilling penetration rates and productivity. Mineral processing can also benefit from the micro-fractures created by this promising novel technique.

The effect of the presence of water during rock microwave heating of rocks is poorly understood and serves as the objective of this thesis. Temperature distributions and mechanical properties (abrasiveness and tensile strength) were measured in stacked basalt disks in saturated and dry conditions after microwave treatment at 2.45 GHz and 3 kW power for three exposure times (40, 60, and 80 s). Water did not affect heat distributions and mechanical properties of basalt after microwave heating. To test if this effect was due to the low porosity of basalt, a more porous sandstone was tested. Saturated specimens burst into fragments during microwave treatment. In addition, a sinusoidal temperature distribution pattern was observed if the basalt specimen size was similar to or larger than the microwave wavelength. Longer exposure times resulted in higher temperatures and larger basalt volumes exhibited a slower heating rate.

Measured and simulated—using the finite element modelling package COMSOL Multiphysics<sup>®</sup>—heat distribution patterns were similar, though simulated temperatures were lower. Similar to experimental results, simulated dry and wet basalt temperatures did not differ after microwave heating. The reliability of this pilot numerical modeling study will facilitate future simulations of processes that are too complex to empirically measure.

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## Résumé

Chaque méthode d'excavation a ses lacunes, tel qu'un manque de productivité ou un manque de compétitivité d'un point de vue économique. Chauffer la roche avec de l'énergie micro-onde est une technique prometteuse qui peut changer les propriétés mécaniques de la roche et réduire sa force. La fragmentation de roche assistée par micro-ondes réduit non seulement l'usure de l'équipement, mais augmente aussi la productivité et le taux de forage. Le traitement de minerais peut aussi bénéficier des micro-fractures créées par les micro-ondes.

Par contre, le rôle de l'eau dans le réchauffement de la roche par micro-ondes n'est pas établi et est le sujet de cette thèse. La répartition de température et les propriétés mécaniques (index d'abrasivité CERCHAR, résistance à la traction) de piles de disques de basalte secs et saturés sont étudiées. Les piles de disques sont exposées aux micro-ondes ayant une fréquence de 2.45 GHz et une puissance de 3 kW pendant 40, 60, ou 80 seconds. Il est démontré que l'eau n'a pas d'impact sur les propriétés mécaniques et la répartition de température dans les disques de basalte après chauffage par micro-ondes. Par contre, l'effet de l'eau sur le chauffage par micro-ondes d'une roche plus poreuse (le grès) est plus prononcé: durant le traitement du grès saturé par micro-ondes, le grès a éclaté en fragments. De plus, une répartition de température sinusoïdale peut être observée lorsque que la taille du spécimen est proche ou plus grande que la longueur d'onde des micro-ondes. Une exposition plus prolongée aux micro-ondes résulte en une plus haute température tandis qu'un plus grand volume ou masse réduit le taux de chauffage.

Finalement, la répartition de température simulée numériquement avec COMSOL Multiphysics<sup>®</sup> concorde avec les résultats de l'expérience. Ainsi, la fiabilité de cette étude va faciliter les travaux futurs qui ne peuvent être réalisés avec de l'expérimentation due à leur complexité.

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## Nomenclature

Symbol	Unit	Definition
A	$mm^2$	Cross-sectional area
$\vec{B}$	Wb/m <sup>2</sup>	Magnetic flux density
С	m/s	Speed of light, $3 \times 10^8$
CAI	unitless	CERCHAR abrasiveness index
$C_p$	J/(kg·°C)	Specific heat capacity
d	mm	Diameter of wear flat
$\overrightarrow{D}$	C/m <sup>2</sup>	Electric flux density
$D_c$	mm	Core diameter
$D_e$	mm	Equivalent core diameter
$D_p$	m	Penetration depth
$ec{E}$	V/m	Electric field strength
$E_i$	V/m	Electric field strength in dielectric load
f	Hz	Microwave frequency
$F_{f}$	Ν	Failure load
$F_m$	Ν	Maximum applied load
$F_n$	kN	Normal force applied from the machine to the cutter
G	g/rev	Grindability
$\vec{H}$	A/m	Magnetic field intensity
$H_i$	A/m	Magnetic field intensity in dielectric load
$I_s$	MPa	Point load strength index
$I_{s(50)}$	MPa	Point load strength index for 50-mm diameter core
$\vec{J}$	A/m <sup>2</sup>	Current density
k	W/(m·K)	Thermal conductivity
L	mm	Core thickness

т	kg	Mass
р	μm	Product discard mesh size opening
$P_a$ , $P_d$	$W/m^3$	Power dissipation density
P <sub>rev</sub>	mm/rev	Tunnel Boring Machine penetration rate
$ec{q}$	$W/m^2$	Heat flux density
Q	W/m <sup>3</sup>	Thermal Energy
R	$\Omega \cdot m$	Electrical resistance
$tan(\delta)$	unitless	Loss tangent
VT	K/m	Temperature gradient
$\Delta T/t$	°C/s	Heating rate
W	kW·h/short ton	Bond work index
З	F/m	Permittivity
arepsilon'	unitless	Relative dielectric constant
arepsilon''	unitless	Relative dielectric loss factor
$\mathcal{E}_{O}$	F/m	Permittivity of free space; $8.854 \times 10^{-12}$
E <sub>r</sub>	unitless	Relative permittivity
λ	m	Microwave wavelength
$\lambda_o$	m	Microwave wavelength in free space
μ	H/m	Permeability
$\mu''$	unitless	Relative magnetic loss factor
$\mu_o$	H/m	Permeability of free space, $1.257 \times 10^{-6}$
ρ	kg/m <sup>3</sup>	Material density
$ ho_v$	C/m <sup>3</sup>	Charge density
σ	S/m	Electrical conductivity
$\sigma_c$	MPa	Uniaxial compressive strength
$\sigma_t$	MPa	Tensile strength
$\phi$	unitless	Rock porosity

## **Chapter 1**

## Introduction

#### 1.1 Background

Drilling-and-blasting and mechanical excavation are common rock breakage techniques during underground excavations for mining or civil engineering purposes. Both methods have advantages and disadvantages, depending on the circumstances.

Drilling-and-blasting initiates explosions in drilled holes to generate shockwaves, which travel radially, creating micro-fractures or enlarging discontinuities in the rock mass. When a shockwave is reflected from a free face, it transforms from a compression wave to a tensile wave. The travel of the reflected wave favours the fracturing process. Meanwhile, gas exploding from the blast holes under high pressure penetrates the fractures, helping to coalesce them.

The casting of rock starts when the radial fractures move to the free face (Lusk & Worsey, 2011). Drilling-and-blasting is a relatively inexpensive way for mining engineers to break large volumes of rock, especially hard rock. Although drilling-and-blasting is the most commonly used method for breaking rock, productivity is limited by cycle times (e.g., allocated to drilling, blasting, and mucking). In addition, safety is a serious concern, and the social license to operate is compromised by noise, dust, and vibration (Lusk & Worsey, 2011).

Mechanical excavation uses high-quality steel cutting tools to entirely extract the rock from the mine face. The indentation of the rock-cutting tool creates a high-stress area in the rock mass until the rock fails (spalling). Compared to drilling-and-blasting, mechanical excavation employs

a high degree of automation and imposes less damage to walls. Common types of mechanical excavation machinery are tunnel boring machines (TBMs), raise boring machines, roadheaders, continuous miners, and longwall drum shearers (Rostami, 2011). However, when cutting rock formations with uniaxial compressive strength (UCS) strengths in the upper ranges of medium-hard to hard (>172 MPa), mechanical fragmentation machinery is not economically competitive nor sufficiently productive, because of rapid bit wear, shallow cutting, and high maintenance requirements (Lindroth et al., 1992).

In light of these limitations, novel techniques and tools for rock breakage have been the subject of research and development activities, including laser drills, projectile impact, flame and water jets, and microwave rock-breakage systems (Rostami, 2011). Among these methods, microwave energy holds promise, because microwaves are ubiquitous in many kinds of applications. Microwaves have been shown to change the mechanical properties of some rock types by heating and weakening the rock. Microwave treatment has the potential to reform the mechanical excavation industry. For example, Lindroth et al. (1990) patented their design of a microwave assisted cutting system for hard rock (Fig. 1.1), which combines a beam of microwave energy and a cutter from a piece of conventional mining machinery.



Figure 1.1: Microwave assisted cutting system for hard rock (Lindroth et al., 1990; Nekoovaght, 2009)

A pilot design for a microwave-assisted system patented by Ouellet et al. (2009) from McGill University comprises a microwave and drilling assembly (Fig. 1.2). It differs from the design above in that the drill rod serves as the waveguide to conduct microwaves to the cutting face.



Figure 1.2: Electromagnetic energy assisted drilling system (Ouellet et al., 2009)

Overall, microwave-assisted rock fragmentation technology confers several advantages to the mining and tunneling industry compared to traditional rock fragmentation, including increased production rates and less drill bit wear. In addition, micro-fractures created during the process contribute to the ease of mineral processing. For instance, microwave-heated iron ores have a 10–24% reduction in the Bond work index, which could increase throughput and decrease comminution costs (Walkiewicz et al., 1991).

#### **1.2** Research Objective

Previous work from our research group was conducted on various types of intact rock in dry conditions. In reality, water is ubiquitous in rock mass. The water molecule has a dipole moment, therefore it is a strong microwave absorber. Water has been shown to facilitate the microwave heating process in foods, but the effect on microwave heating in rocks has not been clearly demonstrated. The overall objective of this research is to investigate the impact of water on microwave heating of basalt. Specific objectives are to:

- develop and apply a methodology to measure the interior temperature distributions of basalt specimens in dry and saturated conditions after microwave treatment;
- 2. measure mechanical properties before and after microwave treatment under dry and saturated conditions using the CERCHAR abrasiveness and Brazilian tensile strength test;
- 3. compare results from objectives 1 and 2 with those from similar experiments on a more porous rock, namely sandstone; and
- evaluate the performance of finite element numerical simulations of heat distribution in basalt relative to experimental results.

#### **1.3** Thesis Structure

This thesis comprises seven chapters and four appendices.

#### **Chapter 1: Introduction**

The research background is introduced, emphasizing the role of microwave-assisted rock breakage systems in underground excavation. The objectives and structure of the thesis are presented.

#### **Chapter 2: Fundamentals of Microwaves**

Basic knowledge is reviewed regarding microwave properties, heating principles, generation and heating rates to form the foundation for the research.

#### **Chapter 3: Literature Review**

This chapter compiles published literature regarding microwave-assisted rock breakage, including the characteristics of common minerals under microwave heating, microwave-assisted grinding and drilling, and previous research in this field at McGill University.

#### **Chapter 4: Experimental Methods**

The experimental procedures, standards, apparatus and materials are detailed in this chapter.

#### **Chapter 5: Experimental Results and Discussion**

The experimental results are presented. Temperature distributions are compared for different microwave exposure times, and basalt volumes, and water contents. Mechanical properties are compared between dry and saturated specimens. Results are evaluated with detailed discussion.

#### **Chapter 6: Numerical Modeling**

A finite element model is developed using COMSOL Multiphysics<sup>®</sup> software. This chapter provides the simulation background, such as governing equations, and methodology. Results are evaluated with detailed discussion.

#### **Chapter 7: Conclusions and Recommendations**

Principal findings of this study are summarized and recommendations for future work are given.

**Appendices A** and **B** are XRD reports for basalt and sandstone specimen, respectively. **Appendix C** is a schematic diagram of the Amana RC 30S commercial microwave oven components. **Appendix D** lists the emissivity values of some common materials provided by the manufacturer for setting up the Raytec Raynger MX4+ infrared thermometer.

## **Chapter 2**

## **Fundamentals of Microwaves**

#### 2.1 Introduction to Microwaves

Microwaves are electromagnetic waves, with a frequency between radio wave frequencies and infrared frequencies. The electromagnetic spectrum can be divided into different bands, of which microwaves are within the ultrahigh (0.3 to 3 GHz), super high (3 to 30 GHz), and extremely high (30 to 300 GHz) frequency, as seen in Fig. 2.1. However, only four frequencies—915 MHz, 2.45 GHz, 5.8 GHz, and 22.125 GHz—are allocated by the United States Federal Communications Commission for industrial, scientific, and medical applications (Haque, 1999). The most widely used is 2.45 GHz, the frequency of the domestic microwave oven. Microwave radiation does not ionize body tissues whereas other high energy electromagnetic waves break chemical bonds and ionize neutral molecules (Santamarina, 1989).



Figure 2.1: Microwave range in the electromagnetic spectrum (Clark & Folz, 2005)

### 2.2 Microwave Properties

All electromagnetic waves propagate in a vacuum at the speed of light. Microwaves transport energy as visible light, therefore they share the same properties as visible light (e.g., diffraction, refraction, reflection). The wavelength and frequency of microwaves can be expressed as (Vorster, 2001):

$$C = \lambda \times f \tag{2.1}$$

Where, *C* is the speed of light, which is  $3 \times 10^8$  m/s;

- $\lambda$  is the microwave wavelength, m; and
- f is the microwave frequency, Hz.

Microwave energy has an extensive range of applications, such as communication and information transfer, processing and manufacturing, diagnostics and analyses, medical treatment, and weaponry (Clark & Folz, 2005). Among those applications, microwave heating has several advantages compared to conventional heating: 1) non-contact heating; 2) energy transfer instead of heat transfer; 3) higher heating rate; 4) selective heating according to the dielectric property of the material; 5) volumetric heating; 6) quick start-up and stopping; 7) heating starts from the interior of the material; and 8) safer and easier to control (Haque, 1999).

### 2.3 Microwave Heating

Conventional heating transfers energy from external to the surface of the material and based on thermal gradients by convection, conduction, and radiation. Conversely, microwave heating delivers the radiation energy to the molecules directly, and it is the molecular interactions that convert microwave energy to thermal energy (Acierno et al., 2003). In general, two mechanisms are associated with microwave absorption by a material: 1) dipole rotation; and 2) ionic conduction (Roberts & Strauss, 1988).

The electromagnetic field of the earth is constantly oscillating at  $4.9 \times 10^9$  times/s at a frequency of 2.45 GHz, as seen in Fig. 2.2 (Roberts & Strauss, 1988). Heated materials usually have polar molecules that can align ("dipole rotation") with the oscillating electromagnetic field. During dipole rotation, the dipole experiences either a "pushing and pulling" force or a torque. Since each dipole of the group exerts these forces against other dipoles, friction results and is converted into heat (Smith, 1999). Friction and heat are also generated by ionic conduction, the migration of dissolved ions with the oscillating electric field (Roberts & Strauss, 1988).



Figure 2.2: Electromagnetic field wave (Nave, 2012)

### 2.4 Dielectric Properties

Materials can be categorized as insulators (transparent), conductors, or absorbers in terms of their ability to transmit, reflect, or absorb microwave energy, respectively (Fig. 2.3). (Haque, 1999). For example, water is an excellent absorber, which is easily heated in a microwave oven. Ceramic is an insulator. It is transparent to microwaves and is suitable as cooking ware material.



Figure 2.3: Material categories based on response to microwave radiation (Haque, 1999)

How a given material reacts to microwaves depends on its dielectric properties (permittivity), expressed as a complex constant  $\varepsilon$  (Santamarina, 1989):

$$\varepsilon = \varepsilon_o \ \varepsilon_r \tag{2.2}$$

Where,  $\varepsilon_o$  is the permittivity of free space, which is approximately  $8.854 \times 10^{-12}$  F/m; and

 $\varepsilon_r$  is the relative permittivity, which is also a complex number, unitless.

Usually, the permittivity is expressed relative to that of free space, called relative permittivity.

$$\varepsilon_r = \varepsilon' - j\varepsilon'' \tag{2.3}$$

Where,  $\varepsilon'$  is the relative dielectric constant, unitless; and

 $\varepsilon''$  is the relative dielectric loss factor, unitless.

The dielectric constant is a measure of how well a material sustains an electromagnetic field. Generally, dielectric constants of minerals range from 3–200, with most values ranging from 4–15. The dielectric loss factor indicates how well a material absorbs electromagnetic energy and convert it to heat (Smith, 1999). Loss factors for minerals range from 0.001–50, depending on microwave frequency and temperature (Santamarina, 1989). Table 2.1 lists dielectric constants and loss factors of some geotechnical-related materials at two frequencies. Note that water has a much higher dielectric constant than dry rocks; therefore, the dielectric constant of dry rocks varies with moisture content. The loss factor is also responsive to changes in moisture content.

Matarial	450 MHz		3000 MHz	
wraterial	ε'	ε″	ε'	ε"
Andesite, Hornblende	5.1	0.02	5.1	0.03
Basalt	5.6–9.6	0.06-0.86	5.4–9.4	0.08-0.88
Gabbro, Bytownite	7	0.14	7	0.13
Granite	5–6	0.02-0.15	5-5.8	0.03-0.2
Muscovite	5.4	0.002	5.4	0.0016
Marble	8.8	0.2	8.7	0.14
Obsidian	5.5-6.8	0.1-0.13	5.5-6.6	0.1-0.2
Peridotite	6.0–7.5	0.06-0.18	5.8–7.5	0.07-0.18
Pumice	2.5	0.02	2.5	0.03
Rhyolite	3.38	0.05	3.4	0.04

Table 2.1: Dielectric constant (ɛ') and loss factor (ɛ'') of some common minerals at 25°C (Santamarina, 1989)

Serpentite	6.4–7	0.07-0.13	6.4–6.8	0.1-0.2
Syenite	8	0.4	7	0.6
Trachyte	5	0.13	5.2	0.13
Tuff	2.6-6.1	0.02-0.36	2.6-5.8	0.04-0.36
Volcanic Ash	2.7-3.4	0.08-0.23	2.7-3.2	0.06-0.15
Sandy Soil (0% water)	2.55	0.028	2.55	0.016
Sandy Soil (2.2% water)	2.5	0.063	2.5	0.075
Sandy Soil (3.9% water)	4.5	0.125	4.4	0.202
Sandy Soil (16.8% water)	20	0.3	20	2.6
Water	77.7	0.1	76.7	12.04
Pure Ice	3.5	0.008	3.2	0.003

The loss tangent is the ratio of the relative dielectric loss factor and the dielectric constant:

$$tan(\delta) = \frac{\varepsilon''}{\varepsilon'}$$
(2.4)

The loss tangent is useful for characterizing the capacity of a material to absorb energy (Santamarina, 1989; Satish, 2005): low loss materials have a loss tangent less than 1, and high loss materials have loss tangents greater than 1. The higher the loss tangent, the higher the capacity to absorb microwave energy, and the easier the conversion of the microwave energy to heat.

In addition to dielectric materials, magnetic dipoles such as magnetite can also react to the electromagnetic field (Clark & Folz, 2005), depending on their magnetic permeability and magnetic loss. Thus, an additional heating mechanism can be involved. However, little investigation has been done on microwave heating of magnetic materials.

#### 2.5 **Power and Heating Rate**

#### 2.5.1 **Power Dissipation Density**

The amount of the microwave power converted into heat can be quantified by the power dissipation density ( $P_d$ ), expressed in W/m<sup>3</sup> (Santamarina, 1989):

$$P_d = 2\pi f \varepsilon_o \varepsilon'' E_i^2 \tag{2.5}$$

Where,  $E_i$  is the strength of the electric field in the dielectric load, V/m.

When magnetic loss is exhibited by the material, the permeability of the material should also be considered (Satish, 2005):

$$P_a = 2\pi f \varepsilon_o \varepsilon'' E_i^2 + 2\pi f \mu_o \mu'' H_i^2$$
(2.6)

Where,  $\mu_o$  is the permeability of the free space, which is approximately 1.257 ×10<sup>-6</sup> H/m;

- $\mu''$  is the relative magnetic loss factor, unitless; and
- $H_i$  is the strength of the magnetic field in the dielectric load, A/m.

#### 2.5.2 Penetration Depth

The penetration depth  $(D_p)$  is the depth at which the power intensity decays to 1/e (approximately 37%) of its incident value (Santamarina, 1989). It is expressed as (Vorster, 2001):

$$D_{p} = \frac{\lambda o}{\left(2\pi (2\varepsilon')^{\frac{1}{2}}\right) \left(\left(1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^{2}\right)^{\frac{1}{2}} - 1\right)^{\frac{1}{2}}}$$
(2.7)

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Where,  $\lambda_o$  is the free space wavelength of microwave radiation (e.g., 0.122 m at 2.45 GHz).

The penetration depth varies from millimeters to tens of meters, mainly depending on the dielectric loss factor. For instance, rocks with dielectric loss factor ranging from 0.1–2 have corresponding penetration depths of approximately 0.5–0.02 m. If the size of the heated material is much larger than the penetration depth, the energy will be primarily deposited at or near the surface (Smith, 1999). However, when the size is smaller than or similar to the penetration depth, significant interior heating will be observed.

#### 2.5.3 Heating Rate

The heating rate of a material,  $\frac{\Delta T}{t}$  (°C/s), under the effect of microwave can be estimated as (Santamarina, 1989; Vorster, 2001):

$$\frac{\Delta T}{t} = \frac{2\pi f \varepsilon_o \varepsilon'' E_i^2}{\rho C_p} = \frac{P_d}{\rho C_p}$$
(2.8)

Where,  $\rho$  is the density of the material, kg/m<sup>3</sup>; and

 $C_p$  is the specific heat capacity of the material, J/(kg °C).

It is clear that the rate of temperature increase in a material is proportional to the dissipated power, which can be improved by higher dielectric loss, microwave frequency, or electric field intensity.

#### 2.6 Microwave Generation

Typical microwave systems comprise a power supply (including transformer and rectifier for smooth operation), generator (such as magnetron), waveguide, and applicator (Fig. 2.4) (Haque, 1999). Among the several types of generators (e.g., magnetron, klystron, gyrotron, traveling wave tube), the magnetron is the most widely used because of its availability and low cost (Fig. 2.5). By comparison, the klystron has precision control in amplitude, frequency, and phase, and the gyrotron can provide higher power output and beam focusing. The traveling wave tube offers more, variable, and controlled frequencies of microwave energy (Clark & Folz, 2005).



Figure 2.4: Typical microwave system (Haque, 1999)



Figure 2.5: Structure of magnetron (Tpoindexter, 2013)

The waveguide is a metallic conduit to transport the microwave energy to the applicator from the generator. The cross-section of the waveguide is usually rectangular or circular, depending on the mode of transmission (Satish, 2005).

The applicator is the cavity (oven) for manipulating microwaves (Clark & Folz, 2005). There are two types of cavities—single- and multi-mode—of which multi-mode is most commonly used in domestic microwave ovens. The mode denotes the distribution pattern of the electric and magnetic field components of an electromagnetic wave excited in a closed cavity (Kingman et al., 2004). The single-mode cavity can only sustain one mode. Multi-mode cavities can sustain many resonant modes around the operating frequency yielded by fixed frequency microwaves (Clark & Folz, 2005). The larger the microwave cavity, the more resonant modes there are (Acierno et al., 2003). The dimensions of the multi-mode cavity are large relative to the wavelength of the microwave, whereas the dimensions of the single-mode cavity are similar to the microwave wavelength (Haque, 1999). In single-mode cavities, the superposition of the reflected and incident microwaves applied generate a well-defined standing wave pattern. With knowledge of electromagnetic field configurations, the material can be placed where the intensity of the electric field is highest, maximizing the heating rate (Kingman et al., 2004).

During microwave generation in magnetron:

- 1. The filament or cathode is first heated to release electrons.
- 2. Under the effect of the electric field, the electrons migrate from the cathode to the anode.
- 3. Two magnets at the top and bottom of the anode create a magnetic field in the electric field perpendicular to the path of electrons. As a result, the electrons perform a circular movement on their path to the anode.

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- 4. When a cloud of electrons approaches the segment between cavities of the anode (a "vane"), a positive charge is induced in the vane and diminished by the electrons.
- 5. An alternating current is generated in the anode and transmitted to the antenna.

The induced current produces the electromagnetic field, which propagates as a sinusoidal wave in the waveguide (Vorster, 2001).

## Chapter 3

## **Literature Review**

### 3.1 Characteristics of Minerals during Microwave Heating

As noted above, minerals can be categorized as insulators, conductors, or absorbers relative to microwave energy. In addition, each type of mineral will possess a different suite of dielectric properties. When rock is irradiated by microwaves, constituent absorber minerals are more responsive and heat more quickly than insulator and conductor minerals. Differential heating rates give rise to temperature gradients and differing magnitudes of volumetric expansion in different areas of the rock. Therefore, internal compressive and shear stresses build up and crack the rock, thereby reducing rock strength (Peinsitt et al., 2010).

Pioneering research by Chen et al. (1989) on 40 purified minerals found that most silicates, carbonates, and sulfates, and some oxides and sulfides (e.g., low Fe sphalerite) are insulators or totally reflective to microwave energy at 2.45 GHz. Furthermore, most sulfides, sulfosalts, and arsenides react rapidly or fuse during heating (Table 3.1). Some metal oxides (e.g., hematite, magnetite, cassiterite) are absorbers of microwaves but are thermally stable (Table 3.2).

Mineral	Power (W)	Heating Response
Arsenopyrite	80	Heats, some sparking
Bornite	20	Readily heats
Chalcopyrite	15	Readily heats with emission of sulfur fumes
Covellite/anilite (60% vol%)	100	Difficult to heat; sulfur fumes emitted
Galena	30	Readily heats with much arcing

Table 3.1: Heating responses of some sulfides, sulfosalts, and arsenides (Chen et al., 1984)

#### CHAPTER 3 Literature Review

100	Difficult to heat
30	Readily heats; emission of sulfur fumes
50	Readily heats with arcing at high temperature
100	Difficult to heat when cold
> 100	Does not heat
> 100	Does not heat
100	Difficult to heat when cold
35	Readily heats
	$     \begin{array}{r}       100 \\       30 \\       50 \\       100 \\       > 100 \\       100 \\       100 \\       35 \\       35     \end{array} $

Table 3.2: Heating responses of some metal oxides (Chen et al., 1984)

Mineral	Power (W)	Heating Response
Allanite	> 150	Does not heat
Cassiterite	40	Readily heats
Columbite (40 vol%)	60	Difficult to heat when cold
Fergusonite	> 150	Does not heat
Hematite	50	Readily heats with arcing at high temperature
Magnetite	30	Readily heats
Monazite	> 150	Does not heat
Pitchblende (90 vol%)	50	Readily heats

Whereas the researchers above were limited to measuring surface temperatures of minerals, Walkiewicz et al. (1988) developed a metal sheathed thermocouple to complete a more detailed and quantitative study of microwave heating characteristics of various minerals and compounds. Results were similar to Chen et al. (1984) and highlighted potential applications for microwave energy in mineral processing. Minerals of value (e.g., galena, ilmenite, magnetite, chalcopyrite) were determined to be microwave absorbers, and common host rock minerals (e.g., quartz, calcite, feldspar) were insulators (did not heat). Also, they observed micro-cracks at grain boundaries generated by thermal stress when the ore was heated in a gangue matrix. Table 3.3 summarizes the maximum temperatures of minerals after microwaving for various time intervals.

Mineral	Maximum Temperature, °C	Time, min
Albite	69	7
Arizonite	290	10
Chalcocite	746	7
Chalcopyrite	920	1
Chromite	155	7
Cinnabar	144	8.5
Galena	956	7
Hematite	182	7
Magnetite	1258	2.75
Marble	74	4.25
Molybdenite	192	7
Orpiment	92	4.5
Orthoclase	67	7
Pyrite	1019	6.75
Pyrrhotite	886	1.75
Quartz	79	7
Sphalerite	88	7
Tetrahedrite	151	7
Zircon	52	7

Table 3.3: Temperatures of natural minerals during microwave heating (Walkiewicz et al., 1988)

### 3.2 Microwave-Assisted Grinding

The grindability of taconite ores was shown to be enhanced by microwave treatment at 2.45 GHz and 3 kW by Walkiewicz et al. (1991), who verified the fracturing along the grain boundaries with a scanning electron microscope. Furthermore, a reduction of 10-24% in the Bond work index (*W*; kW·h/short ton ore)—defined as the energy required to comminute material from theoretically infinite feed size to 67% minus 200 mesh—was observed after irradiation:

$$W = \frac{1.6 \ p^{0.5}}{G^{0.82}} \tag{3.1}$$

Where, p is the product discard mesh size opening,  $\mu$ m; and

*G* is the grindability for the given product mesh size, g/rev.

Equation 3.1 is an empirical simplified derivation from Bond's third comminution theory. The increased grindability indicated by the reduction of work index could lower comminution costs due to less wear of the mill, mill liner, and milling medium. What is more, higher throughput and less recycled ore are expected as additional benefits.

Microwave treatment of commercially exploited ores (i.e., massive ilmenite ore from Norway, a massive sulphide from Portugal, highly refractory gold from Papua New Guinea and an open pit carbonatite from South Africa) demonstrated that, in general, ore minerals are absorbers and principal gangue minerals are insulators (Kingman et al., 2000). Therefore, ores that have consistent mineralogy and contain a good absorber in a transparent gangue matrix show stronger reductions in required grinding energy after microwave treatment. Ores that contain small particles that are finely disseminated in discrete elements show weak reductions in required grinding energy after microwave treatment (Kingman et al., 2000).

	Temperature °C					
Ore	Time (s)					
	10	30	60	90	100	120
	Ilmenite Ore					
Ilmenite	32	46	64	77	81	90
Magnetite	200	324	351	403	452	463
Plagioclase	21	24	25	28	32	34
	Refractory Gold Ore					
K. Feldspar	18	21	24	25	27	31
Pyrite	75	134	177	189	197	202

Table 3.4: Heating rate of main minerals in ores when microwaving (Kingman et al., 2000)

Quartz	18	21	23.6	26	28	28
	Massive Sulphide Ore					
Chalcopyrite	61	98	124	146	148	165
Pyrite	75	134	177	189	197	202
Galena	211	341	422	436	441	453
	Carbonatite Ore					
Magnetite	200	324	351	403	452	463
Dolomite	21	23	25	29	30	33
Chalcopyrite	68	126	153	194	211	245
Phlogophite	19	21	22	23	25	26

Fig. 3.1 shows steep reductions in the Bond work index for massive ilmenite, carbonatite, and massive copper (Kingman et al., 2000). Little reduction was seen for refractory gold because of the finely disseminated nature of pyrite throughout the specimen and the fineness of the pyrite crystals and aggregates (Kingman et al., 2000).



Figure 3.1: Reductions of Bond work indexes of different ores (Kingman et al., 2000)
## 3.3 Effect of Microwave Treatment on Rock Strength

#### 3.3.1 Methods to Measure Rock Strength

The point load test is used to determine the strength of a rock sample by placing the specimen between two cone-shaped tips and applying compressive force until it breaks. The apparatus platens should make contact either along a core diameter or with the smallest diameter of a lump or block. With the dimensions of the specimen and failure strength, an uncorrected point load strength index ( $I_s$ ; MPa) can be calculated (ASTM-D5731-08, 2012):

$$I_s = \frac{F_f}{D_e^2} \tag{3.2}$$

Where,  $F_f$  is the failure load, N; and

 $D_e$  is the equivalent core diameter, mm.

 $(D_e^2 = D_c^2)$  for core specimen;  $D_e^2 = 4A/\pi$  for axial, block, and lump specimen, where A is the minimum cross-sectional area of a plane through the platen contact points)

In most cases, the point load strength index is standardized for 50-mm diameter cores ( $I_{s(50)}$ ; MPa), because 50-mm cores are associated with the rock quality designation:

$$I_{s(50)} = \frac{\left(\frac{D_e}{50}\right)^{0.45} F_f}{D_e^2}$$
(3.3)

The point load test is a common, simple and fast in-situ test to estimate the UCS ( $\sigma_c$ ) of rocks, because the two measures are related (ASTM-D5731-08, 2012):

$$\sigma_c = KI_s \tag{3.4}$$

Where, K is the conversion factor that depends on site-specific correlation between the UCS and point load strength index for a specific test diameter (Table 3.5).

Core Size, mm	Value of "K" (Generalized)
21.5 (EX core)	18
30	19
42 (BX core)	21
50	23
54 (NX core)	24
60	24.5

 Table 3.5: Value of K for different core sizes (ASTM-D5731-08, 2012)

#### 3.3.2 Impact of Microwave Heating on Rock Strength

Microwave treatment can significantly reduce rock strength, depending on the power level, exposure time, and electric field strength. Treatment of a lead-zinc ore from Sweden showed that higher power levels were effective for shorter exposure times, but lower power levels required longer exposure times to achieve the same reduction (Kingman et al., 2004). For example, a 1 s exposure time in a multi-mode cavity reduced rock strength by 50% at 15 kW power and by only 15% at 5 kW power (Fig. 3.2). The 5 kW treatment required 5 s to achieve a 50% reduction in rock strength. In a single-mode cavity, a nearly 50% strength reduction was achieved in only 0.1 s and at a lower power level (10 kW) (Fig. 3.3). Similar to the multi-mode cavity, the 5 kW treatment required a longer exposure time to achieve a 50% reduction in rock strength. Therefore, these observations indicate that high electric field strength is important in reducing the rock strength.



Figure 3.2: Point load test results for multimode cavity (Kingman et al., 2004)



Figure 3.3: Point load test results for single-mode cavity (Kingman et al., 2004)

Satish et al. (2006) from McGill University proposed that microwave energy could facilitate space mining or rock removal. Their preliminary investigation assessed the susceptibility of terrestrial basalts to low power (150 W) microwaves. Basalt was chosen because it is chemically similar to lunar and Martian rocks and it is one of the most hard and ubiquitous igneous rocks. Temperatures increased in basalts at a rate of 14°C/min in response to microwave treatment, which was attributed to the presence of metallic or semi-conducting phases (e.g., sulfides, iron oxides), which are absorbers. Not surprisingly, longer exposure times weakened the basalt more, owing to differential thermal heating of different mineral phases (Fig. 3.4). This result is promising: a cracked and weakened rock matrix is more easily broken during drilling.



Figure 3.4: Uniaxial compressive strength of basalt at different microwave exposure times (Satish et al., 2006)

Researchers from McGill University advanced this work by relating rock strength metrics to the penetration rate of TBMs, and developing a possible drill bit with a filed patent (Fig. 1.2), thus bridging the gap between experimental testing and practical application. They assessed effects on

the strength of norite of microwave treatment in a multi-mode cavity at three power levels (1.2–5 kW) and three exposure times (10–120 s). The TBM penetration rate per revolution ( $P_{rev}$ , mm/rev) was calculated as (Hassani & Nekoovaght, 2011):

$$P_{rev} = 624 \, \frac{F_n}{\sigma_t} \tag{3.5}$$

$$P_{rev} = 3940 \, \frac{F_n}{\sigma_c} \tag{3.6}$$

Where,  $F_n$  is the normal force applied from the machine to the cutter, kN; and

#### $\sigma_t$ is the Brazilian tensile strength, MPa.

Similar to Kingman et al. (2004), higher power levels or longer exposure times achieved greater reductions in strength (Fig. 3.5), which is expected to result in higher TBM penetration rates, regardless of other drilling parameters (Fig. 3.6) (Hassani & Nekoovaght, 2011).



Figure 3.5: Brazilian tensile strength of norite versus power level (Hassani & Nekoovaght, 2011)



Figure 3.6: Predicted TBM penetration rate for norite versus microwave power level for three exposure periods (Hassani & Nekoovaght, 2011)

A prototype design of an excavation bit demonstrates a possible microwave-assisted drilling system (Fig. 3.7). Cutting tools can be attached through inserts on the bit. A horn antenna is located at the front surface of the bit, where a microwave beam can be directed to cover a large area of the rock ahead of the cutting tool (Ouellet et al., 2009; Hassani & Nekoovaght, 2011).



Figure 3.7: Prototype design of an excavation bit (Ouellet et al., 2009; Hassani & Nekoovaght, 2011)

### 3.4 Microwave-Assisted Drilling

Pilot research by Lindroth et al. (1992) evaluated the effect of temperature on drilling rates in blocks of Dresser basalt and St. Cloud gray granodiorite. Researchers applied microwave energy until the blocks reached a preselected temperature, then drilling was performed with a boring machine. The drilling rate increased with temperature in both the basalt (Fig. 3.8) and the granodiorite (Fig. 3.9). In addition, the tungsten carbide spade bits remained cooler than 127°C, without bit melting or braze failure. Their conceptual design was patented (Fig. 1.1).



Figure 3.8: Drilling rate at different temperatures for Dresser basalt (Lindroth et al., 1992)



Figure 3.9: Drilling rate at different temperatures for St. Cloud gray granodiorite (Lindroth et al., 1992)

## 3.5 Microwave Heating of Dry and Water Saturated Rocks

Water can improve the ability of microwaves to weaken rocks, particularly sandstone and to a lesser extent granite; it has negligible effect on basalt strength (Peinsitt et al., 2010). Microwave heating in a multi-mode cavity (3 kW, 2.45 GHz) of dry and water saturated samples was followed by ultrasonic velocity (USV) testing test to identify fissures inside the rocks; a low USV value means there are more fissures. Based on surface temperatures measured with an infrared camera, sandstone heated four times faster and granite heated two times faster when wet than dry, but no difference was detected between wet and dry basalt (Peinsitt et al., 2010). Dry sandstone demonstrated a weak decreasing trend in USV value (more fissures) with increasing irradiation time. However, cracks appeared at 10 s irradiation time in wet sandstone and two of five specimens broke at 30 s. Wet granite generally had lower USV values than dry granite. USV values for dry and water-saturated basalt did not differ, but did show a decreasing trend with exposure time (Peinsitt et al., 2010).

# **Chapter 4**

# **Experimental Methods**

### 4.1 Rock types tested

#### 4.1.1 Basalt

Basalt was selected as the study rock type, because it is a hard rock that is commonly encountered in drilling or excavation. Basalt is an igneous rock and is the most abundant volcanic rock in the Earth's crust. It is dark-colored, fine-grained, and relatively dense. Principal minerals include pyroxene, calcium feldspar, and a minor amount of olivine. The silica content ranges from 40–50% (Chernicoff & Venkatakrishnan, 1995).

Based on X-ray Diffraction (XRD) analysis, the basalt used in this study contains silica (SiO<sub>2</sub>), alumina (Al<sub>2</sub>O<sub>3</sub>), calcium oxide (CaO), and iron oxide (Fe<sub>2</sub>O<sub>3</sub>) (Appendix A). These constituents except silica can be heated by microwave, according to Walkiewicz et al. (1988). The water mass was determined by weighing basalt specimens before and after drying in a thermal oven at  $110 \pm 5^{\circ}$ C for at least 48 h and then calculating the mass difference (ASTM-D2241-10, 2012). Note that this basalt was used only for water mass determinations, and not for microwave treatments, since oven drying could generate fissures that would confound detection of rock breakage solely induced by microwave treatment. The water content was calculated as the ratio of the water mass to the dry specimen mass, expressed as a percentage. The mean water content of saturated basalt was  $1.58 \pm 0.02\%$  (n = 3). In addition, porosity was calculated as the ratio of

pore volume (i.e. water volume if fully saturated) to total volume (ISRM, 1977). The mean porosity was  $4.52 \pm 0.06\%$ . The permittivity was measured with the coaxial probe method at 2.45 GHz at École Polytechnique de Montréal and determined to be 10.12 - 1.34j for saturated basalt and 10.05 - 1.39j for dry basalt.

#### 4.1.2 Sandstone

Sandstone was compared with basalt in terms of reaction to microwave heating, because of its relatively high porosity (see Chapter 5). In general, grain size ranges from 0.06–2 mm. Three main types of sandstone—quartz arenite, arkoses, and graywackes—make up 25% of all sedimentary rocks. They can be distinguished by their distinctive composition and appearance. For example, quartz arenite is generally light in color, varying from white to tan due to a predominant (>90%) quartz component (Stanford & Hagan, 2009).

Based on XRD analysis, the sandstone used in this study is quartz arenite, mainly composed of silica (SiO<sub>2</sub>) and calcium carbonate (CaCO<sub>3</sub>) (Appendix B). The mean water content was 2.64  $\pm 1.33\%$  (*n* = 6) for saturated and 0.63  $\pm 0.03\%$  (*n* = 3) for dry specimens. The mean porosity was 6.32  $\pm 3.19\%$ .

### 4.2 Specimen Preparation

A radial core driller was used to drill a basalt block into cores with a diameter of 5.1 cm (Fig. 4.1). Cores were cut with a diamond saw into  $1 \pm 0.1$  cm thick disks (volume of 20.4 cm<sup>3</sup>). A grinder was used to flatten the top and bottom surfaces of the disks. Disks were stacked to make simulated rock masses of various volumes. The stack could be readily dismantled to easily



measure the temperature of each disk and obtain a full picture of interior temperatures.

Figure 4.1: From left to right: drilling, cutting, and grinding machinery

# 4.3 Experimental Procedure

Rock specimens were treated with an Amana RC 30S multi-mode microwave (3 kW power, 2.45 GHz frequency) that is commercialized for the food industry. Three waveguides are connected to magnetrons, two at the top and one at the bottom (Appendix C).

Immediately after treatment, surface temperatures were measured with a Raytec Raynger MX4+ infrared thermometer (Fig. 4.2a), which projects a perimeter of infrared laser dots and one center dot onto the specimen (Fig. 4.2b). Temperature is calculated by the device from the average amount of infrared energy emitted by each dot. This energy depends on the emissivity of the object (depends on the material and surface characteristics) and temperature. The emissivity was set at 0.7 for basalt, as recommended by the manufacturer (Appendix D).



Figure 4.2: a) Raytec Raynger MX4+ infrared thermometer; b) Infrared laser dots

To confirm that temperatures on the flat surfaces of the disks represent temperatures within an intact core, five basalt cores (5.1 cm diameter, 10 cm thickness) and five stacks of 10 basalt disks (Fig. 4.3) were microwaved for 60 s. Surface temperatures were measured at the top and bottom of the stack/cylinder, and at about 5 cm from the top (i.e. mid-wall), respectively.



Figure 4.3: Intact basalt core and stacked disks, both with a volume of 204 cm<sup>3</sup>

To evaluate the influence of water on microwave heating of basalt, it would be ideal to manipulate the water content in rock specimens to produce a range of water contents. However,

it is difficult to control water contents below the low maximum water content of saturated basalt. Therefore, wet basalt specimens were fully saturated by immersion in water in a vacuum pump for at least 48 h (ISRM, 1977). When the vacuum pump is turned on, the air in the tank is pumped out to generate a vacuum (Fig. 4.4). The relatively high pore pressure in the rock forces out the air trapped in the pores, making room for water.



Figure 4.4: Vacuum saturation apparatus

Triplicate saturated or dry 2-, 5-, and 10-disk (40.9, 102, and 204 cm<sup>3</sup>, respectively; Fig. 4.5) stacks of basalt disks were individually microwaved for 40, 60, or 80 s, for a total of 54 treatment combinations. After each treatment, the oven was cooled to the ambient temperature before the next stack of disks was irradiated. Only the top surface temperature of each disk was measured immediately after microwave treatment, before the disk was subjected to the CERCHAR abrasiveness test and Brazilian (indirect) tensile strength test (Fig. 4.5). Temperatures are reported as means  $\pm 1$  standard deviation.



Figure 4.5: Schematic diagram of experimental procedures

A limited set of experiments was also conducted with sandstone, a more porous rock. Triplicate cylindrical dry and saturated sandstone specimens (5.1 cm in diameter, 10 cm in length) were microwaved for 20 or 60 s. The mid-wall, top and bottom surface temperatures were measured with the Raytec infrared thermometer emissivity set to 0.67 (Mastercool, 2013) and means calculated for each cylinder.

#### 4.4 CERCHAR Abrasiveness Test

The CERCHAR test was developed by the Laboratoire du Center d' Études et Recherches des Charbonnages de France in the mid-1960s. The CERCHAR Abrasiveness Index (CAI) is mainly used to predict excavation rate, tool wear, and replacement costs (Stanford & Hagan, 2009). The test uses a steel pin with a defined shape and hardness (Fig. 4.6, left panel) to scratch the rock specimen surface for 1 s at a speed of 10 mm/s under a static load of 70 N. The diameter of the worn surface of the pin (Fig. 4.6, right panel) is measured and the CAI (unitless) is calculated as (Käsling & Thuro, 2010):

$$CAI = 10 \frac{d}{c} \tag{4.1}$$

Where, d is the diameter of area on pin that is worn flat, mm; and

*c* is the unit correction factor, mm.



Figure 4.6: Steel pin on CERCHAR apparatus (Käsling & Thuro, 2010)

The original CERCHAR apparatus (Fig. 4.7, left panel) uses a vice to hold the specimen. The steel pin is attached to the test lever, which has a load of 70 N. Moving the lever scratches the rock surface. In comparison, the rock surface is scratched using the West apparatus (Fig. 4.7, right panel) by turning the hand crank to move the specimen below the pin.



Figure 4.7: Original (left) and West (right) CERCHAR apparatus (Geotechnik, 2014)

The type of steel pin used is critical to the CAI results, because the test is essentially a measure of the difference in the relative hardness between the steel and the rock. CERCHAR suggests that the steel should have an ultimate tensile strength of 2000 MPa and a reflecting Rockwell Hardness (HRC) of 57. However, West claims that steel with an HRC of 40 will have the most representative results (Stanford & Hagan, 2009).

The west CERCHAR apparatus was used in the project (Fig. 4.8a). A digital microscope (readable to 0.01 mm) linked with a computer (Fig. 4.8b) was used to magnify and measure the diameter of the front wear area on the stylus (Fig. 4.9), which was an HRC 55 stylus (ASTM-D7625-10, 2012). The CERCHAR test was always performed on the top surface of each single piece. The rock surfaces were even and unbroken, and the testing length was 10  $\pm$ 0.5 mm, as recommended (ASTM-D7625-10, 2012). After a stylus was measured, the tip was sharpened into a 90° cone with a grinder, and then immediately cooled with water to maintain the metal hardness.



Figure 4.8: a) West CERCHAR apparatus; b) Microscope computer system



Figure 4.9: Example of magnified stylus under microscope

Sufficient CERCHAR tests were performed on each disk to keep the standard deviation of the CAI at approximately 0.5 (2–5 tests). The CERCHAR test was performed seven times on dry untreated basalt, to serve as a control. The CAI value of the basalt was  $2.7 \pm 0.076$ , which can be classified as highly abrasive (ASTM-D7625-10, 2012). CAI values are reported as means  $\pm 1$  standard deviation.

## 4.5 Brazilian Tensile Strength Test

The Brazilian tensile test is used because it is very difficult and costly to directly determine tensile strength by pulling rock specimens until breakage. The Brazilian test applies compressive force, which generates a tensile force at the center of the specimen, perpendicular to the direction of the applied force (Fig. 4.10, left panel). When the force reaches its critical point, the disk will break lengthwise in tension (Fig. 4.10, right panel). The Brazilian tensile strength test is a destructive method and the value reported therefore characterizes the whole disk.



Figure 4.10: Brazilian tensile strength setup before (left) and after (right) applying compressive force to the disk

The apparatus should have either flat or curved platens with a loading rate of 0.05-0.35 MPa/s, so failure occurs in 1–10 min (ASTM-D3967-08, 2012). The test specimens must be disks with a thickness to diameter ratio of 0.2 to 0.75. The ratio for the disks in these experiments was 0.2. Fig. 4.11 shows the Brazilian tensile strength test workstation used in this study. Four controlled tests were implemented on same sized dry disks without microwave treatment. The tensile strength of the basalt was 19.66 ±1.53 MPa, which is within the range of reported values (approximately 10–30 MPa) in the rock mechanics literature (Farmer, 1983). Similarly, tensile strength values are reported as means ± 1 standard deviation.

Tensile strength ( $\sigma_t$  in MPa) is calculated as (ASTM-D3967-08, 2012):

$$\sigma_t = \frac{2F_m}{\pi LD} \tag{4.2}$$

Where,  $F_m$  is the maximum applied load, N;

- L is the thickness of the specimen, mm; and
- *D* is the diameter of the specimen, mm.



Figure 4.11: Brazilian tensile strength test workstation

# **Chapter 5**

# **Experimental Results and Discussion**

### 5.1 Temperature Distribution

#### 5.1.1 Comparison of Basalt Intact Rock and Stacked Disks

Five stacks of 10 basalt disks exhibited similar mean temperatures (184.1 ±4.8°C) as intact five 10-cm cores (184.5 ±3.8°C) (two-tailed *t*-test, p = 0.908, n = 5), therefore it is feasible to use surface temperatures of stacked disks to simulate interior temperatures of intact rock cores.

#### 5.1.2 Effect of Basalt Volume on Microwave Heating of Wet and Dry Basalt

In the graphs, x-axis is noted as distance from bottom of the stack, as the temperature is taken at the top surface of each piece. For example, the value at 1 cm represents the top surface temperature of the bottom disk which is 1 cm in thickness.

Overall, temperature distributions within three volumes of basalt specimens did not differ between saturated (recall 1.58%) and dry (recall 0.5%) conditions after 60 s of microwave treatment (Fig. 5.1). Temperatures of wet basalt were slightly lower than dry basalt, possibly because of evaporative cooling. Temperatures were the highest for the smallest volume and decreased with increasing volume. Volume 1 was approximately 135°C higher than Volume 2, and approximately 245°C higher than Volume 3. For a given volume, the temperatures differed internally. The sinusoidal temperature distribution of Volume 3 could result from interference of microwaves reflecting from the bottoms and walls of the rock, which formed a standing wave inside specimens. The thickness of Volume 3 (10 cm) is similar to the microwave wavelength (12.2 cm in air and probably shorter in the rock), therefore a complete sinusoidal pattern is apparent. Volume 2 is 5 cm high, approximately half of the microwave wavelength, therefore half of a complete sinusoidal pattern is evident. Overall, regardless of moisture conditions, a larger basalt mass had a lower heating rate for the same microwave exposure time.



Figure 5.1: Temperature distribution of three volumes of basalt after microwaving 60 s

#### 5.1.3 Effect of Exposure Time on Microwave Heating of Wet and Dry Basalt

As was seen above for the 60 s exposure period, after 40 or 80 s of microwave treatment, no differences were detected in temperature distributions between saturated and dry basalt, regardless of specimen volume (Figs. 5.2–5.4).



Figure 5.2: Basalt Volume 1 temperature distribution after microwaving 40, 60, 80 s



Figure 5.3: Basalt Volume 2 temperature distribution after microwaving 40, 60, 80 s



Figure 5.4: Basalt Volume 3 temperature distribution after microwaving 40, 60, 80 s

Across all three volumes, as the microwave exposure time increased, the temperatures increased (Figs. 5.2–5.4). This pattern was most evident for Volume 1, where each 20-s increment increased temperature by approximately 100°C (Fig. 5.2). The effect diminished in Volume 3, where each 20-s increment yielded only a 50°C temperature increase (Fig. 5.4). In addition, the temperature tended to be lowest at the top (data points on right in Figs. 5.2–5.4), probably because heat transfer between the rock and air occurred the top surface of the top piece, particularly when the door of the microwave was opened.

# 5.2 Mechanical Properties

#### 5.2.1 CERCHAR Abrasiveness Test

As with temperature and across all three exposure times, the presence of water did not affect basalt abrasiveness after microwave treatment for Volume 1 (Figs. 5.5–5.7), 2 (Fig. 5.8–5.10) or 3 (Fig. 5.11–5.13) specimens. Similarly, no clear trend is evident for distance from the bottoms of the stacks. It must be noted that variation among triplicates was high, which may confound detection of treatment effects.



Figure 5.5: CERCHAR abrasiveness index for basalt Volume 1 after microwaving 40 s



Figure 5.6: CERCHAR abrasiveness index for basalt Volume 1 after microwaving 60 s



Figure 5.7: CERCHAR abrasiveness index for basalt Volume 1 after microwaving 80 s



Figure 5.8: CERCHAR abrasiveness index for basalt Volume 2 after microwaving 40 s



Figure 5.9: CERCHAR abrasiveness index for basalt Volume 2 after microwaving 60 s



Figure 5.10: CERCHAR abrasiveness index for basalt Volume 2 after microwaving 80 s



Figure 5.11: CERCHAR abrasiveness index for basalt Volume 3 after microwaving 40 s



Figure 5.12: CERCHAR abrasiveness index for basalt Volume 3 after microwaving 60 s



Figure 5.13: CERCHAR abrasiveness index for basalt Volume 3 after microwaving 80 s

#### 5.2.2 Brazilian Tensile Strength Test

Brazilian tensile strength test obtains tensile strength of a single disk, therefore the x-axes in Figs. 5.14–5.22 use disk number from bottom of the stack to indicate the positions of tested pieces. As with temperature and abrasiveness and across all three exposure times, the presence of water did not affect basalt tensile strength after microwave treatment for Volume 1 (Figs. 5.14–5.16), 2 (Figs. 5.17–5.19) or 3 (Figs. 5.20–5.22) specimens. Yet, in two instances (Disk 3 in Figs. 5.18 and Disk 1 in Fig. 5.19), there appears to be a difference in tensile strength between wet and dry basalt, and it is the wet basalt strength that is higher. No clear trend in tensile strength was evident with distance from the bottom of the stacks. As noted above, variation among triplicates was high, which may confound detection of treatment effects.



Figure 5.14: Brazilian tensile strength for basalt Volume 1 after microwaving 40 s



Figure 5.15: Brazilian tensile strength for basalt Volume 1 after microwaving 60 s



Figure 5.16: Brazilian tensile strength for basalt Volume 1 after microwaving 80 s



Figure 5.17: Brazilian tensile strength for basalt Volume 2 after microwaving 40 s



Figure 5.18: Brazilian tensile strength for basalt Volume 2 after microwaving 60 s



Figure 5.19: Brazilian tensile strength for basalt Volume 2 after microwaving 80 s



Figure 5.20: Brazilian tensile strength for basalt Volume 3 after microwaving 40 s



Figure 5.21: Brazilian tensile strength for basalt Volume 3 after microwaving 60 s



Figure 5.22: Brazilian tensile strength for basalt Volume 3 after microwaving 80 s

### 5.3 Discussion of Basalt Findings

Heat distributions did not differ between wet and dry basalt after microwave treatment. This was in part due to high variability among replicates, especially for Volume 1 (Fig. 5.2) and could also be explained by the small difference in permittivity between dry (10.05 - 1.39j) and saturated basalt (10.12 - 1.34j). Also, the porosity and hence the water content of saturated basalts is very low (1.58%), and a small amount of water was present in "dry" basalt specimens (0.5%); a 1% difference in water content might not have been sufficient to influence microwave heating.

When rock undergoes microwave treatment, responsive minerals heat and swell, exerting stress to their surroundings. When this stress exceeds the rock strength, fissures are generated, mostly along grain boundaries (Walkiewicz et al., 1991). Thus, heat changes the mechanical properties of rock. The heat distribution in the basalt demonstrated either a half sinusoidal (Volume 2; Fig. 5.3) or a sinusoidal pattern (Volume 3; Fig. 5.4). Therefore, mechanical properties in the graphs were expected to display a reverse sinusoidal pattern, because more heat causes weaker rock. However, only the tensile strength of the dry Volume 3 basalt after 80 s exposure (Fig. 5.22) and both wet and dry Volume 2 basalt after 40 s exposure (Fig. 5.17) followed this expected pattern to some extent.

# 5.4 Experiments on Sandstone

After approximately 18 s of microwave treatment, two of three saturated sandstone specimens exploded into fragments (Fig. 5.23a–b), as observed by Peinsitt et al. (2010). In contrast, dry sandstone cylinders remained intact for at least 60 s (Fig. 5.23c). Unlike basalt, water clearly played an important role in heating and reducing the strength of the more porous sandstone. When pore water is heated until evaporation, the pore pressure exceeds the limit of rock strength, followed by a sudden explosion.



Figure 5.23: a–b) Exploded saturated sandstone after microwaving for 20 s; c) dry sandstone after microwaving for 60 s

The temperature of dry sandstone cylinders after 60 s of microwave treatment was  $118.9 \pm 7.8^{\circ}$ C. Microwave treatment would not be expected to heat sandstone, since the primary constituents (silica and calcium carbonate) reflect microwaves (Walkiewicz et al., 1988). However, impurities in the sandstone, indicated by minor peaks in the XRD graph (Appendix B) and by the presence of a metallic luster on the cylinder surfaces caused by black spotty mafic minerals (Fig.
5.24), could be microwave absorbers. High concentrations of metallic minerals can increase the strength of rock specimen and improve the cementation of the sandstone and prevent the rock specimen from bursting.



Figure 5.24: Black spotty mafic minerals with metallic luster disseminated on sandstone surface

### 5.5 Summary

Water did not affect the heat distribution, CAI or tensile strength of basalt after microwave heating for 40–80 s at 3 kW power, as was reported by Peinsitt et al. (2010). To test the hypothesis that the low porosity of basalt is primary cause for these results, saturated and dry high-porosity sandstone cylinders were microwaved for up to 60 s. Whereas wet sandstone specimens burst after approximately 18 s, dry sandstone remained intact up to 60 s in the microwave. Given that sandstone comprises minerals that reflect microwaves, water is implicated in playing an important role in the heating and strength reduction of the sandstone. It

is reasonable to deduce that water would similarly affect microwave heating of other porous rocks and not affect microwave heating of other hard rocks like basalt. Future research with hard rocks could evaluate longer exposure times or higher power levels with larger samples sizes to facilitate detecting treatment effects.

Smaller basalt sample volumes and longer exposure times generated higher temperatures. The temperature distribution inside specimens was sinusoidal if the specimen size was similar to the microwave wavelength. The feasibility of using stacked disks to simulate intact rock and measuring the interior temperatures was also validated.

# Chapter 6

## **Numerical Modeling Studies**

### 6.1 Introduction

In this chapter, experimental and simulated basalt heat distributions are compared, to assess the feasibility of applying simulations to much more complex engineering design. The simulation software COMSOL Multiphysics V. 4.4.0.150 employs the finite element method to simulate the problem by solving Maxwell's and heat transfer equations.

## 6.2 Maxwell's Equations

In the nineteenth century, inspired by Michael Faraday's experiments, James Clerk Maxwell introduced a set of partial differential equations to describe how electric and magnetic field are generated and altered by each other and by charges and currents. Later, these equations were developed and rewritten by Oliver Heaviside, and are known today as Maxwell's Equations (Hayt & Buck, 2012).

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{6.1}$$

$$\nabla \times \vec{H} = \vec{J} + \frac{\partial \vec{D}}{\partial t}$$
(6.2)

$$\nabla \cdot \boldsymbol{D} = \boldsymbol{\rho}_{\boldsymbol{v}} \tag{6.3}$$

$$\nabla \cdot \vec{B} = 0 \tag{6.4}$$

- Where,  $\vec{E}$  is the electric field intensity, V/m;
  - $\vec{B}$  is the magnetic flux density, Wb/m<sup>2</sup>;
  - $\vec{H}$  is the magnetic field intensity, A/m;
  - $\vec{J}$  is the current density, A/m<sup>2</sup>;
  - $\vec{D}$  is electric flux density, C/m<sup>2</sup>; and
  - $\rho_{\nu}$  is the charge density, C/m<sup>3</sup>.

Equation 6.1 shows that a time-varying magnetic field produces an electric field, which is derived from Faraday's Law. Equation 6.2 from Ampere's Law means that time-changing electric flux density gives rise to a magnetic field. Gauss' Law for electric field (Equation 6.3) explains that charge density is the source or sink of electric flux lines. Equation 6.4, Gauss' Law for magnetism, indicates that there does not exist magnetic charges or poles and magnetic flux is always found in a closed loop, which never diverges from a point source (Hayt & Buck, 2012).

In reality, the transmission medium characteristics must be accounted for. Simple linear media like air or a vacuum can be approximated as (Eskelinen & Eskelinen, 2003):

$$\vec{D} = \epsilon \vec{E} \tag{6.5}$$

$$\vec{B} = \mu \vec{H} \tag{6.6}$$

$$\vec{J} = \sigma \vec{E} \tag{6.7}$$

Where,  $\epsilon$  is the permittivity and equals  $8.854 \times 10^{-12}$  F/m in a vacuum;

- $\mu$  is the permeability and equals  $4\pi \times 10^{-7}$  H/m in a vacuum; and
- $\sigma$  is the electrical conductivity, S/m.

In the application of microwave heating, Maxwell's Equations are solved to obtain the electromagnetic field distribution in a medium. The power absorbed and converted into heat—the power deposition or power dissipation density—can be calculated by Equation 2.6, which is proportional to the field intensity (Smith, 1999).

#### 6.2.1 Boundary Conditions for Maxwell's Equations

In general, for solving partial differential equations, the absence of boundary conditions or initial conditions will lead to infinite solutions or no solution. Therefore, boundary conditions are essential for solving Maxwell's Equations.

Interfaces that separate two materials are not perfect electric conductors. The tangential components of the electric and magnetic field are continuous, and can be defined as (Gardiol, 1984):

$$n \times (\vec{E}_1 - \vec{E}_2) = 0 \tag{6.8}$$

$$\boldsymbol{n} \times (\vec{H}_1 - \vec{H}_2) = \boldsymbol{0} \tag{6.9}$$

Where, n is the unit vector normal to the interface, directing from medium 2 to medium 1; and

 $\vec{E}_1$ ,  $\vec{H}_1$  and  $\vec{E}_2$ ,  $\vec{H}_2$  are the electric and magnetic fields for medium 1 and 2, respectively.

If surfaces have extremely high conductivity ( $\sigma = \infty$ ), such as a metallic surface, the material is called a perfect electric conductor, and the electric field must have the condition (Gardiol, 1984):

$$\boldsymbol{n} \times \boldsymbol{E} = \boldsymbol{0} \tag{6.10}$$

Similarly, on the surface of a perfect magnetic conductor (permeability  $\mu = \infty$ ) without a surface current, the magnetic field will have (Gardiol, 1984):

$$\boldsymbol{n} \times \vec{\boldsymbol{H}} = \boldsymbol{0} \tag{6.11}$$

Although magnetic materials have high permeability, it is not sufficient to satisfy the above condition. However, the condition for Equation 6.11 can be applied to a geometrical symmetry or an interface separating a material with a very high permittivity and a very low one (Gardiol, 1984).

The last boundary conditions are on the normal components of the electric field or magnetic field (Gardiol, 1984; Hayt & Buck, 2012).

$$\boldsymbol{n} \cdot \left( \vec{\boldsymbol{D}}_1 - \vec{\boldsymbol{D}}_2 \right) = \boldsymbol{n} \cdot \left( \boldsymbol{\epsilon}_1 \vec{\boldsymbol{E}}_1 - \boldsymbol{\epsilon}_2 \vec{\boldsymbol{E}}_2 \right) = \boldsymbol{\rho}_s \tag{6.12}$$

$$\boldsymbol{n} \cdot (\boldsymbol{\mu}_1 \boldsymbol{H}_1 - \boldsymbol{\mu}_2 \boldsymbol{H}_2) = \boldsymbol{0} \tag{6.13}$$

Where,  $\rho_s$  is the surface charge. It can be found for perfect electric conductor and equals zero at a dielectric interface.

In COMSOL, the boundary condition for a perfect electric conductor (Equation 6.10) is used for modeling lossless metallic surfaces, while the boundary condition for a perfect magnetic conductor (Equation 6.11) is used by imposing symmetry upon electric fields and currents. In addition, the impedance boundary condition is used on exterior boundaries where the field is known to penetrate only a short distance outside the boundary, to avoid including another domain in the model (COMSOL, 2012b):

$$\sqrt{\frac{\mu_o \mu_r}{\varepsilon_o}} \mathbf{n} \times \vec{H} + \vec{E} - (\mathbf{n} \cdot \vec{E}) \mathbf{n} = (\mathbf{n} \cdot \vec{E}_s) \mathbf{n} - \vec{E}_s$$
(6.14)

Where,  $\vec{E}_s$  is the source electric field, V/m.

### 6.3 Heat Transfer

When there is a temperature gradient, heat transfer normally occurs from the higher to the lower temperature material. The three main heat transfer mechanisms are conduction, convection and radiation. In the case of a solid such as rock, thermal conduction dominates and consists of the transfer of kinetic energy from one molecule to the adjacent molecule. In 1822, Joseph Fourier proposed an expression to describe how heat is conducted through a solid, known as Fourier's Law (Incropera et al., 2007):

$$\vec{q} = -k\nabla T \tag{6.15}$$

Where,  $\vec{q}$  is the heat flux density, W/m<sup>2</sup>;

k is the material's thermal conductivity,  $W/(m \cdot K)$ ; and

 $\nabla T$  is the temperature gradient, K/m.

To predict the temperature distribution in a stationary medium, conduction analysis should be performed based on the conservation of energy (Incropera et al., 2007):

$$E_{in} - E_{out} + E_{generate} = E_{store}$$
(6.16)

Hence, the three-dimensional heat equation can be written as (Incropera et al., 2007):

$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right) + Q = \rho C_p \frac{\partial T}{\partial t}$$
(6.17)

Or to simplify,

$$\nabla \cdot (k\nabla T) + Q = \rho C_p \frac{\partial T}{\partial t}$$
(6.18)

Where, Q is the generated thermal energy, W/m<sup>3</sup>. In our case, it is the power dissipation density, which can be calculated by Equation 2.6;

- $\rho$  is the density of the material, kg/m<sup>3</sup>; and
- $C_p$  is the specific heat capacity, J/(kg·K).

#### 6.3.1 Boundary and Initial Conditions for Heat Transfer

If the situation is time dependent, called transient convection, as is the case for microwave heating, the heat equation becomes first-order in time. Therefore, the initial condition of the temperature distribution needs to be specified (Incropera et al., 2007).

In relation to boundary conditions, three commonly encountered types of heat transfer are

(Incropera et al., 2007):

- Dirichlet condition at a constant surface temperature such as a melting solid or a boiling liquid;
- Neumann condition at a fixed or constant heat flux (e.g., a perfect insulator will have zero heat flux), which is the default boundary condition for all heat transfer interfaces in COMSOL (COMSOL, 2012a).
- A mix of 1) and 2), corresponding to the existence of convection heating or cooling from a flowing fluid at the solid interfaces.

## 6.4 Simulation Methods

#### 6.4.1 Model Geometry

The model represents a simplified version of a  $330 \times 381 \times 216$  mm aluminum microwave cavity, with a plastic grease shield, like a commercial food-cooking oven (Fig. 6.1). The bottom of the cavity is made of ceramic that is transparent to microwaves. Half of the cavity is simulated by using symmetry (perfect magnetic conductor boundary condition) to make it easier to analyze the interior heat distribution results. Three aluminum  $50 \times 90 \times 45$  mm waveguides—two at the top and one at the bottom—each connect to one magnetron. Simulated rock masses comprise stacks of two, five or ten  $5.1 \times 10$  cm disks, as in the experimental work (hereafter called Volume 1, 2, and 3, respectively).



Figure 6.1: Software simulation model geometry

#### 6.4.2 Model Meshing

The resolution of the finite element mesh is very significant for finite element modeling analysis. Since the finite element method divides the model into small elements of geometrically simple shapes, a set of governing equations applies to each subdomain to simplify the problem. The system then combines all subdomains for the final computation. In this study, a tetrahedral shape is used for meshing (Fig. 6.2). There are two mesh sizes: the rock is divided by extremely fine mesh with a maximum size of 0.76 cm; all the other domains are meshed coarsely with a maximum size of 5.72 cm to reduce the required computing power. It is acceptable that the maximum mesh size is smaller than the wavelength of a 2.45 GHz microwave (12.2 cm).



Figure 6.2: Meshed model

#### 6.4.3 Physics and Material Properties

#### **Physics**

The governing physics equations and associated boundary conditions are explained in Sections 6.2–6.3. The built-in physics model related to electromagnetic waves is applied to all the domains, whereas the solid heat transfer model is only applied to the rock domain. The software computes the distributed heat source in a stationary, frequency-domain electromagnetic analysis, followed by a transient heat transfer simulation. Therefore, the initial (room) temperature of  $25^{\circ}$ C must be entered. In addition, three ports must be specified at the end of waveguides so that the software knows where the microwave is emitted. Each port is assigned 1 kW input power. It should be noted that the excitation of the port is set as TE<sub>10</sub>, which is the only propagating mode through a rectangular waveguide operating at a frequency of 2.45 GHz. Transverse electric (TE) describes a propagation mode where the electric field is perpendicular to the propagation direction (COMSOL, 2014).

#### **Material Properties**

Table 6.1 lists the materials' properties used in this simulation studies.

Material	Density (kg/m³)	Relative Permittivity	Relative Permeability	Thermal Conductivity (W/(m·K))	Specific Heat Capacity (J/(kg·K))	Electrical Conductivity (S/m)
Basalt - Dry	2880	10.05+1.39j	1	1.9 <sup>a</sup>	$840^{a}$	5×10 <sup>-5a</sup>
Basalt - Wet	2880	10.12+1.34j	1	2.36	896	9.44×10 <sup>-5</sup>
Aluminium (Cavity & Waveguide)	2730*	1*	1*	155*	893*	2.326×10 <sup>7</sup> *
Ceramic	3900*	9.6-0.00192j <sup>b</sup>	1*	27*	900*	1×10 <sup>-16b</sup>
Plastic	1190*	2.6 <sup>c</sup>	1*	0.18*	1470*	1×10 <sup>-16c</sup>

Table 6.1: Material properties used in numerical modeling

\* software built-in material value;

a: (Carmichael, 1988)

b: (CoorsTek, 2014)

c: assumed as Polyphenylene Oxide (Eskelinen & Eskelinen, 2003).

In saturated basalt, the presence of water modifies both the thermal and electrical properties. Archie's Law provides a way to calculate the electrical conductivity of saturated rock. Electrical conduction is primarily controlled by the electrolytes in the connected pores of rock defined by the following empirical relationship (Archie, 1942; Robertson, 1988):

$$R_o = \phi^{-a} R_w \tag{6.19}$$

Where,  $R_o$  is the electrical resistance of a completely saturated whole rock,  $\Omega \cdot m$ ;

- $\phi$  is the rock porosity;
- *a* is the correction factor for fitting the plot of resistance and porosity, which is dependent on the pore geometry. In this case, it is assumed as 2; and
- $R_w$  is the electrical resistance of the pore fluid. Water with electrical conductivity of

462  $\mu$ S/cm (KaizenLAB, 2014) is used to calculate wet basalt electrical resistance,  $\Omega$ ·m.

Analogously, thermal conductivity can be calculated using an additional correction factor (Robertson, 1988).

$$k_{ci} = C_i (1 - \phi)^2 k_c \tag{6.20}$$

Where,  $k_{ci}$  is the impedance-corrected conductivity, W/(m·K);

- $k_c$  is the solid intrinsic thermal conductivity, W/(m·K); and
- $C_i$  is the correction factor. For basalt, it equals 0.62 or 0.77 for air or water in pores.

The heat capacity of the wet condition can be simply computed by adding the heat capacities of the different constituents in a unit mass of the rock (Andersland & Ladanyi, 1994).

$$C = \left(\frac{c_s m_s}{m} + \frac{c_w m_w}{m}\right) \tag{6.21}$$

Where, C,  $C_s$ , and  $C_w$  are the heat capacity of the rock, solid and water, respectively, J/(kg·K); and

 $m, m_s$ , and  $m_w$  are the mass of the rock, solid and water respectively, kg.

# 6.5 Results and Discussion

Two hotspots existed in the basalt Volume 3 sample after 80 s of microwave exposure, with the highest temperature being 167°C (Fig. 6.3). Three temperature values exported along three lines drawn on the rock were averaged to compare to observed temperature values. Note that simulated data start from zero on the x-axis as simulation can produce a continuous temperature profile from the bottom to the top of the rock.



Figure 6.3: Simulation results of dry basalt Volume 3

#### 6.5.1 Comparison to Experimental Results with Dry Basalt

The two hotspots are shown in the simulated basalt as two peaks in Fig. 6.4. Similar to the experimental results, the simulated heat distribution is sinusoidal, although the trough is shifted approximately 2 cm to the right (up in the stack). In general, simulated temperatures are 40°C (40 s irradiation) to 180°C (80 s irradiation) lower than simulated temperatures.



Figure 6.4: Simulated and measured heat distributions for dry basalt Volume 3

The Volume 2 simulation produced one hotspot, with the peak shifted left (down in the stack) relative to the experimental data (Fig. 6.5). Similar to the observed distribution pattern, the simulated heat distribution is a half sinusoidal wave. Simulated temperatures are 30°C (40 s irradiation) to 70°C (80 s) lower than experimental data.



Figure 6.5: Simulated and measured heat distributions for dry basalt Volume 2

In the Volume 1 simulation, it is apparent that the temperatures are much lower (240–400°C) than observed temperatures (Fig. 6.6).



Figure 6.6: Simulated and measured heat distributions for dry basalt Volume 1

#### **Discussion**

There are several possible reasons for the large discrepancies between simulated and experimental temperature distributions. The primary reason is the nonuniform distribution of the electric field inside the simulated cavity. The COMSOL software cannot simulate the rotating antenna in the experimental microwave cavity, which facilitates even energy distribution. The rotating antenna has a probe extended into waveguide for coupling with the microwave energy and a dipole radiator with a mode modifier in the cavity to modify the radiation pattern (Ross & Hunter, 1987). Instead, in the simulation, the energy enters from the open-ended waveguides. Fig. 6.7 shows the magnitude of the electric field inside the cavity. The field intensity in some areas is approximately two to three times higher than in other areas. In the experimental microwave cavity, the energy from the rotating antenna creates a uniform chaos of energy distribution, and the energy is more likely to be absorbed by the rock specimen.



Figure 6.7: Electric field unevenly distributed in simulated microwave cavity

Secondly, the dielectric properties of the rock depend on the frequency of the wave and the temperature of the rock (Olhoeft, 1981; Santamarina, 1989). Hence, the elevated temperatures during microwave heating must have changed the dielectric properties of the basalt. The simulation used a static value for the dielectric properties. Other rock properties such as thermal conductivity and specific heat might have changed during microwave treatment (Robertson, 1988), and were not accounted for in the model.

In addition, convection transfers energy between the specimen and the air in the cavity, heating the air surrounding the rock. In the simulation, convective heating of the rock by the hot air is not accounted for; instead, the specimen is heated by radiation and absorption.

Finally, the simulation is sensitive to dielectric properties, and the dielectric and thermal properties of all materials involved in the simulation were not known. For instance, the plastic grease shield was assumed to be polyphenylene oxide.

#### 6.5.2 Comparison of Simulated Temperature Distributions in Dry and Saturated Basalt

In general, simulated temperatures for dry basalt were similar to or higher than simulated temperatures for wet basalt, across all three basalt volumes (Figs. 6.8–6.10). Temperature differences tended to be more marked within 2 cm of either the top or bottom of the stack (Fig. 6.8).



Figure 6.8: Comparison of simulated heat distributions in dry and wet basalt Volume 3



Figure 6.9: Comparison of simulated heat distributions in dry and wet basalt Volume 2



Figure 6.10: Comparison of simulated heat distributions in dry and wet basalt Volume 1

The temperature discrepancy between dry and wet basalt in the simulations can be explained by Equation 2.8, where the heating rate of a material is proportional to the loss factor and the reciprocal of heat capacity. Since dry basalt has a larger loss factor and smaller heat capacity, temperature increases more rapidly in dry than wet basalt. This agrees with experimental data, though measured differences were weaker and confounded by high variability (Figs. 5.3 and 5.4). Temperature differences were larger around peaks in the simulated heat distributions (Figs. 6.8 and 6.9). This can be also explained by the heating rate equation: the peak area has a stronger electric field as a result of the presence of a standing wave. With increasing exposure time, differences between dry and wet basalt accumulate.

## 6.6 Summary

Key elements for finite element modeling method, such as governing equations, geometry, mesh, and materials were described in this chapter. COMSOL software was used to simulate heat distributions in dry and wet basalt for comparison with measured distributions. The simulated heat distribution patterns were similar to the experimental distributions for dry and wet basalt, although absolute temperatures differed. Possible reasons for discrepancies between simulated and observed distribution include the inability of the software to simulate the rotating antenna in the microwave cavity, the use of a static value for the dielectric properties, the fact that the simulation does not account for convective heating of the rock from the surrounding air, and unknown material properties.

With additional refinement, COMSOL software simulations could represent a feasible approach for modeling temperature distributions in rock masses that cannot be directly measured. Recommendations for future simulations include finding a solution for the rotating antenna problem and incorporating dynamic material properties into the simulations.

# Chapter 7

# **Conclusions and Recommendations**

#### 7.1 Conclusions

In the context of the various challenges associated with underground excavation techniques, a novel rock fragmentation technique is proposed that uses microwave energy to assist mechanical excavation. That rock strength can be reduced by microwave has been documented in the published literature. In this thesis, the effect of water on temperature distributions and mechanical properties of a low-porosity hard rock after microwave heating is empirically measured and simulated.

An approach to measuring the internal temperature of basalt was developed by preparing basalt disks and assembling them together to simulate an intact rock core of either 2, 5 or 10 cm thickness. Temperature distributions and mechanical properties (CAI and tensile strength) in dry and saturated basalt disks did not differ after microwave heating, which was attributed to the low porosity of basalt. This was supported by similar experiments with intact 10-cm cores made of a more porous sandstone, which was highly susceptible to microwave-induced strength reduction if wet. Wet sandstone cores burst into fragments within 20 s of microwave treatment, whereas dry sandstone cores remained intact for at least 60 s. Other significant findings include the sinusoidal temperature distribution for specimens with thicknesses similar to the microwave wavelength (12.2 cm). Also, longer exposure times led to higher temperatures and smaller specimen volumes had a higher heating rate.

A finite element model built and analyzed using COMSOL showed good agreement with the experimental heat distribution patterns in basalt, including a negligible temperature difference between wet and dry basalt. The inability of the model to simulate the rotating antenna in the microwave cavity and account for convective heating, as well as model input limitations, contributed to the small discrepancies between the measured and simulated results.

#### 7.2 **Recommendations for Future Work**

- Repeat experiments with more replicates to decrease variability and improve the probability of detecting treatment effects.
- Repeat experiments with longer microwave treatment exposure times and higher power levels.
- Conduct a more detailed investigation of sandstone.
- Extend the work to other hard and soft rocks.
- Incorporate the rotating antenna into the model.
- Incorporate dynamic material properties into the simulation.

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# Appendix A – Basalt XRD Report



#### Pattern List

Visibl	e Ref.Code	Score	Compound Name	Displ.[°2Th]	Scale Fac.
Chem.	Formula		-		
*	00-052-1344	32	Calcium Aluminum S	-0.018	0.879
Ca0.88	Ä0.12 All.7				
*	01-088-2359	13	Iron Oxide	-0.292	0.242
Fe2 03					

#### **Graphics**



# Appendix B – Sandstone XRD Report



#### <u>Pattern List</u>

Visible	Ref.Code	Score	Compound Name	Displ.[°2Th]	Scale Fac.	Chem.
Formula						
*	01-078-1252	85	Silicon Oxide	-0.069	0.895	Si 02
*	04-012-0489	43	Calcium Carbonate	-0.035	0.200	Ca ( C O3 )

**Graphics** 



# **Appendix C – Commercial Microwave Oven Amana RC 30S**



H.V. System # 1	H.V. System # 2	H.V. System # 3
Top Rear Magnetron	Top Front Magnetron	Bottom Magnetron
Center Transformer	Left Transformer	Right Transformer
Bottom Center Capacitor	Top Left Capacitor	Right Capacitor
Diode	Diode	Diode
Center Triac	Left Triac	Right Triac

# **Appendix D – Emissivity Values of Some Common Materials**

Aluminum*	Aluminium*	Aluminium*	Alumínio*	Aluminio*	0.30
Asbestos	Asbest	Amiante	Asbesto	Asbesto	0.95
Asphalt	Asphalt	Asphalte	Asfalto	Asfalto	0.95
Basalt	Basalt	Basalte	Basalto	Basalto	0.70
Brass*	Messing*	Laiton*	Latón*	Latão*	0.50
Brick	Ziegel	Brique	Ladrillo	Tijolo	0.90
Carbon	Kohlenstoff	Carbone	Carbono	Carbono	0.85
Ceramic	Keramik	Céramique	Cerámica	Cerâmica	0.95
Concrete	Beton	Béton	Hormigón	Concreto	0.95
Copper*	Kupfer*	Cuivre*	Cobre*	Cobrer*	0.95
Dirt	Schmutz	Saleté	Polvo	Poeira	0.94
Food,	Lebensmittel,	Nourriture,	Alimento,	Alimentos,	0.90
frozen	gefroren	surgelée	congelado	congelados	
Food,	Lebensmittel,	Nourriture,	Alimento,	Alimentos,	0.93
hot	heiß	chaude	caliente	quentes	
Glass	Glas	Verre	Vidrio	Vidro	0.85
(plate)	(Platte)	(plaque)	(placa)	(prato)	
Ice	Eis	Glace	Hielo	Gelo	0.98
Iron*	Eisen*	Fer*	Hierro*	Gelo	0.70
Lead*	Blei*	Plomb*	Plomo*	Chumbo*	0.50
Limestone	Kalkstein	Calcaire	Piedra	Pedra	0.98
			caliza	calcária	
Oil	Öl	Huile	Aceite	Óleo	0.94
Paint	Farbe	Peinture	Pintura	Tinta	0.93
Paper	Papier	Papier	Pape	Papel	0.95
Plastic**	Kunststoff**	Plastique**	* Plástico**	Plástico**	0.95
Rubber	Gummi	Caoutchoud	c Caucho	Borracha	0.95
Sand	Sand	Sable	Arena	Areia	0.90
Skin	Haut	Peau	Piel	Pele	0.98
Snow	Schnee	Neige	Nieve	Neve	0.90
Steel*	Stahl*	Acier*	Acero*	Aço*	0.80
Textiles	Textilien	Textiles	Textiles	Tecidos	0.94
Water	Wasser	Eau	Agua	Água	0.93
Wood***	Holz***	Bois***	Madera***	Madeira**	*0.94

\* oxidized; oxidiert; oxydé; oxidado; oxidado

\*\* opaque, over 20 mils; lichtundurchlässig, über 50 µm; opaque, plus de 20 mils; opaco, más de 20 mils; opaco, acima de 20 mils

\*\*\*natural; natürlich; naturel; natural; natural