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The effect of microwave irradiation and shock cooling on rock properties- A review

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ABSTRACT

Understanding rock properties and rock behavior under varying conditions is essential for predicting and managing rock behavior across different engineering applications. This study focuses on how rock properties respond to temperature variations, specifically through Microwave Irradiation (MI) and Shock Cooling (SC), and the implications of these changes for civil engineering, oil and gas drilling, and mining. In civil engineering, such knowledge is vital for designing stable and durable foundations. In drilling and excavation, altering rock properties to weaken rocks can enhance drilling efficiency, increase the Drilling Rate of Penetration (ROP), and reduce operational costs. The objective of this review is to consolidate research findings on the impact of MI and SC on rock properties, such as mechanical strength and mineral composition. By assessing these studies, the review aims to identify the potential benefits of using MI and SC to improve drilling performance, extend the lifespan of drill bits, and minimize drilling expenses. The review also explores the mechanisms through which these temperature-induced treatments create micro-fractures that facilitate easier drilling. In conclusion, the compiled research demonstrates that both MI and SC can significantly alter rock properties, offering practical applications in drilling and excavation. These techniques can effectively reduce rock strength, leading to improved ROP and cost savings in drilling operations. The insights provided by this review could guide future developments in engineering practices, particularly in enhancing the efficiency and sustainability of drilling activities.

تأثير اشعت الميكروويف والتبريد المفاجئ على خصائص الصخور– دراسة مرجعيه

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الكلمات المفتاحية:
التنقيب عن المعادن
إشعاع الميكروويف
خواص الصخور
معدل حفر و اختراق الصخور
هندسة الحفر

الملخص

يعد فهم خصائص الصخور وسلوكها في ظل ظروف مختلفة أمرًا ضروريًا للتنبؤ بسلوك الصخور وإدارته عبر التطبيقات الهندسية المختلفة. تركز هذه الدراسة على كيفية استجابة خصائص الصخور للتغيرات في درجات الحرارة، وتحديداً من خلال اشعاع الميكروويف (MI) والتبريد المفاجئ (SC)، وآثار هذه التغييرات على الهندسة المدنية وحفر النفط والغاز والتعدين. في الهندسة المدنية، تعتبر هذه المعرفة حيوية لتصميم أسس مستقرة ودائمة. في الحفر والتنقيب، يمكن أن يؤدي تغيير خصائص الصخور لإضعاف الصخور إلى تعزيز كفاءة الحفر، وزيادة معدل اختراق الحفر (ROP)، وتقليل تكاليف التشغيل. الهدف من هذه الدراسة المرجعية هو تجميع نتائج البحوث حول تأثير MI وSC على خصائص الصخور، مثل القوة الميكانيكية والتركيب المعدني. ومن خلال تقييم هذه الدراسات، تهدف المراجعة إلى تحديد الفوائد المحتملة لاستخدام MI وSC لتحسين أداء الحفر، وإطالة عمر رأس الحفر، وتقليل نفقات الحفر. تستكشف المراجعة أيضًا الآليات التي من خلالها تؤدي هذه المعالجات المستحثة بدرجة الحرارة إلى إنشاء كسور وتشققات دقيقة تسهل عملية الحفر. في الختام، توضح

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نتايج الدراسة المرجعية أن كلا من MI وSC يمكنهما تغيير خصائص الصخور بشكل كبير، مما يوفر تطبيقات عملية في الحفر والتنقيب. يمكن لهذه التقنيات أن تقلل بشكل فعال من قوة الصخور، مما يؤدي إلى تحسين معدل اختراق الحفر (ROP) وتوفير التكاليف في عمليات الحفر. يمكن للأفكار التي قدمتها هذه المراجعة توجيه التطورات المستقبلية في الممارسات الهندسية، وخاصة في تعزيز كفاءة واستدامة أنشطة الحفر والتعدين والهندسة المدنية.

1. Introduction

This literature review examines how microwave heating and shock cooling affect the physical and mechanical properties of different rock including sedimentary and igneous rocks. While research into microwave heating of rocks is expanding, studies concentrating on the combined impacts of microwave heating and shock cooling are limited. The purpose of this review is to provide a wide-ranging Summary of significant findings and identify knowledge gaps that require additional investigation via microwave heating and shock cooling procedures.

1.1. Microwave Irradiation and its Effect on Rocks

Various innovative technologies in recent years have been developed to change rock property, weaken the rocks, increase Drilling Rate of Penetration (ROP) and improve drilling performance. One technology is the use of microwave irradiation on rocks. Microwave irradiation has shown encouraging results in changing the mechanical characteristics of rocks, resulting in better drilling performance and lower energy consumption via decreasing the strength of the rocks exposed to. Other innovative technologies, like vibro-drilling and laser-assisted drilling, have also been investigated to increase ROP and overcome drilling problems in varied formations through lowering the strength of the drilled rocks via localized heat, but in a different concept of using the microwave irradiations. The review examines the effect of microwave irradiation on several rock properties, including mainly rock strength as a key of rock mechanical properties. It involves investigating the underlying mechanisms that affect rock behavior that could enhance drilling performance.

1.2. Microwave Irradiation and Its Applications

1.2.1. Tunnel Boring and Disc cutter

The use of microwaves was first proposed to break down natural rocks without the need for mechanical devices [1]. Later the use of microwaves was for rock preparation before utilizing mechanical discs could serve as a practical alternative to traditional rock fracturing technology [2].

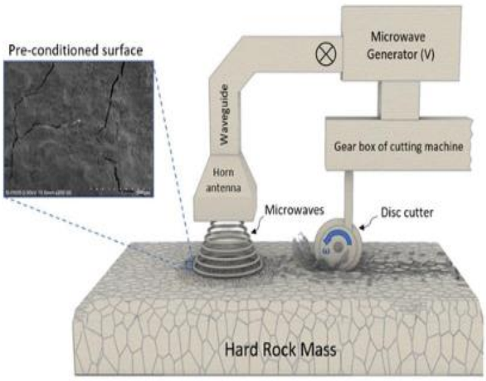
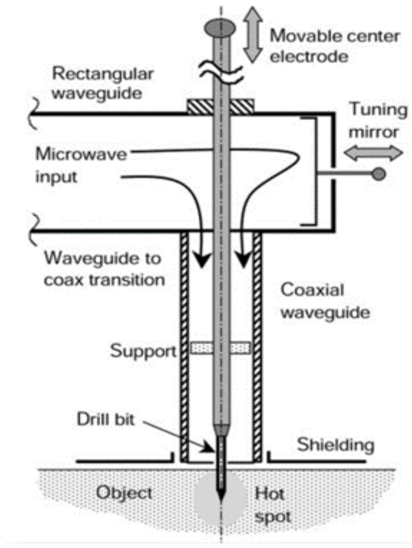


Fig. 1: A conceptual representation of a microwave-assisted rock pre-conditioning system before undergoing breakage by a disc cutter [2].

Since then, various researchers explored the use of microwaves in rock pre-conditioning as an inventive technique for future rock-breaking operations. Figure 1 shows a conceptual illustration of the core concept, a microwave-assisted rock pre-conditioning system before the use of mechanical tools such as a Tunnel Boring Machine (TBM) disc cutter, or road header.

1.2.2. Microwave Drilling

A unique device was developed to transmit microwave radiation from a 1 kW magnetron to a waveguide and, ultimately, into the material. The design ensured that the microwaves were precisely directed at a specific point on the material creating a hot spot beneath the drill bit as shown in Figure 2 (top). Later, an enhanced concept was introduced featuring a novel design for a Microwave Drill (MWD) system, which aimed to develop a localized hot spot on the object's surface as shown in Figure 2 (a) and (b) [3,4].



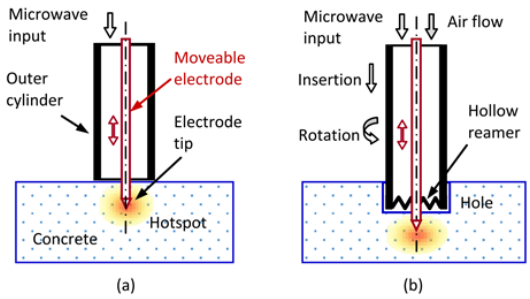


Fig. 2: Operational principles of a microwave-drill system (top). Schemes of Microwave Drill (MWD) application, including a basic MWD with a coaxial waveguide and movable centre electrode for creating holes (bottom a and b, respectively) [3, 4]

Figure 2 (bottom a) shows the microwaves that are transmitted from a rectangular waveguide to a coaxial waveguide. The central electrode, acting on the drill bit and focuses on the microwaves, creates a hot spot on the surface, and weakening the rock for making the break of the rock easier and therefore making drilling faster. Moreover, a basic microwave drill that could create holes 26 cm deep with a 12 mm diameter in concrete was developed as shown in Figure 2 (bottom b). Operating silently at a 2.45 GHz frequency, this technology could drill 1.5 cm holes. While successfully applied to materials like glass, basalt, concrete, ceramics, and silicon, it remains at the bench scale [3,4].

1.2.3. Percussive Drilling

A published study plots microwave exposure times versus penetration rate for the percussive drilling process. The study indicates a 42% increase in penetration at 360s microwave exposure compared to untreated samples of basalt formation. Additionally, visually evident thermally induced cracks were observed only after 180s and 360s exposures as shown in Figure 3(a). Furthermore, this study concludes that basaltic rock has significant responsiveness to microwave exposure at low power levels, with temperatures displaying a linear increase with irradiation time [5].

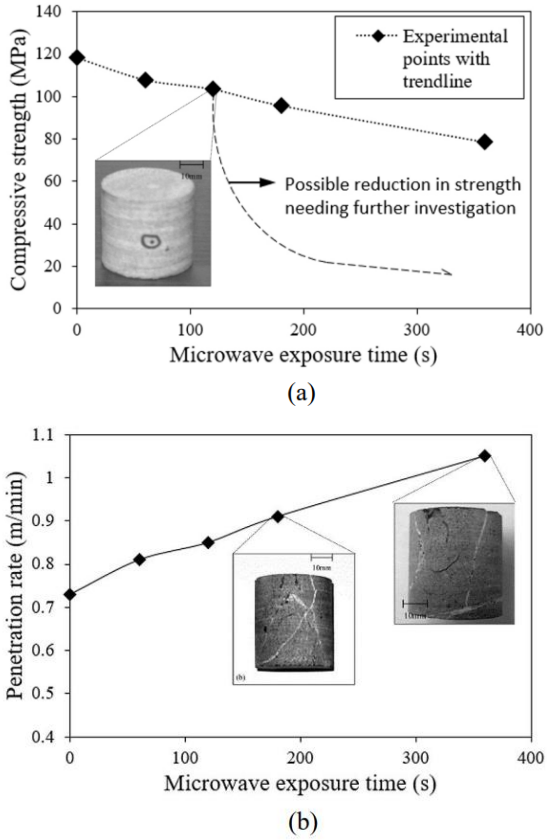


Fig. 3: Demonstration of the influence of microwave treatment on basaltic rocks with a power density of 1 W/g, at different exposure times, showing the samples' mean compressive strength (a) and basalt penetration rate during a percussive drilling (b) [5].

The effect of low-energy microwave radiation (100 W to 150 W) on basaltic rocks was also studied [6]. The tested cylindrical samples were exposed with multiple microwave cavity at 2.45 GHz 60, 120, 180, and 240. Infrared Radiation (IR) cameras were used to check the temperature change. The work showed that the performed mechanical test indicated temperature increase with longer exposure time, where cracking was generated and strength of the formation was decreased, as shown on the rock samples displayed in Figure 3(b).

1.2.4. Mining Excavation

Another study established that the rate of penetration (ROP) can be increased by applying constant thrust to previously softened rocks [7]. The study introduced the concept of affixing a microwave antenna to the cutter head of a continuous Tunnel Boring Machine (TBM) (Figure 4). The study showed an increase in ROP with increasing microwave power. Moreover, the study examined the changes in rock properties resulting from microwave radiation and their implications for drilling operations. The results demonstrate changes in rock strength, ductility, permeability, and highlight the potential for microwave radiation to influence rock behavior during drilling, tunneling, and mining excavation.

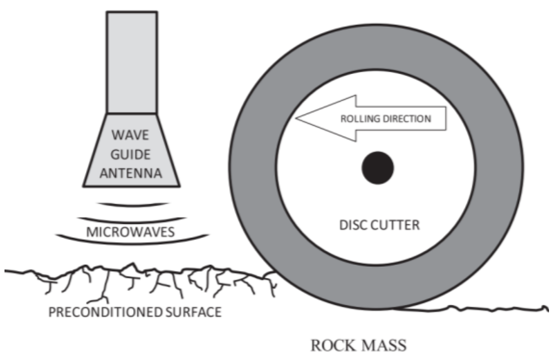


Fig. 4: A schematic diagram of a microwave-assisted disc cutter used in a continuous tunnel boring machine (TBM), as further demonstrated by Hassani et al. [7].

A comprehensive review [8] reported 20 years of experimental and numerical studies of microwave assisted rock and mineral fractures. This review thoroughly examines a detailed analysis of the mechanisms through which microwave irradiation impacts rock behavior. The study also covers both thermal and non-thermal phenomena, such as temperature fluctuations, thermal stress, and changes in rock mechanical and chemical characteristics. The work provided a deep understanding of the complicated interactions between microwaves and rocks, allowing researchers to optimize the use of microwave radiation for rock treatment.

1.2.5. Rotary Drilling and Coring

Another study [9] investigated the effects of microwave irradiation (MI) on rock characteristics and their impact on drilling and coring performance in hard formation of granite. The study carried the Drill-Off performance Tests (DOT) on granite samples before and after Microwave Irradiation (MI) exposure. The work was performed at the initial room temperature for each sample at 22.2 degrees. Subsequently, at intervals of 75 seconds, the MI for each sample progressively rose, reaching a maximum of 183 degrees after 450 seconds. The DOT was then performed on all samples using a dual cutter Polycrystalline Diamond Compact (PDC) bit. The Drilling Rate of Penetration (D- ROP) was increased during the experiment, which was impacted by the Weight on Bit (WOB) and the increased effects of MI heating on the granite rock. The results indicated that MI treatment reduced rock strength. Furthermore, the results of the enhancement of the drilling rate of penetration support previous researchers reported the same findings of the positive impact of MI on weakening the rocks by creating microcracks.

2. Factors Influencing Microwave Heating of Rocks

Researchers reported that there are several factors that affect the efficiency of microwave heating in rocks, including mineralogy and chemical composition, rock physical properties, and microwave radiation parameters. For example, highly volatile minerals such as sulfides and oxides readily absorb microwave energy and convert it to heat, while many loss minerals such as quartz and feldspar are non-MI energy absorbent [1]. Studies found that once the MI energy is absorbed by the MI energy absorbent rocks, the coefficient of thermal expansion among minerals can cause intergranular cracking during heating. [10, 11].

2.1. Rock properties

Rock properties including grain size, texture, porosity, and water content are found to have a great effect on microwave heat response. Furthermore, fine-grained rocks absorb more microwave energy, porosity and water content affect heat transfer and potential for pressure build-up especially as water is a good microwave absorber, its presence can lead to significant temperature increases and can lead to stress build-up and cracking of the rocks exposed to microwave irradiations [12].

2.2. Microwave irradiation factors

Microwave irradiation factors, including power level, exposure time, and frequency, have a direct influence on the heating process and the consequent changes in rock properties. Researchers reported that higher power levels heat faster, but energy levels can be degraded. Furthermore, research shows that a longer exposure time results in higher energy absorption and higher temperatures, and microwave frequency influences penetration depth and thermal efficiency. However, the higher frequencies produce more heat, but less penetration, while the lower frequencies produce deeper penetration, but less heat [13].

2.3. Rock mineralogy and chemical composition

Rock mineralogy and chemical composition are also found to be important factors. Minerals with high dielectric loss, such as sulfides and oxides, absorb microwave energy more effectively and experience increasing temperatures compared to low-loss minerals such as quartz and feldspar. This differential absorption causes various heating rates within the rock which affects its overall thermal response. In addition, the thermal expansion coefficient of the minerals in the rock contributes to the generation of internal stresses as these minerals expand thermally, causing micro cracks and fractures [14, 15].

3. Shock Cooling Effects in Rock

The rapid cooling of heated rocks, known as shock cooling, is an important factor in determining the final state of rocks that can have a significant impact on rock's mechanical properties. This rapid temperature change causes a significant amount of thermal stress, which can lead to micro cracks and fracture propagation, which eventually results in weakening the rocks and can change its permeability. This damage is caused by a combination of factors (i) thermal expansion of anomalies, where different minerals in the rock expand at different rates during heating, causing internal compression during rapid cooling, (ii) changes in minerals that can change their volume and create additional pressure as they cool, and (iii) hydration occurrence, where water molecules are absorbed into clay minerals as they cool, creating volume and internal pressure increases, especially in rocks containing clay minerals. [16- 18].

In addition, research shows that the choice of cooling medium has a significant impact on the severity of thermal shock. Liquid nitrogen (LN2), with its extremely low temperature, causes the most significant damage due to its rapid cooling rate [19]. While water is readily available and inexpensive, it can still cause significant damage, especially in rocks containing clay minerals, due to hydration expansion. Air cooling is less effective than liquid nitrogen or water cooling, but it can still cause damage if it is done quickly.

To reduce undesirable damage and optimize the effects of shock cooling, researchers investigate the relationship between cooling mechanisms, cooling rates, and resultant damage in rock types. Thus, understanding this relation is important in predicting and controlling the resultant damage, as researchers develop models and methods for testing damage to reach the desired level of optimal cooling reduction techniques requires adaptation between cooling rate, selective cooling medium, and rock properties.

The comprehensive review is summarized in Tables 1, 2, 3, and 4. Table 1 presents an overview of the conducted studies involving microwave irradiation on various rock types, including the applications, objectives, and experimental setups used across different microwave powers and frequencies. Table 2 offers a review of the factors influencing the microwave heating of rocks, detailing the methods employed and the conclusions drawn. Table 3 provides a summary of the effects of shock cooling methods on different rock types. Table 4 provides a detailed comparative analysis of the influence of microwave heating and shock cooling on different rock types, focusing on aspects such as faster responsiveness, effectiveness, type of fractures (e.g., shear, tensile, micro or macro cracks, etc.), and an overall percentual efficiency.

Table 1: A review summary studies conducted using microwave irradiation on various rock types and the applications, setups used at different Microwave powers and frequencies.

Rock Type	Method	Experimental Setup	Power (kW)	Frequency (GHz)	Result and discussion	Conclusion	Reference
Various Materials	Microwave Drilling	Laboratory with waveguide and electrode	0.6	2.45	Microwave drill successfully penetrated concrete, ceramics, basalt, glass, and silicon.	Microwave drilling is technically feasible for a range of materials.	[3]
Andesite	Microwave Heating & Melting	Domestic oven	0.9	2.45	Andesite specimens completely melted after 30 minutes of exposure to 900W power.	Microwave heating can melt rocks, potentially useful for rock modification applications.	[20]
Basalt	Microwave Heating & Strength Reduction	Laboratory with cavity	0.75	2.45	Compressive strength and CERCHAR abrasively index decreased with microwave energy.	Microwave heating can weaken basalt, indicating its potential for rock pre-conditioning before mechanical excavation.	[5]
Basalt	Microwave Heating & Strength Reduction	Laboratory with cavity	0.75	2.45	Longer exposure to low-power microwaves caused the sample to spall and chip off.	Microwave heating can weaken basaltic rock, potentially facilitating drilling operations.	[6]
Basalt	Microwave Heating & Strength Reduction	Laboratory with waveguide	17.5	2.45	Significant changes in mechanical properties were observed with high-power microwave heating.	Microwave heating can cause significant cracking in basalt, suggesting its potential for rock weakening applications.	[17]
Shale	Microwave Heating & Fracturing	Laboratory	-	-	Microwave heating can enhance hydraulic fracturing in shale gas reservoirs.	Microwave heating can increase shale permeability, potentially improving gas extraction.	[21]
Basalt	Microwave Heating & Strength Reduction	Laboratory with cavity	1.2-5	2.45	Compressive strength and Cerchar abrasively index decreased with microwave energy.	Microwave heating can weaken basalt, indicating its potential for rock pre-conditioning before mechanical excavation.	[7]
Gabbro	Microwave Heating & Strength Reduction	Laboratory with cavity	2	2.45	P-wave velocity and strength decreased with microwave treatment.	Microwave heating can effectively weaken gabbro, suggesting potential for rock modification applications.	[22]
Granite	Microwave Heating & Cutting	Laboratory with waveguide	24	2.45	Cutting forces reduced by 10% after microwave treatment.	Microwave assisted cutting is technically feasible.	[23]
Basalt	Microwave Heating & Strength Reduction	Laboratory with waveguide	17.5	2.45	Significant changes in mechanical properties were observed with high-power microwave heating.	Microwave heating can cause significant cracking in basalt, suggesting its potential for rock weakening applications.	[24]
Basalt	Microwave Heating, Strength Reduction & Fragmentation	Laboratory with cavity	2	2.45	Strength decreased, and fragmentation occurred with increasing power and time. Cracks formed around olivine grains.	Microwave heating can effectively weaken basalt, suggesting potential for rock modification applications.	[14]
Granite	Water & Antifreeze Cooling	Laboratory	-	-	Cooling shock can significantly alter the temperature profile and	A systematic experimental study is needed to evaluate the influence of different cooling	[26]

					cracking behavior of granite.	media on the cracking behavior and mechanical properties of granite at different temperature gradients.	
Granite	Microwave Heating & Structural Evolution	Laboratory with cavity	6	2.45	The strength of granite decreased with increasing temperature, especially above 600°C.	Microwave heating can induce significant structural changes in granite, requiring further research.	[28]

Table 2: A review summary of the factors influencing microwave heating of rocks, providing information on methods employed and conclusions drawn.

Factors	Description	Methods & Conclusion
Mineralogy and Chemical Composition	• Dielectric Properties: [1- 34] Defines how well a mineral absorbs microwave energy and converts it into heat. • Thermal Expansion Coefficient: [13-15] Determines the extent of expansion and contraction during heating, influencing stress generation. • Chemical Bonding: [8, 10, 11] Affects how readily molecules or atoms within the mineral structure respond to the microwave field.	• X-Ray Diffraction (XRD), Scanning Electron Microscopy (SEM) with Energy Dispersive X-Ray Analysis (EDX) • Concluded that high-loss minerals like sulfides and oxides are more susceptible to microwave heating than low-loss minerals like quartz and feldspar, and that thermal expansion mismatch can lead to intergranular cracking.
Physical Properties of Rocks	• Grain Size and Texture: [15, 22] Larger surface areas in fine-grained rocks increase absorption. Texture influences heat transfer and stress distribution. • Porosity and Water Content: [12, 32] Water acts as a powerful microwave absorber, significantly enhancing heating and potentially leading to pressure build-up and cracking.	• Optical microscopy, SEM, and Mercury Intrusion Porosimeter • Concluded that finer-grained rocks with higher water content heat more rapidly and experience greater cracking due to steam pressure.
Microwave Parameters	• Power Level: [11- 14] Higher power levels increase heating but risk hotspots and damage. • Exposure Time: [8, 9] Longer exposure leads to higher temperatures and greater potential for modification. • Frequency: [1-3] Affects penetration depth and heating efficiency. Higher frequencies (shorter wavelengths) lead to more heat generation but shallower penetration.	• **Microwave** heating experiments with varying power levels and exposure times. • Concluded that higher power levels and longer exposure times lead to greater temperature increases and more significant rock modifications.
Cooling Method and Rate	• **Shock Cooling**: [16, 18, 19] Rapidly cooling a heated rock induces significant thermal stress, potentially causing micro cracking and fracture propagation. • **Cooling** Media: [25, 29, 30] The choice of cooling media affects the cooling rate and the severity of thermal shock.	• **Shock cooling** experiments using various media (water, air, liquid nitrogen) and **cooling** rates. • Concluded that faster cooling rates and greater temperature differences between the rock and the cooling medium result in more severe crack formation and changes in mechanical properties.

Table 3: A review summary of shock cooling method effects on various rock types.

Rock Type	Cooling Method	Result and discussion	Conclusion	Reference
Various Rocks	Liquid Nitrogen Cooling	Liquid Nitrogen cooling significantly altered the pore structure of rocks.	Rapid cooling can induce significant changes in rock porosity and permeability.	[30]
Various Rocks	Water and Liquid Nitrogen Cooling	Rapid cooling (thermal shock) leads to significant changes in rock properties, especially compressive wave velocity.	Thermal shock has a weakening effect on rock strength and integrity.	[16]
Granite	Water Cooling	Cooling rate influences the mechanical behavior of heated granite.	The faster the cooling rate, the greater the damage induced in the rock.	[31]
Granite	Liquid Nitrogen, Water, Air Cooling	Different cooling methods (LN2, water, air) produce significant differences in physical and mechanical properties of heated granite.	Liquid nitrogen cooling induces the greatest degree of thermal damage, followed by water cooling and air cooling.	[19]
Sandstone	Water Cooling	Water cooling can induce the highest degree of thermal damage in sandstone compared to LN2 or air cooling.	Hydration expansion of clay minerals in sandstone during water cooling can significantly weaken the rock.	[18]
Sandstone	Water Cooling	Water cooling causes greater damage to sandstone's mechanical properties compared to air cooling.	Rapid cooling aggravates the damage degree of specimens.	[25]
Granite	Thermal Shock	The UCS, tensile strength, and cohesion of granite decreased with increasing cooling media temperature.	The study highlights the importance of cooling media temperature in the thermal shock process.	[29]

Table 4: A comparative analysis of the influence of microwave heating and shock cooling on different rock types.

Rock Type	Microwave Heating	Shock Cooling	Type of Fractures	Overall Percental Efficiency %	References
Granite	**Responsiveness:** Fast due to high microwave absorption. **Effectiveness:** Highly effective in inducing thermal stress and microcracks.	**Responsiveness:** Slow due to high strength and thermal resistance. **Effectiveness:** Effective in creating larger fractures with repeated cycles.	**Microwave:** Tensile and shear fractures. Minor macrocracks. **Shock Cooling:** Primarily tensile fractures. Larger macrocracks.	**Microwave:** 75% **Shock Cooling:** 65%	[33], [34]
Basalt	**Responsiveness:** Rapid due to high microwave absorption. **Effectiveness:** Effective in inducing small fractures and thermal expansion.	**Responsiveness:** Slow, requiring intense shock waves. **Effectiveness:** Effective in creating large fractures.	**Microwave:** Shear and tensile fractures. Microcracks and minor macrocracks. **Shock Cooling:** Predominantly tensile fractures. Larger macrocracks.	**Microwave:** 70% **Shock Cooling:** 68%	[35], [36]
Sandstone	**Responsiveness:** Moderate due to lower microwave absorption. **Effectiveness:** Moderately	**Responsiveness:** Fast with high shock wave penetration. **Effectiveness:** Highly effective	**Microwave:** Tensile fractures. Predominantly microcracks.	**Microwave:** 60% **Shock Cooling:**	[34], [37]

	effective in creating small fractures.	in inducing fractures.	**Shock Cooling:** Both tensile and shear fractures. Both micro and macrocracks.	80%	
Limestone	**Responsiveness:** Slow due to low microwave absorption. **Effectiveness:** Less effective in creating fractures.	**Responsiveness:** Moderate due to higher shock sensitivity. **Effectiveness:** Moderately effective, depending on shock intensity.	**Microwave:** Minor tensile fractures. Minor microcracks. **Shock Cooling:** Predominantly tensile fractures. Larger macrocracks.	**Microwave:** 55% **Shock Cooling:** 70%	[33], [35]
Shale	**Responsiveness:** Moderate to slow. **Effectiveness:** Effective in creating microcracks.	**Responsiveness:** Fast compared to microwave. **Effectiveness:** Highly effective in inducing fractures.	**Microwave:** Tensile fractures. Predominantly microcracks. **Shock Cooling:** Both tensile and shear fractures. Both micro and macrocracks.	**Microwave:** 65% **Shock Cooling:** 75%	[36], [37]

4. Conclusion

This paper provided a comprehensive review of the effect of microwave irradiations on different rock types including granite and basalt as igneous rocks, and shale, Limestone, and sandstone as sedimentary rocks. Research conducted on the application of the use of the microwave on weakening the rocks through lowering rocks' strength led to enhancing the oil and gas drilling penetration, improving mining excavations, and constructing safe civil structures. The paper also investigated the factors influencing the rock heating by microwave irradiation and presented recommended practices that resulted the optimal outcomes on rocks including exposure time, microwave frequencies, microwave powers, etc., with respect to the type of rock and its mineral, chemical, and physical properties.

Moreover, this review highlighted that microwave and shock cooling as both are innovative techniques used to weaken rocks by inducing fractures, but they operate through different mechanisms. The microwave treatment works by rapidly heating the minerals within the rock, causing thermal expansion and generating microcracks due to differential expansion rates between minerals. This method is particularly effective in creating tensile fractures as the rapid heating leads to internal stress. Research shows that microwaves are especially efficient in weakening fine-grained rocks and rocks with high moisture content, as the water molecules absorb microwave energy and intensify the heating process.

On the other hand, shock cooling exploits the principle of rapid temperature reduction, typically after pre-heating, causing the rock to contract suddenly. This rapid contraction induces both tensile and shear fractures, with the intensity of these fractures depending on the rock's thermal properties and the cooling rate. Furthermore, shock cooling tends to create more extensive shear fractures compared to microwave treatment, making it highly effective for rocks with pre-existing weaknesses or inhomogeneities. When comparing both methods (microwave and shock cooling), shock cooling may generate more pronounced shear fractures, while microwaves are more effective in inducing tensile fractures, especially in homogenous and moisture-rich rocks.

5. Abbreviations

DTL	Drilling Technology Laboratory
LN	Liquefied Nitrogen
MI	Microwave Irradiation
MWD	Microwave Drill
PDC	Polycrystalline Diamond Compact
ROP/D-ROP	Rate of Penetration
SC	Shock Cooling
SEM	Scanning Electron Microscopy (SEM)
TBM	Tunnel Boring Machine
UCS	Unconfined Compressive Strength
XRD	X-Ray Diffraction

6. Acknowledgement

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