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INTEGRATED ANALYSIS OF MINERALOGICAL AND TEXTURAL FACTORS ON STRESS-INDUCED FRACTAL ROCK DAMAGE: A MULTISCALE ANALYSIS

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Abstract: This study explores the influence of textural properties and mineralogical composition on micro and mesoscale mechanical behaviors of three different rock types. Employing laboratory experiments, discrete element modeling (DEM), mineralogical examinations, and fractal analysis, we quantitatively assess rock damage evolution. Fractal dimension (D_B) calculations on crack patterns, identified on thin sections prepared parallel and perpendicular to the uniaxial compressive loading direction at critical stress thresholds (σ_{ci}, σ_{cd}, σ_{peak}), provide insights. Our findings indicate that post-critical stress (σ_{cd}) highlights textural properties as primary factors determining rock damage extent, with mesoscale fractures aligning in response to mineralogical composition.

1. Introduction

The construction of engineering structures within rocks subjects these materials to secondary stresses, resulting in deformation and potentially irreversible damage. For many decades, researchers have focused on deciphering microscale deformations leading to mesoscale and macroscale rock damage (e.g., [5], [14], [7], [16], [15], etc.). Investigations delve into microscopic examinations to understand microcracking processes in various rock types while exploring the relationship between their petrographic characteristics and engineering properties ([10], [8], [18], [9]). Additionally, studies highlight geometric features governing rock damage, often exhibiting fractal properties [1], [3]). To understand cracking patterns under different stress conditions, fractal dimensions of microcracking in various rock types have been calculated [22]. Researchers have also focused on critical stress levels governing rock deformation, such as microcrack initiation (σ_{ci}), progressive coalescence (σ_{cd}), and ultimate fracture (σ_{peak}) ([7], [14]). Techniques like Acoustic Emission (AE) ([2], [12], [21]) and X-ray tomography Digital Image Correlation (DIC) signify complete rock failure ([4], [13]). These methods contribute valuable insights to rock mechanics but demand expertise and significant financial investments.

This study investigates crack initiation and propagation from micro to mesoscale in diabase, ignimbrite, and marble rocks using laboratory experiments, discrete element modeling, mineralogical examinations, and fractal analysis. Our findings offer numerical data for predicting deformation and damage mechanisms in brittle rocks, advancing our understanding of mineralogical and textural controls on stress-induced fractal rock damage.

2. Methodology

The methodology employed in this study is structured into four main components:

a. Macro Mechanical Parameters Determination: Key macro mechanical parameters, including uniaxial compressive strength (UCS), tensile strength (UTS), elasticity modulus (E), and Poisson's ratio (ν), were determined through laboratory experiments involving uniaxial and triaxial compressive and tensile stress tests (Figure 1a).

b. Discrete Element Methodology (DEM) Implementation: Utilizing the open-source code Yade, discrete element methodology (DEM) was employed to generate numerical models simulating the stress-strain behaviors of real rocks (Figure 1a) (see [19, 20] for the details of the method). Critical stress thresholds (σ_{ci}, σ_{cd}, σ_{peak}) indicative of microscale cracking leading to meso fractures were identified within these models for diabase (38, 55, 75.5 MPa), ignimbrite (25, 37, 47 MPa), and marble (21, 30, 38.5 MPa), respectively.
c. Microscopic Examination and Analysis: Core samples were subjected to uniaxial loading up to these critical stress levels, followed by thin section preparation for microscopic analysis. Examination under a polarizing microscope allowed for the detailed observation of mechanisms governing crack propagation (Figure 1b).
d. Fractal Analysis: A quantitative assessment of rock damage evolution was conducted through fractal analysis of crack patterns (Figure 1c). The fractal dimensions (D_B) of the cracking network at each stress level were calculated using the box-counting (grid) method [17]. This involved counting the number of square cells (N_{box}) surrounding any part of crack traces over the whole area of the thin section binary images. The fractal dimension (D_B) was estimated based on the relationship between $N_{box(r)}$ and the box size (r), where $D_B = -\beta$, and β is the slope of the log-log plot of $N_{box(r)}$ versus r. Here, it should be noted that the higher the fractal dimension, the more complex pattern of cracks.

This comprehensive methodology enables a thorough investigation of stress-induced fractal rock damage for providing quantitively insights presented in the following section into the cracking processes of different rock types.

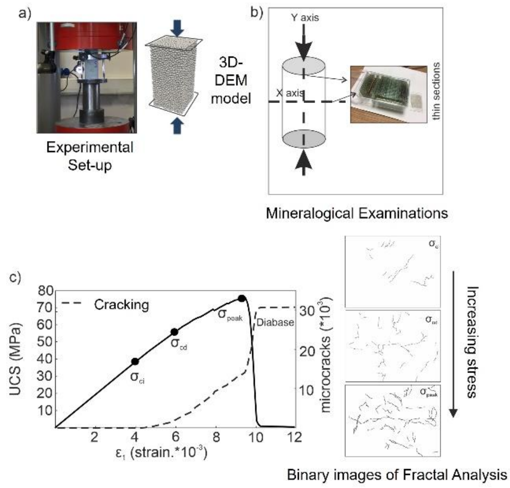

Figure 1. Integrated methodology incorporating a) laboratory and numerical experiments, b) mineralogical analysis c) fractal patterns of the cracking process during rock damage evolution.

3. Results and Discussions

The results derived from fractal dimension (D_B) analyses at critical stress levels, detected representatively by the DEM approach for each rock type, offer quantitative insights into the progression of rock damage (Table 1). The D_B values obtained from fractal analyses were interpreted concerning various factors including the mechanical properties of rocks, the constituent minerals, mineral hardness, interlocking mechanisms, and spatial distribution (texture) within the rock matrix. The research revealed a consistent rise in D_B values correlating with the increased complexity of cracking networks under escalating critical stresses across diverse rock types ([22], [17]).

Fractal analyses unveiled that diabase displayed the highest cracking among the studied rock types, attributed to its intricate texture characterized by the interlocking of hard plagioclase and pyroxene crystals. Despite its elevated strength, the presence of cleavages in hard pyroxenes made diabase more prone to cracking, particularly when oriented parallel or semi-parallel to the loading direction. In contrast, ignimbrite showcased higher compressive and tensile strength compared to marble, and fractal analysis revealed distinct patterns of damage evolution, underscoring the influence of groundmass texture on the cracking behavior of the rocks [6].

Critical Stress Levels	D_B (X axis-perpendicular to the loading direction)			D_B (Y axis-parallel to the loading direction)		
	Diabase	Ignimbrite	Marble	Diabase	Ignimbrite	Marble
σ_{ci}	1.011	1.026	1.018	1.048	1.046	1.046
σ_{cd}	1.040	1.132	1.086	1.095	1.054	1.092
σ_{peak}	1.114	1.391	1.290	1.248	1.091	1.203

Table 1 D_B values of cracking patterns calculated on thin-section images of rock samples (4x magnification ratio)

In an overall assessment, our fractal dimension (D_B) values range between 1.011 and 1.391 as seen in Table 1. At first sight, one may think that the variation of these values is in a narrow bandwidth. As it can be easily recognized from the literature, the use of the fractal box-counting method for the characterization of natural and/or induced crack networks in rocks in various scales has become a very common and practical approach for almost the last four decades. For the macro-scale characterization; the works by Berkowitz and Hadad [3] and Roy et al. [17], and for the micro-scale characterization; the works by Zhao [22] and Ju et al. [11], are just some of the examples. The range of our D_B values is not far from those reported by these researchers, on the contrary, it is in accordance with theirs.

4. Conclusions

In this comprehensive study, we employed fractal analysis using the box-counting method to evaluate cracking in three distinct rock types—diabase, ignimbrite, and marble—across various loading stages. Our interdisciplinary approach integrated diverse disciplines and methodologies to explore the qualitative and quantitative interplay between the mechanical properties and structural attributes of rocks at different scales. Diabase exhibited the highest D_B values on sections parallel to the loading direction, while ignimbrite and marble demonstrated comparable D_B values. Conversely, diabase displayed the least propensity for cracking on sections perpendicular to the loading direction, followed by marble, with ignimbrite exhibiting the highest cracking. These findings provide valuable insights into the evolution of rock damage and have implications for rock engineering applications and damage assessments related to these three distinct rock types. By better understanding the behavior of diabase, ignimbrite, and marble under various stress conditions, engineers and researchers can enhance the design and assessment of structures built within or upon these materials. (*This study was funded by the Scientific and Technological Research Council of Turkey (TUBITAK) under project number 121Y031*).

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