USING MICROWAVE THERMAL TREATMENT TO OPTIMIZE TUNNEL EXCAVATION EFFICIENCY: A PROSPECTIVE APPROACH FOR MINING AND CIVIL PROJECTS IN LIBYA

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الملخص

تتناول هذه الدراسة استخدام المعالجة الحرارية بالموجات الدقيقة (الميكروويف) في عمليات حفر الأنفاق لتهيئة الصخور الصلبة مسبقًا قبل تفتيتها. في هذا العمل ، خضعت عينات من صخور البازلت التي جُمعت من منطقة الهيرة في ليبيا، لأشعة الميكروويف لفترات زمنية مختلفة عند مستويات طاقة 800 وات و1000 وات. أُجريت اختبارات متنوعة على عينات الصخور المعالجة وغير المعالجة، بما في ذلك اختبار قوة الشد البرازيلي (BTS) واختبار قوة الانضغاط أحادية المحور (UCS). كما خضعت العينات لتحليلات فيزيائية ومعدنية. تشير النتائج إلى أن التأثيرات المترتبة على زيادة مدة التعرض وزيادة قدرة الميكروويف لا تزيد فقط من درجة حرارة سطح البازلت، بل تُؤدي أيضًا إلى انخفاض شبه خطي في قيمتي قوة الشد البرازيلي (BTS) وقوة الانضغاط أحادية المحور (UCS). علاوة على ذلك، تُؤكد تحليلات الانحدار التي تم التحقق من صحتها باستخدام برنامج MATLAB، موثوقية وكفاءة القياسات التجريبية مُقارنةً بالاستراتيجيات الميكانيكية التقليدية. كما تُوضح التحليلات كيف تُسرِّع المعالجة المُحسَّنة بالموجات الدقيقة للصخور المُستهدفة من إضعافها مع تعزيز كفاءة الطاقة. وتظهر النتائج أن استخدام المعالجة الحرارية للميكروويف لتحسين حفر الأنفاق لا يقلل من تآكل ادوات الحفر فحسب، بل يوفر أيضًا عمليات حفر أنفاق أكثر كفاءة واستدامة في بيئات الصخور الصلبة.

ABSTRACT

The present study explores the use of microwave thermal treatment in tunnel excavations to pre-condition hard rock prior to fragmentation. In this work, basalt rock specimens collected at Al-Hirah, Libya, undergo microwave irradiation for different durations at 800 W and 1000 W power levels. Various tests are performed on both the untreated and treated rock samples, including the Brazilian Tensile Strength (BTS) and Uniaxial Compressive Strength (UCS) tests. The samples are also subjected to physical and mineralogical analyses. The results indicate that the combined effects of longer exposure times and enhanced microwave power not only increase the basalt's surface temperature, but result in a near linear reduction of BTS and UCS. Furthermore, the regression analyses, which are validated in MATLAB, confirm the experimental measurements' reliability and efficiency compared to traditional mechanical strategies. The analyses also demonstrate how the microwave-enhanced pre-treatment of the targeted rock accelerates its weakening while also boosting energy efficiency. The findings show that using microwave thermal treatment to optimize tunnel excavations not only decreases tool wear, but offers more efficient and sustainable tunneling operations in hard rock environments.

KEYWORDS: Microwave irradiation, Rock fragmentation, Pre-conditioning, MATLAB validation, Basalt

INTRODUCTION

Finding a safe, effective, and efficient means to break hard rock during the construction, excavation, and processing stages of engineering and mining projects is a major challenge for those industries. Conventional techniques, e.g., drilling and blasting, can cause significant safety and environmental concerns, especially when conducted in urban environments. In light of these issues, innovative solutions are urgently needed, such as non-explosive rock-breaking techniques or continuous excavation systems. These and other innovations can resolve safety and environmental concerns while also satisfying efficiency requirements and adhering to industry standards.

The global demand for resource extraction that is both sustainable and responsible is increasing exponentially [1,2]. In extracting hard rock like basalt, conventional excavation methods are both expensive and inefficient due to the slowness of the operations and the wear and tear on the mechanical cutting equipment. A promising alternative to mechanical approaches is electromagnetic-assisted rock formation weakening. Rocks heat up when exposed to high-frequency radiation, thanks to the dual processes of dipolar rotation and ionic migration. The effectiveness of the radiation process depends on the dissipation factor, which can be calculated by determining the ratio of the dielectric constant to the dielectric loss.

In most cases, the materials that heat up the easiest and fastest also have the highest dielectric loss, but other factors can play a role in the rock's response as well. These factors include temperature, moisture, applied frequency, microstructure, mineral composition, etc., all of which can result in complex behavior that diverges significantly from the material's individual minerals. Gaining a better understanding of how these factors interact will aid in the formation of more practical and efficient dielectric heating strategies in mining endeavors [3-5].

Previous Research on Microwave-Assisted Rock Weakening

Several studies have investigated how microwave radiation impacts rocks during mineral processing and rock excavation, aiming to improve the efficiency and effectiveness of these processes. In Reference [1], the researchers explored the effects of microwave radiation exposure on kimberlite and granite rock structural strength. After testing power levels between 2 and 15 kW, a significant weakening of tensile and compressive strength was observed in both rock types. In Reference [6], the researchers conducted lab experiments on strength degradation and temperature distribution in hard rock (e.g., granite, norite, and basalt) during microwave radiation. Different power levels and exposure times were tested. The findings showed the feasibility of using microwave-assisted rock fragmentation within certain parameters. In Reference [7], the researchers investigated the use of microwave technologies (namely, Mode I fracture mechanics) to weaken basalt. They discovered that optimized material placement improves heat absorption efficiency by up to 40%, while pre-cutting the material decreases fracture toughness (KIC) by up to 35%. They also found that longer periods of microwave exposure can reduce the effect of weakening over microwave energy (WOME), despite KIC's continued decline. The presence of non-uniform cracks indicates significant weakening, thus highlighting the potential of this optimized microwave-assisted approach for mining applications.

In Reference [8], the pre-conditioning technique of microwave treatment was explored to determine its efficiency in weakening basalt during mining procedures. The researchers focused on microwave irradiation parameters and temperature-dependent material characteristics to determine optimal mechanical performance. The researchers in Reference [9] studied the impact of microwave irradiation on compact basalts. The rock's mechanical properties were tested under different confining pressures that are typical in mining and tunneling environments. The experiments employed a 2.45 GHz multi-mode microwave system that treated the basalt samples at 1–5 kW power levels and with up to 300 seconds of exposure time. The samples were then subjected to Uniaxial Compressive Strength (UCS) and Conventional Triaxial Compressive Strength (CTCS) tests, with promising results.

In Reference [10], the researchers used thermally induced intergranular fracturing (starting at 100°C) along with transgranular fracturing (starting at 300°C) to demonstrate how microwave irradiation (100–400°C) weakens basalt. At 100°C, mechanical degradation showed maximal reduction in fracture toughness and compressive strength, while at 200°C, there was maximal reduction in elastic modulus, with Poisson's ratio exhibiting substantial increases as a result of fracture network development. Full structural failure was achieved at 400°C. Notably, this strategy was able to pre-condition rock at temperatures that were 50% lower than traditional thermal approaches, indicating this method's enormous potential in hard rock excavation efficiency.

In Reference [11], the authors used microwave irradiation (2.45 GHz, 2.1 kW) to generate fractures and weaken basalt as an energy-efficient rock pre-conditioning approach. The results revealed a significant reduction in compressive strength (~50%) as well as in tool wear (~26% on the Cerchar Abrasivity Index). The technology also led to slight volume expansion (0.81%) and overall mass loss (0.35%). In Reference [12], the researchers tested the rock-breaking efficiency of microwave irradiation on limestone and Tuffistic Kimberlite, while in Reference [13], the authors studied post-microwave irradiation cooling rates and how these impact reductions on the mechanical strength of basalt.

In Reference [14], a microwave-assisted rock-breaking system was developed to be integrated into the disc cutters of Tunnel Boring Machines (TBMs). The study showed that microwave irradiation weakens hard rocks such as basalt and granite by generating thermal cracks and reducing their strength. Although intended for field application, all experiments were conducted in the laboratory using slabs and cores to simulate rock-mass behavior and determine optimal irradiation conditions.

Objectives of the Present Study

The objective of this study is to evaluate the potential of microwave thermal treatment as an effective rock pre-conditioning method for mining, tunneling, and civil engineering projects. Specifically, the research investigates the influence of different microwave power levels and exposure times on the strength characteristics of basalt collected from Al-Hirah, Libya. By analyzing the reduction in Brazilian Tensile Strength (BTS) and Uniaxial Compressive Strength (UCS), the study aims to demonstrate how microwave-assisted excavation can minimize tool wear, reduce energy consumption, and lower excavation costs, while enhancing safety and sustainability compared to conventional drilling and blasting. Although microwave-assisted rock weakening has been explored in projects worldwide, it has not yet been applied in Libya. The findings of this work are therefore expected to provide experimental insights that can support the introduction of microwave technology into future large-scale excavation, tunneling, and infrastructure development projects across Libya.

METHODOLOGY

Materials and Sample Preparation

Basalt comprises the main foundational material of Earth's continental and oceanic crust. In its compact form, basalt has high UCS values, giving it substantial load-bearing capacity. However, in its porous form, basalt has a fractured microstructure and so has relatively low UCS. The present research explores basalt's thermal and mechanical characteristics when tested under lab conditions. The testing specimens come from Al-Hirah, Libya, which is located around 65 km SW of Libya's capital, Tripoli, and close to the Wadi Ghann Dam (32°17'11.1"N, 13°10'11.7"E).

The samples were obtained as intact blocks at the field site and later reshaped for microwave and mechanical testing purposes Figure (1). For the UCS experiments, cylindrical specimens were prepared by using a radial drilling machine to extract 40 mm diameter cores. The extracted cores were subsequently cut to a two-to-one, height-to-diameter ratio (H/D = 2:1), as per testing standards[15]. Further cuts were made to create disk-shaped specimens whose height equaled half their diameter (H = 0.5D). These disks were then used in additional mechanical tests.

To ensure uniform stress distribution in the USC tests, the ends of the specimens were ground and polished to obtain the requisite flatness and parallelism. Fluctuations in the samples' surface temperature were recorded by a thermal imaging camera immediately after the microwave irradiation stage. This allowed for any heat-induced structural changes in the basalt to be analyzed in detail. Figure (2) presents a flowchart summarizing the methodology employed in the present research.

Figure 1: Cylindrical specimens cut from intact blocks of basalt.

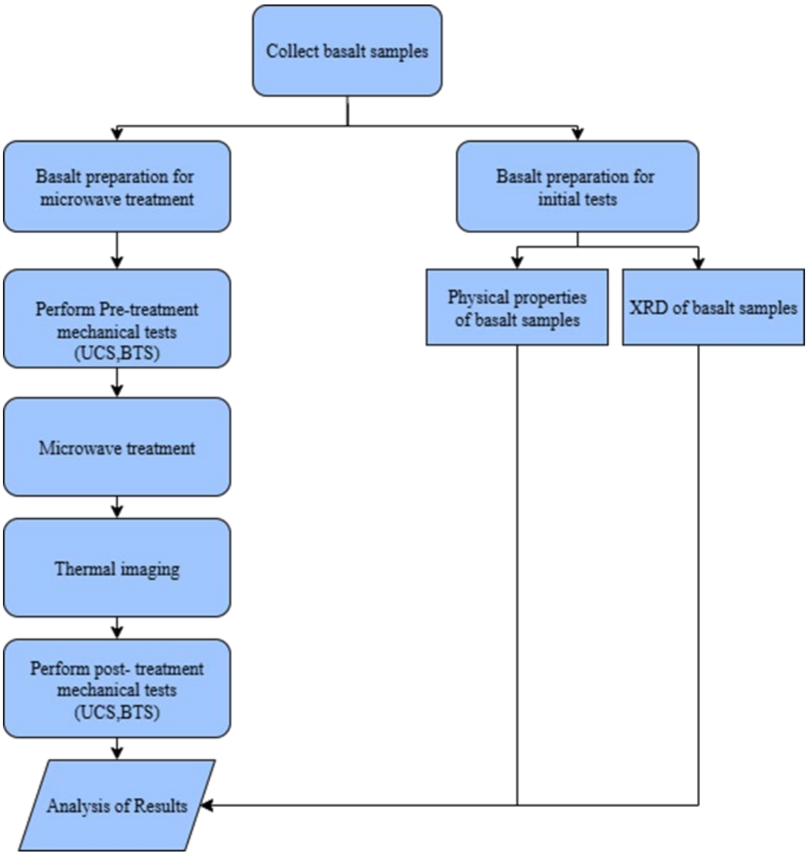

Figure 2:Experimental procedure for basalt samples.

Mineralogical Composition and Microwave Absorption analysis

The basalt samples' mineralogical composition and interactions with microwave radiation were analyzed in detail. The dominant mineral phases were identified using semi-quantitative X-Ray Diffraction (XRD) analysis, which was also used to estimate the proportional distribution of each mineral in the rock matrix. The corresponding XRD pattern is shown in Figure (3), displaying the diffraction peaks obtained using Cu–Kα radiation. These peaks were matched with standard reference codes, and the identified mineral phases are summarized in Table (1). In addition, established findings in the literature were used as evaluation markers for the identified minerals' microwave absorption traits. Table (1) below shows the chemical formulations, compound classifications, and percentage proportions of the different minerals in the basalt samples.

In the basalt samples used in this research, anorthite ($CaAl_2Si_2O_8$) was the dominant mineral phase, making up nearly 59% of the rock's composition. Anorthite is a calcium aluminum silicate classified in the plagioclase feldspar group. As a silicate mineral, it typically has low microwave absorption rates. The researchers in [16] categorize silicates As Group 1 materials that exhibit no or only negligible amounts of heating during microwave exposure. This characteristic is the result of the non-conductive nature of Group 1 materials and their relatively low dielectric loss.

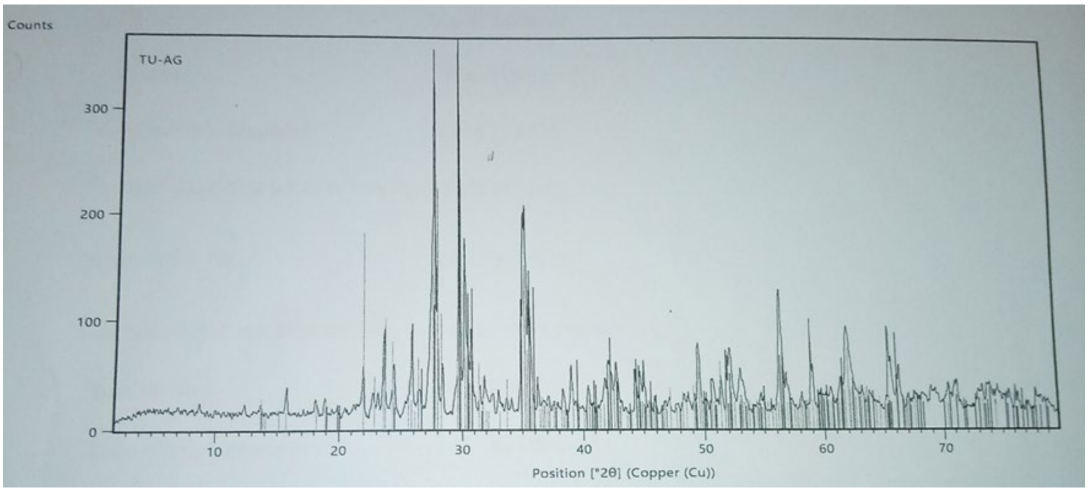

Figure 3: XRD pattern of the basalt samples.

The major diffraction peaks correspond to anorthite (01-083-6377), augite (01-076-0544), and magnesioferrite (01-076-9725), as confirmed by the semi-quantitative analysis.

Table 1: Mineralogical Composition of Basalt Samples.

Mineral Name	Chemical Formula	Compound Type	Semi-Quantitative %
Anorthite (Plagioclase)	$CaAl_2Si_2O_8$	Calcium Aluminum Silicate	59
Augite (Pyroxene)	$(Ca,Mg,Fe)_2Si_2O_6$	Calcium Magnesium Iron Silicate	36
Magnesioferrite	$MgFe_2O_4$	Magnesium Iron Oxide	5

Augite ($(Ca,Mg,Fe)_2Si_2O_6$), which is also a silicate (ferromagnesian), constituted around 36% of the study's basalt samples. Although silicates are generally weak absorbers, the augite's iron ions enable partial microwave interaction via magnetic loss and dielectric mechanisms. Consequently, the augite in our study responded moderately to the applied microwave radiation during testing. This type of response is typical of polymineralic systems and leads to differential heating that results in microcracking and other internal stresses [16], [17].

Unlike anorthite and augite, magnesioferrite ($MgFe_2O_4$) has robust microwave absorption abilities. This spinel-type ferrite constituted only around 5% of the samples' total composition, but its efficiency comes from its dielectric polarization and magnetic hysteresis. These key features in magnesioferrite allow the mineral to convert microwave energy into heat, thus playing a pivotal role in the basalt's structural weakening and thermal expansion [18] [19].

Physical Characteristics of the Samples

Density, moisture content, porosity, and permeability were the main physical characteristics experimentally measured in the laboratory for the basalt rock samples used in this study. The procedures for measuring density, moisture content, and porosity followed the guidance outlined in [20],while permeability was measured using the method described in [21]. The measured values of these four properties are presented in the bar chart in Figure (4), in which the density of the basalt sample is quite high (3.0 g/cm³), which indicates its compactness and solidity as a material. At the same time, the sample's moisture content is quite low (0.39%), representing the *as-tested value* measured in the laboratory according to the standard procedure. This indicates that the rock has minimal water retention capacity, likely due to the compact and dense structure of its grains. The porosity was measured to be (0.78%), and the permeability was (0.01 millidarcies (mD)). These experimentally determined values confirm the basalt's dense and nearly impermeable structure. Such characteristics may limit its suitability for reservoir applications but make it highly favorable for construction and other engineering purposes.

Furthermore, heat transfer in basalt occurs mainly through conduction due to the ultra-low permeability and porosity. Basalt with such high density and compactness may respond positively to microwave irradiation, as microwave energy is absorbed near the boundaries of the mineral grains. This leads to internal heating, thermal expansion, and the development of microcracks, supporting the use of microwave treatment for improving the breakability of hard rocks.

These values are consistent with findings by [22], who showed that dense igneous rocks such as basalt, granite, and norite exhibit low porosity and permeability prior to microwave exposure. Their results support the structural and thermal behavior observed in the present study.

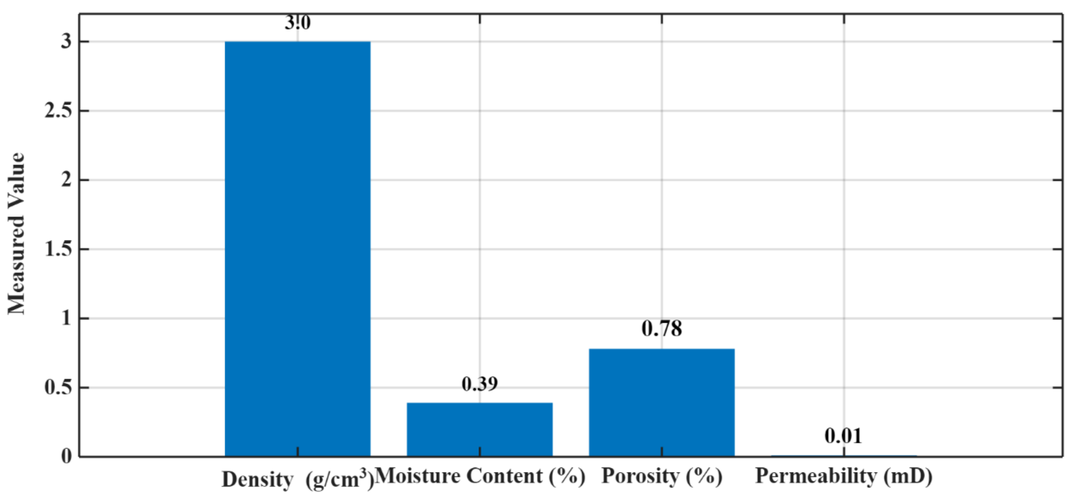

Figure 4: Physical characteristics of the studied basalt samples.

Mechanical Characteristics Tests

Evaluation of the sample rock's mechanical characteristics was carried out using the UCS and BTS tests. The UCS test is a particularly useful tool for predicting Tunnel Boring Machine (TBM) performance, as it easily and accurately quantifies rock strength. Based on the guidance provided in [23], a compression device was used to test both the untreated and treated samples. Each sample was positioned between the compressor's upper and lower plates and then activated the device, raising the lower plate until it made contact with the upper one. The load was subsequently increased incrementally until sample failure occurred, and the device readings at the point of collapse were recorded. These readings represented the quantification of the sample's strength characteristics.

To test the samples' tensile strength, the BTS test was employed. Similar to the UCS test, the BTS is also a useful indicator for predicting TBM performance. Both the treated and untreated basalt samples underwent BTS testing, and the standards provided in [24] were followed for procedural guidance.

Microwave Heating Tests

Two single-mode 2.45 GHz microwave ovens (commercial grade) were used to treat the rock disks and cylinders. The microwaves had different power outputs and internal capacity dimensions. As shown in Figure 5(a), the first microwave was smaller and generated 800 W of power, whereas the second, as shown in Figure 5(b), was larger and generated 1000W of power. Specifically, the second microwave, which was a Litton Moffat MG0873 model with output from a single magnetron, had an internal capacity measuring 37 cm (length) × 30 cm (width) × 25 cm (height). The Litton microwave also had a waveguide orientated at an angle to direct and optimize the distribution of the microwaves. Both microwaves operated at maximum power throughout the testing phase to maintain consistency in the treatment of the samples. Table (2) summarizes the testing parameters for both UCS and BTS experiments.

Table 2: Microwave Heating and Mechanical Strength Tests on Basalt Specimens.

Test	Specimen Shape	Specimen Size (d × h mm)	Microwave Power(W)	Exposure Time (s)	Number of Tests
UCS	Cylinder	40 × 80	800, 1000	0, 30, 60, 120, 240	15
BTS	Disc	40 × 20	800, 1000	0, 30, 60, 120, 240	15

(a) (b)

Figure 5: (a) Front and top views and photographs of the 800W and (b) 1000W single-mode commercial microwave ovens used in this study.

Figure (6) shows the experimental setup previously used with a 15 kW single-mode industrial microwave system. In this arrangement, the cylindrical basalt specimen was placed on a non-conductive foam block inside the microwave cavity, directly beneath the waveguide. This positioning ensured maximum surface exposure to the incident microwave energy in a controlled and focused mode pattern, while the foam base acted as an insulator to minimize conductive heat loss to the cavity floor. The single-mode design provided uniform and concentrated irradiation from above, enabling efficient heating throughout the specimen. In the present work, microwave powers of 800 W and 1000 W were used, following the same sample placement concept.

(a) (b)

Figure 6: Single-mode microwave at the Geomechanics Laboratory, McGill University, Canada, showing (a) the cavity and (b) the basalt specimen beneath the waveguide.

Thermal Analysis

To analyze the rock samples' thermal behavior, the cylindrical and disc-shaped specimens were subjected to 800W and 1000W of microwave power, aiming to determine the amount of time required to achieve peak temperature.

EXPERIMENTAL RESULTS AND DISCUSSION

Thermal Analysis of Basalt Discs

Figures (7) and (8) depict how microwave exposure time at 800 W and 1000 W power levels affects surface temperature in the basalt disc samples. The linear data points, originally plotted in Excel Figure (7), were later validated with MATLAB Figure (8). As is clearly seen in both figures, the surface temperature shows strong linear rises with increased exposure time, though the slope for the 1000 W power level is steeper. This difference indicates that for the samples under testing, the higher the microwave power, the faster the heating rate.

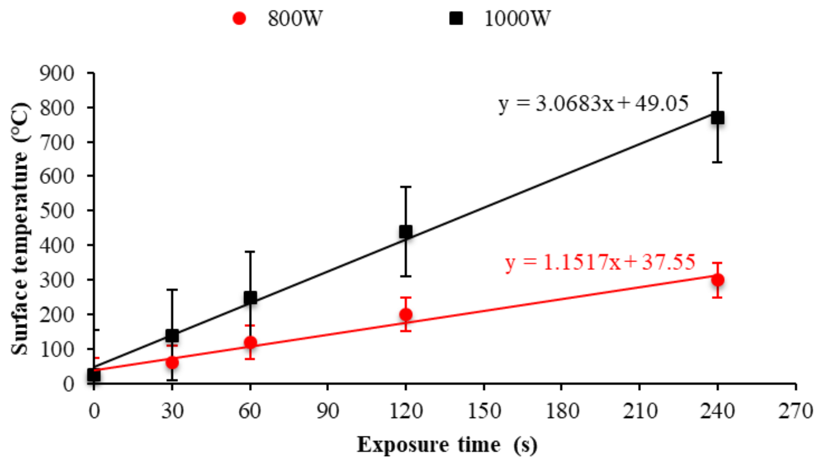

Figure 7: Basalt disc microwave exposure time to two different power levels vs. mean surface temperature change.

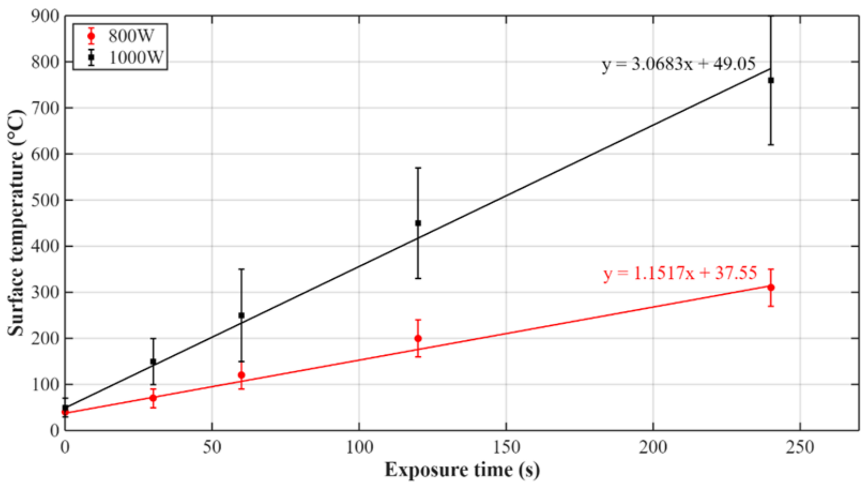

Figure 8: MATLAB validation of surface temperature response in basalt discs irradiated at 800 W and 1000 W.

Furthermore, the near-identical plot-points of the Excel and MATLAB trendlines in the two charts validates the data analysis accuracy, confirming the experimental measurements' reliability. Each data point also has standard deviation error bars that show the variabilities, which increase with longer exposure durations and higher power levels. Overall, the validation process clearly demonstrates the robust impact of microwave irradiation on the basalt's thermal response, showing how thermal treatments can be applied to optimize engineering and mining projects.

Thermal Analysis of Basalt Cylinders

Figures (9) and (10) depict how microwave exposure time at 800 W and 1000 W power levels affects surface temperature in the basalt cylinder samples. The linear data points, originally plotted in Excel Figure (9), were later validated with MATLAB Figure (10). As shown, the surface temperature topped ~243 °C at 800 W and ~309 °C at 1000 W at 240 seconds, clearly indicating that power level affects heating rates. As with the basalt disc test results, the results for the cylinders demonstrate that the higher the microwave power, the faster the rate of temperature rise. Further, the robust agreement between Excel and MATLAB plot points underscores MATLAB's reliability in regression analysis. The overall results support the use of microwave power to enhance thermal response in rock fragmentation during tunnelling operations.

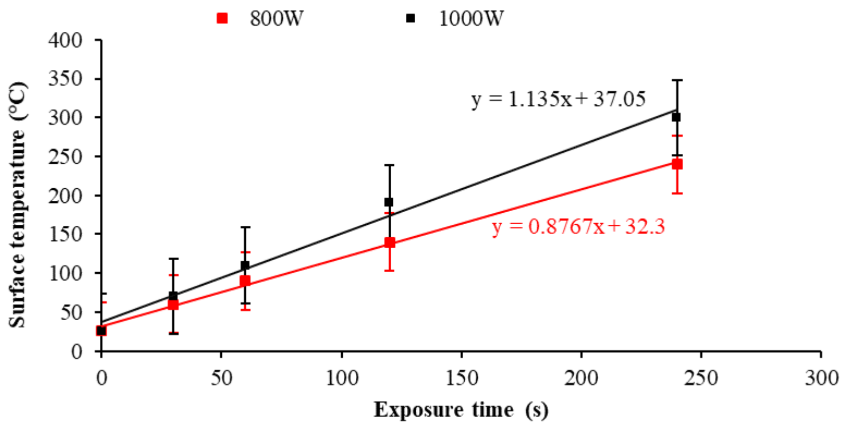

Figure 9: Basalt cylinder microwave exposure time to two different power levels vs. mean surface temperature change.

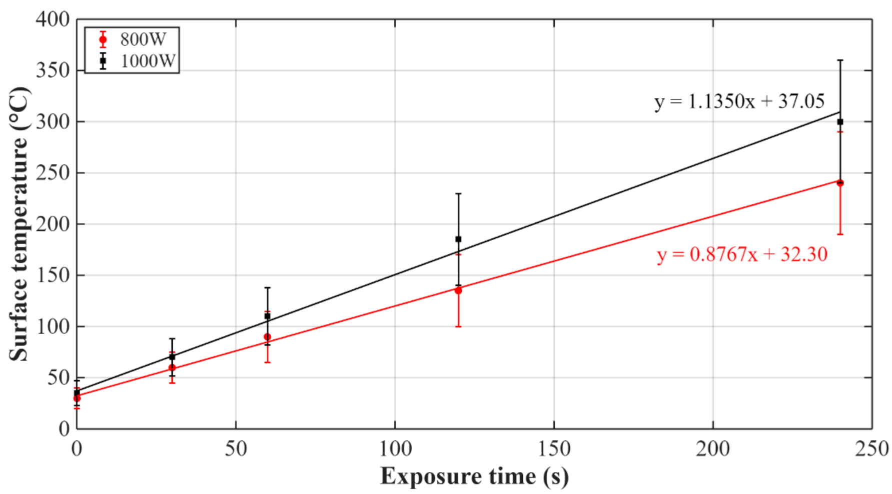

Figure 10: MATLAB validation of surface temperature response in basalt cylinders irradiated at 800 W and 1000 W.

Analysis of Mechanical Properties

Figures (11) and (12) show that increasing the basalt samples' microwave exposure time leads to significant decreases in the BTS under the two power levels of 800 W and 1000 W. The longer the exposure time, the more drastic the decline in BTS and the greater the weakening of the rock. When subject to microwave energy of 800 W, the strength of the basalt drops from approximately 13.1 MPa to 7.7 MPa, representing a decline of around 41%. At 1000 W, the basalt's strength drops from approximately 12.9 MPa to 4.0 MPa, which represents an impressive decrease of 69%. Based on these outcomes, it is evident that by applying higher levels of microwave power, the material's degradation is accelerated and its overall weakening is amplified. The robust agreement of the Excel and MATLAB results confirms MATLAB's reliability in regression analysis and data visualization while also validating the data's consistency.

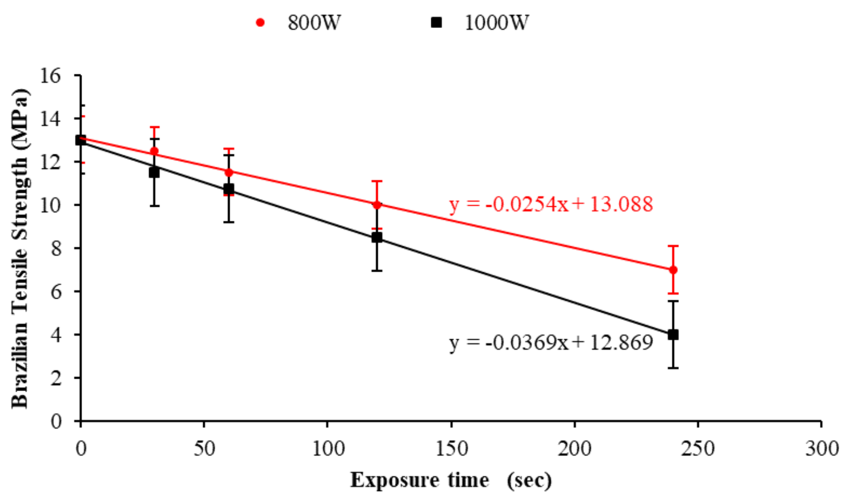

Figure 11: Microwave exposure time vs. Brazilian tensile strength in basalt irradiated at 800 W and 1000 W.

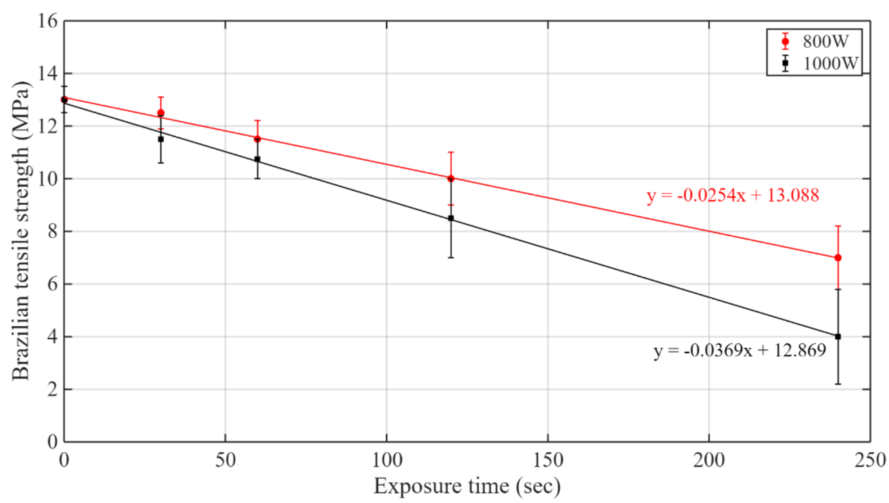

Figure 12: MATLAB validation of microwave exposure time vs. Brazilian tensile strength in basalt irradiated at 800 W and 1000 W.

Figures (13) and (14) depict variations in the uniaxial compressive strength of the tested basalt. The variations occur as a function of microwave exposure time under the two power levels of 800 W and 1000 W. As can be seen, with increases in exposure time, the USC declines almost linearly. At a power level of 800 W, the UCS drops to 65 MPa from 105 MPa, which is a reduction of around 38%. At a power level of 1000 W, the UCS drops to 55 MPa from 105 MPa, which represents a decrease of around 48%. The findings indicate that the UCS reductions are more robust under higher microwave power levels, which confirms the interplay of basalt's mechanical properties and microwave treatment intensity. Furthermore, the consistency of the results obtained from the MATLAB visualizations highlights the data's reproducibility as well as the reliability of the analytical techniques employed in the present study. The consistency of the results also underscores the validity of the data processing approach and experimental methodology used in this work.

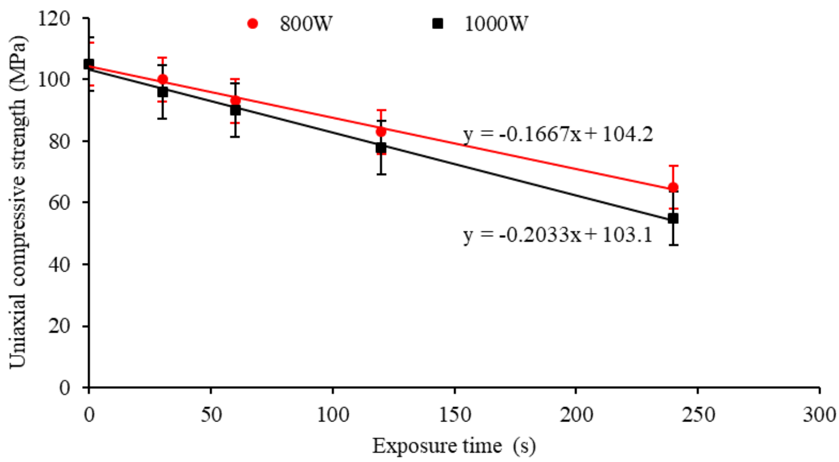

Figure 13: Microwave exposure time vs. uniaxial compression strength in basalt irradiated at 800 W and 1000 W.

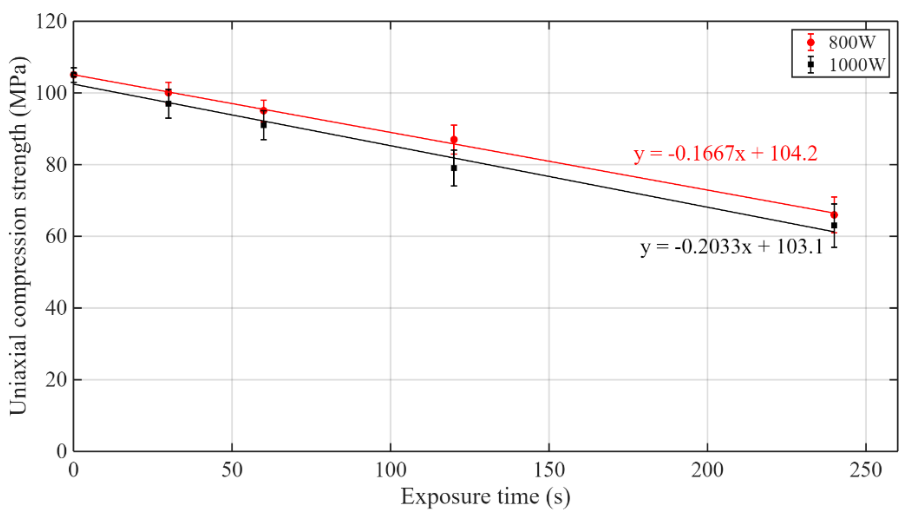

Figure 14: MATLAB validation of microwave exposure time vs. uniaxial compressive strength in basalt irradiated at 800 W and 1000 W.

CONCLUSIONS

Based on the experimental results obtained in this research as well as in the relevant literature, microwave irradiation is a robust and efficient pre-conditioning treatment for weakening basalt. Under BTS and UCS testing, microwave energy significantly reduced both uniaxial compressive and tensile strength. Specifically, at a power level of 800 W, the basalt disc samples decreased to 7 MPa from 13 MPa (a drop of around 46%) over the tested exposure times, while at a power level of 1000 W, the samples declined to 4 MPa from 13 MPa (a drop of around 69%). For UCS, the samples decreased to 65 MPa from 105 MPa at a power level of 800 W, which represents a decline of around 38%, while at a power level of 1000 W, the samples dropped to 55 MPa from 105 MPa, representing a 48% reduction. The test results also showed that the rock's surface temperature increased nearly linearly both with power level and exposure time, with the greatest and fastest weakening occurring under higher microwave energy conditions. Additionally, the findings' reliability and reproducibility were soundly underscored by the MATLAB validation of the data. The study's results strongly support the application of microwave thermal treatment prior to mechanical excavation, as the pre-conditioning of rock can substantially boost the efficiency of rock fragmentation during tunnel excavations while also increasing the lifespan of tools and enhancing overall productivity.

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