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STUDY OF THE INFLUENCE OF MICROWAVE IRRADIATION ON HARD FORMATION PROPERTY ALTERATION THROUGH NONDESTRUCTIVE/DESTRUCTIVE TESTS AND DRILLING/CORING OPERATIONS

Abdelsalam Abugharara[1,2] **Salum Mafazy[1]** **Stephen Butt[1]**

Memorial University of Newfoundland, St. John's, Newfoundland, Canada[1]
Sebha University, Sebha, Libya[2]

ABSTRACT

Enhancing the Drilling Rate of Penetration (D-ROP) is a target for lowering the ultimate cost in reaching hydrocarbon reservoirs, evaluating reservoir formation, and extracting minerals and reducing rock crushing consumed energy through mining operations. It has been reported that ROP can be positively influenced depending on optimization of several factors such as drilling parameters alteration and rock fragmentation process. In this research, D-ROP is evaluated by altering the status of the formations being drilled by the use of Microwave Irradiation (MI) while all other applied parameters are kept constant. Unlike published works, this research collectively investigates the influence of MI on D-ROP of hard formation providing confirmation on rock property alteration through non-destructive tests including ultrasonic wave velocities measurement and destructive tests including Indirect Tensile Strength (ITS). Results show gradual alteration in rock properties as per MI exposure time including a reduction in P-wave and S-wave velocity, a decrease in Young's Modulus of elasticity (E) as well as Poisson's ratio (v). Results also show formation fractures occur when exposed to MI, which lead to a decrease in the rock strength and ultimately lead to the increase of D-ROP.

Keywords: Drilling Rate of Penetration, Microwave Irradiation, Destructive and Non-destructive tests.

NOMENCLATURE

ASTM	American Society for Testing Materials
D-ROP	Drilling Rate of Penetration
DTL	Drilling Technology Laboratory
GHz	Gigahertz
GR	Granite
IT/ITS	Indirect Tensile Strength
MI /MWI	Microwave irradiation
MUN	Memorial University of Newfoundland
PDC	Polycrystalline Diamond Compacts
SDS	Small-scale Drilling Simulator
SS	Sandstone
TBM	Tunnel Boring Machine

1. INTRODUCTION

1.1 Background

Breaking and fragmenting a hard rock has some difficulty in rock-application industries such as oil and gas, mining, civil, etc. Microwave energy is one of the newest technology for assisting rock breakage or rock micro-fracture initiation before breakage. The main rock type used for this research were granite and sandstone. The purpose of selecting these two rock types include (i) it is previously and intensively characterized and (ii) its predetermined strength and isotropic properties [1, 2, 3, 4, and 5]. A laboratory examination of rock strength for Granite (GR) and Sandstone (SS) represented by Indirect Tensile strength (ITS) and ultrasonic wave velocity measurement (Vp and Vs) was conducted only on GR. Additionally, a drilling operation was conducted on a granite sample before and after they have exposed to MI. A small scale drilling simulator (SDS) in the laboratory was used for drilling operation. This work determine the effect of the rock properties on pre-and post-microwave radiation treatment using a 2.45 GHz and 1200 Watts microwave by varying (an increasing) temperature exposure time of the MI. The study findings showed a temperature increase for both rocks and a decrease in Vp, Vs, and elastic property of the rock (*E* and *v*) and reduction in IT strength of the rock was observed. The reduction in rock properties was caused by crack formation or fracture initiation on the rocks as MI increased.

An optimal mechanical technology and pre-treating rock by microwave irradiation to break and causes rock fragmentation could bring advantages in terms of large-scale drilling or rock removal process. The main application, including drilling and blasting or mechanical miners, is one of the methods used to excavate rocks [6]. Therefore, some limitations hinder drilling ROP on hard rock, such as low cleaning efficiency and excessive cutter wear for different reasons, including high rock strength.

A mechanical test determination used to analyze rock properties and correlate with drilling log data for optimizing drilling performance. Mafazy et al. 2022 presented a detailed investigation of mafic and quartz rocks for analyzing rock properties. The reported results noted that rock microstructures decreased rock strength and caused a reduction in ROP. Kolapo 2021 as one recent similar research also proved the reversed relationship between ROP and rock strength.

1.2 Literature Review

1.2.1 Application of Microwaves Irradiation (MWI)

The use of microwaves increased dramatically after World War II. Various applications include communications, medical purposes, domestic services, and industrial applications. Gwarek and Celuch 2004 identified microwaves applications in 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, plasma generation, mineral processing (rock crushing, comminution) and waste treatment and recycling. Pre-treating rock using microwave radiation is widely used in the mining industry for rock crushing and comminution. Different Researchers analyze the use of MWI to assist rock breakage [3, 10 and 11]. Lin elal. 2022 also studied the effects of electrical conductivity on natural ores (Hongtoushan copper ore, Sishanling iron ore, and Dandong gold ore) by conducting microwave heating. The reported results showed that under

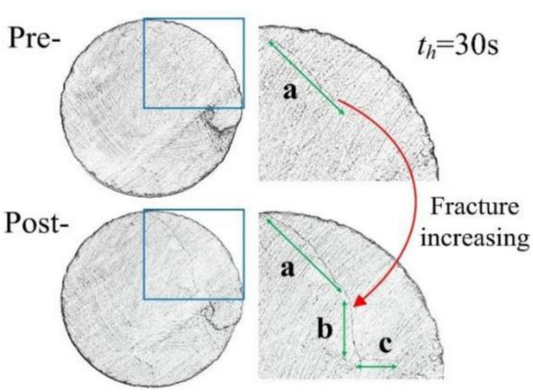


FIGURE 1: CRACK PROPAGATION ON THE SURFACE OF THE COAL SAMPLE [13].

microwave irradiation, the stronger the electrical conductivity of the metal minerals, the smaller the penetration depth. Lu el al. 2019 analyzed the effect of microwave different exposure power levels on the strength of basalt rock.

It carried out X-ray diffraction and scanning electron microscopy/energy-dispersive X-ray spectroscopy for mineral composition and distribution analyses. Zhao et al. 2020 analyzed the influence of microwave power and water saturation on rocks and mineral analyses. The mineral groups are the most significant influence on microwave sensitivity, followed by crystal structure and iron content. Also, the effect of water depends on how much water saturation is on the heating mineral. Moreover, the microwave is applicable for degassing coalbed methane [13]. He uses coal cores to evaluate fracture initiation and propagation. The fractures increased as the microwave temperature rose, and the ultrasound wave velocities (P&S-wave) decreased as the tested samples induced new fractures. Figure 1 shows the fracture propagation after the coal sample is heated for the 30s. Also, in rock breakage applications, there is a challenge of abnormal disc cutter wear of during rock excavation using a Tunnel Boring Machine (TBM) and unstable borehole caused by complex geology. Pre-treatment of rock by microwave heating can reduce high rock mass strength to a certain extent [16]. Hassani el al. 2016 proved that ROP can be increased on the pre-weakened rock surface by applying the same thrust. He demonstrated the concept of attaching a microwave antenna to a continuous TBM's cutter head. ROP was observed to increase as the microwave power increased. Figure 2 shows the microwave antenna for pre-treating rock.

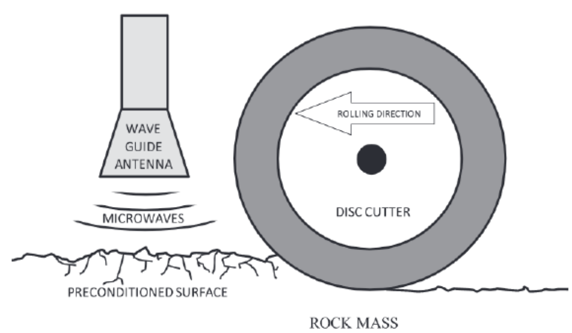


FIGURE 2: SCHEMATIC DIAGRAM OF MICROWAVE ASSISTED DISC CUTTER OF CONTINUOUS TBM [17].

1.2.2 Fundamentals of Microwaves Heating and Mechanisms

Microwave irradiation represents the mechanisms of transfer of electromagnetic to thermal energy. Hence, microwave irradiations are electromagnetic radiation with electric and magnetic forces traveling perpendicular to each other, converting to a new form of energy, thermal energy. Microwave energy reacts differently based on the material's nature and responses, and they are classified as conductors, insulators (transparent), and absorbers (Figure 3). Usually, conductors such as copper and aluminum reflect Microwaves. Insulators allow microwaves to pass through. Absorbers soak up some part of the microwave energy and produce heat, known as dielectric materials [6].

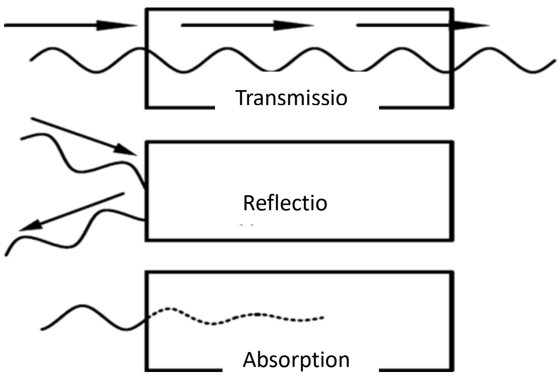


FIGURE 3: DIFFERENT MATERIALS UNDER MICROWAVE IRRADIATION [18].

A loss occurs when electromagnetic waves pass through a material consisting of an electromagnetic field and the temperature. The complex relative permittivity of the materials introduced is equal to the dielectric constant and dielectric loss factor, as shown in equation (1) [19]. Dielectric constants define the ability of a material to store microwave energy and depend on many factors, including molecular structures, moisture, heating temperature, and frequencies of the wave [16]. The dielectric loss factor on the imaginary part represents the degree of energy loss (under an electric field) being converted to heat [20].

$$\varepsilon_r = \varepsilon' - j\varepsilon'' \quad (1)$$

ε_r = Complex relative permittivity of the material or relative dielectric constant;
ε' = Dielectric constant;
ε'' = Dielectric loss factor;
i and j are $\sqrt{-1}$

A microwave system consists of three main parts: a wave generator (magnetron), waveguide and heating cavity. A magnetron produces microwave energy and is transmitted to the cavity by a waveguide. Specification of the microwave is related to microwave frequency [17]. Each material has an optimal frequency that may determine. In practice, however, the nearest possible permissible frequency used in the industry for interference considerations, such as 0.915 and 2.45 GHz [22, 23]. Also, most laboratory experiments were conducted using commercial microwave ovens with a fixed frequency of 2.45 GHz since high frequencies are unsafe [18]. Microwave frequency affects heating performance by determining its penetration depth and electromagnetic field distribution and influences the dielectric property of the material. The energy mode can be categorized as a single-mode cavity, the only mode applied in the system, and has the exact dimensions as a waveguide. A multimode cavity is a closed metallic box with dimensions several times the wavelength, and this mode have high energy than the single mode [17].

1.2.3 Microwave Energy (Power) and Exposure Time

Each mineral has a dielectric constant (D.C.), which determines the heating capacity of the microwave energy. Therefore, rock-forming minerals have different capabilities to absorb microwave energy, which may lead to differences in thermal expansion when exposed to microwaves and result in the internal stresses of the rock structure inducing internal fractures. Hence, expansion of the rock on heating's mineral constituents creates stress along grain boundaries and causes inter-and trans-granular cracks, weakening the rock.

Metallic minerals, such as magnetite and pyrite, absorb microwave energy. Mafic minerals are good microwave absorbers as they heat and expand faster such as amphibole and pyroxene. On the other hand, silicate minerals like quartz and feldspar are weak microwave absorbers [6]. Hassani el al. 2016 investigated the influence of microwave heating on three different rocks at three different exposure times (10, 65, and 120 seconds) using 1.2, 3, and 5 kW microwaves. The reported work showed that the norite (mafic intrusive) rock and granite were fractured and basalt observed surface spalling. Therefore, the authors concluded that not only the minerals affect temperature distribution on the rock but also the microwave power and size of the sample exposed to microwave irradiation.

2. MATERIALS AND METHODS

2.1 Samples Material Preparation

This study analyzes two types of rocks, Granite (GR) and sandstone (SS). The samples were obtained by coring process from Small Scale Drilling Simulator (SDS) in the Laboratory. The coring bit used is a core barrel size, 47.33 mm in diameter. Then, the samples were cut into different sizes for strength tests (IT) and ultrasonic wave measurements. Figure 4 and 5 show prepared rock samples for the IT and ultrasonic velocity tests to observe the effect of before and after microwave heating.

FIGURE 4: LEFT AND MIDDLE: UNHEATED-IT SAMPLES AND RIGHT: HEATED SAMPLES FOR ULTRASONIC WAVE TEST.

IT samples for SS and GR were prepared by following dimensions, thickness: t=16mm, and diameter: D=46.7mm, for the ratio: t/D=0.34 [23]. Likewise, the ultrasonic measurements were taking from samples prepared with t=100 mm and D=46.7 mm.

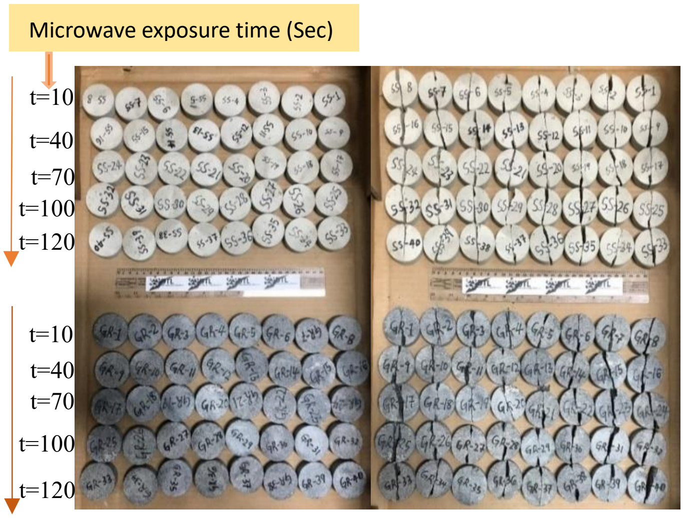


FIGURE 5: HEATED SAMPLES. LEFT: BEFORE IT TEST, RIGHT: AFTER IT TEST.

A series of Drill-Off-Test (DOT) was conducted using a Small-scale laboratory Drilling Simulator (SDS) (Figure 6). The main parts of the SDS included a dual Polycrystalline Diamond Compacts (PDC) bit of a diameter 35 (mm). The applied Weight-On-Bit (WOB) was ranging between 113.48 to 226.8 (Kg). Samples were prepared for the drilling and coring tests. This research report only the data analysis of drilling tests. Figure 7 shows samples after drilling. DOT was conducted for the granite

FIGURE 6: DOT SET-UP ON SMALL-SCALE DRILLING SIMULATOR FOR THE GRANITE ROCK SAMPLE BEFORE AND AFTER MI.

before and after microwaves irradiations (MI) to analyze the influence of MI on the D-ROP.

FIGURE 7: GRANITE SAMPLE AFTER DOT TEST ON SDS.

2.2 Test and Experimental Set-up

Figure 8 shows the experimental setup and equipment for all tests including a geomechanics frame, ultrasonic wave set-up [23], a microwave of 1200 Watts, and an infrared gun for IT-strength determination, P and S wave measurements, microwave heating, and temperature recording, respectively.

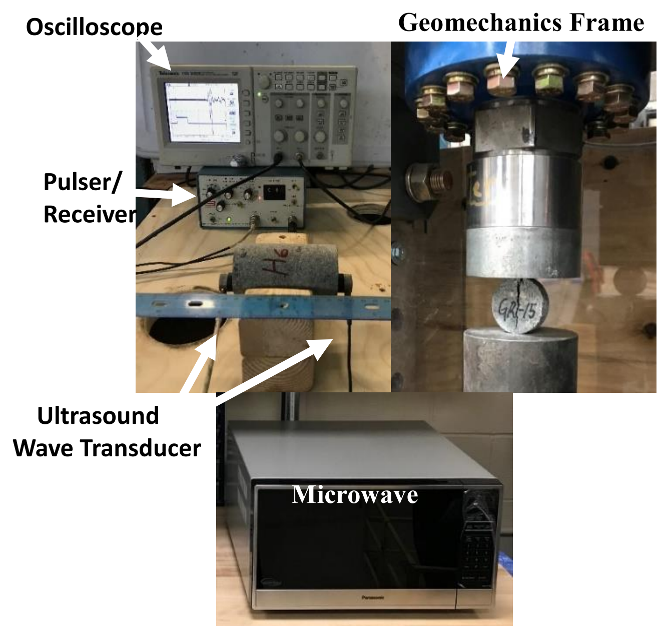


FIGURE 8: EQUIPMENT AND EXPERIMENTAL SET UP.

2.3 Testing Matrix and Procedures for MWI-Test

After the sample preparation. For an ultrasonic wave measurement, the test matrix is as follows:

- The test was designed for two heating cycles. 1st cycle followed an exposure time from 1 min to 5 min with an increment of 1 min. After cooling, the 2nd cycle re-heated the same Sample from 2 min to 6 min in 1 min increments.

- Ultrasound wave was measured before and after each cycle.

The IT test follows the procedure below:

- There were six sets of samples; each group of an IT test had eight samples. One set of IT tests was conducted without being heated/ exposed to a microwave to obtain the IT strength of GR before microwave irradiation effects.
- Then, the remaining five sets of an IT test were tested with an increment of 30 seconds for each group from 10 sec to 120 sec. After the samples completed microwave heating, the pieces were let to be cooled down, and the IT test was conducted.

Figure 9 shows the procedure followed for taking and recording the temperature of specimens after exposure to the microwave irradiation.

FIGURE 10: RECORDING TEMPERATURE OF A GRANITE SAMPLE BY USING AN INFRARED GUN.

3. RESULTS AND DISCUSSION

Two proposed tests were carried out for precise data determination and analysis, destructive and non-destructive tests. Also, relating the experimental laboratory work to the practical operation in the field is essential for finding solutions for enhancing ROP. The focus of the field drilling application is to optimize or increase ROP for the cost reduction of the project. The strength test was chosen because of its direct effect on ROP and ultrasonic wave velocity helps to support the strength analysis and to avoid destroying the sample for future laboratory experiments.

3.1 Ultrasound Wave Velocities Results

3.1.1 Effect of Heating Temperature on the Rock Samples

The results shown in Figures 10 and 11 are for the two groups of ultrasonic measurement and IT test, respectively. Both testing samples show a direct proportional heating temperature with an increase in heating time.

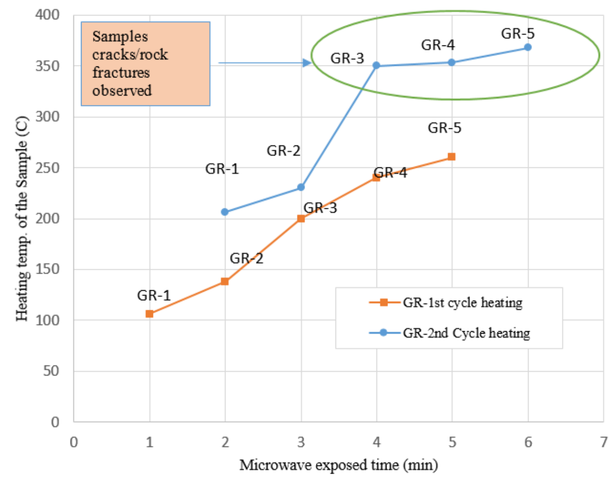


FIGURE 11: GR_SAMPLES AT 1ST AND 2ND HEATING CYCLES.

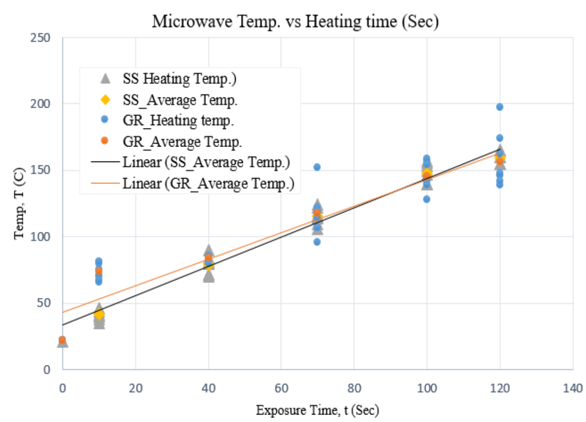


FIGURE 9: MICROWAVE HEATING FOR IT SAMPLE (SS AND GR).

In Figure 10, two heating cycles were conducted for GR samples for ultrasound measurements. GR-1 and G-2, after MWI temperature at 2nd cycle heating, were nearly the same as GR-3 and GR-4 of 1st cycle heating, respectively. Also, the heating temperature for the 2nd cycle was observed to increase more due to the micro fracture created on the 1st cycle heating, which allows the samples to absorb more heat in samples. The crack formation was observed for samples GR-3, GR-4, and GR-5, as shown in figure 12. Also, after a microwave heating of the IT sample, the average temperature was taken for each group set of IT-test. An increasing temperature trend was observed. The GR samples have higher temperatures at the early exposure time than the SS samples. Hence, as time increased, the samples were observed to have similar temperatures, as shown in figure 11.

3.1.2 Application of Microwaves Irradiation (MI)

a. Fractures Induced on the Rock under Microwave Heating

The ultrasonic wave velocities, Vp and Vs, were observed to decrease as the exposure time increased because the fracture was initiated as the sample absorbed more heat. The cracks induced will cause a longer travel time and shorten the travel velocity. The visible cracks were observed after the set of ultrasonic wave samples was re-heated for the 2nd cycle. Figure 12 show GR-3, GR-4, and GR-5 specimens with fractures.

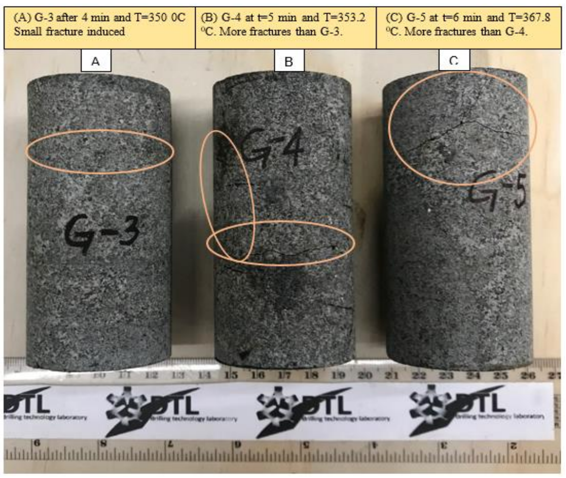


FIGURE 12: FRACTURES INDUCED ON 4IN- GR SAMPLE AFTER THE EFFECT OF RE-HEATED.

b. Effect of Microwave Heating on P & S Wave Velocity

Figure 13 shows a plot of the GR-3 sample showing time arrival for P and S wave velocity for before and after microwave heating.

Figure 14 shows V_P and V_S decreased after all the specimens were exposed to microwave radiation. Also, the elastic constants such as Young's Modulus (E) and Poisson's ratio (v) were calculated, as the results observed to decrease in elastic constants as MI exposure time increased as shown in Table 1. Elastic constants was computed using the following eq. (2,3,4 & 5):

$$V_P = L_P/T_P \qquad (2)$$

$$V_s = L_P/T_P \qquad (3)$$

Where:

V_P & V_s = P- and S- wave velocity constants, respectively, m/s

L&T = Core sample length (m) and travel-time (sec), respectively.

$$E = [\rho V_s^2(3V_P^2 - 4V_s^2)]/(V_P^2 - V_s^2) \qquad (4)$$

Where:

E = Young's modulus of elasticity, Pa

ρ = density, kg/m3

$$\upsilon = (V_P^2 - 2V_s^2)/[2(V_p^2 - V_s^2)] \qquad (5)$$

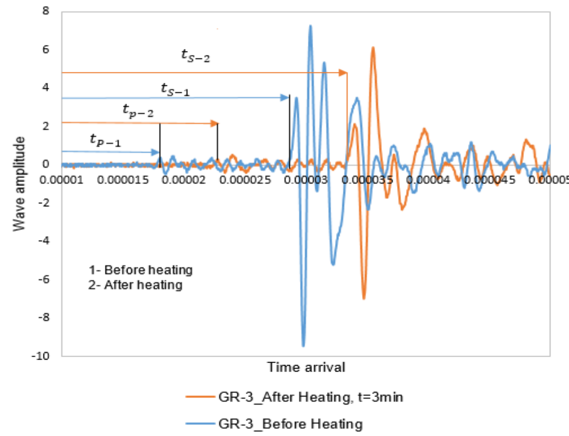


FIGURE 13: TIME ARRIVAL FOR P&S WAVE VELOCITY BEFORE AND AFTER - MI FOR GR-3 SAMPLE.

Where:

v = Poisson's ratio

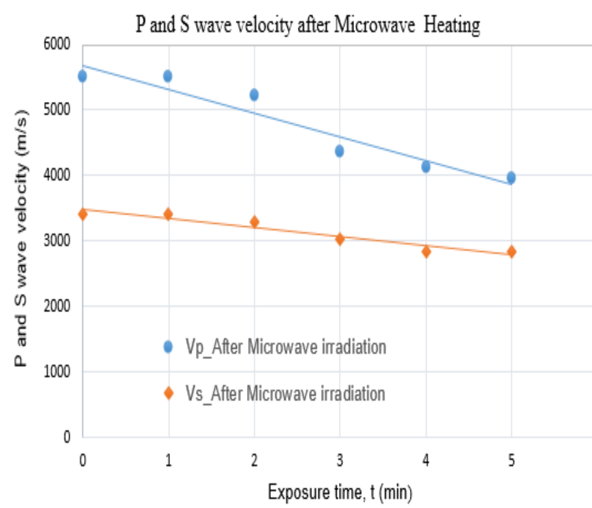


FIGURE 14: EFFECT OF MICROWAVE IRRADIATION ON ULTRASOUND WAVE VELOCITY.

3.2 Strength Tests Analysis

TABLE 1: ELASTIC PROPERTIES OF THE ROCK BEFORE AND AFTER MI

Core Sample	Diameter	Length	Density	Arrival time (Sec)		Velocities		Young Modulus	Poissons ratio
4in	(m)	L(m)	kg/m3	tP-wave	tS-wave	Vp	Vs	E (Gpa)	v
GR_Before-MI	0.0473	0.0990	2885.73	0.000018	0.000029	5500	3414	79.82	0.187
GR-1_1m	0.0473	0.0990	2884.76	0.000018	0.000029	5500	3414	79.79	0.187
GR-2_2m	0.0473	0.0992	2881.37	0.000019	0.000030	5211	3300	73.12	0.165
GR-3_3m	0.0473	0.0998	2862.50	0.000023	0.000033	4348	3030	54.03	0.028
GR-4_4m	0.0473	0.0995	2871.33	0.000024	0.000035	4125	2829	48.53	0.056
GR-5_5m	0.0473	0.0992	2880.21	0.000025	0.000035	4060	2829	47.40	0.028

3.2.1 Effect of Microwave Heating on IT Strength of the Rock

The indirect tensile strength of the rock was determined following ASTM D3967 [23]. The rock strength shows a decrease as heating temperature of the samples increased as shown in Figure 15 for SS and GR Samples. The decrease in rock strength is because of fracture initiation as the heating temperature increases, as shown in figure 10 for (100mm diameters) GR samples.

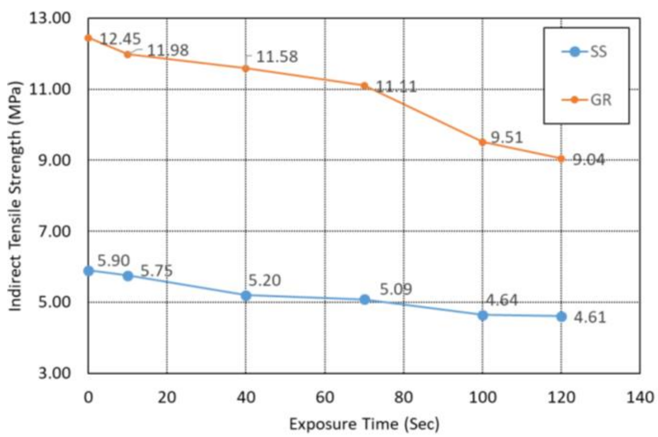
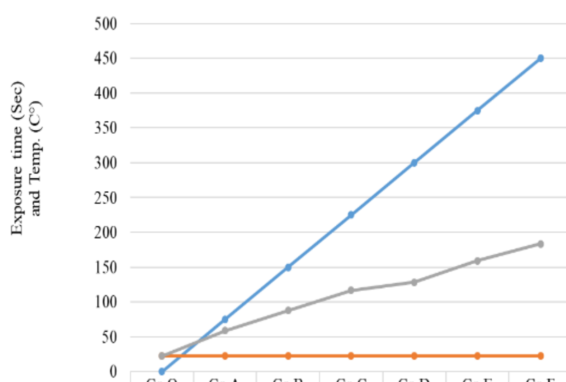


FIGURE 15. IT STRENGTH FOR SS AND GR AS A FUNCTION OF MICROWAVE EXPOSURE TIME.

3.3 Drill-off-Test (DOT) Results

DOT was conducted for the granite samples without and after the samples exposed to MI. Figure 16 shows the MI heating temperature of the rocks, where the room temperature was 22.2^0 for each sample and then with an increments of 75 seconds, the MI of each sample was observed to increase to the maximum of 183^0 with 450 seconds.



	Gr-O	Gr-A	Gr-B	Gr-C	Gr-D	Gr-E	Gr-F
Exposure time (Sec)	0	75	150	225	300	375	450
Original Temp. (C°)	22.2	22.2	22.2	22.2	22.2	22.2	22.2
Temp. after heating (C°)	22.2	58.5	87.8	116.8	128.4	159.2	183.2

Sample #

FIGURE 16: HEATING OF GRANITE SAMPLES AS AFUNCTION OF MICROWAVES EXPOSURE TIME.

Then, using dual PDC bit, DOT was conducted for all samples. D-ROP was observed to increase as (i) the WOB increased and (ii) the MI heating effects increased for granite rock as shown in Figure 17.

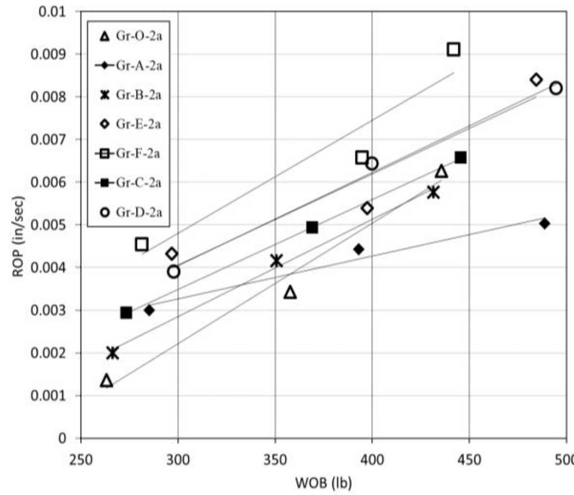


FIGURE 17: DRILL-OFF TESTS FOR GRANITE SAMPLES WITH INCREASING IRRADIATION TIME AND TEMPERATURE.

4. CONCLUSION

This work explains the effects of microwave irradiation (MI) on the elastic properties of the rock and the influence of weakening rock for an increasing D-ROP. The summary of the work can be presented as follow:

The elastic properties of the rock including P-wave and S-wave velocities, Young's modulus (E) and Poisson's ration was observed to decrease as the MI of the rock increased.

An induced fractures observed as the MI increased on the rocks. Also, the strength of the rock observed to decrease as MI increased.

Drilling ROP shows a remarkable increase after the samples exposed to MI heating, this shows a good indication of the MI weakening the rock.

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