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Experimental Investigation of Microwave-induced Strength Reduction in Basalt for Efficient Rock Excavation

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Microwave irradiation has emerged as a promising technique for weakening high-strength rocks prior to excavation, with the potential to improve cutting efficiency and reduce mechanical energy consumption. In this study, we investigate the microwave-induced weakening behavior of two types of basalt—one from Vietnam and the other from Cheorwon, South Korea—under controlled laboratory conditions. Cylindrical rock specimens were exposed to 1000 W microwave energy for durations ranging from 1 to 10 min, and key physical and mechanical properties, including surface temperature, P-wave velocity, Schmidt rebound hardness, Leeb hardness, uniaxial compressive strength (UCS), and dry density, were measured before and after exposure. Results indicate that Cheorwon basalt is significantly more susceptible to microwave-induced weakening than Vietnamese basalt. Cheorwon basalt exhibited a UCS reduction of up to 20% after 5 min of exposure, a 28% decrease in Schmidt hardness, and a 10–12% decline in P-wave velocity, all of which point to internal microcrack propagation and surface degradation. Interestingly, the UCS of Cheorwon basalt partially recovered after 10 min of exposure, likely due to microcrack closure or stress redistribution at elevated temperatures. In contrast, Vietnamese basalt displayed only modest reductions in UCS and Schmidt hardness and only minimal changes in density or Leeb hardness. Dry density remained nearly unchanged in both rock types across all exposure durations, indicating that microwave damage is primarily microstructural and not volumetric. These findings demonstrate that microwave pretreatment can selectively and effectively weaken basalt without altering bulk geometry. The differential response between the two types of basalt highlights the influence of mineral composition and microstructure on microwave sensitivity. We conclude that microwave-assisted rock weakening offers a viable path toward more energy-efficient excavation in microwave-responsive lithologies.

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1. Introduction

Mechanical and blasting methods have traditionally dominated rock excavation in mining and civil engineering applications. However, these conventional techniques encounter significant limitations when applied to hard and abrasive rocks, including excessive energy consumption, accelerated equipment wear, and diminished excavation rates, all of which pose substantial economic and operational challenges.[1] These limitations become particularly pronounced in extreme environments such as deep tunnel excavation through strong igneous formations or extraterrestrial (e.g., lunar) excavation scenarios, where purely mechanical means often fail to achieve acceptable performance metrics.[1]

To address these challenges, researchers have explored various rock pretreatment technologies aimed at reducing rock strength prior to mechanical excavation. In recent years, noncontact energy delivery methods that physically weaken rock *in situ* have attracted considerable attention.[2] Among these, microwave irradiation has emerged as a promising technique for enhancing rock breakage efficiency. Microwaves—electromagnetic waves with frequencies ranging from approximately 300 MHz to 300 GHz—can penetrate materials and generate dielectric heating throughout their volume.[3] When high-power microwaves interact with heterogeneous rock materials, constituent minerals absorb electromagnetic energy differentially in accordance with their specific dielectric properties, resulting in selective internal heating. The consequent differential thermal expansion between adjacent mineral grains, coupled with steep temperature gradients, generates thermal stresses that induce microcracks and extend existing discontinuities within the rock matrix.[4] This microstructural damage compromises the rock's structural integrity. Previous investigations have documented significant reductions in strength parameters, elastic moduli, and comminution energy requirements following microwave treatment.[4–6]

In practical excavation scenarios, such induced damage can potentially manifest as reduced cutting forces, enhanced penetration rates, and more efficient fragmentation processes. The concept of microwave-assisted rock breakage was initially pioneered in the 1970s by Soviet researchers who integrated microwave energy delivery systems with tunnel boring machines (TBMs).[7] Since this early implementation, numerous experimental studies have validated the efficacy of microwave irradiation across diverse high-strength rock types. In investigations involving granite, basalt, diorite, and other hard rocks, the relationships between microwave power, exposure duration, mineral composition, and the resultant extent of rock fracturing and mechanical weakening have been examined.[4–6,8,9]

Lu *et al.* demonstrated the development of microwave-induced fracture networks in hard rock and established their dependence on exposure parameters.[4] Similarly, Hassani *et al.* reported substantial reductions in strength and hardness indices for various rock types subjected to microwave treatment.[5] Hartlieb *et al.* conducted systematic observations of crack pattern evolution in igneous rocks under controlled microwave exposure conditions,[6] while Yang *et al.* specifically documented alterations in the internal structure and mechanical properties of basalt following microwave heating.[9] Notably, microwave pretreatment has been shown to substantially reduce the energy requirements for subsequent mechanical breakage; Kingman *et* *al.* demonstrated that the comminution energy of certain ores can be decreased by more than 50% after appropriate microwave exposure.[10]

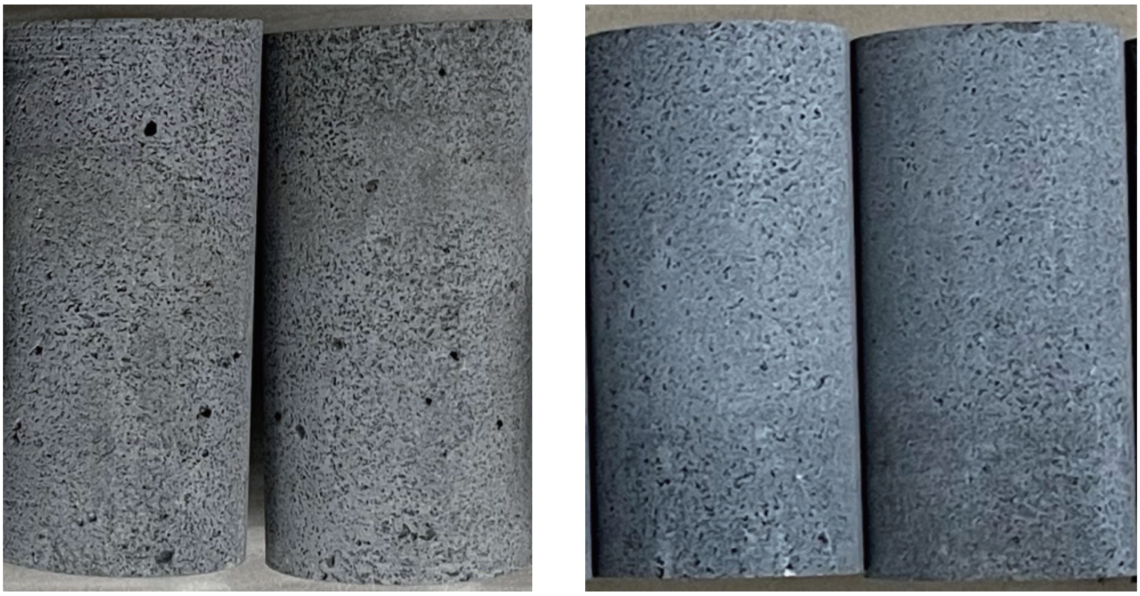
While these previous studies revealed the considerable potential of microwave technology to enhance rock excavation processes, they also suggest that treatment efficacy varies significantly with rock type, mineralogical composition, and microstructural characteristics. This variability necessitates systematic investigation of specific rock types under controlled conditions to optimize treatment parameters for practical applications.

Motivated by the challenges of excavating strong basalts and the promising results of prior microwave experiments, we investigate the efficacy of microwave irradiation as a pretreatment to reduce basalt strength to enable more efficient rock excavation. In particular, we focus on two geologically distinct basalts: one from a quarry in Vietnam and the other from the Cheorwon region of South Korea. These basalt types provide a useful contrast in mineralogical composition and origin, allowing us to examine how each responds to the same microwave exposure conditions. Controlled laboratory experiments were conducted in which cylindrical basalt specimens from each source were exposed to microwave energy for varying durations. Key physical and mechanical properties—including P-wave velocity (as an indicator of internal structural integrity), surface hardness (Schmidt rebound and Leeb hardness), and uniaxial compressive strength—were measured before and after irradiation. By quantifying the property changes induced by microwaves, we assess the degree of strength reduction achieved in each basalt type and compare their susceptibility to microwave-induced damage. The objective is to determine whether microwave pretreatment can meaningfully weaken these high-strength basalts, thereby potentially improving the efficiency of mechanical excavation, and to evaluate the influence of basalt geology (mineral composition and texture) on the treatment's effectiveness. In the following, we present the experimental setup and the results of microwave irradiation tests on Vietnamese and Cheorwon basalt. We then discuss the extent of the strength reduction observed, analyze the differences between the two basalt types, and consider the practical implications of using microwave-assisted weakening for rock excavation in the field. The findings of this work should help to advance the development of novel excavation technologies by demonstrating how microwave-induced thermal damage can facilitate the breakage of tough basaltic rock, ultimately contributing to more efficient and cost-effective excavation operations.

2. Materials and Methods

2.1 Basalt samples

Basalt rock samples were obtained from two distinct geological sources: Cheorwon (Republic of Korea) and northern Vietnam. Cylindrical core specimens were prepared with nominal dimensions of 54 mm diameter and 110 mm length, conforming to the recommended length-to-diameter ratio (approximately 2:1) for standard geomechanical testing. Both basalt types exhibited a dense, fine-grained aphanitic texture with occasional microscopic pores and vesicles, as shown in Fig. 1.



(a) (b)

Fig. 1. (Color online) Experimental samples of (a) Vietnamese basalt and (b) Cheorwon basalt.

All rock samples were oven-dried at 105 ℃ for at least 24 h to eliminate free moisture and simulate low-humidity excavation environments. After drying, the samples were cooled to room temperature in a desiccator (relative humidity <10%) prior to testing. Table 1 summarizes the number of samples used and the testing conditions.

2.2 Microwave irradiation procedure

Microwave treatment was performed using a commercially available microwave oven operating at 2.45 GHz with a maximum power output of 1000 W. Each basalt specimen was irradiated individually at full power. The samples were placed at the center of the rotating turntable to ensure uniform exposure. Irradiation durations were set to 1, 3, 5, 7, and 10 min for Cheorwon basalt, while Vietnamese basalt was tested only up to 5 min.

Immediately after irradiation, the surface temperature of each specimen was recorded using a handheld infrared thermometer. The procedure was conducted under atmospheric pressure and ambient room temperature (approximately 25 ℃).

Vietnamese basalt specimens were exposed only up to 5 min because preliminary results showed significantly lower sensitivity to microwave irradiation than Cheorwon basalt. Moreover, additional identical Vietnamese basalt specimens could not be secured, which also restricted the experimental exposure time to 5 min.

2.3 Measurement of physical and mechanical properties

The physical and mechanical properties of the rock samples were assessed before and after microwave irradiation. P-wave velocity was measured using an ultrasonic pulse transmission

Table 1
Classification and number of basalt samples used for testing.

Rock type	Irradiation time	Number of samples	Measurement parameters
Vietnamese Basalt	0 min (control)	9	Density, P-wave vel., Schmidt, Leeb, Temp., UCS
	1 min	5	Density, P-wave vel., Schmidt, Leeb, Temp.
	3 min	5	Density, P-wave vel., Schmidt, Leeb, Temp.
	5 min	5	Density, P-wave vel., Schmidt, Leeb, Temp., UCS
Cheorwon Basalt	0 min (control)	10	Density, P-wave vel., Schmidt, Leeb, Temp., UCS
	1 min	10	Density, P-wave vel., Schmidt, Leeb, Temp.
	3 min	10	Density, P-wave vel., Schmidt, Leeb, Temp.
	5 min	10	Density, P-wave vel., Schmidt, Leeb, Temp., UCS
	7 min	10	Density, P-wave vel., Schmidt, Leeb, Temp.
	10 min	10	Density, P-wave vel., Schmidt, Leeb, Temp., UCS

system in accordance with ASTM D2845-08.(11) Transducers were applied to both ends of each specimen to record the P-wave transit time. P-wave velocity was then calculated by dividing the specimen length by the measured transit time. Schmidt rebound hardness was determined using a Type L Schmidt hammer following ASTM D5873-14.(12) Each specimen was struck 20 times along its side surface, and the average of the upper 50% of rebound values was used after applying correction factors. Leeb hardness was measured with a portable Leeb hardness tester (D-type). Ten readings were taken on the top and bottom surfaces of each specimen, and the average was calculated after excluding the highest and lowest values. Although there is no standardized ASTM procedure for measuring Leeb hardness on rock, this methodology follows practices reported in recent geotechnical literature.(13) Density was calculated by dividing the oven-dry mass of the sample by its volume calculated using diameter and height measured with calipers. The uniaxial compressive strength (UCS) was tested in accordance with ASTM D7012-14.(14) UCS was measured using a uniaxial loading machine and calculated as the peak load at failure divided by the cross-sectional area. To preserve material for other tests, UCS was measured only for control (0 min) samples and those with long durations of exposure to microwaves (≥5 min). The surface temperature was recorded immediately after microwave irradiation with an infrared thermometer.

2.4 Data analysis

All experimental results were statistically analyzed to assess the significance of property changes across irradiation times. Analysis of variance (ANOVA) was applied to evaluate the effects of microwave exposure duration on each measured property. Where applicable, comparisons between Vietnamese and Cheorwon basalt were conducted to determine material-specific responses to microwave energy. Quantitative analysis was conducted using one-way analysis of variance (ANOVA) with a significance level of 0.05. ANOVA results indicated statistically significant variations for Cheorwon basalt in P-wave velocity ($F = 56.11$, $p < 0.001$), Schmidt rebound hardness ($F = 4.82$, $p = 0.016$), and Leeb hardness ($F = 7.98$, $p = 0.002$). Vietnamese basalt exhibited significant variations in P-wave velocity ($F = 7.08$, $p = 0.021$) and Schmidt rebound hardness ($F = 14.15$, $p = 0.003$), while no significant differences were observed in the density and UCS for either basalt.

3. Results

Microwave irradiation caused noticeable changes in the measured physical and mechanical properties of both Cheorwon and Vietnamese basalt. The key results are presented below for each parameter, with direct comparisons between the two rock types to highlight differences in microwave-induced weakening.

3.1 Temperature rise in basalt specimens

Basalt specimens from both sources experienced significant heating during microwave exposure. Starting from near room temperature (25 °C), the surface temperature of the rocks rose rapidly within the first minute and continued to increase with longer exposure though at a slowing rate. For example, after 1 min of 1000 W microwave irradiation, the temperature of Cheorwon basalt reached approximately 62 °C and further climbed to 113 °C by 3 min and 159 °C by 5 min. Vietnamese basalt showed a similar heating trend but attained slightly lower temperatures: about 56 °C after 1 min, 96 °C after 3 min, and 138 °C at 5 min. This indicates that Cheorwon basalt absorbed microwave energy somewhat more efficiently, attaining higher surface temperatures under the same conditions. The rate of temperature increase was highest in the initial interval and diminished over time as the specimens grew hotter. By the end of the 5 min exposure, both rock surfaces were well above the boiling point of water, demonstrating the intense heating effect of microwave irradiation on basalt. For Cheorwon basalt, 7 and 10 min exposures further elevated the surface temperature to 243.6 °C and 306.7 °C, respectively (Fig. 2). This trend indicates more efficient microwave absorption in Cheorwon basalt, possibly due to differences in mineral composition and grain structure.

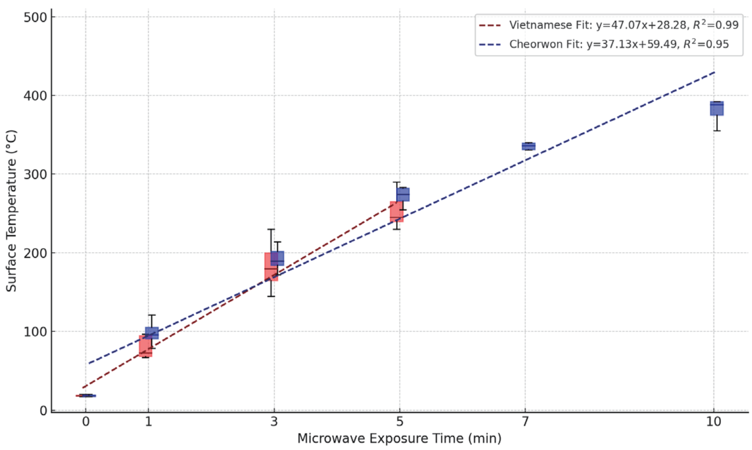


Fig. 2. (Color online) Surface temperature rise as a function of microwave exposure time for Cheorwon and Vietnamese basalts.

3.2 P-wave velocity reduction

Both basalt types exhibited a clear decline in P-wave velocity with increasing microwave exposure time, indicating internal structural damage due to the microwave treatment. Figure 3 illustrates the trend of decreasing P-wave velocity as irradiation time increases for the two rock types. Cheorwon basalt had an initial P-wave velocity of about 4445 m/s, which dropped steadily to approximately 4003 m/s after 5 min of microwave exposure. This corresponds to roughly a 10% reduction in wave speed. Vietnamese basalt showed a similar downward trend but with a smaller magnitude of change: its P-wave velocity declined from about 4352 m/s initially to 4105 m/s at 5 min, about a 6% decrease overall. The measurements at intermediate times reinforce this pattern. By 3 min, Cheorwon basalt's P-wave speed had already fallen to 4190 m/s (a noticeable drop), whereas that of Vietnamese basalt was around 4260 m/s. In all cases beyond 1 min, specimens showed lower sonic velocities than their unheated counterparts, confirming that microwave irradiation progressively deteriorated the ability of the rocks to transmit compressional waves. The more pronounced velocity loss in Cheorwon basalt suggests it suffered greater internal cracking due to the microwaves, consistent with its higher observed temperature rise. Statistically, the reduction in P-wave speed for Cheorwon basalt was highly significant ($p < 0.001$), while that for Vietnamese basalt, though evident in magnitude, showed more variability among samples. The continuous decline in P-wave velocity is strong evidence of microwave-induced microcrack formation within the basalt. As microcracks proliferate, they disrupt the continuity of the rock and force seismic waves to take longer, more tortuous paths, thereby reducing wave velocity. In essence, the P-wave velocity results indicate that thermal shock from microwave heating (via rapid internal temperature increase and differential expansion of minerals) generated new cracks and expanded existing flaws inside the basalt. This internal damage was more severe in the Cheorwon basalt, reflected by its steeper P-wave velocity reduction curve than that of Vietnamese basalt (Fig. 3). Extended irradiation of Cheorwon basalt to 7 and 10 min caused further velocity declines to 3782.4 and 3520.2 m/s,

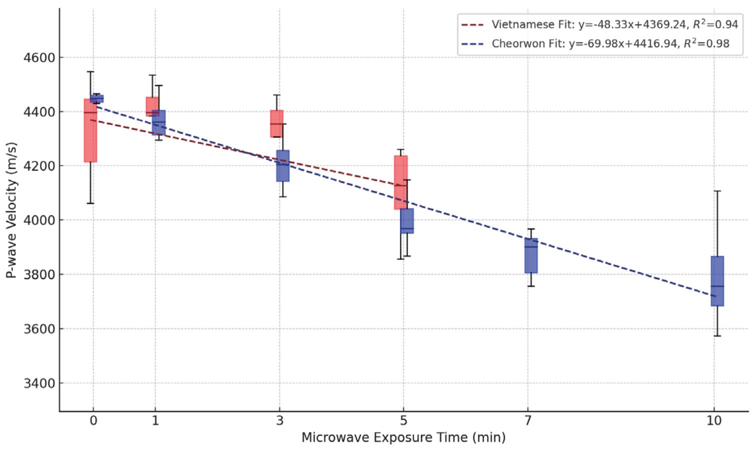


Fig. 3. (Color online) P-wave velocity variations with microwave exposure time for Cheorwon and Vietnamese basalt specimens.

respectively, representing a total reduction of 20.8% from that under the untreated condition. These reductions in P-wave velocity suggest significant microcracking and internal damage, with Cheorwon basalt exhibiting greater sensitivity to microwave exposure than Vietnamese basalt.

3.3 Hardness changes

Microwave irradiation caused a clear reduction in the surface hardness of both Cheorwon and Vietnamese basalt specimens, as confirmed by Schmidt rebound and Leeb hardness measurements. However, the degree and pattern of degradation differed significantly between the two rock types, and between the short-term (0–5 min) and extended (7–10 min) exposure durations. Table 2 presents the measured Schmidt and Leeb hardness values for both basalts across the full range of exposure durations. Figures 4 and 5 show these trends graphically, enabling direct comparison between the two materials and over time.

For Cheorwon basalt, Schmidt rebound hardness exhibited a steep and progressive decline with increasing microwave exposure. The initial hardness of 40.8 dropped sharply to 32.5 after just 1 min of exposure, corresponding to a 20% reduction. A minor increase to 34.3 at 3 min suggests local variability or transient stress redistribution. However, by 5 min, the value had dropped again to 32.1. Further decreases to 30.6 at 7 min and 29.4 at 10 min were observed,

Table 2
Surface hardness of Cheorwon and Vietnamese basalt under microwave exposure.

Exposure time (min)	Schmidt hardness (Cheorwon)	Schmidt hardness (Vietnamese)	Leeb hardness (Cheorwon)	Leeb hardness (Vietnamese)
0	40.8	52.0	715.0	725.9
1	32.5	49.8	696.2	716.0
3	34.3	48.2	643.1	711.1
5	32.1	47.0	667.2	715.5
7	30.6		650.4	
10	29.4		642.3	

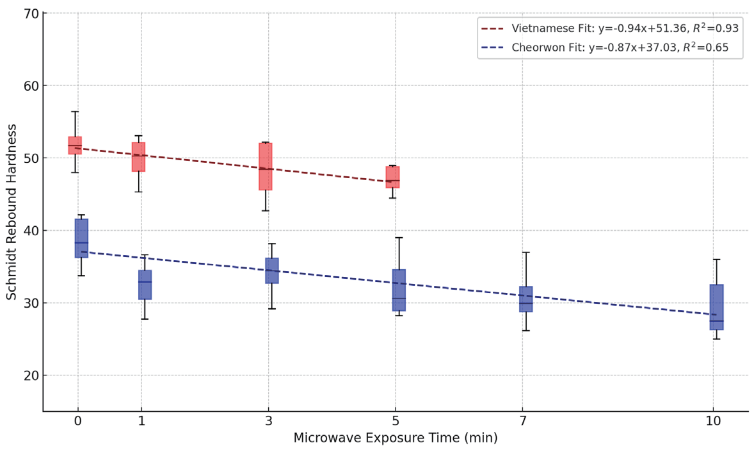


Fig. 4. (Color online) Schmidt rebound hardness variations with microwave exposure time for Cheorwon and Vietnamese basalt specimens.

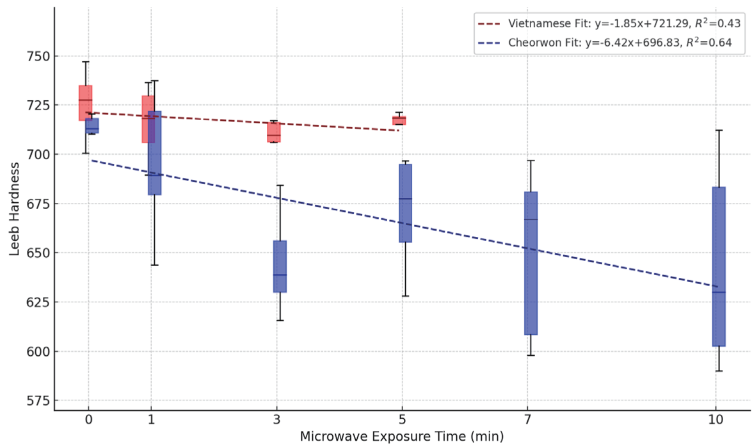


Fig. 5. (Color online) Leeb hardness variations with microwave exposure time for Cheorwon and Vietnamese basalt specimens.

resulting in a total reduction of approximately 28% from that under the unheated state. This trend reflects the cumulative effect of thermal-stress-driven surface microcrack propagation, which compromises the rock's ability to elastically rebound after impact. In comparison, Vietnamese basalt began with a higher Schmidt hardness of 52.0, and this value decreased gradually to 47.0 at 5 min. This 10% reduction indicates better resistance to surface weakening.

Leeb hardness for Cheorwon basalt also showed notable changes. The initial value of 715.0 decreased to 696.2 at 1 min and dropped more significantly to 643.1 at 3 min, a reduction of approximately 10%. This was followed by a partial rebound to 667.2 at 5 min, potentially owing to localized crack closure or thermal rearrangement at the grain boundaries. Extended exposure reduced the hardness again, reaching 650.4 at 7 min and 642.3 at 10 min, confirming continued but slower surface degradation. Vietnamese basalt, on the other hand, showed stable Leeb hardness values: from 725.9 initially to 715.5 after 5 min, with minor fluctuations within 2%, all within a typical measurement uncertainty.

The differences between the two basalts suggest that the surface of Cheorwon basalt is more sensitive to microwave-induced damage. Schmidt and Leeb hardnesses both showed larger absolute and relative decreases in Cheorwon samples, while Vietnamese basalt retained most of its original surface hardness. The Leeb hardness results also indicate nonlinear behavior, particularly in Cheorwon basalt, with an early steep decline, midterm partial recovery, and renewed reduction with extended exposure. This complex response reflects the interplay between microcrack generation and thermal stress relaxation. These findings confirm that microwave-induced weakening occurs more rapidly and significantly in Cheorwon basalt, both at the surface and internally.

3.4 Changes in density

Microwave exposure caused negligible changes in the dry density of both Cheorwon and Vietnamese basalt specimens, even when the exposure duration was extended up to 10 min. For

Cheorwon basalt, the initial dry density was measured at 2.52 g/cm^3 at 0 min, with no change observed at 1 min. A minor dip to 2.49 g/cm^3 was recorded at 3 min, possibly reflecting early-stage microcrack formation or slight thermal expansion. However, the value returned to 2.51 g/cm^3 at 5 min and slightly increased to 2.54 g/cm^3 and 2.55 g/cm^3 at 7 and 10 min, respectively. These variations, all within ±0.03 g/cm^3 of the initial value, fall within the range of experimental measurement uncertainty and are not considered statistically significant. The subtle increase in measured density at longer durations may be attributed to microcrack closure, compaction of the internal structure under thermal stress, or minor rearrangement of grains as the rock reaches higher internal temperatures. Nevertheless, the overall density remained effectively constant across all exposure durations, confirming that microwave treatment—even up to 10 min—does not alter the bulk density of Cheorwon basalt in a meaningful way.

Vietnamese basalt exhibited even greater density stability. The dry density remained unchanged at 2.41 g/cm^3 across all tested durations from 0 to 5 min, with no observable trend or deviation. The constancy of the density of Vietnamese basalt further supports the conclusion that this material is less sensitive to microwave energy, and that its internal structure resists expansion, compaction, or crack-induced volumetric change under the tested conditions. From a geomechanical standpoint, the preservation of density indicates that microwave irradiation primarily induces internal structural damage rather than macroscopic volumetric effects.

3.5 Uniaxial compressive strength variation

Microwave irradiation influenced the UCS of both Cheorwon and Vietnamese basalt, but the degree and temporal pattern of strength degradation differed between the two rock types. Figure 6 shows their changes with increasing exposure time. For Cheorwon basalt, the initial UCS was measured at 98.2 MPa in the untreated state. After 5 min of microwave exposure, UCS decreased significantly to 84.3 MPa, representing a 14.2% reduction in strength, which aligns with the observed decrease in P-wave velocity and Schmidt hardness. This drop is attributed to internal

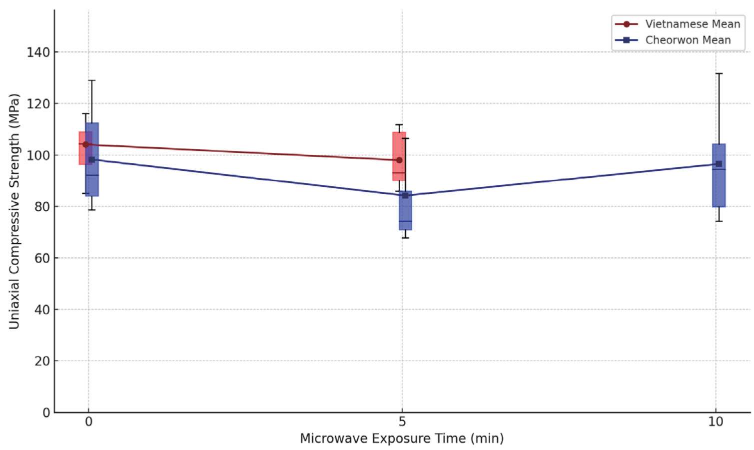


Fig. 6. (Color online) UCS variations with microwave exposure time for Cheorwon and Vietnamese basalt specimens.

thermal-stress-induced microcracking, which weakens the load-bearing capacity of the material. Interestingly, after 10 min of exposure, UCS increased again to 96.5 MPa, recovering to within 2% of the original value. This nonmonotonic trend suggests that while early microwave exposure causes rapid crack initiation and mechanical softening, prolonged exposure might lead to thermal stabilization effects such as crack closure, stress redistribution, or microstructural realignment under high internal temperatures. These mechanisms are often observed in thermally loaded crystalline rocks and can explain the apparent partial recovery of strength at extended durations.(8,15)

Vietnamese basalt, in comparison, exhibited a more modest and monotonic strength reduction. UCS declined from 104.1 MPa at 0 min to 98.0 MPa at 5 min, amounting to a 5.9% loss. No data were available for 10 min, but the trend suggests a more stable internal structure under microwave heating. This lower sensitivity aligns with the observed stability in surface hardness and P-wave velocity for Vietnamese basalt, indicating that its mineral composition and texture are more resistant to microwave-induced damage within the tested time frame.

Overall, UCS results confirm that Cheorwon basalt is more susceptible to microwave weakening in the early exposure period, but also demonstrates dynamic recovery characteristics during prolonged heating. Vietnamese basalt, while stronger in the unheated state, experiences only minor weakening, making it less responsive to the same microwave treatment. These behaviors are important for the design of microwave-assisted excavation systems, as they suggest that Cheorwon-type basalts can be softened effectively within short treatment times, whereas more resistant materials such as Vietnamese basalt may require higher power or longer exposure to achieve similar effects.

4. Discussion

The experimental results presented in Sect. 3 demonstrate that microwave irradiation can induce measurable changes in the mechanical, thermal, and structural properties of basalt. To interpret these outcomes in the context of rock behavior and engineering application, in this section, we discuss the mechanisms underlying strength reduction, differences in material response between rock types, and practical implications for excavation technologies. Recent research on granite has shown noticeable but relatively moderate reductions in strength and P-wave velocity owing to microwave-induced microcracks, primarily because of its quartz-rich composition, which poorly absorbs microwaves.(5,16–18) In contrast, basalt's iron-rich minerals significantly enhance microwave absorption, leading to more intense thermal stresses and substantial property degradation. Specifically, Cheorwon basalt's pronounced weakening aligns closely with the extensive thermal cracking observed in basalt compared with granite under equivalent microwave exposure conditions.(5,17) The more subdued response of Vietnamese basalt resembles granite's moderate reaction to microwave treatment, emphasizing the influence of mineralogical composition on microwave responsiveness.

Mineralogical analysis via petrographic microscopy revealed distinct differences between Cheorwon and Vietnamese basalt specimens. Specifically, biotite, an iron-rich mineral known for its microwave-absorbing properties, was observed exclusively in Cheorwon basalt, enhancing its microwave sensitivity. In contrast, Vietnamese basalt lacked biotite and featured smaller mineral grain sizes and larger pore sizes, factors contributing to its relatively low microwave responsiveness. These mineralogical distinctions clearly explain the observed variations in microwave-induced weakening between the two basalt types.

4.1 Mechanisms of strength reduction upon microwave irradiation

The degradation of basalt mechanical properties under microwave exposure is primarily driven by thermally induced microcracking initiated by rapid and uneven internal heating. When microwave energy is absorbed by the rock matrix, dielectric heating occurs as a result of the interaction between the alternating electromagnetic field and polar or conductive mineral constituents.[3,10] This heating is often spatially heterogeneous because different minerals possess varying dielectric loss factors, leading to localized temperature gradients at grain boundaries.[4,6] These thermal mismatches result in differential expansion, which generates tensile stress concentrations that exceed the rock's intrinsic fracture toughness and thus initiate microcracks.[9]

Experimental observations in this study support this mechanism: P-wave velocity and UCS showed significant reductions after short-term microwave exposure, particularly within the first 5 min. The decline in these properties corresponds to the development of an internal network of cracks that disrupts wave transmission and reduces load-bearing capacity. Such reductions in mechanical performance have been reported across various rock types exposed to microwave energy.[5,6,9]

Interestingly, Cheorwon basalt exhibited a partial recovery in UCS at 10 min, after a sharp decline at 5 min. This behavior suggests that thermal stress saturation may have occurred, followed by microcrack closure or stress redistribution as the internal temperature rose and thermal gradients diminished. Similar phenomena have been described in thermally treated crystalline rocks, where prolonged high-temperature exposure (>300 ℃) can result in mineral interlocking, pore collapse, or viscous sintering, thereby increasing stiffness or strength after an initial weakening phase.[8,15] These thermally activated recovery mechanisms provide a plausible explanation for the rebound of UCS observed in Cheorwon basalt and underline the nonlinear nature of microwave-induced damage evolution.

In summary, the primary weakening mechanism under microwave irradiation is microcrack accumulation due to rapid internal heating and differential thermal expansion. At longer durations, secondary mechanisms such as microcrack healing, stress relaxation, or thermal consolidation may influence mechanical behavior, particularly in rocks that remain structurally intact after initial damage.

4.2 Differences between Vietnamese and Cheorwon basalt

The experimental results reveal a consistent and substantial difference in microwave responsiveness between Vietnamese and Cheorwon basalt. Despite undergoing the same treatment conditions (1000 W microwave power for up to 10 min), Cheorwon basalt exhibited greater reductions in P-wave velocity, UCS, Schmidt rebound hardness, and Leeb hardness. In contrast, Vietnamese basalt maintained relatively stable mechanical properties, with only minor changes observed in UCS (6% reduction at 5 min) and no significant shifts in density or Leeb hardness.

Several factors account for this divergence in behavior. First, mineralogical composition plays a key role in microwave interaction. Cheorwon basalt contains a higher proportion of iron-bearing minerals such as biotite, magnetite, and pyroxenes (approximately 15–20% by volume), which have higher dielectric loss factors and thus absorb microwave energy more efficiently, leading to more rapid internal heating and greater thermal stress development.[16] Vietnamese basalt, by contrast, has a finer grained and more homogeneous texture with a potentially lower concentration of microwave-sensitive phases, resulting in less internal heating and fewer thermal stress gradients.

Second, microstructural differences, including grain size distribution and initial porosity, influence the rock's thermal and mechanical response. The coarser grains and tighter interlocking structures of Cheorwon basalt tend to cause the concentration of thermal stress at grain boundaries, promoting crack initiation.[4,9] Vietnamese basalt has finer grains and more isotropic fabric that may allow for more uniform thermal expansion, reducing stress concentrations and suppressing crack development.

Moreover, the surface hardness trends align with the above interpretation. Cheorwon basalt showed a clear and progressive decline in both Schmidt and Leeb hardness values up to 10 min, reflecting the cumulative damage in the near-surface region. Vietnamese basalt, on the other hand, exhibited minimal changes in Leeb hardness (within 2%), suggesting minimal surface deterioration under the same exposure.

Another key difference was observed in the density trends. While the dry density of Vietnamese basalt remained unchanged throughout all exposure durations, that of Cheorwon basalt showed slight fluctuations and even an increase in density at longer durations. This unexpected increase may be due to microcrack closure or thermal densification processes during extended heating, which may not occur in Vietnamese basalt because of the lower internal temperatures.

Collectively, these results confirm that Cheorwon basalt is significantly more susceptible to microwave-induced damage owing to its material properties, while Vietnamese basalt remains comparatively stable. This emphasizes the need for rock-specific calibration when applying microwave-assisted techniques in excavation or weakening applications.

4.3 Implications for mechanical excavation efficiency

The observed strength and stiffness reductions in Cheorwon basalt following microwave irradiation have direct implications in improving the efficiency of mechanical excavation. Reductions in UCS of up to 20% and in P-wave velocity by 10–12% within 5 min indicate that substantial internal weakening can be achieved rapidly with minimal changes to the bulk density and geometry. These changes are expected to translate into lower cutting forces, reduced bit wear, and higher penetration rates during drilling or mechanical excavation operations.[1,2]

The results of prior studies have demonstrated that prefracturing of rock using microwave energy can significantly reduce mechanical cutting resistance. For example, Hassani *et al.* (2016)[(5)] observed reductions in rock indentation strength and cutting energy after microwave exposure in hard rocks, while Gushchin *et al.* (1979)[(7)] demonstrated the successful integration of microwave-assisted cutting into tunnel-boring machine designs. Our current findings reinforce these outcomes by showing that even at moderate power and exposure time, meaningful degradation in mechanical integrity can be achieved—particularly in basalt types with favorable mineralogy.

Moreover, the selectivity of damage is advantageous. Cheorwon basalt was weakened internally and at the surface, but its bulk density remained stable, which is ideal for controlled excavation. No catastrophic spalling or mass loss occurred, indicating that microwave pretreatment can weaken a rock without compromising block integrity. This is especially valuable in underground construction, where dimensional stability is essential, or in precision mining, where minimizing overbreak and maintaining wall integrity are important. Conversely, the relative insensitivity of Vietnamese basalt to microwave treatment highlights the limitations of a uniform treatment protocol. For lithologies with low microwave absorption, alternative methods or higher energy densities may be required to achieve comparable weakening.

4.4 Operational considerations and future research

While the laboratory results are promising, translating microwave-induced weakening into field applications requires careful consideration of operational constraints. One important factor is the optimal exposure window: beyond a certain duration, as seen with Cheorwon basalt, additional microwave input causes diminishing returns and can even lead to partial strength recovery. Field systems must therefore be engineered to deliver adequate energy within efficient time frames, avoiding unnecessary energy expenditure. The design of microwave delivery apparatus for in-field use (e.g., integrated with tunnel-boring machines or drill rigs) will also need to ensure consistent coverage and penetration of rock volumes while managing heat dissipation. Safety considerations, such as shielding against microwave leakage and managing fumes from heated rock, must be addressed. Another consideration is the energy cost–benefit aspect. The goal of microwave pretreatment is to reduce total excavation energy by lowering mechanical demands; thus, the energy spent on microwaves should be justified by equal or greater savings in mechanical energy. In the laboratory, a 1000 W microwave was used, but on the larger scale, power requirements and energy efficiency must be carefully optimized. This is especially relevant given the varied response of different lithologies; for rocks such as Vietnamese basalt, higher energy or supplementary methods might be needed, which can affect the economics of implementation. Future research should focus on optimizing microwave parameters (frequency, power density, and exposure patterns) for specific rock types, developing portable microwave systems for field applications, and quantifying energy efficiency metrics to establish cost–benefit assessments for industrial implementation. Additionally, investigations into combining microwave pretreatment with conventional excavation technologies will provide valuable insights for practical engineering applications. In summary, microwave irradiation offers a technically feasible and controllable means of enhancing the breakability of high-strength rock formation. The outcomes of this research provide a basis for optimizing microwave pretreatment parameters and advancing the practical integration of microwave technologies into tunneling, mining, and space resource excavation systems.

5. Conclusions

In this study, we evaluated the mechanical weakening of basalt under microwave irradiation, comparing two geologically distinct rock types—Cheorwon and Vietnamese basalt—subjected to identical treatment conditions. The results lead to the following conclusions.

1) Microwave exposure effectively weakens basaltic rock, particularly within the first 5 min of irradiation. Cheorwon basalt exhibited reductions in UCS (up to 20%), P-wave velocity (~12%), and surface hardness (~28%) after 5 min of exposure, indicating substantial internal and near-surface damage as a result of thermal stress.
2) Vietnamese basalt was less responsive to microwave treatment, showing only modest reductions in strength and surface properties. Its P-wave velocity and density remained stable, and Leeb hardness varied by less than 2%, highlighting its greater resistance to microwave-induced thermal cracking.
3) Microwave-induced damage was largely microstructural, as evidenced by negligible changes in dry density for both rock types. This suggests that weakening occurred via internal crack propagation rather than volumetric expansion or mass loss, making microwave treatment suitable for maintaining geometric stability during excavation.
4) Extended exposure beyond 5 min produced diminishing returns. In Cheorwon basalt, UCS partially recovered by 10 min, likely owing to high-temperature effects such as microcrack closure or stress redistribution. This finding suggests the presence of an optimal exposure window for maximizing damage while avoiding unnecessary energy use.
5) Differences in mineral composition and microstructure are critical determinants of microwave sensitivity. Cheorwon basalt, with more microwave-absorbing minerals and coarser grain boundaries, responded more strongly than the finer grained, more homogeneous Vietnamese basalt. This highlights the need for rock-specific treatment protocols.
6) Microwave-assisted rock weakening has clear implications in excavation engineering. For microwave-responsive lithologies, pretreatment can reduce cutting forces, improve fragmentation, and extend equipment life. However, treatment strategies must be tailored to specific rock properties to ensure operational and energy efficiency.
7) Future research should focus on optimizing the microwave parameters (frequency, power density, and exposure patterns) for specific rock types, developing portable microwave systems for field applications, and quantifying energy efficiency metrics to establish cost–benefit assessments for industrial implementation. Additionally, investigations into combining microwave pretreatment with conventional excavation technologies would provide valuable insights for practical engineering applications.

In conclusion, the results of this study confirmed that microwave irradiation can be an effective method for inducing the controlled weakening of basalt, with significant benefits to excavation efficiency in suitable rock types. The contrasting behaviors of Cheorwon and Vietnamese basalts under microwave exposure underscore the importance of tailoring the approach to the geological conditions. As the technology advances from the laboratory to the field, it holds promise for enabling more energy-efficient and effective rock excavation in challenging environments. We recommend that in future studies, comparative analyses between conventional thermal treatments (e.g., oven heating) and microwave irradiation be included to better understand the distinct weakening mechanisms and practical efficiencies of these methods

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