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EMI database analysis focusing on relationship between density and mechanical properties of sedimentary rocks

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Abstract. The Earth Mechanics Institute (EMI) was established at the Colorado School of Mines (CSM) in 1974 to develop innovations in rock mechanics research and education. During the last four decades, extensive rock mechanics research has been conducted at the EMI. Results from uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), point load index (PLI), punch penetration (PP), and many other types of tests have been recorded in a database that has been unexamined for research purposes. The EMI database includes over 20,000 tests from over 1,000 different projects including mining and underground construction, and analysis of this database to identify relationships has been started with preliminary results reported here. Overall, statistically significant correlations are identified between bulk density and mechanical strength properties through UCS, BTS, PLI, and PP testing of sedimentary, igneous, and metamorphic rocks. In this paper, bulk density is considered as a surrogate metric that reflects both mineralogy and porosity. From this analysis, sedimentary rocks show the strongest correlation between the UCS and bulk density, whereas metamorphic rocks exhibit the strongest correlation between UCS and PP. Data trends in the EMI database also reveal a linear relationship between UCS and BTS tests. For the singular case of rock coral, the database permits correlations between bulk density of the core versus the deposition depth and porosity. The EMI database will continue under analysis, and will provide additional insightful and comprehensive understanding of the variation and predictability of rock mechanical strength properties and density. This knowledge will contribute significantly toward the increasingly safe and cost-effective geostructures and construction.

Keywords: rock mechanics database; earth mechanics institute (EMI); bulk density, mechanical properties of rock; uniaxial compressive strength (UCS); Brazilian tensile strength (BTS); point load index (PLI), and punch penetration (PP) test

1. Introduction

Understanding the mechanical properties of rocks is crucial in rock engineering applications for safe and cost effective geostructures, enhanced energy and material production, and improved understanding of the science of rock behavior to reduce construction hazards (Goetze and Evans 1979, Jing 2003, Ghassemi 2012, Perras and Diederichs 2014). Rock mechanics properties can significantly influence engineering processes such as drilling, excavating, blasting, crushing, and intact rock and rock mass failures. Our understanding of these influential rock mechanical properties must also include consideration of a number of other factors (e.g., density, porosity, permeability, mineral composition, water content, etc.) (Deere and Miller 1966, Vutukuri *et al.* 1974, Kim 2015, Chen *et al.* 2016, Kim and Changani 2016). Thus, it is important to have a rock mechanics database as a resource for rock engineering design and prediction of engineering performance (Schumacher and Kim 2013, Schumacher and Kim 2014), including excavation by tunnel boring machine, road header, continuous miner (Kim and Colvin 2012, Kim *et al.* 2012a, b), and surface miner equipment.

Few comprehensive database studies related to the physical and mechanical properties of rock have been reported, whereas there are several databases related to the geochemical properties of rock and tectonic stresses exist in the regionally and worldwide (Steinhauser *et al.* 2006, Zang *et al.* 2012). In addition, the usefulness of data reported in publications is often limited due to incomplete descriptions of different equipment and test procedures used among the various testing laboratories. A comprehensive assembly and analysis of data is essential to understand and predict the interrelationships between physical, mineralogical and mechanical rock properties.

The massive database of the Earth Mechanics Institute (EMI) offers an opportunity for just such a study (Kim and Hunt 2017). The database at the EMI at the Colorado School of Mines (CSM) contains results from over 20,000 tests from over 1,000 different projects including mining and underground construction projects since 1974 (Acaroglu *et al.* 2008, Yagiz 2008, 2009, Yagiz and Gokceoglu 2010, Acaroglu 2011, Marinos *et al.* 2012). Over the four decades of its existence, the EMI has been a leader in rock mechanical property evaluation, performance

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prediction of cutting tools, and design of excavation equipment for infrastructure and mining projects. Importantly, the established test procedures and the performance prediction methodologies developed by EMI have been confirmed with a large amount of field data from drilling and excavation projects throughout the world.

Therefore, the EMI database offers a unique opportunity to study the interrelationships among the properties of rocks. In this report, we focus mainly on sedimentary rocks (e.g., shale, limestone, mudstone, gypsum, and coral) as sedimentary rocks are more uniform in density or pore size than igneous or metamorphic rocks (Sperl and Trckova 2008). Our results obtained from the EMI database provide comprehensive and insightful information for understanding rock mechanics, contributing to enhanced geostructure safety and cost-effectiveness.

2. Materıals and methods

2.1 Sample preparation and testing load frame used in EMI database

After samples were cored, cut, and ground in the sample preparation laboratory, the dimensions of samples were measured using a caliper and scale. Testing for UCS and BTS was conducted using a servo-controlled MTS stiff testing machine with a capacity of 220 kips (978.6 kN). Loading data and all other tested parameters were recorded with a data acquisition system, and the data were added to the database.

2.2 Testing categories and standards used in EMI database

Uniaxial compressive strength (UCS), Brazilian tensile strength (BTS), Point load index (PLI), and Punch penetration (PP) tests were performed in accordance with the American Society for Testing and Materials (ASTM) standards widely accepted in rock mechanics community as a reliable reference for rock mechanics testing procedures.

2.2.1 Uniaxial compressive strength (UCS) test

UCS tests were performed using ASTM D2938-95 (1995 historical version) (ASTM D2938-95 1995) and ASTM D7012-14 (current standard) (ASTM D7012-14 2014) standards where test cylindrical test samples were cut to a length to diameter (L/D) ratio of 2. A force was applied on the top surface of the cylinder sample to compress the sample until breaking occurred. The force was then divided by the area, resulting in the UCS strength (σ_c) as shown in Eq. (1). Eq. (1): UCS test calculation

$$\sigma_c = \frac{F}{A} \tag{1}$$

where F is the force applied, and A is the area of the sample.

2.2.2 Brazilian tensile strength (BTS) test

BTS tests were conducted following the procedure recommended in ASTM D3967 (ASTM D3967-08 2008). A continuously increasing line compressive force was applied on the disk sample. The two opposite edges across the diameter of a disk sample was under approximately constant loading rate until the sample failed. Additionally, bearing strips were used to promote even stress distribution on BTS samples. The indirect tensile strength (σ_T) was calculated using Eq. (2) below. Eq. (2): BTS test calculation

$$\sigma_T = \frac{2F}{(\pi LD)} \tag{2}$$

where F is the force applied, L is the length of the sample, and D is the diameter of the sample.

2.2.3 Point load index (PLI) test

PLI tests are useful for estimating compressive strength of a rock sample in a way that can reduce time and cost for tests. PLI test was run in accordance with ASTM D5731(ASTM D5731-08 2008). A sample was held by two points across the diameter of sample until the sample was broken by a point load. The PLI (I_s) was then calculated as the failure load over equivalent diameter of the sample shown in Eq. (3). Eq. (3): PLI test calculation

$$I_s = \frac{F}{D_e^2} \tag{3}$$

where F is the force applied, and D_e is the equivalent diameter of the sample.

2.2.4 Punch penetration (PP) test

The PP tests are widely used to understand rock behavior under an indenter, with the results used to estimate the brittleness of rock samples and predict the cuttability of rock. As performed at EMI, tests were performed on cylindrical samples cast in gypsum cement (Cigla 2006, Yagiz 2009). The indenter was forced into the sample until the sample was broken or reached to 6.5 mm penetration. Indenter penetration was at a constant displacement rate of 0.0254 mm s^{-1}. The indentor was made of tungsten carbide with a conical shaped tip with 3.175 mm tip radius and 120° angle. During the test, force and displacement were recorded. The PP (kN mm^{-1}) was calculated as ratio of the peak failure force over the indenter-travel-distance shown in Eq. (4). Eq. (4): PP test calculation

$$PP(kN/mm) = \frac{F}{L} \tag{4}$$

where F is the force applied at failure, and L is the amount of indentation. More detail on the test method is presented by Yagiz (2009).

2.2.5 Bulk density

Bulk density was measured following the procedure recommended in (ASTM D4543-08 2008).

2.3 Data analysis

Statistical data analyses were conducted using regression analysis producing R^2 and p-value for each correlation using Excel and Minitab software. R^2 is the square value of Peterson correlation coefficient representing the distribution of data, and p-value means the probability of calculated statistical results. The project data in the EMI database were filtered in this study to exclude projects with incomplete records.

3. Results and discussion

3.1 Database analysis of all three rock types: strength correlation with bulk density

This analysis of the EMI database focuses mainly on the correlations between different measures of the mechanical strength and the bulk density. The rock density is an important physical property of interest and is the most direct proxy for the combined effects of mineralogy and porosity. An important feature of this study is that it includes a significantly large number of lithologies, and statistically significant numbers of test results for each rock type (sedimentary, igneous, and metaphorphic) (Deere and Miller 1966, Kahraman 2001). Since all tests were performed at the EMI, potential variations due to test procedures and equipment are minimized.

Fig. 1 presents bulk density and UCS data for all available test results for all rock types. The UCS increased with an increasing rock density. In this paper, statistics were generated for an exponential fit, the best fit in most cases, reflecting the observation that as porosity decreases, the bulk density increasingly reflects the mineral densities, which are typically on the order of 2.7 g cm^{-3} for most rock-forming minerals. In the regression analysis, the R^2 value represents how well a regression model explains the distribution of the data, with an R^2 of 1.0 indicating a 'perfect' fit. However, R^2 cannot be used to predict the testing of the regression model hypotheses and to indicate whether the regression model is adequate, as adequateness of the regression model should be determined by p-value; a low p-value (< 0.05) suggests a statistical significance.

The R^2 value for the correlation between UCS and the bulk density was 0.4. This correlation was statistically significant as the p-value was quite small ($p < 0.01$). The R^2 and p-value suggest that the bulk density has a meaningful relationship to the UCS, and the regression model is adequate. This result clearly indicates that rock bulk density positively influences UCS. Therefore, rock density can be used as a strong determinant to predict the mechanical strength of rocks.

The correlation between bulk density and BTS was also analyzed. In the EMI database, 490 samples had both bulk density and BTS values recorded. As for the relationship between bulk density and BTS, BTS increased exponentially with the increase of rock density (Fig. 2). The R^2 value obtained for the relation between rock density and BTS was very similar to that of UCS (Table 1), supporting that the effects of rock density on UCS and BTS are similar based on the large-scale database analysis.

In addition, the point load index (PLI) was also compared with the bulk density. A total of 96 samples were

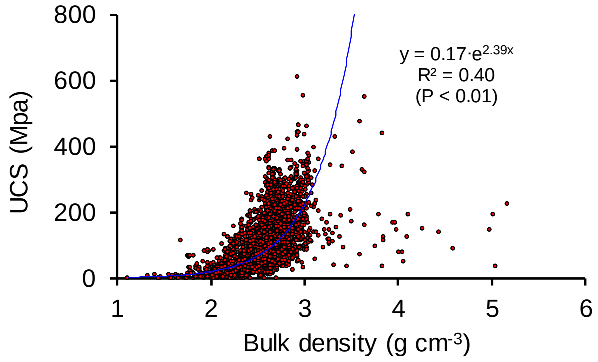

Fig. 1 Correlation of bulk density and compressive strength obtained with all UCS tests (*n*=3900)

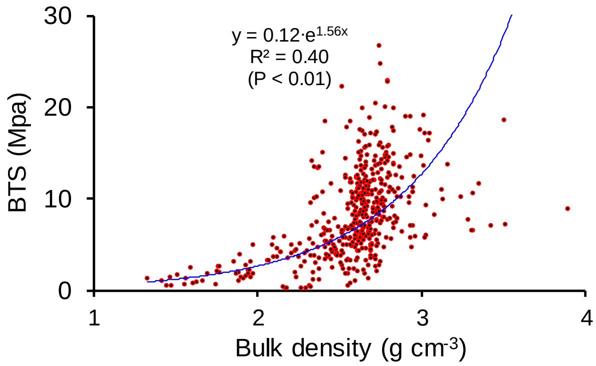

Fig. 2 Correlation of bulk density and tensile strength observed with BTS test (*n*=490)

Table 1 Summary of statistical analyses between bulk density and mechanical strength of rocks obtained from the EMI database

Tests		All rock types	Sedimentary rocks			Igneous rocks		Metamorphic rocks	
		Density (g cm^{-3})	Density (g cm^{-3})	BTS (MPa)	PP (KN mm^{-1})	Density (g cm^{-3})	PP (KN mm^{-1})	Density (g cm^{-3})	PP (KN mm^{-1})
UCS (MPa)	p-value	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01
	R^2	0.40	0.45	0.49	0.29	0.36	0.19	0.02	0.58
BTS (MPa)	p-value	< 0.01	< 0.01	-	< 0.01	< 0.01	0.01	0.05	< 0.01
	R^2	0.40	0.27	-	0.3	0.16	0.07	0.01	0.23

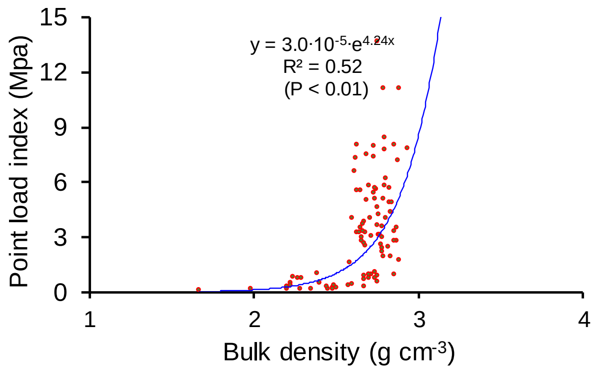

Fig. 3 Correlation between bulk density and point load index (PLI) (*n* = 96)

analyzed for all rock types. The R^2 value of the relationship between bulk density and PLI was 0.52, which was higher than for the UCS and BTS data (Fig. 3). This suggests that the bulk density effect of rock is more important for PLI prediction than for the prediction of UCS and BTS. These results indicate that the PLI is also significantly correlated with rock density.

For more detailed analyses, test results for sedimentary, igneous, and metamorphic rocks were separated. Fig. 4 shows records of all rock type data points: 1,507 for sedimentary, 739 for igneous, and 1,210 for metamorphic rocks. The UCS significantly increased with rock density for each of the three rock types. Sedimentary rocks showed the strongest correlation between density and UCS, whereas metamorphic rocks exhibited the weakest correlation (Fig. 4). The correlation between the PP peak and UCS was the strongest for metamorphic rocks and weakest in igneous rocks (Fig. 5).

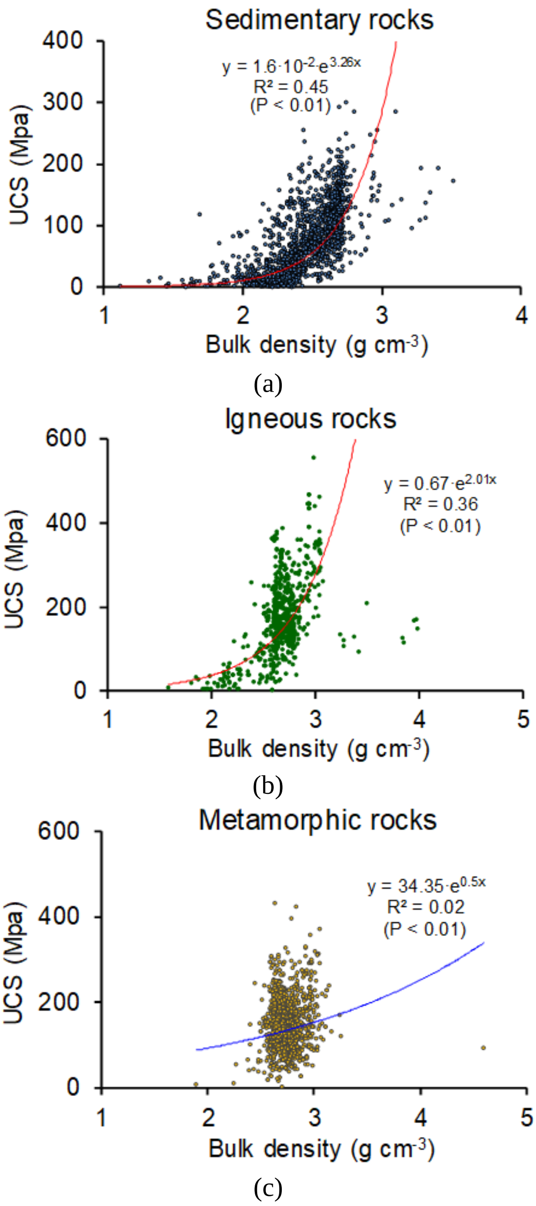

Fig. 4 Correlation of bulk density and compressive strength obtained with the UCS test. (a) Sedimentary rocks (n=1,507), (b) igneous rocks (n=739) and (c) metamorphic rocks (n=1,210)

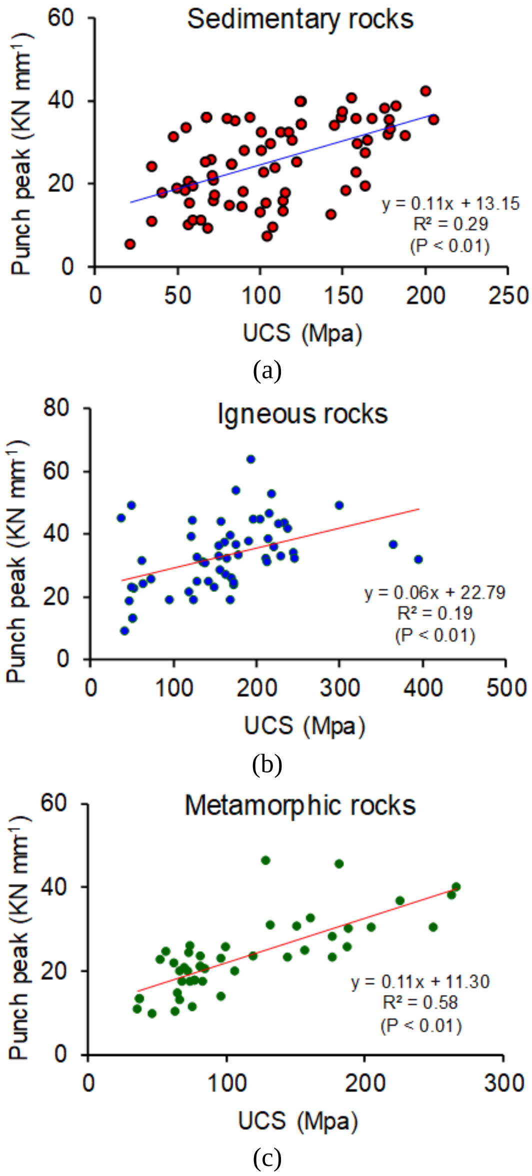

Fig. 5 Correlation of punch penetration and compressive strength measured by the UCS test. (a) Sedimentary rocks (n=74), (b) igneous rocks (n=56) and (c) metamorphic rocks (n=46). Each p-value was calculated with linear regression analysis

The R^2 values of the bulk density effects on rock mechanical strengths are variable among rock types, suggesting that rock mechanical strengths can be also affected by other physical properties of rocks (e.g., porosity, mineral composition, etc.) other than the bulk density. Thus, R^2 values are not necessarily high for all rock types, and the differences of R^2 value among rock types exhibit how the density effects on mechanical strengths can vary depending upon rock types (e.g., sedimentary, igneous, and metamorphic). However, it is noticeable that all correlations shown in between the bulk density and mechanical strength are significant because p-values are lower than 0.05.

3.2 Database analysis of sedimentary rocks

As sedimentary rocks exhibited the highest correlation

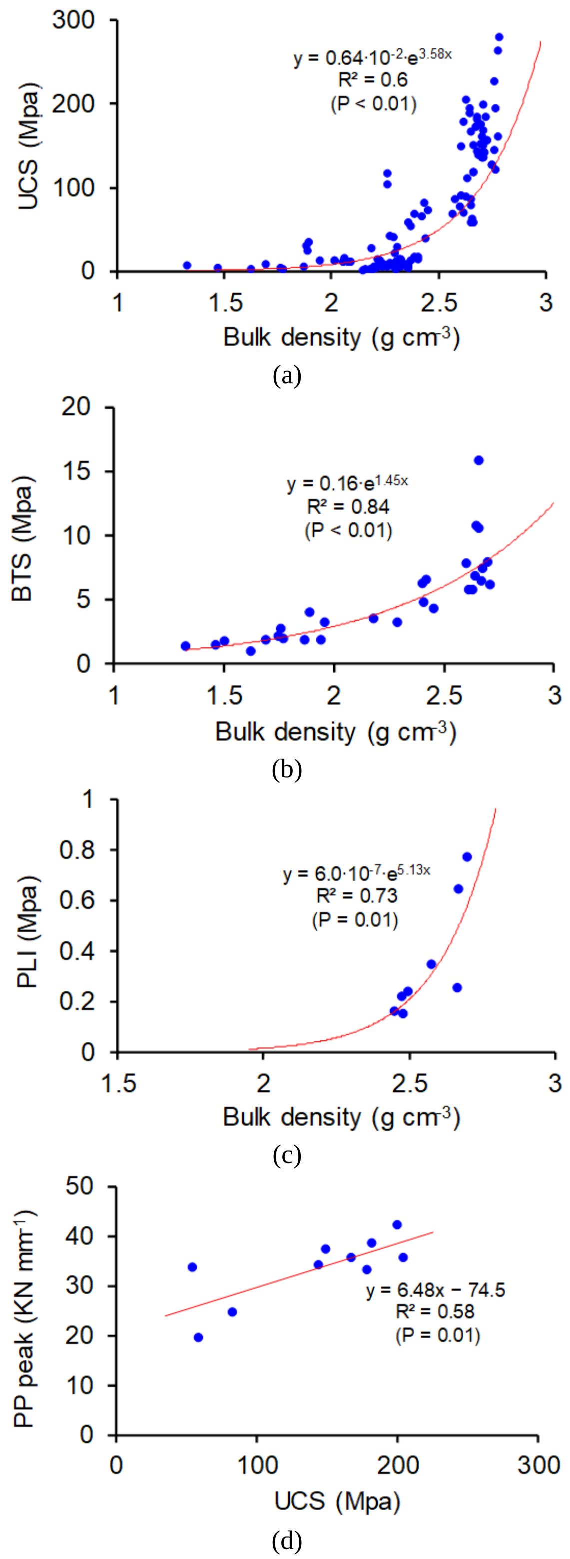

Fig. 6 Correlation of bulk density and mechanical strength of limestone. (a) UCS (n=129), (b) BTS (n =29), (c) PLI (n=8) and (d) PP (n=10)

between UCS and rock density with more than 1,000 tested samples (Fig. 4), we focused on sedimentary rocks for the remainder of this paper (shale, limestone, mudstone, gypsum, and coral). Five different sedimentary rocks were further analyzed using data from the EMI database.

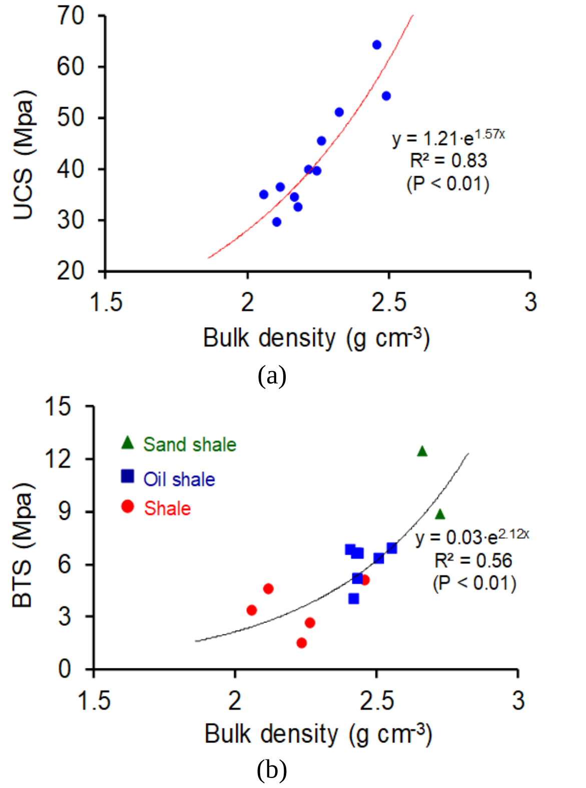

Fig. 7 Correlation of bulk density and mechanical strength of shales. (a) Correlation between bulk density and compressive strength of oil shale (n=11) and (b) relationship of bulk density and tensile strength of shales (n=14)

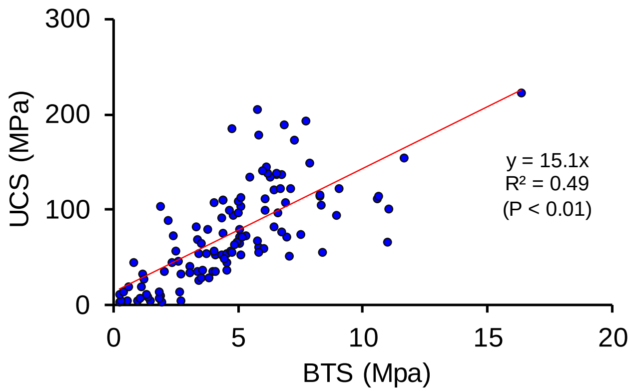

Fig. 8 Comparison of UCS and BTS tests of sedimentary rocks (n=115)

3.2.1 Limestone

Limestone is mainly composed of calcium carbonate with a particle density of ~2.71 g cm^{-3}. Fig. 6(a) shows the relationship between UCS results and bulk density of limestone samples. The correlation between the UCS and density was strong.

Strong correlations were also observed for BTS and PLI test results when plotted versus bulk density (Fig. 6(b) and 6(c). This comparison of BTS and bulk density was analyzed with nonstructural failures. For the PLI analysis, results for some specimen exhibiting structural failures were included to increase the size of the data set for analysis. In spite of the limited data set, the correlation between PLI and bulk density was high (R^2=0.73). Also, UCS and PP test results from limestone samples were analyzed (Fig. 6(d)) Although the data set only included 10 results, the correlation between the UCS and PP tests was decent (R^2=0.58). These results indicate that the homogeneous mineralogy of limestone samples yield consistently strong correlations between density and mechanical strength measures.

3.2.2 Shale

The shale database included rock specimens with descriptions such as shale, sand shale, and oil shale, which typically contains oil or gas in the rock matrix (Horsrud 2001). For the UCS analysis, oil shale data were statistically analyzed by creating a plot comparing the UCS and bulk density (Fig. 7(a)). The R^2 was 0.83, suggesting that bulk density of oil shale was highly correlated with UCS. For the BTS versus bulk density analysis, test results of all three shale varieties (shale, sandy, and oil shale) were plotted in the same chart (Fig. 7(b)). In this regression analysis, the results showed that the BTS for three types of shale were also significantly correlated to the bulk density. Additionally, the UCS and BTS exhibited a correlation (R^2=0.49) for all sedimentary rock groups (Fig. 8).
Interestingly, the UCS of oil shale (R^2=0.83) was more strongly correlated with its density than was the combined BTS (R^2=0.56) of shale, sand shale, and oil shale. These results suggest that the different mineralogy, grain size, porosity and pore fluid of three shales can substantially affect compressive and tensile strength.

3.2.3 Mudstone

Mudstones are typically composed of clay or silt sized grains, and they may be of varying mineralogy and be lithified through compaction or cementation processes (Schieber *et al.* 2000). Following the same process used for analysis of shales and limestones, the correlation between the UCS and bulk density was quite similar (Fig. 9 and Table 2). The R^2 value was high (0.78) even though the sample size was not large (n =12).

3.2.4 Gypsum

Pure gypsum is mainly made up of calcium sulfate dihydrate with a particle density of ~2.32 g cm^{-3}. The bulk density of gypsum samples tested in EMI was ~2.28-2.31 g cm^{-3} (Fig. 10), reflecting the homogeneous bulk density of gypsum samples. It is clear that, for gypsum rock, bulk density is not a strong predictor of compressive strength.

3.2.5 Coral

The coral rock tested typically consisted of coral fragments, with the major constituent being calcium carbonate. In this study of coral rock test results, the structural and non-structural failures were included to increase the data set size for analysis data. The sample depth was also recorded, along with the bulk density (Fig. 11). Bulk densities were found to increase as depth increased. This is likely correlated to the decrease in porosity related to increasing compressive strength with depth, although increased cementation may also be a factor.

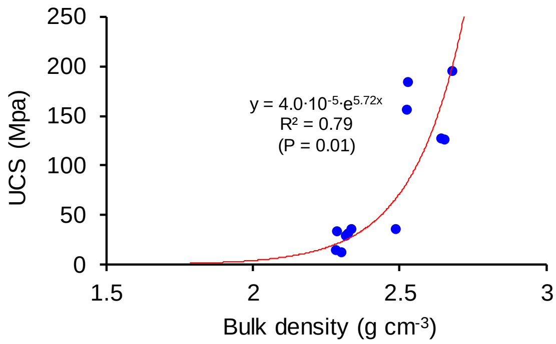

Fig. 9 Correlation between bulk density and compressive strength of mudstone (n=12)

Table 2 Summary of statistical analyses between bulk density and mechanical strength of sedimentary rocks obtained from the EMI database

Tests		Shales	Limestone		Mudstone	Gypsum
		Density (g cm^{-3})	Density (g cm^{-3})	PP (KN mm^{-1})	Density (g cm^{-3})	Density (g cm^{-3})
UCS (MPa)	p-value	< 0.01	< 0.01	0.01	0.01	0.03
	R^2	0.83	0.61	0.58	0.78	0.58
BTS (MPa)	p-value	< 0.01	< 0.01	> 0.56	< 0.01	-
	R^2	0.56	0.84	0.03	0.98	-

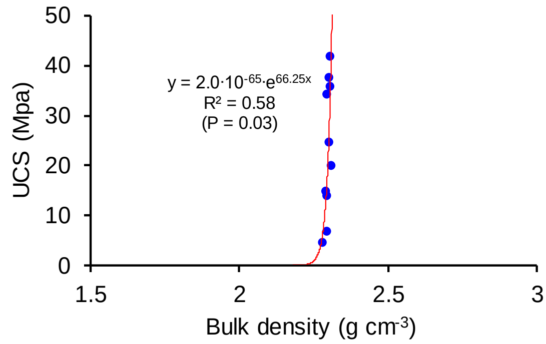

Fig. 10 Correlation between bulk density and compressive strength of gypsum rocks (n=10)

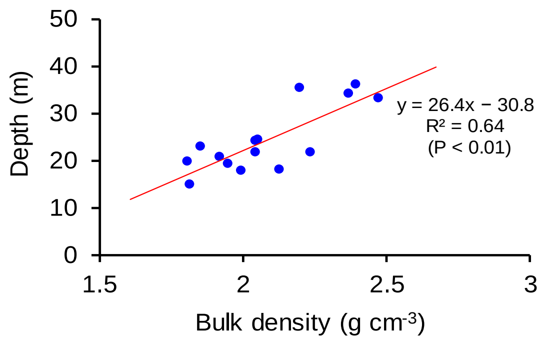

Fig. 11 Correlation between bulk density and depth (n=15) for coral rock

Noticeably, the R^2 values of the bulk density effects on UCS and BTS were much greater when analyzed with individual sedimentary rock species ($0.56 \leq R^2 \leq 0.98$) than analyzed with all sedimentary rock types ($0.27 \leq R^2 \leq 0.45$) (Tables 1 and 2), suggesting significant variations among

Table 3 Summary of statistical analyses equations obtained from the EMI database analysis

Rock types		UCS (MPa), y-value	BTS (MPa), y-value	PP (kN mm^{-1}), y-value
		Density (g cm^{-3}), x-value	Density (g cm^{-3}), x-value	Density (g cm^{-3}), x-value
All types		$y = 0.17 \cdot e^{(2.39x)}$	$y = 0.12 \cdot e^{(1.56x)}$	-
All sedimentary		$y = 0.16 \cdot 10^{-1} \cdot e^{(3.26x)}$	$y = 67.15 \cdot e^{(0.02x)}$	$y = 0.11x + 13.15$
Sedimentary	Limestone	$y = 0.64 \cdot 10^{-2} \cdot e^{(3.58x)}$	$y = 0.16 \cdot e^{(1.45x)}$	$y = 6.48x - 74.5$
	Shale	$y = 1.2 \cdot e^{(1.57x)}$	$y = 3.07 \cdot 10^{-2} \cdot e^{(2.12x)}$	$y = 4.59 \cdot e^{(0.03x)}$
	Mudstone	$y = 4 \cdot 10^{-5} \cdot e^{(5.72x)}$	$y = 0.04 \cdot e^{(0.06x)}$	-
	Gypsum	$y = 2 \cdot 10^{-65} \cdot e^{(66.25x)}$	-	-
Igneous		$y = 0.67 \cdot e^{(2.01x)}$	$y = 300.12 \cdot e^{(0.01x)}$	$y = 0.06x + 22.79$
Metamorphic		$y = 34.35 \cdot e^{(0.5x)}$	$y = 738.72 \cdot e^{(0.001x)}$	$y = 0.11x + 11.3$

sedimentary rock species with respect to other physical properties such as porosity, mineral composition, and inhomogeneities other than the bulk density. Thus, the R^2 values between the density and mechanical strengths tend to decrease when analyzed rock categories become broader as rock porosity, mineral composition, and inhomogeneities can also significantly affect its mechanical strengths.

3.3 Perspective

This study focused mainly on correlations between bulk density and mechanical properties (UCS, BTS, and PP) of rocks. If the bulk density of a rock sample is known, mechanical strength can be estimated with the equations presented in the Table 3. There are many additional analyses possible with the database. In this study, as a start, we focused on sedimentary rock. In the future, additional analyses of igneous and metamorphic rock test results and of other tests will be completed. For example, other mechanical properties (e.g., dynamic mechanical strength, seismic velocities, etc.) are important to understanding rock mechanical behavior. Future database analyses including dynamic strengths and seismic velocities can contribute greatly to an improved knowledge of rock mechanics.

4. Conclusions

The EMI database represents over 40 years of testing of rock, and it contains more than 20,000 data points. The main findings of this initial study are as follows: (1) in general, sedimentary, igneous, and metamorphic rock data revealed significant exponential correlations between mechanical strengths and bulk density; (2) sedimentary rocks (e.g., limestone, shale and mudstone) showed the strongest correlation between the UCS and bulk density; (3) the data trend of sedimentary rock samples exhibited a linear relationship between the UCS and BTS tests; (4) the relationship between rock density and compressive strength can be significantly affected by rock mineralogy and porosity. Our results obtained from the EMI database analysis provide insightful and comprehensive information for understanding mechanical behaviors of rocks with the change of physical properties, contributing significantly to the improvement of geostructure and infrastructure safety and cost-effectiveness.

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References

Acaroglu, O. (2011), "Prediction of thrust and torque requirements of TBMs with fuzzy logic models", *Tunn*. *Undergr*. *Sp*. *Technol*., **26**(2), 267-275.

Acaroglu, O., Ozdemir, L. and Asbury, B. (2008), "A fuzzy logic model to predict specific energy requirement for TBM performance prediction", *Tunn*. *Undergr*. *Sp*. *Technol*., **23**(5), 600-608.

Astm D2938-95 (1995), *Standard Test Method for Unconfined Compressive Strength of Intact Rock Core Specimens*, West Conshohocken, Pennsylvania, U.S.A.

ASTM D4543-08 (2008), *Standard Practices for Preparing Rock Core as Cylindrical Test Specimens and Verifying Conformance to Dimensional and Shape Tolerances*, West Conshohocken, Pennsylvania, U.S.A.

ASTM D5731-08 (2008), *Standard Test Method for Determination of the Point Load Strength Index of Rock and Application to Rock Strength Classifications*, West Conshohocken, Pennsylvania, U.S.A.

ASTM D7012-14 (2014), *Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperatures*, ASTM International

Chen, J., Du, C., Jiang, D., Fan, J. and He, Y. (2016), "The mechanical properties of rock salt under cyclic loading-unloading experiments", *Geomech*. *Eng*., **10**(3), 325-334.

Cigla, M. (2006), "Prediction and modeling of disc cutting forces for hard rock excavation based on assessment of punch penetration index for quantifying rock toughness and resistance to chipping", Ph.D. Dissertation, Colorado School of Mines, Golden, Colorado, U.S.A.

Deere, D.U. and Miller, R.P. (1966), *Engineering Classification and Index Properties for Intact Rocks*, Kirtland Air Force Base, New Mexico, U.S.A.

Ghassemi, A. (2012), "A review of some rock mechanics issues in geothermal reservoir development", *Geotech*. *Geol*. *Eng*., **30**(3), 647-664.

Goetze, C. and Evans, B. (1979), "Stress and temperature in the bending lithosphere as constrained by experimental rock mechanics", *Geophys*. *J*., **59**(3), 463-478.

Horsrud, P. (2001), "Estimating mechanical properties of shale from empirical correlations", *SPE Drill*. *Complet*., **16**(2), 68-73.

Jing, L. (2003), "A review of techniques, advances and outstanding issues in numerical modelling for rock mechanics and rock engineering", *J*. *Rock Mech*. *Min*. *Sci*., **40**(3), 283-353.

Kahraman, S. (2001), "Evaluation of simple methods for assessing the uniaxial compressive strength of rock", *J*. *Rock Mech*. *Min*. *Sci*., **38**(7), 981-994.

Kim, E. (2015), “Effect of skew angle on main precursor of frictional ignition in bench-scale simulation of excavation processes”, *J. Rock Mech. Min. Sci.*, **80**, 101-106.

Kim, E. and Changani, H. (2016), “Effect of water saturation and loading rate on the mechanical properties of Red and Buff Sandstones”, *J. Rock Mech. Min. Sci.*, **88**, 23-28.

Kim, E. and Colvin, S. (2012), “A preliminary full scale cutting test to find pre-cursor parameters of frictional ignition”, *Proceedings of the 14th US Mine Ventilation Symposium*, Salt Lake City, Utah, U.S.A., June.

Kim, E., Rostami, J. and Swope, C. (2012a), “Full scale linear cutting experiment to examine conical bit rotation”, *J. Min. Sci.*, **48**(5), 882-895.

Kim, E., Rostami, J., Swope, C. and Colvin, S. (2012b), “Study of conical bit rotation using full-scale rotary cutting experiments”, *J. Min. Sci.*, **48**(4), 717-731.

Kim, E. and Hunt, R. (2017), “A public website of rock mechanics database from Earth mechanics institute (EMI) at Colorado School of Mines (CSM)”, *Rock Mech. Rock Eng.*, **50**(12), 3245-3252.

Marinos, V., Prountzopoulos, G., Fortsakis, P., Koumoutsakos, D., Korkaris, K. and Papouli, D. (2012), “Tunnel information and analysis system: A geotechnical database for tunnels”, *Geotech. Geol. Eng.*, **31**(3), 891-910.

Perras, M. and Diederichs, M. (2014), “A review of the tensile strength of rock: Concepts and testing”, *Geotech. Geol. Eng.*, **32**(2), 525-546.

Schieber, J., Krinsley, D. and Riciputi, L. (2000), “Diagenetic origin of quartz silt in mudstones and implications for silica cycling”, *Nature*, **406**(6799), 981-985.

Schumacher, F.P. and Kim, E. (2013), “Modeling the pipe umbrella roof support system in a western US underground coal mine”, *J. Rock Mech. Min. Sci.*, **60**, 114-124.

Schumacher, F.P. and Kim, E. (2014), “Evaluation of directional drilling implication of double layered pipe umbrella system for the coal mine roof support with composite material and beam element methods using FLAC3D”, *J. Min. Sci.*, **50**(2), 336-349.

Sperl, J. and Trckova, J. (2008), “Permeability and porosity of rocks and their relationship based on laboratory testing”, *Acta Geodyn. Geomater.*, **5**(1), 41-47.

Steinhauser, G., Sterba, J.H., Bichler, M. and Huber, H. (2006), “Neutron activation analysis of Mediterranean volcanic rocks-An analytical database for archaeological stratigraphy”, *Appl. Geochem.*, **21**(8), 1362-1375.

Vutukuri, V.S., Lama, R.D. and Saluja, S.S. (1974), *Handbook on Mechanical Properties of Rocks: Testing Techniques and Results*, Trans Tech Publications, Clausthal, Germany.

Yagiz, S. (2008), “Utilizing rock mass properties for predicting TBM performance in hard rock condition”, *Tunn. Undergr. Sp. Technol.*, **23**(3), 326-339.

Yagiz, S. (2009), “Assessment of brittleness using rock strength and density with punch penetration test”, *Tunn. Undergr. Sp. Technol.*, **24**(1), 66-74.

Yagiz, S. and Gokceoglu, C. (2010), “Application of fuzzy inference system and nonlinear regression models for predicting rock brittleness”, *Expert Syst. Appl.*, **37**(3), 2265-2272.

Yagiz, S., Gokceoglu, C., Sezer, E. and Iplikci, S. (2009), “Application of two non-linear prediction tools to the estimation of tunnel boring machine performance”, *Eng. Appl. Artif. Intel.*, **22**(4-5), 808-814.

Zang, A., Stephansson, O., Heidbach, O. and Janouschkowetz, S. (2012), “World stress map database as a resource for rock mechanics and rock engineering”, *Geotech. Geol. Eng.*, **30**(3), 625-646.

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