**Microcracking Indicators Predict Critical Failure in Berea Sandstone Analog: Insights using the Discrete Element Method and Machine Learning**

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1. **Introduction**

Before and after relatively large earthquakes, seismic activity surrounding the source area exhibits generally higher activity than the long-term average. Seismologists have tried to improve earthquake prediction techniques by retroactive statistical analysis of observed foreshocks and aftershock sequences associated with these large earthquakes. Statistical variations in seismic event rate, seismic energy and moment magnitude preceding large earthquakes are observed widely but not systematically [Buochon et al., 2013; Wyss, 1997; Mignan 2014; Cicerone et al. 2009]. Since earthquakes have been suggested as scale-independent, self-organized critical phenomenon [Main, 1996; Scholz, 1968], rock deformation experiments have been employed to understand the statistical variation in seismicity during slip along faults. Precursory variations in microcracking, porosity and fracture energy are routinely observed prior to catastrophic rock failure during laboratory stick-slip and biaxial experiments [Rouet-Leduc et al., 2017; Ojala et al., 2004; Lockner 1993]. An integrated analysis of precursors to critical failure can help improve current earthquake and fracture prediction techniques.

Recent advances in laboratory experiments using acoustic emissions (AE’s) have improved our understanding of observed seismic variations by providing a spatio-temporal understanding of microcracking precursors to critical failure. Experimental AE analyses to show that macroscopic shear fracture growth in brittle materials is preceded by pervasive evolution of microcrack rate, spatial distribution, energy and seismic moment. Biaxial experiments reveal accelerated pre-failure microcracking rate across several crystalline rock types [Lei et al., 2006; Baud et al., 2004; Stanchits et al., 2006]. Additionally, biaxial and stick slip experiments conducted on non-cohesive granular rock show exponential pre-failure AE energy release prior to catastrophic failure [Rouet-Leduc et al., 2017; Johnson et al., 2013]. Laboratory stick-slip experiments reveal an increase in range of seismic moments observed from AE and a corresponding decline in b-values prior to catastrophic failure [Rivière et al., 2018; Goebel et al., 2017]. Finally, biaxial experiments reveal that pre-failure damage evolution prior to catastrophic failure in crystalline rocks is characterized by localization of microcracking, resulting in a decline in fractal dimension of observed AE [Lei et al., 2004; Lockner, 1993]. While experimental observations have helped identify spatio-temporal precursory signatures to catastrophic failure, they are largely applicable to non-cohesive granular media and crystalline rocks. The constraints over precursory signatures of critical failure in sedimentary rocks of widespread interest such as sandstone remain unexplored.

AE analyses indicate that shear fracture growth in sandstone is a complex process of coalescence between tensile and shear microcracks [Fortin et al., 2009]. The relative abundance of shear and tensile microcracks during sandstone deformation is primarily controlled by confining pressure [Menendez et al., 1996; Vora and Morgan, 2019]. While fracture mechanisms in sandstones have been calibrated, the effect of confining pressure and microcracking mode over observed proposed precursory signatures of microcracking rate, energy and moment remain unexplored. The accurate quantification of experimental precursory AE deformation signatures in sandstone remains challenging due to difficulty in recognizing microcrack mode [Modiriasari et al., 2017] and seismic attenuation [Toksöz et al., 1979] and pore-fluid effects [Winkler and Nur, 1982]. Thus, there is need for a micromechanical numerical study to complement laboratory AE studies to analyze precursory deformation signatures in sandstone.

Several studies combine the observed precursory signatures with machine learning techniques to predict time-to-critical failure in rocks across scales. Rouet-Leduc et al., 2017 use random forest shows that stick-slip behavior in granular media can be predicted using observations of AE energy. Florido et al., 2015 employ the temporal variations in observed seismic b-values to predict time to earthquake greater than magnitude 7 in Chile. ONE MORE STUDY. While several studies have tried to predict critical failure in laboratory samples and in the earth’s crust, they do not employ the entire range of observable precursory signatures in their models. An integrated study can improve failure prediction techniques by linking micromechanical patterns with observed statistical precursory signatures in microcracking rate and distribution, AE energy release and seismic moment.

Numerical methods provide the ability to monitor stresses and displacement of grains on a micro-scale, complementing the deformation signatures observed from microstructural and AE analyses. Discrete numerical methods are attractive to study brittle fracturing because, much like real rocks, the numerical materials are composed of assemblages of grains [Vora and Morgan, 2019]. The grains are bonded to impart cohesion and simulate rock properties. Bond breakage, in response to applied boundary conditions, simulates microcracking allowing us to study the distribution and mode of individual microcracks and associated elastic energy release. In this study, we use the Discrete Element Method [Cundall and Strack, 1979] to examine the behavior of calibrated models of Berea Sandstone during confined biaxial experiments in which cracks and fractures form spontaneously and release elastic energy analogous to acoustic emissions. By monitoring microcracking activity, we seek to constrain precursory signatures of rock deformation during shear fracture growth and nucleation. We then employ machine learning techniques and use the calculated temporal precursory signatures to predict catastrophic failure.

1. **The Discrete Element Method**

The discrete element method is a particle-based numerical technique that employs a time stepping, finite difference approach to solve Newton’s equations of motion for every particle in a system. The method first solves for forces imposed on the surfaces of each particle by neighboring particles or boundaries and then calculates a displacement based on the acceleration caused by sum of the forces. Particle motions are induced by external forces prescribed by stress or strain rate boundary conditions, and by forces resolved at interparticle contacts. The disequilibrium of forces drives particle displacements. The Discrete Element Method (DEM) has been employed to simulate rock deformation from laboratory scale experiments to large scale geodynamic processes, including formation of deformation bands in sandstones [Wang et al.,2008], analyze changes in porosity and stress during biaxial experiments [Longjohn et al., 2018], calculate energy budgets during deformation experiments [Vora and Morgan, 2019], and deformation of fold and thrust belts [Morgan and Boettcher, 1999]. The numerical code used is RICEBAL, based on open-source code TRUBAL [Cundall and Strack, 1979]. RICEBAL resembles a numerical sandbox but offers added value by allowing material properties and mechanical states to be monitored throughout simulations and be correlated with deformation behavior and structure. The interparticle mechanics of RICEBAL are described in detail in supplementary Text S1 and Fig. S1.

* 1. **Biaxial Experiments and Geomechanical Calibration of Berea Sandstone using RICEBAL**

Detailed descriptions of biaxial setup and bulk calibration of numerical analogs can be found in Vora and Morgan, 2019. We simulate samples as granular assemblage of ~6,000 particles with particle radii of 10-40 µm within an initial spatial domain of 0.04 m x 0.03 m. To prepare cohesive samples for biaxial experiments, we preconsolidate our samples to a confining pressure of 10 MPa. The two horizontal confining walls, constructed of rows of particles, are moved inward between rigid vertical walls of particles until preconsolidation stress of 10 MPa is achieved. After consolidation, sample dimensions are 0.0775 m x 0.038 m. We assume plane strain conditions, and out of plane stresses are zero. Following preconsolidation, we reset the particles along horizontal walls to move independently in the vertical direction, while maintaining their constant confining stress, thus acting as a “membrane” that confines the sample during biaxial experiments. Porosity of all samples after preconsolidation is 17.6%. At this stage, we introduce interparticle bonds to simulate cohesive rock material. Axial compression is conducted by moving vertical platens inward at a constant velocity. As the lateral platens move inwards, local differential stresses increase, which causes failure of interparticle bonds, generating microcracks (Fig. 1a-1c). With increasing deformation, the induced asperities coalesce to form one or more shear fractures, ultimately resulting in the failure of the sample (Fig. 1d). Biaxial experiments are run under confining pressures of 0, 5, 10, 15, 20, 25, 30, 35, 40, 45 and 50 MPa. Macromechanical properties of the sample are collected at increments of 2000 cycles, associated with axial strain increments of 0.001 corresponding to incremental platen displacements of 0.008 mm. All simulations of biaxial experiments are conducted up to axial strain of 10.3%.

In our study, we simulate Berea Sandstone, defined by the micromechanical properties of the discrete particles and bonds within the assemblage. The micromechanical model properties are adjusted, and the bulk behavior of our model materials is calibrated to replicate experimental laboratory data for Berea Sandstone [Bobich, 2005; Schellart, 2000]. To capture the range of geomechanical rock behavior under both unconfined and confined conditions, we sought to reproduce to experimental datasets for Unconfined Compressive Strength (*UCS*), Young’s modulus (*E*), Mohr-Coulomb cohesion (*C*), and internal friction coefficient (*µ*). The pertinent input microparameters include (1) mechanical properties of the particles - Shear modulus of particles (*Gp*), Poisson’s ratio of particles (*νp*), (2) mechanical properties of interparticle bonds - Young’s and shear moduli of bonds (*Eb* and *Gb*), tensile strength and cohesion of bonds (*Tb* and *Cb*), and (3) interparticle friction (*µp*). The selected values of input microparameters that best reproduce the bulk properties of the Berea Sandstone are presented in Table 1. The calibration of numerical samples to experimental datasets is explained in detail in supporting Text S2 and supporting Fig. S2 and Fig. S3. The bulk behavior of numerical samples under confined and unconfined conditions is shown in Table 2, replicating the experimental geomechanical character of Berea Sandstone.

1. **Methods: Microcracking Signatures of Deformation**

Each bond breakage event is assumed to be a microcrack in the during biaxial tests on modeled rock samples. As axial stress is applied to the platens during the numerical biaxial experiments, fractures grow by the coalescence of emergent microcracks. During each simulated biaxial experiment, we track microcrack growth at axial strain intervals of 0.103% and calculate the corresponding AE energy and seismic moment. Our goal is to record precursory signatures derived from microcracking events, using local, moving time windows of the modeled microcracking and associated AE data. We employ continuous, moving axial strain windows of 1.03%, corresponding to ten axial strain steps (*ASwindow*=10). The microcrack data and modeled AE data are employed to calculate five characteristic deformation signatures: (1) Shear microcrack fraction, (2) Fractal dimension (3) Microcrack Variance, (4) AE energy Variance, and (5) Seismic b-value.

**3. 1.** **Mode and Rate of Microcracking**

Interparticle bonds can fail in either tension or shear [Text S1]. A tensile microcrack forms when interparticle normal stress exceeds the tensile strength of the bond, resulting in a mode 1 microcrack. Similarly, a shear microcrack results when local shear stress exceeds the shear strength of the bond in compression, resulting in a mode 2 microcrack. During our biaxial tests, we document the mode of each microcrack generated in association with the applied axial stress (Fig. 2a), along with the failure stress at the time of bond breakage. We use the number of microcracking events per unit strain (*Ni*) to compute microcracking variance (*MCvar*) as:

(Eq. 1)

Where *μMC* is the mean of number of microcracks per unit strain calculated as:

(Eq. 2)

The evolution of *MCvar* with axial strain provides a temporal understanding of variations in microcracking rate during shear fracture growth [Fig. 2b]. We also we compute the fraction of microcracks in shear mode (*SF*) within each strain window as:

(Eq. 3)

The evolution of *SF* with axial strain provides a temporal understanding of variations in AE source mechanisms during shear fracture growth [Fig. 2b].

**3.2. Spatial and Temporal Evolution of Microcracks**

We document the location of each microcrack during simulated biaxial tests. The documented bond breakages are plotted as a function of their mode and applied axial strain during formation [Fig. 1], providing a qualitative spatial understanding of fracture growth. The spatial distributions of microcracks are referenced back to their initial position at the onset of the biaxial test to maintain a consistent framework across biaxial experiments of varying confining pressures and lithologies. From each time window, we compute the fractal dimension of microcrack location to develop a measure of damage distribution during fracture growth. We use the number of microcrack pairs (*Np*) within a radius *R*, to calculate the fractal dimension (*D-value*) [Hirata et. al, 1987] within each strain window as:

(Eq. 4)

(Eq. 5)

Where *C(R)* is known as the correlation integral. The *D-value* within a strain window is calculated from slope of log(*C(R)*) vs *R* [Fig. S4]. A low D-value (~1) indicates localized microcracking in sample; whereas, a high *D-value* (~2) indicates distributed microcracking. The evolution of *D-value* with axial strain provides a temporal understanding of variations distribution of microcrack locations [Fig. 2c].

**3.3. Energy of Acoustic Emissions from Microcracking**

As axial stress is applied to the platens, interparticle bonds become distorted prior to failure, accumulating elastic strain energy. Bond failure that accompanies microcrack formation releases this energy instantly, emitting an elastic signal analogous to seismic energy. The fracture energy associated with each microcracking event is calculated using the following equation [Tang and Kaiser, 1998]:

(Eq. 6)  
Where *Wfrac* is the energy associated with an individual micro-fracture, *Cf* is the elastic modulus of the bond broken, *σcf* is the peak strength of the failed element and *vf* is the volume of microcrack. RICEBAL provides us with the ability to monitor stress associated with each broken bond *σcf*. Volume of a microcrack (*vf*) is taken as the sum of the areas of the two particles bounding the broken bond. If the microcrack fails in shear, *Cf* takes the value of shear modulus of the bond (*Gb*); if the microcrack fails in tension, *Cf* takes the value of Young’s modulus of the bond (*Eb*). During our biaxial tests, we calculate the acoustic energy (*AEenergy*) released during formation of each microcrack as 10% of released elastic fracture energy, in accordance with estimated energy budgets from laboratory and experimental studies [REFERENCES]. The calculated *AEenergy* is documented as a function of axial strain [Fig. 2d]. Total acoustic energy released is calculated as the sum of acoustic energy from all microcracking events during a biaxial experiment, up to an axial strain of 10.3%. We use the acoustic energy released at each time step (*AEi*) to compute the variance of acoustic emissions released (*AEvar*) within each strain window as:

(Eq. 7)

Where *μAE* is the mean of acoustic energy per unit strain calculated as:

(Eq. 8)

The evolution of *AEvar* with axial strain provides a temporal understanding of variations in acoustic energy during shear fracture growth [Fig. 2e].

**3.4. Seismic Moment and b-value from Microcracking**

Microcracks in real rocks defines a broad range of seismic moments, showing strong spatial and temporal correlation [Main et al., 1989]. Due to the narrow range grain size distribution in our models, the energy associated with microcrack formation, which corresponds to individual bond breakage events, also falls into a narrow range. To correct for the limitations of the discrete element approach, we implement a spatial and temporal clustering algorithm developed by Hazzard and Young, 2000 [Fig. S5]. When a bond breaks, we define its location as a source region of a macro-event, initializing the acoustic energy released as zero. We implement a source dimension of three times the radius of the largest particle in our domain (r=0.0012 m), as used by Hazzard and Young, 2000. The even duration is calculated by assuming that each crack is an expanding shear fracture, which can propagate as slowly as 0.5 times the shear wave velocity of the material [Madariaga, 1976]. We assume a constant shear wave velocity of 1500 m/s for Berea Sandstone [Mavko et al., 2009], corresponding to a maximum microcrack propagation duration of 1.6x10-6 s. Since we apply a constant strain rate of 0.8x10-7 m/s in our simulations, we calculate an event duration of 2% of axial strain. The energy of all the individual microcracks occurring in the source region and through the duration of the macro-event are summed and constitute the energy of a macro-event. We calculate the moment magnitude (*M*) associated with the energy of each clustered event (*Ec*) using the relationship defined by Kanamori, 1983 as:

(Eq. 9)

The clustered magnitudes range from .. to .. in our simulated experiments. The AE amplitude distribution during fracturing experiments has been shown to obey the Gutenberg-Richter relationship [Richter, 1958]. The AE amplitude distribution during fracturing experiments has been shown to obey a power law relationship expressed by the Gutenberg-Richter law as [Richter, 1958]:

(Eq. 10)

where *N* is the number of number of microcrack clusters with moment greater than M, and *a* and *b* are the intercept and the slope of the frequency-magnitude relationship respectively [Fig. S6]. We employ the seismic moments from clustered microcracks (*M*) and re-arrange the Gutenberg-Richter law to calculate seismic b-value within each strain window as:

(Eq. 11)

The evolution of *\b* with axial strain provides a temporal understanding of variations in seismic moment observed during shear fracture growth [Fig. 2e].

1. **Results**

Experimental and numerical analyses show that the damage process in characterized by four distinct phases of microcracking activity: Initiation, Nucleation, Rupture and Frictional Sliding [Amitrano, 2003; Lei et al., 2006; Renard et al., 2017; Vora and Morgan, 2019]. The initiation phase reflects initial distributed microcracking and rupture of pre-existing asperities [Fig. 1a]. The nucleation phase involves sub-critical growth of the microcrack population [Fig. 1b]. The rupture phase corresponds to accelerated growth of the accelerated growth of the ultimate fracture along one or more incipient fracture planes [Fig. 1c]. The frictional sliding phase represents the sliding of fractured blocks along the developed fracture planes and associated microcracking in gouge [Fig. 1d]. In terms of critical point concepts, failure occurs at peak stress during biaxial tests, represented by the end of the nucleation phase. We identify precursory signatures of critical failure by analyzing variations in calculated damage indicators in the nucleation phase. The evolution of damage indicators in the rupture phase and frictional sliding phase allows for analysis of post-failure characteristics in comparison to precursory signatures.

* 1. **Evolution of Damage Indicators in Berea Sandstone at 10 MPa Confining Pressure**

As a first demonstration of our simulation results, we examine the growth of fractures in Berea Sandstone under a confining pressure of 10 MPa. Critical failure of the sample occurs at a peak stress of 117.72 MPa, occurring at *εa*=0.031 during the biaxial experiment [Fig. 2a]. Stage 1 (initiation) corresponding to *εa*=0-0.022 is characterized by increasing rock strength from 9.79 MPa to 94.67 MPa and a linear stress-strain curve [Fig. 2a]. This initial stage of the biaxial experiment is characterized by very low microcracking activity; we document a total of 14 microcracks in this phase of this experiment. The low microcracking rate with respect to axial strain results in small values of microcracking variance ranging from 0 to 2.1 [Fig. 2b]. Six of the total 14 microcracks generated during fracture initiation occur in shear mode, resulting in a shear fraction ranging from zero to 0.33 [Fig. 2b] . While initiation stage corresponds to low microcracking activity, the microcracks generated are distributed widely through the sample [Fig. 1a], resulting in relatively high values of fractal dimension of microcracks increasing from zero to 1.73 [Fig. 2c]. We calculate that cumulative AE energy released during fracture initiation is 1.86 J [Fig. 2d], and the associated AE energy variance ranges from zero to 0.024 [Fig. 2e]. Seismic b-values calculated from clustered microcracks exhibit high values ranging from zero to 1.88 in the initiation phase of the experiment [Fig. 2e].

Stage 2 (nucleation) corresponding to *εa*=0.022-0.031 is characterized by increasing rock strength from 94.67 MPa to 117.72 MPa and a non-linear stress-strain curve [Fig. 2a]. The nucleation stage is characterized by very high microcracking activity; we document a total of 394 microcracks in this phase of this experiment. The high microcracking rate with respect to axial strain results in large values of microcracking variance, which increase from 3.6 to 1047.9 [Fig. 2b]. 118 of the total 394 microcracks are generated during the nucleation phase are in shear mode. We calculate a shear fraction ranging from 0.30 to 0.46, with peak shear fraction occurring at *εa*=0.028 prior to critical failure at *εa*=0.031. The microcracking activity in the nucleation phase is localized, resulting in the formation of the primary shear fracture [Fig. 1b]. As a result of localized microcracking, we calculate a decline in the fractal dimension of microcracks from 1.76 to 1.38 [Fig. 2c], with the minimum values occurring at critical failure at *εa*=0.031. We calculate that cumulative AE energy released during fracture nucleation is 48.38 J [Fig. 2d], and the associated AE energy variance shows an increasing trend, with values ranging from 0.1 to 14.64 [Fig. 2e]. Seismic b-values calculated from clustered microcracks exhibit a decline in values from 1.85 to 1.27 in the nucleation phase of the experiment [Fig. 2e]. The minimum value of *b* occurs at critical failure, corresponding to *εa*=0.031 [Fig. 2e].

Stage 3 (rupture) corresponding to *εa*=0.031 to 0.056 is characterized by declining rock strength from 117.72 MPa to 47.61 MPa [Fig. 2a]. The rupture stage is characterized by high but declining microcracking activity; we document a total of 863 microcracks in this phase of this experiment. The high but declining microcracking rate with respect to axial strain results in values of microcracking variance ranging from 98.93 to 1327.3 [Fig. 2b]. The peak microcracking variance occurs at *εa*=0.033 occurring shortly after critical failure (*εa*=0.031). 131 of the total 863 microcracks are generated during the rupture phase are in shear mode. We calculate a steady decline in shear fraction from 0.30 at *εa*=0.031 to 0.07 at *εa*=0.056 [Fig. 2b]. The microcracking activity in the rupture phase is localized around the emergent shear fracture and associated conjugate fractures [Fig. 1c]. As a result of increased gouge deformation around primary fracture and the formation of conjugate fractures, we observe an increase in fractal deformation from the nucleation phase between *εa*=0.031 – 0.034. We calculate relatively constant values of fractal dimension of microcracks ranging from 1.44 to 1.57 in the rupture phase [Fig. 2c]. We calculate that cumulative AE energy released during fracture initiation is 84.98 J [Fig. 2d], and the associated AE energy variance ranges from 0.71 to 19.99 [Fig. 2e]. AE energy variance shows a systematic decline after attaining peak value of 19.99 at *εa*=0.033, coinciding with the peak microcracking variance and preceded by critical failure point at *εa*=0.031.Seismic b-values calculated from clustered microcracks range from 1.54 to 1.87, exhibiting larger magnitudes than the suppressed values calculated at critical point [Fig. 2e].

Stage 4 (frictional sliding) corresponding to *εa*=0.057-0.103 is characterized by relatively constant residual stress ranging from 45.22 MPa to 51.85 MPa [Fig. 2a]. The frictional sliding stage is characterized by low and constant microcracking activity; we document a total of 398 microcracks in this phase of this experiment. The low microcracking rate with respect to axial strain results in slow decay in microcracking variance from 128.1 to 8.49 [Fig. 2b]. 17 of the total 381 microcracks are generated during the frictional sliding phase are in shear mode, resulting in a shear fraction ranging from 0.01 to 0.08 [Fig. 2b]. The microcracking activity in the frictional sliding phase is localized around the fully developed fractures [Fig. 1d]. As a result of localized gouge deformation around the developed fractures, we observe an increase in fractal deformation from the rupture phase. We calculate relatively constant values of fractal dimension of microcracks ranging from 1.30 to 1.56 in the frictional sliding phase [Fig. 2c]. We calculate that cumulative AE energy released during fractional sliding is 26.58 J [Fig. 2d], and the associated AE energy variance ranges from 0.04 to 0.88 [Fig. 2e], exhibiting a declining trend with axial strain. Seismic b-values calculated from clustered microcracks range from 1.28 to 1.83, exhibiting a relatively noisy pattern in the frictional sliding phase of the experiment [Fig. 2e].

The documented damage indicators demonstrate distinct strain-to-failure characteristics over the biaxial experiment on Berea Sandstone analog under 10 MPa confining pressure. The calculated microcracking variance trend exhibits a sharp increase pre-failure from 2.1 at *εa*=0.022 to 984.54 at *εa*=0.031, attains maximum value of 1327.3 at *εa*=0.033 immediately after critical point, and declines steadily post-failure to values ranging from 10.71 to 52.04 [Fig. 2b]. The calculated shear fraction trend exhibits a peak value of 0.46 at *εa*=0.024 preceding critical point and declines steadily post-failure to low values of 0.01 – 0.08 [Fig. 2b]. The calculated fractal dimension trend exhibits high values of 1.53 – 1.72 pre-failure, a sharp decline to 1.39 at critical point (*εa*=0.031), and rebounds to relatively steady values of 1.41 – 1.51 [Fig. 2c]. The calculated energy variance trend exhibits a sharp increase pre-failure from 0.024 at *εa*=0.022 to 12.26 at *εa*=0.031, attains maximum value of 19.89 at *εa*=0.033 immediately after critical point, and declines steadily post-failure to values ranging from 0.11 to 0.87 [Fig. 2e]. The calculated seismic b-value trend exhibits high pre-failure values ranging from .. to .. , attains a minimum value at critical point (*εa*=0.031) and rebounds to higher values ranging from .. to .. post-failure [Fig. 2e].

1. Discussion
2. Critical Failure Prediction

Our goal is to predict the stress to failure and axial strain to failure using local, moving time windows of microcracking and associated AE data.

**Tables**

Table 1: Microparameters used in DEM modeling of Berea Sandstone.

|  |  |
| --- | --- |
| Micromechanical Parameter | Berea Sandstone |
| Young’s Modulus of Bonds (*Eb*)  *GPa* | 0.2 |
| Shear Modulus of Bonds (G*b*)  *GPa* | 0.5 |
| *σc/σt* | 10 |
| Tensile Strength of Bonds (T*b*)  *MPa* | 30 |
| Cohesion of Bonds (*Cb*)  *MPa* | 300 |
| Shear Modulus of Particles (*Gp*)  *GPa* | 29 |
| Poisson’s Ratio of Particles (*νp*) | 0.33 |
| Interparticle friction (*µp*) | 0.4 |

Table 2: Macromechanical behavior of models calibrated to Berea Sandstone.

|  |  |  |
| --- | --- | --- |
| Macromechanical Property | Model Values for Berea Sandstone | Experimental Values for Berea Sandstone |
| Unconfined Compressive Strength (UCS)  *MPa* | 89.37 | 95.00 |
| Young’s Modulus (*E*)  *GPa* | 6.48 | 8.00 |
| Mohr-Coulomb Cohesion (*C*)  *MPa* | 28.03 | 26.10 |
| Mohr Coulomb Slope (*µ*) | 0.44 | 0.49 |