Mechanical properties of carbonate fault rocks

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ABSTRACT: The tectonic processes that take place inside a fault zone change the initial structure of the parent rocks and impact their properties. In the present study, the mechanical properties of five (5) types of carbonate fault rocks from Lefkada Island, Greece, are investigated and compared to the corresponding properties of the parent carbonate rocks. Due to their tectonic disturbance and weak nature, the studied fault rocks are difficult to sample and test using the methodologies suggested by the international standards in Rock Mechanics (ISRM, ASTM). Therefore, a new methodology to sample and perform laboratory tests in such materials is used. The mechanical properties of each studied type presented a high variance which relates to the different structural and textural properties of the tested samples. Those properties were quantified to shed light on the factors that control the strength of the studied fault rocks.

Keywords: Carbonate fault rocks, Mechanical properties, Structural properties, Textural properties, Sample preparation, Uniaxial Compressive Strength.

1 INTRODUCTION

Fault rocks (Sibson, 1977) form as a result of localized strain within a fault zone. Under the influence of stresses developing from within the Earth, the rock masses adjust themselves either by bending, when they lie deep below the surface or by fracturing with or without any additional displacement, in the upper depths. The fault's deformation causes internal processes that ultimately affect the physical and mechanical properties of the parent rocks.

Fault zones are generally characterized by their architectural elements which include: a) the core, b) the damage zones, and c) the unaffected parent rocks (Kim et al., 2004; Liao et al., 2020). The fault slippage deformation is mainly accumulated in the core zone which is referred to as the high-strain region (Ferraro et al., 2019). This zone consists of fault rocks (e.g., fault breccias and fault gouges). The rock texture found in the core zones is made of fragments that follow a fractal size distribution from the microscale to, occasionally, hundreds of meters in length (Billi et al., 2003). Fault zones typically exhibit substantial heterogeneity since they comprise intact, unaltered stiff rock fragments which are surrounded by a mainly soft, weak matrix.

In the present study, five (5) types of fault rocks (two types of limestone fault breccia, one type of tectono-diagenetic dolomite breccia and two types of fractured marly limestone of tectonic origin) retrieved from western Lefkada Island, Greece are studied to assess their mechanical properties. The fault rocks belong to two geotectonic zones, i.e., the Ionian and Paxos zone. Their mechanical properties have not been investigated before as severe issues in sample preparation and laboratory testing procedures, associated with their weak nature, were detected. In particular, conventional core drilling results in extreme disintegration and specimens could not be prepared. To remedy this, a novel sample preparation technique to obtain prismatic specimens was used (Kallimogiannis and Saroglou, 2023). Moreover, two additional types of parent rocks from the two geotectonic zones of interest were studied as a reference to compare the different mechanical properties of parent and fault rocks. Those were prepared using conventional methodologies (ISRM, 1979).

2 MINERALOGICAL/PETROGRAPHIC ANALYSIS OF THE STUDIED ROCKS

Carbonate rocks present significant variance in terms of physical and mechanical properties. Those can be associated with their mineralogical and petrographic characteristics. The studied parent and fault rocks were analyzed in terms of composition, lithology, fabric, fragment size, mineralogy of matrix and fragments-to-matrix distribution (for breccias). The methods that were employed included macroscopic investigation, examination of thin sections using a polarizing petrographic microscope (Zeiss Axio Scope A1) equipped with a Zeiss Microscopy camera and X-ray powder diffraction (XRD) analyses. The characterization of the studied rock types and a code name assigned for each one are provided in Table 1. Note that Types E-I and E-II as well as Types A-I and A-II are similar but present different textural/structural characteristics (see section 4)

Table 1. Petrographic characterization of the parent and fault rocks studied.

Type	Material Characterization	Geotectonic Zone	Code used
Parent rocks	Intact dolomite–limestone breccia	Paxos	ATH
	Intact limestone; peloidal packstone/grainstone texture (Dunham, 1962).	Ionian	X
Fault rocks	Single facies limestone fault breccia; Crackle Fault Breccia (Woodcock and Mort, 2008)	Paxos	E-I
	Multi facies limestone fault breccia; Crackle to Mosaic Fault breccia (Woodcock and Mort, 2008)	Paxos	E-II
	Single facies tectono-diagenetic dolomite breccia	Ionian	P
	Fractured, marly micritic limestone	Ionian	A-I
	Highly fractured, marly micritic limestone	Ionian	A-II

3 MECHANICAL PROPERTIES OF PARENT ROCKS AND FAULT ROCKS

3.1 Uniaxial Compressive Strength

The investigation of the parent rocks establishes an upper limit of the material's strength and aids in assessing its subsequent degradation as tectonic processes evolve. The average Uniaxial Compressive Strength (UCS) for the intact limestone (Type X) and the intact limestone breccia (Type ATH) were equal to 96.9MPa and 86.2MPa, respectively. Both are classified as "strong rocks" in ISRM's (1981) classification. The average UCS for Types E-I, E-II, P, A-I and A-II were 22.6 MPa, 8.5MPa, 38.3MPa, 34.5MPa and 8.8MPa, respectively. Types E-I, E-II and A-II can be entirely classified as weak rocks (<25MPa) whilst Types A-I and P are medium-strong rocks (25-50MPa). The results are indicative of the high disintegration of the material that occurs in situ, which originates from its weak nature due to tectonic processes.

The two types of fault limestone breccias (E-I and E-II) have different mechanical properties with E-I having the highest average UCS. Subsequently, slightly fractured marly limestones (A-I) also differed from fractured marly limestones (A-II) due to the different degrees of tectonization. The latter type presented lower mechanical properties. The observed differences are associated with the different structural/textural properties that each rock type presented (see section 4).

3.2 Stress-strain response

The stress-strain data of parent and fault rocks revealed that the latter feature reduced stiffness and present a more ductile behavior. The average Young's moduli for the Type X and ATH were equal to 65.6GPa and 43.9GPa, respectively. The corresponding average Young's moduli for Types E-I, E-II, P, A-I and A-II were 29.3GPa, 9.4GPa, 24.2GPa, 24.5GPa and 6.7GPa, respectively.

Typical stress-strain curves of a Type X specimen (parent limestone) and a Type P specimen (tectono-diagenetic breccia) allow to observe the differences between the studied rocks and are presented in Figure 1a, b. The latter has its tangent moduli of elasticity significantly reduced when the stress-strain curve departs from linearity and acquires a ductile behavior towards the ultimate stress while the former presents a more brittle behavior (i.e., the axial stress almost increases linearly towards the rock's failure; Munoz et al., 2016). This is in agreement with the literature since an increase in UCS indicates a corresponding increase in brittleness (Taheri et al., 2020).

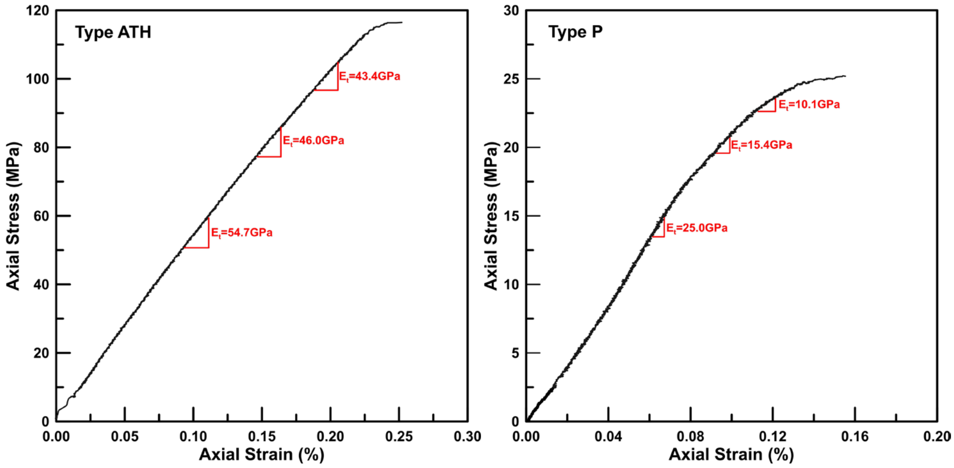

Figure 1. Stress-strain curves of a representative sample of Type ATH and Type P. The decline of the tangent modulus of elasticity is incorporated.

4 STRUCTURAL AND TEXTURAL PROPERTIES OF FAULT ROCKS

4.1 Incentive

Apart from the observed differences compared to the parent rocks, the mechanical properties of the fault rocks significantly vary for samples from the same Type. The range of the measured UCS for each rock Type is illustrated in Figure 2.

The large differences in the observed strength can be attributed to the different structural and textural properties that each sample presented. Structural properties are related to the fracturing degree while texture regards the geometrical aspects of the constituent components of the tested rocks, i.e., the characteristics of the fragments and matrix (size, shape, distribution). To further understand this complex behavior of the fault rocks, these elements were quantified and correlated with the mechanical properties of the samples. In particular, we focused on 1. Identifying and quantifying the areal distribution between matrix and fragments on each specimen and 2. Quantifying the fracturing degree on the external surface of the specimens.

Those properties are evaluated depending on the fault rock type as:

- Types E-I, E-II: The limestone fault breccias comprise limestone fragments cemented in a calcite matrix. The matrix affects the properties of the samples and therefore, the impact of the textural properties is evaluated. The specimens were generally devoid of fractures.
- Type A-II*: The fractured, marly limestone is homogenous therefore, no textural properties are assessed. However, the samples were fractured as a result of intense tectonic activity and thus, the structural properties control their mechanical response.
- Type P: The tectono-diagenetic dolomite breccia features dolomitic fragments cemented in a crystalline dolomite matrix. Thus, its textural properties are assessed.

**Type A-I was not assessed in terms of structural properties due to the small number of available specimens (2).*

3D models of each specimen were created based on the Structure from Motion (Sfm) technique and orthophotos of each sample's side were generated. The orthophotos were assessed in terms of matrix-fragments distribution and fracturing degree. To quantify these two elements, 2 discrete algorithms programmed in MATLAB (Mathworks, 2019) were established. The first algorithm (*Fragments-Matrix Algorithm or **FMA***) aims at measuring the surface that fragments and matrix occupy in a given orthophoto and deriving their ratio. The purpose of the second algorithm (*Fracturing Degree Algorithm or **FDA***) is twofold: 1. Determine a sample's fracturing network and 2. Quantify the surface's fracturing degree via the P_{10} index (Dershowitz and Herda, 1992).

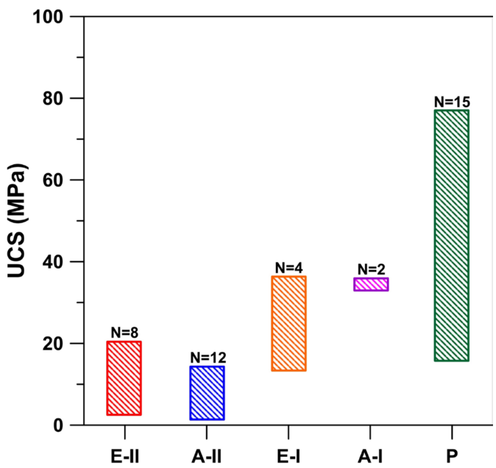

Figure 2. UCS range of each fault rock type studied. N represents the number of specimens subjected to the Uniaxial Compression Test (UCT).

4.2 *Correlation of structural/textural properties with UCS*

Types E-I, E-II:

Based on the FMA results, the samples from Type E-I present a matrix ratio with an average value of 14%. The corresponding ratio of E-II type is 39% with a single sample comprising pure calcite matrix. Since the matrix is weaker than the limestone fragments, a logical assumption is that the mechanical properties of the material decrease with increasing matrix ratio, a fact that is validated by the findings. Figure 3a depicts the correlation between the UCS of E-I and E-II types and their derived matrix ratio. The data indicate that the matrix ratio controls the UCS of Types E-I and E-II. Type E-I presented a higher average UCS due to its reduced matrix ratio and vice versa.

Moreover, the findings suggest that when the matrix ratio is higher than 40% (dotted line in Figure 3a) the UCS of the fault breccia is equal to that of the matrix. Therefore, it is deduced that the matrix controls the strength of the material even when it occupies less than 50% of the total sample's volume. This is a paramount finding suggesting that the mechanical properties of fault rocks with composite nature and weak matrix would behave in correspondence with the matrix's mechanical properties given that it occupies a minimum proportion of the sample's volume. The best-fit equation derived for the UCS-matrix ratio data taking into consideration that the lower boundary UCS value is that of the matrix is:

$$UCS_{E-I,E-II}(MPa) = 2347 * M(\%)^{-1.84} + UCS_{MR} \leq UCS_{FR} \quad (1)$$

Where M (%) is the matrix ratio, UCS_{MR} (MPa) the UCS of the matrix and UCS_{FR} (MPa) the UCS of the limestone fragments which can be assumed to be equal to the UCS of the intact limestone breccia from the same geotectonic zone (Type ATH), i.e., 86MPa.

Equation [1] is asymptotic to the y-axis in Figure 3a, meaning that the UCS value approaches infinity for very low values of M(%). To remedy this, if the M(%) ratio is less than 5%, the UCS of the material is considered equal to the UCS_{FR}.

Type P: Type P specimens presented a narrower range of matrix ratio (47%-76%) compared to Types E-I and E-II. The correlation between UCS and matrix ratio indicates (Figure 3b) an increasing trend of UCS as the matrix ratio increases, i.e., a behavior contradictory to the previous findings. This response is interpreted as follows: An increase in the matrix percentage decreases the area of the boundaries between the matrix and the fragments and thus, the failure surface has to traverse the strong matrix. Therefore, the overall strength of the material increases. The correlation can be approximated by a power function and applies in the tested range:

$$UCS_P = 3.2 * 10^{-4} * M(\%)^{2.82}, R^2 = 0.79 \quad (2)$$

Type A-II: The impact of the fracturing degree on the UCS of Type A-II is unambiguous. The specimens with the highest fracturing degrees presented the lowest mechanical properties. The correlation between the UCS and P_{10} is illustrated in Figure 3c. The strong correlation between the fracturing degree and the UCS indicates that the mechanical properties of Type A-II samples are controlled by secondary fracturing. The best-fit curve is represented by an exponential decay in the UCS as follows:

$$UCS_{A-II} = 18.45 * e^{-1.33 P_{10}}, R^2 = 0.82 \quad (3)$$

In Equation (3) P_{10} is measured in traces/cm.

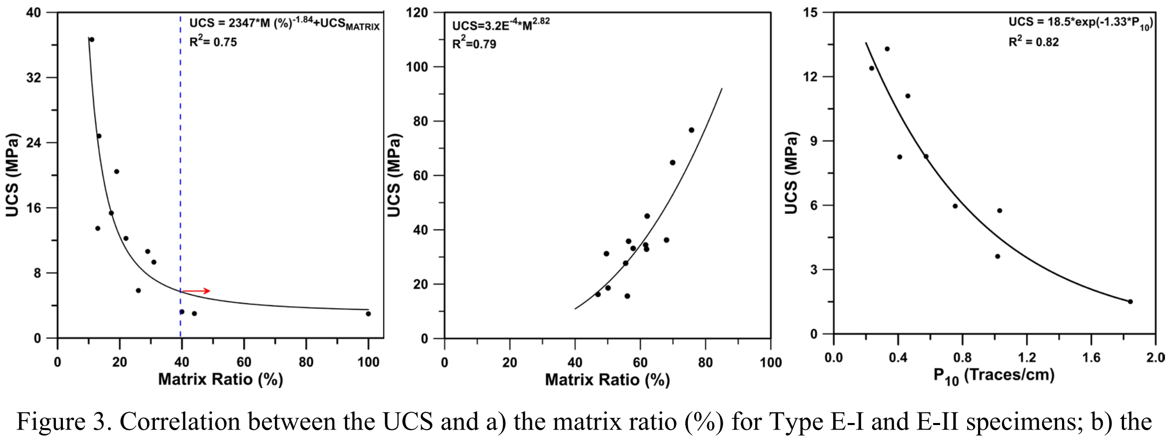

Figure 3. Correlation between the UCS and a) the matrix ratio (%) for Type E-I and E-II specimens; b) the matrix ratio (%) for Type P specimens; and c) the P_{10} fracture index for Type A-II specimens.

5 DISCUSSION-CONCLUSIONS

In the present study, five (5) types of carbonate fault rocks were studied to investigate their mechanical properties and the factors that control them. These were consistently lower compared to the corresponding parent rocks which were assessed as a reference.

The mechanical properties of the crackle fault limestone breccia (Type E-I) and crackle to mosaic fault limestone breccia (Type E-II) were controlled by the presence of calcite matrix that bounds the limestone fragments. The tectono-diagenetic dolomite breccia (type P) comprised dolomitic fragments cemented in a strong, fine crystalline dolomitic matrix. Type P presented a diametrically opposite response compared to Types E-I and E-II due to the increased strength of its matrix. Finally, the fractured marly limestone samples (Types A-I and A-II) presented secondary cracks as a result of tectonization processes. Those significantly reduced their mechanical properties.

In conclusion, the studied fault rocks from Lefkada Island are representative of a wide spectrum of weak carbonate fault rocks. Their complex behavior cannot be adequately quantified using the existing methodologies as the structural and textural properties severely impact their mechanical properties. It is strongly believed that future research should focus on quantifying the structural/textural elements of fault rocks in situ, aiming to develop a reliable methodology to predict their strength and deformation properties.

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