The importance of classification for carbonates and mudrocks in engineering

2011 Pan-Am CGS Geotechnical Conference

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ABSTRACT
Geological classification systems for carbonates and mudrocks were developed to more accurately describe these sedimentary rock types. There appears to be a correlation between the mechanical properties examined in this paper and the geological classification system of Dunham. It was found that the Modulus Ratio of mudrocks is lower than packstones, which is lower than Dolomite. Grains weaker in tension, than the matrix, begin to control the failure process at around 35-40% total volume of the sample, in 2-dimensions. This volume will be lower for real samples. Many characteristics affect fracture initiation and propagation in carbonates and mudrocks. Fractures initiate around grains or pore spaces and propagate through matrix and grains. They can also propagate easily along bedding planes, although the argillaceous content, in carbonates, may arrest propagation. The micro-mechanical behaviour of these materials is a key research focus for storage of nuclear waste in sedimentary rocks.

RÉSUMÉ
Systèmes de classification géologique de carbonates et de pélites ont été élaborés pour décrire plus précisément ces types de roches sédimentaires. Il semble y avoir une corrélation entre les propriétés mécaniques examinées dans le présent document et le système de classification géologique de Dunham. Il a été constaté que le rapport des modules d'argilites est inférieur packstones, ce qui est inférieur Dolomites. Grains plus faible de la tension, que la matrice, de commencer à contrôler le processus de rupture à environ 35-40% du volume total de l'échantillon, en 2-dimensions. Ce volume sera plus faible pour les échantillons réels. Caractéristiques ont une influence sur l'initiation et la propagation de fracture dans les carbonates et pélites. Fractures ouvrir autour des grains ou des pores et se propagent à travers la matrice et des céréales. Ils peuvent également propager facilement le long des plans de stratification, bien que la teneur argileuse, dans les carbonates, peut arrêter la propagation. Le comportement de micro-mécanique de ces matériaux est un domaine de recherche clé pour l'entreposage des déchets nucléaires dans les roches sédimentaires.

1 INTRODUCTION

Carbonate rocks are used for many purposes around the world; for building stone, cement and steel production, and as aggregate. It has been in use for centuries and is one of the most frequently used materials for aggregate (Cargill and Shakoor 1990). Geologists use the term carbonate to describe sedimentary rocks composed of predominately CO_3^{-2}. Limestone is a generic name and typically is used to describe $CaCO_3$ bearing rocks and dolomite to describe $CaMg(CO_3)_2$ bearing rocks.

Underground construction in carbonates has largely been limited to shallow excavations, in North America, ranging from underground quarries and mines to more recent infrastructure projects. The relatively high strength of most carbonates, with unconfined compressive strengths (UCS) on average around 100 MPa, make it an ideal material for constructing with, on or in.

There is however; a large variation in the strength and behavior of carbonate rocks, both at laboratory and excavation scales. UCS values can range from 50 – 250 MPa according to Hoek (2007) and this wide range of strength values is influenced by many factors. Some of these factors include grain size variations, pore volume, cement type and pervasiveness, fossil content, non-calcareous content, burial depth, dolomitization and karstification. In addition to peak strength, the nature of the carbonate matrix, fabric and grain components control the relationship between damage initiation (onset of fracture damage) and the propagation of fractures, thereby controlling the brittleness of the material or conversely the ability to sustain damage without failure. These characteristics are of importance for slab resilience, aggregate durability and long term stability of sensitive underground works such as nuclear waste repositories.

1.1 Classification Systems

Geotechnically the rock in consideration for a project is classified according a rockmass scheme, such as Rock Mass Rating, (RMR), system of Bieniawski (1973, 1989), Q system of Barton et al. (1974) or Geological Strength Index, (GSI), of Hoek (1994) and Hoek et al. (1995). The GSI system was developed to reduce intact rock properties based on geological conditions and was largely due to the increasing use of continuum codes for design.

Grabau (1904) realized the large grouping of rocks called limestones was inadequate to distinguish between the many varieties. Further development in geological classification systems by Folk (1959, 1962) and Dunham (1962) are still widely used today. Dunham's 1962 classification system is the most widely used in geological sciences because of its ease of use in the field and does not require thin section analysis, such as Folk's (1962) system. Additions to Dunham's 1962 classification system have been presented by Embry and Klovian (1971) and James (1984), to help account for larger fossil fragments and different binding organisms and agents.

1.2 Carbonates in Geological Engineering

The geological systems have largely been ignored by the geological engineering community when classifying rockmasses. This may be due to the fact that standard compressive testing typically yields a wide range of values for all rock types and carbonates are no exception. Also, average values for standard mechanical properties, such as Young's Modulus (E_i) or Unconfined Compressive Strength (UCS), are typically used and variations maybe acceptably captured by considering the range for design. However; at the grain scale there can be significant changes in the limestone character, which can influence the micro-mechanical behaviour, particularly the fracture initiation and propagation thresholds.

The lack of consistent terminology, used in geological engineering, for carbonate rockmasses makes reviewing past projects difficult and challenging to apply to current designs because the question arises; what types of carbonate rock were they dealing with and does it apply to this project? It may not be sufficient to apply the same findings from one project site to another, even if they are within the same formation, as slight variations in the depositional environment can change the character significantly and thus influence its micro-mechanical properties and behavior. The same is true for mudrocks, although the influencing factors on the micro-mechanical properties may be less. By applying the correct terminology to describe carbonates and mudrocks an implied general behavior should be properly communicated.

The work presented in this paper is part of a larger research project which will investigate the influence of various carbonate and mudrock features on the micro-mechanical behavior. Future investigations will include laboratory testing and excavation site visits, to ultimately determine the most appropriate numerical method(s) to model underground excavations in these rock types.

2 CLASSIFICATION OF CARBONATE ROCKS

The two main geological classification systems of Folk (1959) and Dunham (1962) are currently widely used and other variations of classification systems have been developed and include systems which address the relationship between carbonate and siliciclastic grains (Mount 1985). However; the later have not gained widespread use in the geological community due to their complex nature, but may be important when considering rockmass behaviour for a geotechnical characterization system for carbonates, as mudrocks are often found to co-exist at the outcrop scale.

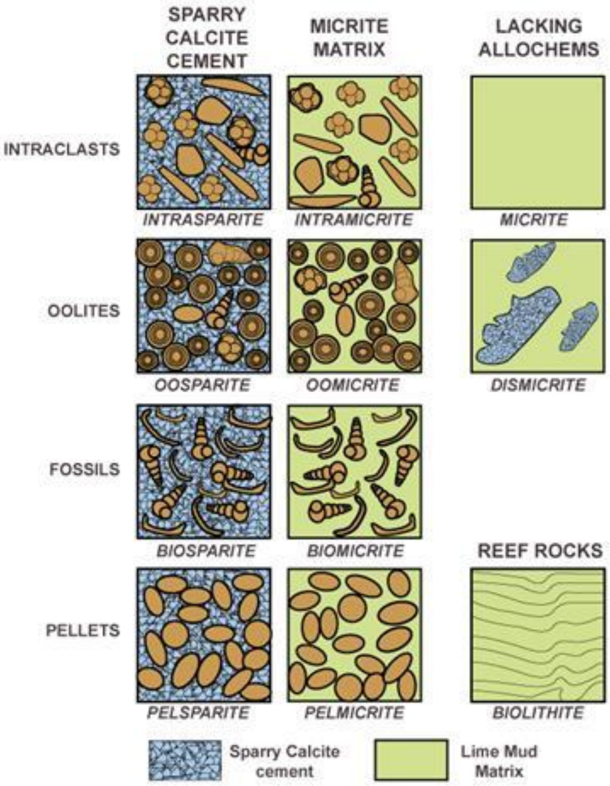

Figure 1: Folk's (1959, 1962) textural classification of carbonate rocks.

2.1 Folk's Classification System

Folk (1959, 1962) laid out a method of classifying carbonate rocks based on petrographic thin section analysis. The main classification system is shown in Figure 1. This system is based on two principal components, matrix and allochems (grains). Distinction is made between four different types of allochems, as well as those lacking allochems or reefs builders.

In this system the matrix material, either sparry or micrite calcite cement, is used as a major division. The definitions given by Folk (1962) are;

- *Sparry:* coarse calcite cement, clear crystals >10 μm
- *Micrite:* very fine, sub-translucent crystals 1-4 μm, also called microcrystalline cement

These terms are conjugated with the type of allochems present and the terminology can get confusing. The terminology only indirectly indicates the environment of deposition.

2.2 Dunham's Classification System

Dunham's (1962) system addresses the issue of depositional environment by considering the allochem-matrix relationship, in terms of percent volume or packing arrangement and is outlined in Figure 2.

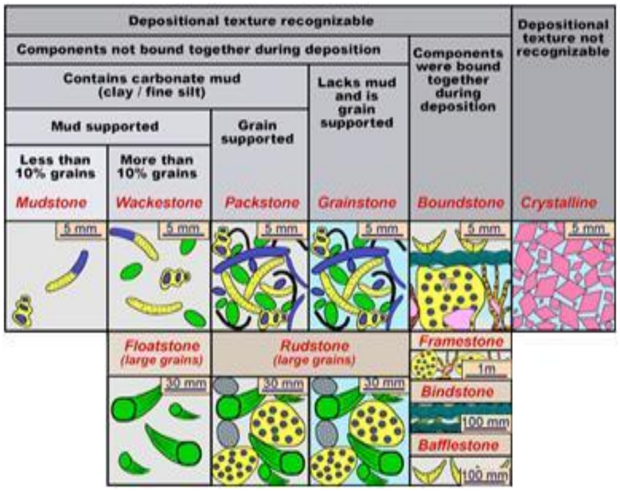

Figure 2: Dunham's (1962) depositional classification of carbonate rocks (from Loucks et al. 2003).

The definitions of the classes considered in this paper are as follows, as outlined by Jones and Desrochers (1992), unless otherwise indicated;

- *Mudstone:* fine grained, < 20 μm (Dunham 1962), originating from ooze, disintegration of fossils or grains, or possibly from inorganic precipitation. Associated with low energy or binding organisms in medium-high energy
- *Wackestone:* transitional, matrix supported 10% < % volume grains < 20-30%
- *Packstone:* transitional sediment, grain support, volume of grains 20-30% (Tucker and Wright 1990)
- *Grainstone:* high energy, no mud, typical of shoals, beaches, areas
- *Dolomite:* 1:1 ratio of Ca^{2+} to Mg^{2+} ions, predominately $CaMg(CO_3)_2$. considered to be crystalline in this paper
- *Crystalline:* recrystallization of limestone, change in grain/crystal size without a change in mineralogy

Both dolomitization and recrystallization are gradational processes and affect the structure of the rockmass at the micro scale. Crystalline in Dunham's systems can be considered for both Dolomite and crystalline limestone.

The naming convention using Dunham's classification is to select the appropriate root word from Figure 2 and add a prefix to describe the most appropriate allochem(s) or other features. For instance; a packstone is grain supported with a fine carbonate mud matrix. An appropriate prefix might be oolitic, which would imply that the rock is composed on ooids. This implies the environment of deposition was near the carbonate factory, where the grains were being produced, but far enough away that the energy of the environment did not remove the fine grained mud which was deposited along with the grains. Dunham (1962) also used terminology from siliciclastic sedimentology, which every Geological Engineer is accustomed to using. This means that the descriptive terminology is more easily understood than that of Folk (1959,1962).

Dunham's (1962) system is adopted for its ease of use in the field and for the more commonly used terminology. In this study we look at the characteristics which contribute to fracture initiation and propagation in mudstones, wackestones, packstones, and crystalline limestone. These carbonate types are typical for construction projects around the world. The other types are less commonly utilized in the construction industry.

The depositional environment controls the type of carbonate rock which will form. The water temperature, depth, salinity and siliciclastic input are all important factors and James and Choquette (1990) state that to "understand limestones for any purpose it is imperative to decipher the often complex series of processes that have modified their texture and composition." After deposition the main processes of diagenesis include compaction, cementation, dissolution and recrystallization. These processes also influence the micro-mechanical behavior of carbonates.

2.3 Mixed Sediment Classification

Siliciclastic input inhibits growth of carbonate producing organisms (Mount 1985). However; siliciclastic material does occur mixed with carbonate material and attempts have been made to create mixed sediment classification systems. Mixing can be observed as interbedded layers or as disseminated grains. The later can be indicative of depositional environment changes or sporadic input from siliciclastic sources, such as windblown sands. Some organisms build quartz into their skeletal structure, such as sponges which leave siliceous skeletal fragments, called spicules, behind in the rock record (Uriz et al. 2003). 50% carbonate is used as the cut-off point between siliciclastic and carbonate rocks.

Mount (1985) proposed a mixed siliciclastic-carbonate classification system based on texture and composition. At its simplest level the system divides material into four components; siliciclastic sand or mud and carbonate sand or mud. The system is complicated, although Mount (1985) does provide the frame work for understanding the relationship between siliciclastic and carbonate materials.

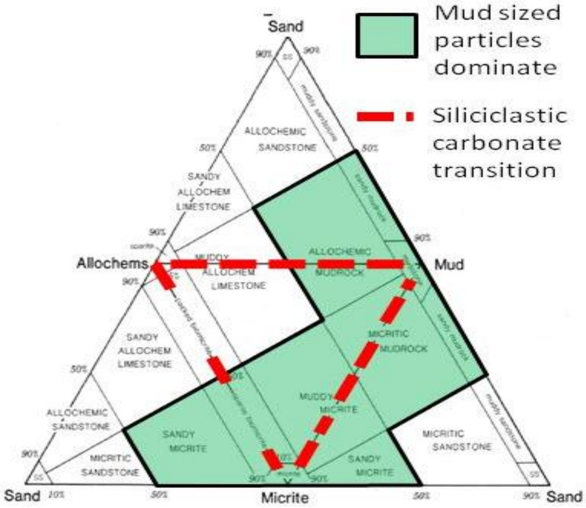

Figure 3: Mount's (1985) mixed classification systems.

The transition from carbonate to siliciclastic material occurs largely at the limemud-siliciclastic mud transition as highlighted in Figure 3. There is a small window of transition for larger grains. The authors would argue that this would be uncommon in nature due to the input energy required to make such a transition. It is more likely that the input energy would decrease first allowing mud sized grains to be deposited. This leads to the important role which mudrocks play on the mechanical behavior of carbonates, both at the laboratory scale and the excavation scale.

2.4 Mudrock Classification

Lundegard and Samuels (1980) developed a fine grained classification system for use in the field. They state that a distinction between fine grained rocks is needed and proposed subdivisions, shown in Figure 4, based on grain size and induration. Lundegard and Samuels (1980) define these fine grained rocks as mudrocks, which includes the sub-group shale (mud or clay). The term shale is often used in geotechnical literature to describe all fine grained sedimentary rocks which are not sandstones or carbonates. The distinction between shales and siltstones may prove to be useful when describing their mechanical behaviour.

The feature's presented in the above geological classification systems are only indirectly captured in geotechnical classification systems and the use of the geological terminology to describe the different rock types for carbonates and mudrocks are rarely used in geotechnical literature. This makes correlating rock properties and rockmass behavior from different sites to a newly developing project difficult, as the carbonate rockmass from one site maybe a completely different type of carbonate at the site in question. At the macro scale the materials may be similar and have similar UCS values. However; these materials may have largely different micro-mechanical characteristics which influence fracture initiation and propagation.

To answer the fundamental question of what is a limestone, from a geotechnical point of view, we must start at the different geological classes of carbonates. The different properties which distinguish a mudstone from a packstone should also influence the fracture initiation and propagation processes in carbonates.

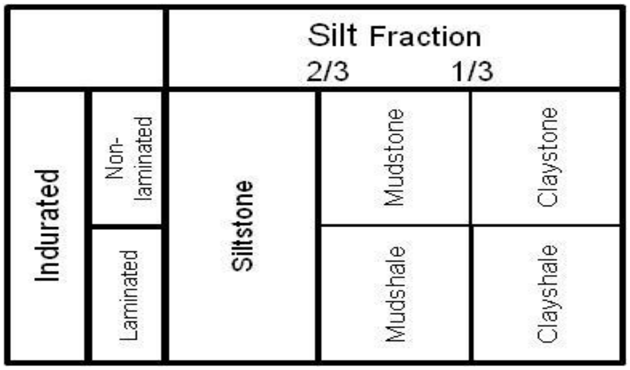

Figure 4: Mudrock classification based on texture and silt content (Lundegard and Samuels 1980).

Table 1: Estimated mi values for carbonate rock types by Hoek and Marinos (2000) and MR values from Hoek and Diedeirchs (2006)

Carbonate Type	Crystalline	Sparitic	Micritic	Dolomites
m_i	12 ± 3	10 ± 2	9 ± 2	9 ± 2
MR	400-600	600-800	800-1000	350-500

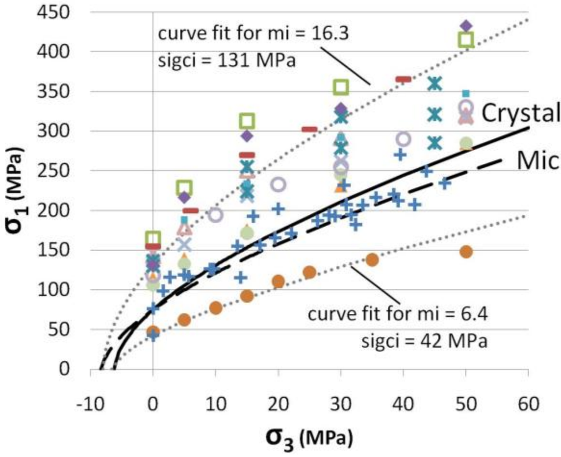

Figure 5: Triaxial carbonate data (courtesy of Dr. Evert Hoek) with curves used in the numerical modeling

3 MECHANICAL PROPERTIES OF CARBONATES

A review of the geotechnical literature pertaining to carbonates was undertaken and the test data was classified, where possible, using Dunham's (1962) classification system. Lime mudstone, wackestone, and packstone data was the most commonly found, with limited grainstone data. Dolomite is included as an end member and can be considered to be crystalline in Dunham's classification.

Hoek and Marinos (2000) made a distinction between four different types of carbonate for estimating the Hoek and Brown (1997) parameter mi, as shown in Table 1. Hoek and Diederichs (2006) were the first to establish different Modulus Ratios (MR) for the same four types (Table 1), which are similar to Folk's (1962) terminology.

3.1 Carbonate Laboratory Data

Triaxial test data, courtesy of Dr. Evert Hoek, show a wide range of mi values, from 6.4 to 16.3, for some carbonate rocks (Fig. 5). Such variation is not uncommon. A problem arises when two carbonate units have similar UCS values. In this case adjusting the mi value has a small influence on the failure envelop, as the sig1-sig3 curves (Fig. 5) are similar.

Plotting carbonate testing data indicates that the different classes have different mechanical properties (Fig. 6) and MR lines help highlight the ranges. The classification systems are subjective and this results in overlap between the different rock types. As well the carbonate types are gradational and can result in

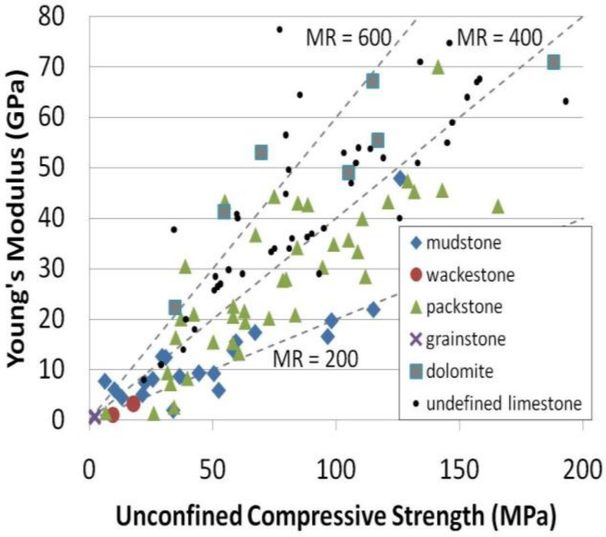

Figure 6: Carbonate strength versus stiffness sorted according to Dunham's (1962) classification system.

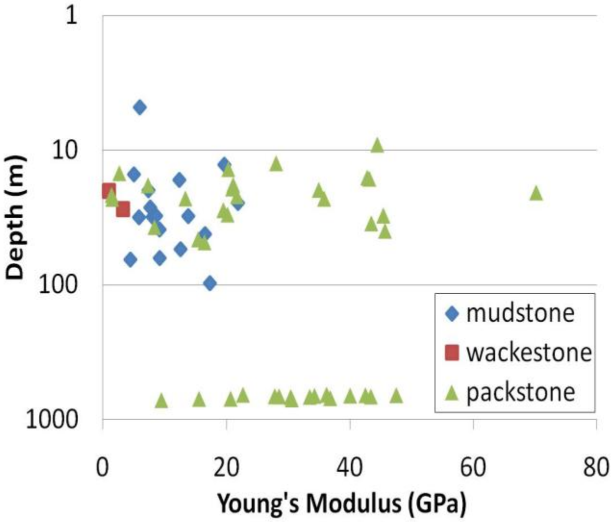

Figure 7: Young's modulus versus depth for a select group of data from a variety of sources, sorted according to Dunham's (1962) classification system.

miss-designation. This can occur if the general description of the formation, rather than the test specimen, is given in the literature. None the less, there is a clear indication that there is an influence on the mechanical properties, which is due in part to the nature of the type of carbonate according to Dunham's (1962).

Burial diagenesis changes the character of carbonate sediments, porosity can decrease due to compaction or due to recrystallization or dolomitization. The latter two can also increase porosity under the right conditions. Diagenesis should affect the stiffness of carbonate materials, with greater burial making stiffer units typically. On inspection of the limited available data, (Fig. 7), the only conclusion that can be drawn is perhaps that there is an upper bound for the stiffness of mudstones around 20 GPa. Based on Shinn and Robbin's (1983) work it is possible that an upper bound stiffness could exist, as they found that less than 100 m of burial was required to reduce the sediment to half its original thickness. Significant further burial (up to 3000 m) resulted in only minor reductions of several millimeters (Shinn and Robbin 1983) suggesting that fine grained mudstones reach a closest packing arrangement early in their diagenetic history. Shinn and Robbin (1983) also found that during burial wackestones convert to packstones and that shell breakage only occurs when large shells contact each other, not when surrounded by mud. Further diagenetic processes continue after mechanical compaction.

The process of recrystallization or dolomitization occurs at zones of ground water mixing (James and Choquette 1990) and as ground water levels fluctuate, this process is a gradational phenomenon. Recrystallization can change the crystal structure of the carbonate minerals, can fill voids and fractures with new cement and can create new pore space. Dolomitization changes calcite or aragonite grains into dolomite and can cause significant increases in porosity. These processes can increase the number of sites for stress localization and fracture initiation.

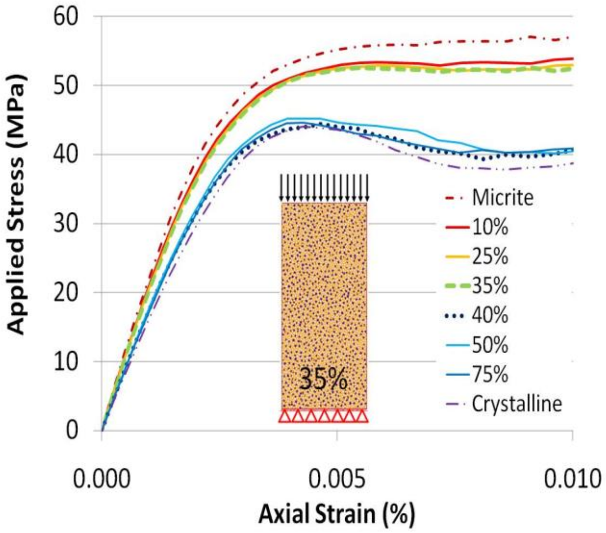

Figure 8: Synthetic UCS test results with varying percentage of crystalline grains in a micritic matrix.

3.2 Synthetic UCS Modelling

To test the influence of the lime mudstone to packstone transition and the influence of recrystallization, synthetic UCS models in 2D were evaluated. The properties of micrite and crystalline carbonate, from table 1, were used as a starting point. A voronoi joint network was used to simulate grain boundaries and the percentage of crystalline grains was increased uniformly across the sample to determine the influence on the UCS. An "intact" UCS of 75 MPa and a Poisson's ratio of 0.3 were used for both micritic and crystalline grains. The joint properties of; tensile strength = 8 MPa, cohesion = 15 MPa and friction angle = 40^0, were chosen to be similar to the intact strength.

The model results, shown in Figure 8, indicate that the end members (100% micrite and 100% crystalline grains) have a peak UCS value difference of 13 MPa, within the range of variability of real laboratory tests. The crystalline sample shows a minor strain softening behavior post peak, which is not present in the micritic sample. This is because the crystalline grains are weaker in tensile strength and begin to fail first, but the micrite grains pick up more load once the crystalline grains fail.

One would expect that with evenly distributed grains, that at 50% crystalline, would fall between the end members. At 50% crystalline grains however; the behavior is similar to the crystalline end member, indicating that the crystalline grains are dominating the failure process. The crystalline grains begin to dominate the failure process at 35-40%. The 20-30% level indicating grain-grain contact of a packstone come from 3D samples (Tucker and Wright 1990), but Dunham (1962) states that a 2D view at this volume of grains will show grains floating in the matrix. If the modeling were conducted in 3D the crystalline grains may begin to influence the failure process at volume levels close to the wackestone-packstone transition (20-30%).

Similarly the synthetic UCS model could be considered a recrystallization model. Here the addition of “crystalline” grains is in fact simulating the gradual conversion of micritic grains to crystalline. Therefore at 35-40% recrystallization or dolomitization is a threshold where a change in behavior occurs in 2D. Further research is necessary to confirm these thresholds, both numerically (2D & 3D) and on laboratory samples.

Both the laboratory test data and the synthetic UCS data indicate influences on the mechanical properties of carbonates, which can be correlated to Dunham’s (1962) classification system. The influence on crack initiation (CI) and crack damage (CD) thresholds has largely been unstudied, to the best of the author’s knowledge, in terms of different carbonate types. CI and CD are important parameters used to describe the brittle failure process of rock and potential influencing properties of carbonates and mudrocks are discussed below.

4 THE BRITTLE FAILURE PROCESS

Brady and Brown (2006) define the brittle fracture process as a sudden loss of strength across a plane with little to no permanent or plastic deformation and suggests that it s associated with strain-weakening behaviour.

The brittle failure process initiates at flaws within the rockmass or sample. This is called the damage initiation and is a lower bound strength, typically corresponding to 33%-50% of the intact UCS (Diederichs 2003). This is the CI threshold and can be detected most using a variety of methods, as discussed by Ghazvinian (2010).

As fractures propagate away from the initiating site they begin to interact with each other and eventually form a macro-scale fracture. This threshold corresponds to the onset of nonlinearity in axial stress-strain curves (Diederichs 2003) and is the CD threshold.

In carbonate rocks initial flaws can include mud-carbonate interfaces, fossil fragments, or pores. In mudrocks these sites can occur at grain size transitions, large clasts or other larger than typical mud sized grains randomly distributed in the rockmass. Argillaceous content of carbonate rocks maybe an important property which is able to arrest fracture propagation, limiting the degree of the brittle failure process.

4.1 Characteristics Affecting Initiation & Propagation

The initiation of fractures in brittle materials is an extensile phenomenon as indicated by many researchers (e.g. Lee and Haimson 1993; Myer et al. 1992; Stacey 1981; Tapponier and Brace 1976 and Griffith 1921). Materials such as granite and gneiss have long been known to behave in a brittle fashion. Many studies have shown, however; that tensile fracturing can be anticipated for a wide range of rock types (Hoek 1968; Fairhurst and Cook 1966; Brace et al. 1966; Tapponier and Brace 1976; Martin 1997; Amann et al. 2011).

4.1.1 Carbonates

Studies on the brittle-ductile transition for limestone indicate an inverse relationship between strength and grain size (e.g. Brace 1961, Handin and Hager 1957 and Fredrich et al. 1990). This is also influenced by the crystal structure.

Different grain stiffnesses can also induce tensile stress at the grain to grain contact, inducing a fracture. Different grain stiffnesses can arise in carbonate rocks through the processes of recrystallization or dolomitization, where grains are gradually changed into either a different crystal structure or different composition, respectively. Recrystallization and dolomitization can also create void space, which can be a site for fracture initiation.

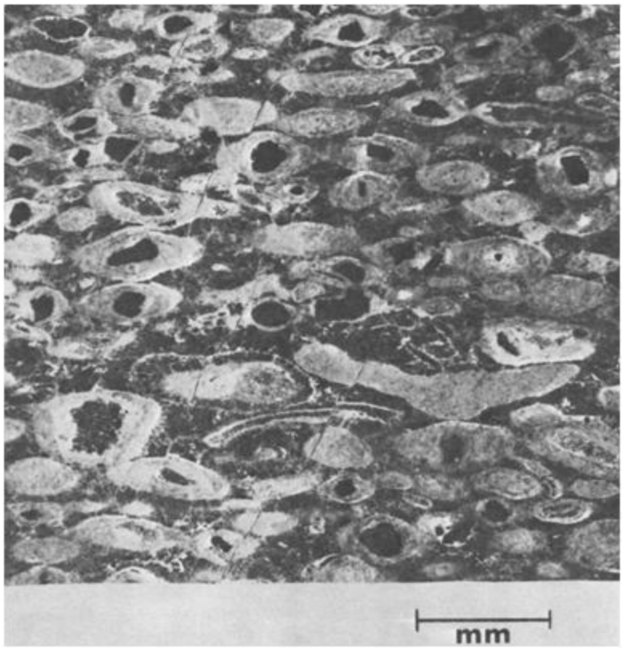

Figure 9: Fractures propagating through both the matrix and peliod grains of a sample from the Westington Quarry of the Inferior Oolite (from Holm 1983).

Experimental fracture propagation studies conducted by Hoagland et al. (1973) showed that it requires substantially less energy to propagate a fracture along bedding rather than perpendicular to it, in the Salem limestone. Another study (Holm 1983) showed that fractures propagate through the matrix and grains, since both have similar properties (Fig. 9). The non-tortuous fracture path means they can propagate easily and quickly. However; argillaceous components can arrest propagating fractures. This gives rise to the common appearance of carbonate outcrops with continuous horizontal beds and short vertical fractures which terminate at bedding planes, often of an argillaceous nature.

4.1.2 Mudrocks

The deposition of fine siliciclastic material, forming mudrocks, inherently leaves a bedding fabric. The bedding fabric can be indicated by different grain sizes, visible fabric or alternating colours (Lundegard and Samuels 1980). Fracture initiation can occur at the site of grain-grain contacts or at micro-stiffness variations between beds of different grain size. Amann (2011) indicates that clast inclusions are an important factor in the initiation of fractures during UCS tests on mudrocks of the Opalinus clay. Once fractures are initiated in mudrocks they propagate along bedding planes relatively easily and quickly, as this is the plane of least resistance. This process of brittle fracturing was observed by the authors in the Queenston Formation, a siltstone, at the Niagara Tunnel Project in Niagara Falls, Ontario.

The nature of carbonates and mudrocks hold unique characteristics which govern the initiation and propagation of fractures. These characteristics are captured in geological classification systems. The initiation and propagation of fractures in these rock types is important for several applications in geological engineering and a better understanding of the influencing characteristics will help future project designs.

5 CONCLUSIONS

Geological classification systems for carbonates and mudrocks were developed to more accurately describe these sedimentary rock types. There appears to be a correlation between the mechanical properties examined in this paper and the geological classification system of Dunham (1962) for carbonates. Carbonates, in particular, have many natural sites for fracture initiation and where the matrix and grains are both carbonate, fractures can propagate more easily even through the grains. However; often associated with carbonates is an argillaceous component, as beds or blebs, which can arrest fracture propagation. Bedding planes can also act as fracture initiation sites and due to their low tensile strength act as fracture propagation path ways. This is especially true with mudrocks, where there is a lack of stiffer and stronger layers (in between the bedding) to resist deformation. These characteristics, as well as others, influence the brittle behaviour of carbonates and mudrocks.

Geological classification systems, such as Dunham’s (1962), seem to provide a useful starting point for delineating the micro-mechanical differences between various types of carbonates. Further study is necessary to determine the influential characteristics of the material which affect the fracture initiation and propagation in carbonates and mudrocks. This will require detailed laboratory testing and site visits, so as to be able to implement these findings appropriately into numerical models of sensitive underground structures, such as nuclear waste repositories.

6 ACKNOWLEDGEMENTS

Funding for this research has been provided by the Natural Sciences and Engineering Research Council of Canada through the Industrial Postgraduate Scholarships program and sponsorship is provided by the Nuclear Waste Management Organization (NWMO) of Canada. The authors would like to thank Dr. Evert Hoek for use of the triaxial data, Mr. Tom Lam, of NWMO, and Dr. Florian Amann, of ETH Zurich, for their discussions on various aspects of this research.

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