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Fractal Quantification of Crack Networks: Predicting Rock Damage in Thermally Exposed Rock Environments

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Abstract

Engineering activities such as mining, tunneling, and underground energy storage expose rock masses to coupled mechanical loading and thermal disturbances, resulting in progressive damage and long-term performance degradation. Thermal exposure modifies mineral structures, accelerates microcrack initiation and coalescence, and significantly alters the mechanical behavior of rocks. Quantitative characterization of these thermally induced damage processes is therefore critical for reliable risk assessment in rock engineering applications. In this study, fractal analysis is employed to quantify the complexity and evolution of crack networks developed in andesite and andesitic–basaltic rock specimens subjected to thermal treatment and uniaxial compression. Six core specimens were tested, three in their natural state and three after heating to 200 °C. Following uniaxial compressive strength tests, crack surfaces were digitized, converted into binary images, and analyzed using the box-counting method to determine fractal dimensions (D). The results indicate that D values provide a sensitive measure of crack network complexity and exhibit systematic relationships with both thermal exposure and mechanical degradation, including reductions in uniaxial compressive strength (UCS) and elastic modulus (E). The findings suggest that fractal-based descriptors provide a useful framework for linking microstructural damage to macroscopic mechanical response in thermally affected rocks through experimentally observed relationships between crack geometry and mechanical response. This approach contributes to improved prediction of rock damage evolution and supports sustainable design and risk management in geotechnical and environmental engineering applications.

Keywords

Cracking, Environmental effects, Fractal dimension, Rock damage, Uniaxial loading.

1 Introduction

Rocks in both natural and engineered environments may be exposed to moderate thermal loads resulting from surface and near-surface fires, underground coal and tunnel fires, and accidental thermal events in underground facilities. At temperatures up to approximately 200 °C, differential thermal expansion of mineral grains and the weakening of grain boundaries drive the initiation and opening of pre-existing microcracks, leading to irreversible rock damage (e.g., Saiang and Miskovsky 2012; Zhang et al. 2016; Gautam et al. 2018; Yin et al. 2021). Although these temperature levels do

not induce significant mineralogical transformations, they can substantially alter the mechanical behavior of rocks by reducing stiffness, strength, and post-peak stability. Recent experimental studies have further demonstrated that moderate thermal treatment significantly degrades the mechanical properties of igneous and volcanic rocks and accelerates damage accumulation under stress (e.g., Li et al. 2023; Zhang et al. 2025; Bao et al. 2025). However, conventional mechanical parameters alone are often insufficient to fully capture the internal damage mechanisms associated with thermally induced microcracking. Beyond these parameters, the geometric complexity of crack networks has gained increasing attention as a quantitative indicator of rock damage. Since Mandelbrot's (1982) introduction of fractal theory, fractal concepts have been widely and successfully applied to characterize rock fracture processes, making fractal geometry a robust and powerful framework for quantifying damage and fracture complexity(Anderson, 1989; Zhao, 1998; Ju et al., 2018; Wang et al., 2021). Roy et al. (2007) introduced an improved box-counting method for the fractal characterization of crack networks, demonstrating that fractal dimension effectively captures crack density and connectivity. More recent studies have further shown that the evolution of fractal parameters correlates closely with meso-scale damage development and mechanical degradation during rock failure processes (e.g., Dinç Göğüş et al. 2023; Lan et al. 2024; Dinç Göğüş et al. 2025). Despite these advances, the fractal characterization of crack networks in volcanic rocks subjected to moderate thermal exposure remains limited. In particular, the combined effects of fire-representative thermal treatment (≈200 °C) and mechanical loading on the crack network complexity of andesite and andesitic–basaltic rocks have not yet been sufficiently quantified. Addressing this gap is important, as such lithologies are widespread in volcanic regions and are frequently encountered underground structures, tunnels, and energy-related infrastructure.

In this study, the crack network complexity in thermally treated and untreated andesite and andesitic–basaltic rock specimens are quantitatively evaluated using fractal analysis. Six core samples were subjected to uniaxial compression tests, with half of the specimens exposed to a thermal treatment of 200 °C, representing fire-related thermal damage conditions, prior to loading. Although the number of tested specimens is limited, the study aims to provide a preliminary assessment of the applicability of fractal crack characterization to thermally affected volcanic rocks. Post-failure crack surfaces were digitized and converted into binary images, and fractal dimensions were calculated using the box-counting method. The fractal parameters were interpreted together with uniaxial compressive strength and elastic modulus values to reveal the relationships between moderate thermal exposure, mechanical behavior, and crack network complexity.

2 Material and Methodology

The rock types investigated in this study were obtained from drill cores provided by Miryıldız Mining Company in Gaziantep, Türkiye. Within the scope of the research, which aims to quantitatively evaluate the thermal response of the rock specimens, samples selected for comparison were taken from the same drilling depths to ensure lithological homogeneity. The rocks, recovered from depths between 124 and 139 m, were transported to the laboratory in core boxes (Fig. 1a), and preliminary observations identified them as having andesite and andesitic–basaltic composition. A total of ten core specimens with a length-to-diameter (L/D) ratio of 2.4 were prepared, of which five specimens were subjected to thermal treatment and five specimens were left untreated. This L/D ratio was selected based on the optimum value recommended by Tuncay et al. (2019) for basaltic–andesitic rocks. All specimens were prepared in accordance with the relevant standards of the American Society for Testing and Materials (ASTM D2938-86/95 and D4543-85, 2000).

2.1 Laboratory experiments

Among the ten core specimens prepared for laboratory testing, four specimens were used during the calibration of the uniaxial compressive strength (UCS) testing machine, which was adjusted to suit andesite and andesitic–basaltic rock types. Based on sensitivity analyses conducted at the rock mechanics laboratory of Zemin Etüdve Tasarım A.Ş., the tests were performed using a hydraulic press with a maximum capacity of 10 tons to obtain reliable data (Fig. 1b).Accordingly, the loading rate was set to 0.1 MPa/s. Among the remaining six core specimens, three specimens (1T, 2T, and 3T) were heated to 200 °C prior to testing in order to evaluate the effect of thermal treatment on crack-induced rock damage (Fig. 1c), while the other three specimens (1, 2, and 3) were preserved in their natural state and were not subjected to any thermal treatment. During the experiments, deformation measurements were recorded using an extensometer integrated into the uniaxial compression testing

equipment, and loading was continued until specimen failure. Specimens 1 and 1T consist of an andesitic, intermediate volcanic rock, characterized by calcite-filled fractures and pocket fillings (Fig. 1d). Specimens 2 and 2T exhibit an andesitic–basaltic composition, containing greenish chloritized surfaces, while reddish discolorations caused by iron oxidation occur parallel to calcite fillings. Specimens 3 and 3T also have an andesitic composition, in which calcite veins and calcite pocket fillings are more pronounced compared to the other specimens (Figure 1d). Following the uniaxial compressive strength tests, stress–strain curves were obtained for all specimens, and the uniaxial compressive strength (UCS), elastic modulus (E), and Poisson's ratio (v) were determined. The obtained results are discussed in detail in the "Results and Discussion" section.

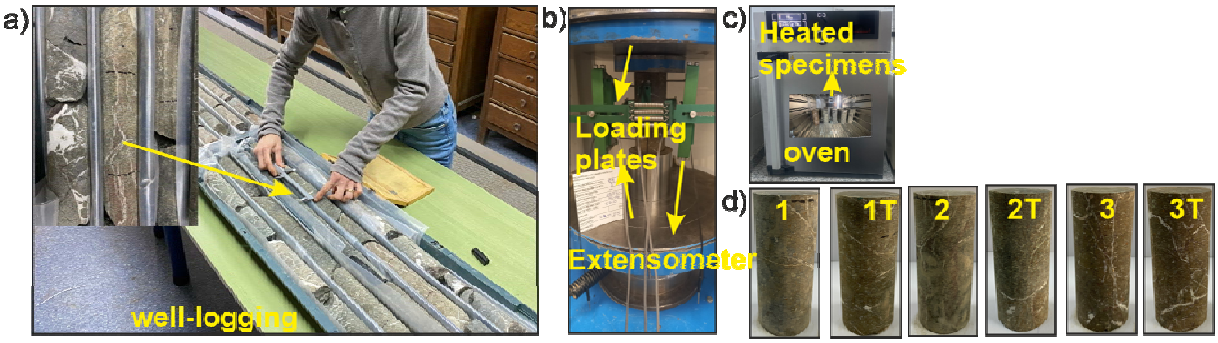


Fig. 1a) Rock sample selection process; b) uniaxial compressive strength testing apparatus c) heating process at 200 °C; d) core specimens prepared with an L/D ratio of ≈ 2.4.

2.2 Box Counting Method Based on Fractal Theory

Fractal theory was first introduced by Mandelbrot (1982) and has since become a powerful mathematical approach widely used in earth science to describe complex systems and irregular geometries. Based on the principles of self-similarity, this theory enables the quantitative characterization of geometries that are otherwise difficult to measure. Consequently, in geomechanical studies, fractal theory has been widely applied as a reliable and practical method for the quantitative description of rock/soil damage, fractured media, and other complex and heterogeneous structures (Barton and Larsen 1985; Anderson 1989; Barton 1995; Berkowitz and Hadad 1997; Hirata 1998; Roy et al. 2007). In this study, fractal analyses were performed using the box-counting method based on fractal theory (Mandelbrot 1982; Feder 1988) on areal structures, such as crack surfaces projected onto a two-dimensional plane (Roy et al. 2007). In this method, the crack network developed in each core specimen is analyzed using a gridding system composed of square boxes of equal size, and the variation in the complexity of crack-induced rock damage is examined as a function of the box size (r). For each box, the area covering any part of the crack network is counted based on the grid size (Nr). This procedure is repeated for different box sizes, allowing the behavior of complex features to be evaluated across multiple scales. The relationship between N(r) and r is given in Eq. 1;

$$N(r) \propto 1/r^{D} \tag{1}$$

When the relationship between N(r) and r is plotted on a logarithmic scale, the slope (β) of the resulting linear trend represents the fractal dimension (D) (Eq. 2).

$$D = -\beta \tag{2}$$

In fractal theory, a higher D indicates a more complex network of cracks that help to characterize damage accumulation of rocks under stress.

3 Results and Discussion

In the laboratory investigations, the mechanical parameters of andesite and andesitic–basaltic rock specimens subjected to uniaxial compressive strength tests under natural (specimens 1, 2, and 3) and thermally treated conditions (specimens 1T, 2T, and 3T) are summarized in Table 1. In addition, stress–strain curves were obtained for each specimen (Fig. 2a).The comparison ofmechanical parameters of the natural and thermally treated specimens shows that the UCS values of specimens 1 and 2 remain nearly unchanged after thermal treatment (1–1T and 2–2T), whereas specimen 3 exhibits a noticeable reduction after heating (3–3T). In contrast, the E values exhibit a clear reduction in all thermally treated specimens compared to their natural ones, with the most pronounced decrease

observed for specimen 2 (2–2T). This reduction may reflect the development of thermally induced microcracks along grain boundaries and an overall loss of rock stiffness. Furthermore, the ν values of the thermally treated specimens (1T, 2T, and 3T) converge within a narrow range (0.20–0.21), indicating a more uniform lateral deformation behavior following thermal exposure.

The results indicate that thermal treatment up to 200 °C, followed by cooling, primarily influences the mechanical behavior of the tested rocks by reducing their stiffness rather than their peak strength, which is consistent with previous studies (e.g., Saiang and Miskovsky 2012; Zhang et al. 2016; Yin et al. 2021). It is well known that with increasing depth, lithostatic pressure, and ambient temperature, rocks undergo a transition from brittle to ductile behavior (e.g., Handin and Hager 1957; Hadizadeh and Rutter 1983; Tullis and Yund 1992; Brantut et al. 2011). Examination of the mechanical response of the core specimens used in this studyreveals that thermal exposure induces a measurable shift from brittle to more ductile deformation behavior.

After the completion of the laboratory tests, fractal analyses were performed using the box-counting method, as described in the Methodology section. The analyses were carried out using the FracLac plugin within the open-source software ImageJ to determine the D values of two-dimensional crack patterns. These patterns were digitized as 8-bit black-and-white binary images obtained from the surfaces of failed core specimens (Fig. 2b).

Table 1. Mechanical parameters of core specimens.

Specimen No	UCS(MPa)	E (GPa)	υ (-)
1	56,23	67,98	0,32
2	37,22	52,29	0,22
3	40,03	16,36	0,21
1T	55,75	55,34	0,20
2T	37,43	20,55	0,20
3T	32,32	13,79	0,21

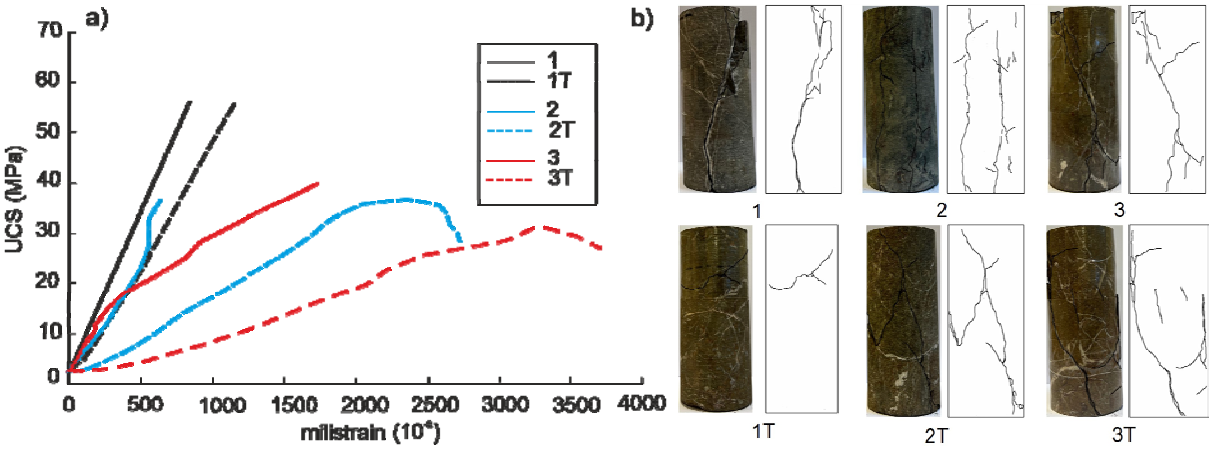


Fig. 2 a) Stress–strain responses of core samples under uniaxial loading conditions; b) failed core specimens and corresponding crack patterns digitized as 8-bit black-and-white binary images.

Within FracLac, the minimum box size was set to 3 pixels, while the maximum box size was defined as 45% of the binary image size. Log N(r)–log r plots were generated, and the slopes (β) of the linear regressions fitted to these plots were recorded as "D". The D values for all specimens, along with an example log N(r)–log (r) plot and the corresponding coefficient of determination (R^2) obtained from box-counting analysis, are presented in Fig. 3.An increase in D value is generally associated with enhanced microcrack development and increased crack network complexity in rocks. Among the tested specimens, only specimen 2 exhibits a slight increase in D after thermal treatment (from 1.214 to 1.228), accompanied by a substantial reduction in E while the UCS remains nearly unchanged. The slight increase in D observed in specimen 2T, together with nearly unchanged UCS values, suggests that thermal treatment may have altered the spatial distribution and connectivity of existing microcracks rather than inducing a clear strength-controlling damage mechanism. In contrast,

specimens 1T and 3T show a decrease in D compared to their natural forms, together with significant reductions in stiffness. In the case of specimen 1T, the reduction in D accompanied by minimal change in UCS suggests crack coalescence and redistribution within an already developed crack network, resulting in stiffness degradation without significant strength loss. For specimen 3T, the simultaneous decrease in D, E, and UCS reflects a more intense damage state, where thermally induced cracking leads to both reduced stiffness and strength, despite a slight reduction in overall crack network complexity.

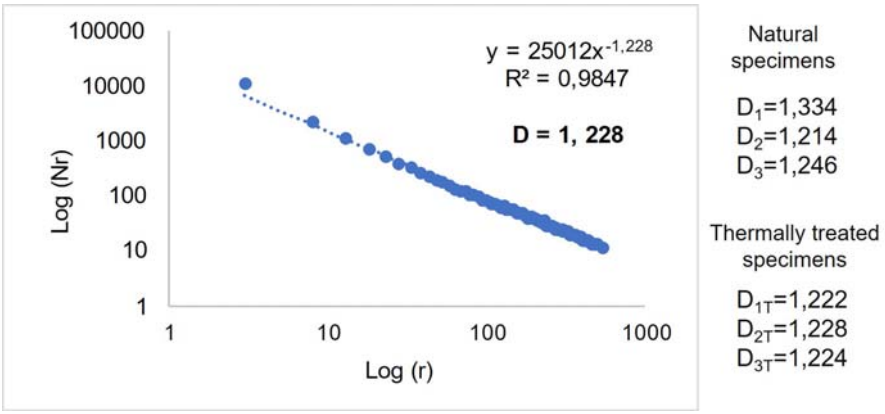


Fig. 3 Representative log N_box(r)–log r plot of binary crack pattern images obtained using the box-counting method (specimen 2T), together with the calculated D values for crack patterns digitized from core surfaces.

4 Conclusions

In this study, the effects of moderate thermal exposure on rock damage were evaluated with a focus on cracking behavior. At 200 °C, thermal treatment has a limited influence on peak strength (UCS) but leads to a pronounced reduction in E values, indicating stiffness degradation due to microcracking. Variations in D are closely linked to deformation behavior rather than strength, with specimen 2T showing microcrack redistribution without strength loss, and specimens 1T and 3T exhibiting crack coalescence within the fracture network.

Overall, the obtained results indicate that fractal analysis can contribute to the characterization of thermally induced damage by reflecting the transition from strength-dominated to deformation-controlled mechanical behavior in volcanic rocks commonly used as engineering materials. Nevertheless, additional experimental studies involving larger datasets and different thermal conditions are required to further validate the observed trends.

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