Classification of weak, carbonate fault rocks

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ABSTRACT: The most common rock mass classification systems have been developed around hard rocks and do not fully apply to the characterization of weak rocks. Moreover, fault carbonate rocks present unique properties that cannot be accounted for when using these systems. Therefore, a new classification scheme is needed to accurately predict their mechanical properties. Weak, carbonate fault rocks from Lefkada island, Greece, are studied via a series of laboratory tests. Based on the geological background and our findings, the fault rocks are classified into four main types: Parent rocks, Welded breccias, Unwelded breccias and Matrix material. A methodology to estimate the Uniaxial Compressive Strength (UCS_i) of each fault rock type is proposed. The results indicate that the Uniaxial Compressive Strength of the welded/unwelded breccias is a function of the corresponding strength of their components (fragments and matrix) and the matrix ratio (the percentage of matrix in a given volume).

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

1 INTRODUCTION

Common rock mass classification systems (Q, RMR, SMR) are mostly applicable to hard rocks and do not fully apply for the characterization of weak materials (Kanji, 2014; Zhai et al., 2017). Moon et al. (2001) suggest that if the conditions exist for weak rocks to fail along discontinuities, then the basic rock mechanics principles and classification systems can be applied. Nonetheless, when a weak rock fails as a homogenous material, those classification systems tend to overestimate its overall strength.

In addition, studies on weak rocks of tectonic origin suggest that the material experiences a transition in terms of failure mechanism from interblock shear failure to a failure mechanism that is mainly controlled by the intact part of the rock. The former is well-described by the Hoek-Brown failure criterion (Hoek and Brown, 1980) for rock masses in which the Geological Strength Index (GSI) and the disturbance factor (D) are used to reduce the mechanical properties of the intact rock (Hoek et al., 2002). However, when the UCS of the material is less than 15MPa, the conventional approach does not account for the actual response of the material (Diederichs et al., 2007; Carter et al., 2008). In particular, the reduction of the rockmass UCS (UCS_m) is less profound as the UCS of the intact rock decreases (Carter et al., 2008). Currently, there is no well-accepted engineering classification methodology that can be easily applied in the field for carbonate fault rocks. The existing classification systems (e.g., Higgins, 1971; Killick, 2003; Woodcock and Mort, 2008) approach these materials more from a geological rather than a geotechnical perspective. In addition, laboratory tests to derive the mechanical properties of such materials are halted due to their weak nature and the difficulties associated with sample preparation.

Ferraro et al. (2018) analyze the formations that evolve around carbonate fault zones (Figure 1a). Those include fault breccias that may either be matrix- or fragment-supported and fragmented/fractured carbonate parent rocks (limestones-dolomites in the case studied herein-Figure1b). In the case of the breccias, the strength of the intact rock is lower compared to the parent rocks (apart from the breccias that feature a strongly cemented matrix). However, they feature a less developed fracturing degree (see Figure 1a, b) and therefore their mechanical properties are mainly controlled by the intact rock strength.

According to the theory of bimrocks (Medley, 1994), depending on the properties of their components (fragments and matrix) and the contact strength between them, fault breccias may behave as welded or unwelded breccias. In welded breccias, the strength of the contacts between the matrix and fragments is approximately equal to the strength of the matrix whereas, in unwelded bimrocks, the contact strength between the matrix and fragments is assumed to be less than the strength of the matrix (Riedmüller et al., 2001).

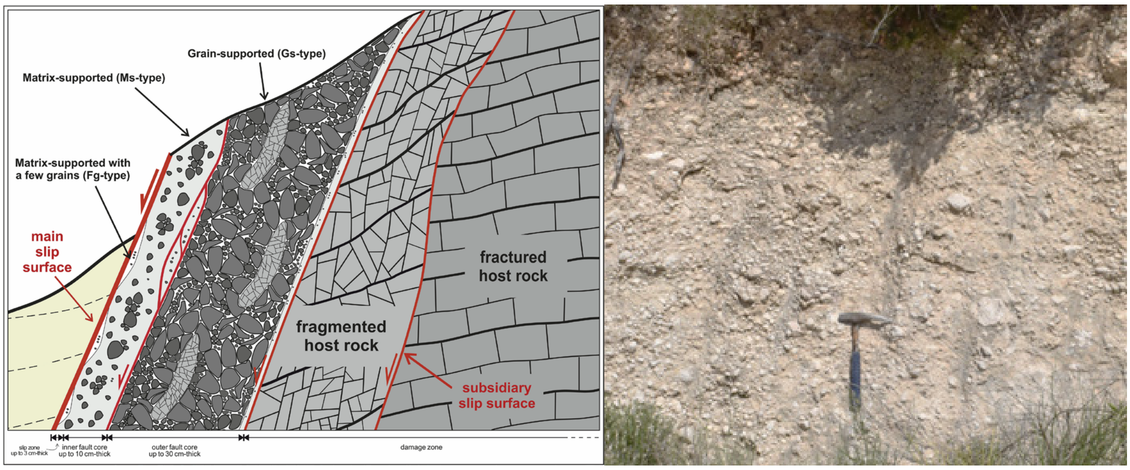

Figure 1. a) Schematic cross-section of a carbonate fault core presenting the lateral distribution of the main fault rock textures (Ferraro et al., 2018) b) Outcrop of limestone fault breccia in Lefkada Island, Greece.

2 METHODOLOGY

Herein, two types of carbonate fault breccias from Lefkada Island, Greece, are studied via Uniaxial Compressive Tests (UCTs) to establish a new classification methodology. The first is a limestone fault breccia (Type E) that features a weak calcite matrix and the second is a dolomite tectono-diagenetic breccia (Type P) which features fine crystalline dolomite (strong) matrix.

Before the UCTs were performed, the matrix ratio (i.e., the percentage of matrix within the volume) of each specimen was measured. To achieve this, three-dimensional models of the samples were reconstructed based on the Structure from motion (SfM) technique. An image analysis technique was subsequently developed and allowed to measure the surface that fragments and matrix occupy in each specimen and derive their ratio was established. The results of this quantification were correlated with the UCS of each sample from each type tested.

3 RESULTS

The aforementioned process allowed to correlate the UCS of the studied specimens (per Type) with the matrix ratio. The results prove that the UCS of Type's E specimens is reduced with an increase in the matrix ratio. In fact, the findings indicate that the matrix proportion controls the overall strength of the material when it exceeds about 40%. This is due to the weak nature of the calcite matrix. Therefore, Type E behaves as a welded breccia, according to the theory of bimrocks. Figure 2a presents the normalized UCS of the welded rock types, i.e., UCS_{Wbr}/UCS_{FR} (Wbr: Welded breccia/FR: Fragments). The data allow to derive a relationship between the matrix ratio and the intermediate strength of the welded breccias. The following equation is established:

$$UCS_{Wbr} = UCS_{MR} + (UCS_{FR} - UCS_{MR}) * \mathrm{e}^{-1.04\mathrm{M}(\%)} \tag{1}$$

Where UCS_{Wbr} is the UCS of the welded breccia, UCS_{FR} is the UCS of the fragments, UCS_{MR} is the UCS of the matrix and M (%) is the matrix ratio. If the strength parameters are normalized to the UCS_{FR}, the mathematical correlation is transformed into:

$$UCS_{Wbr}/UCS_{FR} = \frac{1}{R} + (R-1)\mathrm{e}^{-1.04\mathrm{M}(\%)} \tag{2}$$

$$R = \frac{UCS_{FR}}{UCS_{MR}} \tag{3}$$

The R parameter is critical because it allows the establishment of a universal model for welded breccias independent of the strength of the fragments and the matrix. Note that equation (2) should only be applied for welded breccias. As the strength of the matrix increases, i.e., R decreases, the material may transit from a welded to an unwelded state, meaning that the boundaries of the matrix and the fragments would control the strength.

On the contrary, the UCS of Type's P specimens increases with an increase in the matrix. This is associated with the presence of the strong dolomite matrix. Therefore, according to the theory of bimrocks, Type P behaves as an unwelded breccia. The contact strength between fragments and matrix is less than the strength of the matrix and hence, the boundaries between the two components control the response of the dolomite tectono-diagenetic breccia. The maximum UCS of an unwelded breccia is that of its matrix (UCS_{MR}) and the lowest is observed when the matrix ratio approximates low values. Our data do not include matrix ratios between 47% and thus do not cover the entire range of interest. To account for the lack of data below ratios of 47%, the corresponding data of Alber and Kahraman (2009), which are in agreement with the findings of the present study, are used. The ratio between the UCS of the unwelded rock types and the UCS of the matrix, i.e., UCS_{Ubr}/UCS_{MR} (*Ubr*: Unwelded breccia/*MR*: Matrix) versus the matrix ratio based on the aforementioned assumptions is presented in Figure 2b. The UCS of the unwelded breccia can be estimated from the following equation:

$$UCS_{Ubr}/UCS_{MR} = 4.6 * 10^{-7} * M(\%)^{3.16} + 0.084 \tag{4}$$

Where UCS_{Ubr} is the UCS of the unwelded breccia.

The intercept (0.084) represents the UCS of the unwelded breccia once the matrix ratio approximates 0. It is equal to 8.4% of the UCS of the matrix. Therefore, the estimation requires the derivation of the UCS_{MR} and the matrix ratio M(%). Note that the strength of the fragments is not used in this case but it is assumed to be higher than the strength of the boundaries between the matrix and the fragments (which is always the case). Otherwise, the failure surface would traverse the fragments.

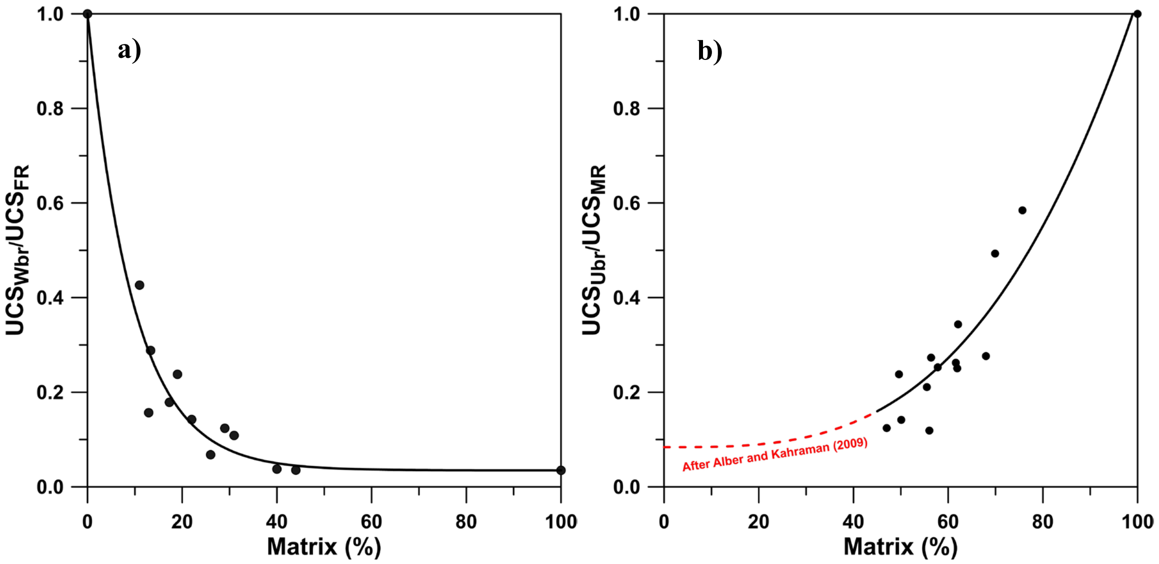

Figure 2. a) Normalized UCS of welded breccias UCS_{Wbr}/UCS_{FR} versus matrix ratio (%) and b) Normalized UCS of unwelded breccias UCS_{Ubr}/UCS_{MR} versus matrix ratio. The curve has been extrapolated based on the findings of Alber and Kahraman (2009) to account for low matrix ratios (<47%).

4 CLASSIFICATION OF WEAK CARBONATE FAULT ROCKS

Coupling the geologic/tectonic regime of fault rocks, the insights of the theory of bimrocks and the experimental findings, the carbonate fault rocks are classified based on their engineering behavior as described below:

- **Parent Rocks:** The intact carbonate rocks outside the fault's damage zone that have not been impacted by the fault slippage. Their mechanical properties are not affected by the fault.
- **Welded carbonate breccias:** The fault rocks that have been brecciated due to the fault's slippage forming a fault breccia. The strength of the contact surface between the fragments and the matrix is equal to the matrix (welded). This is indicative of two conditions: 1) Strong cementation between matrix and fragments or 2) The existence of weak matrix. Type E represents a welded limestone breccia.
- **Unwelded carbonate breccias:** The formations are similar to the welded breccias, however, the contact strength between fragments and matrix is lower than the strength of the matrix. This is observed when: 1) The matrix is strong and 2) The cementation between the matrix and fragments is weak. Type P represents an unwelded dolomite breccia.
- **Matrix:** In matrix-supported breccias (Figure 1), the matrix may be completely isolated from the fragments and studied individually. This is not a frequent incident and also depends on the scale of the study. Type E includes one specimen solely comprising calcite matrix which is representative of this condition.

It is suggested to classify a material as a (welded or unwelded) breccia only when the matrix ratio is at least 10%. For a lower matrix ratio, the behavior of the material approximates that of the parent rock or interlocked fragments therefore, it cannot be classified as a breccia.

The different methodologies presented above to derive the UCS in each case are summarized in Table 1. Regarding the strength of the matrix in fault breccias, when it is strong and cylindrical samples can be obtained, the international standard guidelines (ISRM, 1979; 2007) can be used to prepare samples and measure its UCS (UCS_{MR}). If the matrix is very weak (<1.5MPa), sampling and testing would be infeasible even if elegant sampling/preparation processes are used. In that case, the field properties suggested by ISRM (2007) and Waltham (2009) can be used to approximate the UCS_{MR} (Table 2). If the matrix lies between the very weak-weak rock range (1.0-12.5 MPa), sampling and testing procedures can be employed but it would still be challenging to measure its mechanical properties. In that case, Point Load tests (PLTs) can be performed in situ using irregular matrix specimens. If those prove to be also infeasible, again the field properties summarized in Table 2 can be used.

Table 1. Summary of the methodologies employed to derive the UCS of fault carbonate rocks based on the new engineering classification.

Description	Methodology
Parent rocks (UCS_{PR})	Derive the UCS via laboratory tests on intact parent rock specimens.
Welded breccias (UCS_{Wbr})	Derive the UCS of the fragments and the matrix and use the corresponding curve/equation for welded breccias (Equation 2)
Unwelded breccias (UCS_{Ubr})	Derive the UCS of the matrix and use the corresponding curve/equation for unwelded breccias (Equation 4)
Matrix (UCS_{MR})	Derive the UCS of the matrix via laboratory tests or use the field estimations for rock strength approximation (Table 2)

Table 2. Approximation of the UCS of the matrix (UCS_{MR}) in the field (modified from ISRM, 2007 and Waltham, 2009).

Matrix description	UCS_{MR} (MPa)	Field test guidelines	Is laboratory testing enabled?
Very soft soil	<0.025	*Head of geological pick can easily be pushed into the shaft of the handle. Molded easily by fingers.*	No
Soft soil	0.025-0.05	*Easily penetrated by thumb. Sharp end of pick can be pushed in to 30-40mm. Molded by fingers with some pressure.*	No
Firm soil	0.05-0.10	*Indented by thumb with effort. Sharp end of pick can be pushed in to 10mm. Can just be penetrated with an ordinary spade.*	No
Stiff soil	0.10-0.20	*Penetrated by thumbnail. Slight indentation produced by pushing pick point into soil. Cannot be molded by fingers. Requires hand pick for excavation.*	No
Very stiff soil/extremely weak rock	0.20-0.40	*Indented by thumbnail with difficulty. Slight indentation produced by blow of a pick point. Requires power tools for excavation.*	No
Extremely weak rock	0.4-1.0	*Break by hand. Requires power tools for excavation.*	No
Very weak rock	1.0-5.0	*Crumbles under firm blows with point of geological hammer. Can be peeled by a putty knife.*	Yes, but challenging. *Alternative method: Point Load tests*
Weak rock	5.0-12.5	*Cannot cut by hand. Can be peeled by putty knife with difficulty. Indentations made with firm blows with point of a geological hammer.*	Yes, still problematic. *Alternative method: Point Load tests*
Moderately weak rock	12.5-25.0	*Dent with hammer pick. Shallow indentations made with firm blows with point of a geological hammer.*	Yes
Medium-strong rock	25.0-50.0	*Cannot be scraped or peeled by a putty. knife. Specimen can be fractured with a single firm blow of a geological hammer.*	Yes

Strong rock	50.0-100.0	*Specimen requires more than one blow of a geological hammer to fracture it.*	Yes
Very Strong rock	100.0-250.0	*Specimen requires many blows of a geological hammer to fracture it.*	Yes
Extremely Strong	>250.0	*Specimen can only be chipped with a geological hammer.*	Yes

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