

Article

Effect of Physical Properties on Mechanical Behaviors of Sandstone under Uniaxial and Triaxial Compressions

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Abstract: Mechanical properties of sandstone, such as compressive strength and young's modulus, are commonly used in the design of geotechnical structures and numerical simulation of underground reservoirs using models such as the digital groundwater, equivalent porous medium, and Discrete Fracture Network (DFN) models. A better understanding of the mechanical behaviors of sandstone under different loading conditions is imperative when assessing the stability of geotechnical structures. This paper highlights the effect of the physical properties (i.e., porosity, mean grain size) and environmental conditions (i.e., water content and confining stress) on uniaxial compressive strength, triaxial compressive strength, and young's modulus of sandstone. A series of uniaxial and triaxial compression experiments are conducted on sandstone formations from Wyoming. In addition, experimental data on sandstones from the literature are compiled and integrated into this study. Prediction equations for the compressive strengths and young's modulus of sandstone are established based on commonly available physical properties and known environmental conditions. The results show that the mean Uniaxial Compressive Strength (UCS) decreases as the porosity, water content, and mean grain size increase. Furthermore, a predictive empirical relationship for the triaxial compressive strength is established under different confinements and porosity. The relationship suggests that the mean peak compressive strength increases at a higher confinement and decreases at a higher porosity. The results and recommendations provide a useful framework for evaluating the strength and deformation of most sandstone.

Keywords: compressive strength; confining stress; porosity; water content; young's modulus



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1. Introduction

Sandstone is a common sedimentary rock that is widely distributed on the crust surface of the earth [1]. Sandstone is considered a major reservoir system that can be an oil- and gas-rich depositional basin such as the Permian Shanxi sandstone on the southern edge of the Yimeng uplift in China [2]. Also, sandstones can be major aquifers for groundwater flow and contaminants transportation [3]. An understanding of the strength and deformation behaviors of sandstone is essential for the design and simulation of geotechnical structures for underground environments and underground reservoirs for mineral extraction and subsurface storage [4]. Although the mechanical behaviors of sandstone have been investigated in past studies, a more comprehensive study that involves a wide variety of sandstone formations under different loading conditions is important to understand sandstone behaviors and application in engineering designs and constructions. This study will investigate the uniaxial compressive strength (i.e., the compressive strength under zero confinement) and the triaxial compressive strength (under different confinements), followed by the deformation behavior of sandstone based on Young's modulus.

The uniaxial compressive strength (UCS) of sandstone can be affected by several factors like water content, pore space, and mean size of grain particles. The water weakening effect

can be problematic for the stability of rock structures due to interactions between water and silicate minerals. Water weakens the hydrogen bonds, promotes the dissolution of clay minerals, and creates voids that can change the rock microstructure and ultimately weakens the rock [5–10]. In addition, pores inside a rock matrix act as flaws that create stress concentration and lead to macroscopic failure [11]. Therefore, a rock with more porous microstructures has more voids that can reduce the strength and stiffness of the rock matrix [12–15]. However, past studies considered the individual effect of water content and porosity while their coupled effect on the mechanical behavior of sandstone is rarely understood even though sandstone is typically situated in a moist or saturated environment rather than a dry condition. In addition, the UCS of sandstone tends to decrease as the mean grain size increases [16,17].

The triaxial compressive strength of sandstone is affected by several factors, such as water content, confining stress, and porosity. Triaxial compression test results revealed a positive effect of confinement on compressive strength [1,7,18–20]. The influence of confining stress on the triaxial compressive strength of sandstone has been a subject of earlier investigations. However, the effect of rock porosity on the triaxial compressive strength of sandstone under different confinements is rarely understood and deserves further investigation.

This paper presents the major factors influencing the uniaxial and triaxial compressive strengths and Young's modulus. A study is completed to achieve the following objectives:

- i. Systematically investigate the influence of physical and environmental factors on the mechanical and deformation behaviors of sandstone;
- ii. Developing empirical models to predict the compressive strength of sandstone based upon commonly measured properties such as water content, porosity, mean grain size, and confining stress;
- iii. Providing valuable findings to improve the understanding and prediction of mechanical behaviors of sandstone that will help to increase the safety and the cost-effectiveness of the built environment and structures supported by sandstone.

2. Regression Modeling

Linear and nonlinear models are used to examine the relationship between a response variable Y_i and an observed vector of predictors x_i for observation i as follows:

$$Y_i = f(x_i, \beta) + E_i \quad (1)$$

where β is a vector of regression coefficients, E_i is a random error term, and f is a linear or nonlinear function with respect to β . Thus, the model in (1) involves the specification of f and the choice of predictors x_i .

A dataset is split randomly into a training dataset and a testing dataset [21]. The training set is used to fit and select a model. The testing set is used to evaluate the predictive ability of the model. However, it is important that the training set is sufficiently large for an adequate model to be developed. The selected model in Equation (1) is fit to the training data to obtain the estimated vector of regression coefficients ($\hat{\beta}$). This fitted model is then used to generate the predicted values of the response variable ($\hat{y}_i$) as follows.

$$\hat{y}_{(i)} = f(x_{(i)}, \hat{\beta}) \quad (2)$$

The selected model can be evaluated by comparing the observed values of the response variable (y_i) to the predicted values of the response variable ($\hat{y}_i$). Two commonly used measures for this comparison are the Root Mean Square Error (RMSE) given by Equation (3) and the Mean Absolute Deviation (MAD) given by Equation (4):

$$\text{RMSE} = \sqrt{\frac{\sum (y_{(i)} - \hat{y}_{(i)})^2}{\text{num}}} \quad (3)$$

$$\text{MAD} = \frac{\sum |y_{(i)} - \hat{y}_{(i)}|}{\text{num}} \quad (4)$$

where *num* is the number of observations. It is desirable to have a small RMSE and MAD for a reasonable candidate model. Predictions are generated for both the training dataset and the testing dataset. Predictions based on the training dataset are used to assess the goodness-of-fit of a set of initially proposed models. Predictions based upon the testing dataset are used to assess the predictive ability of models proposed by this research and the models appearing in the literature.

When there are multiple predictors, the choice of the predictors in Equation (1) can be difficult since these predictors could have relationships with the true mean of the response that is linear, nonlinear, or some combination of both. Thus, the relationships between the response and the predictors are examined visually using scatterplots. The scatterplots are enhanced by adding a locally weighted polynomial regression fit to emphasize the relationship [22]. Additive regression models are also fit to statistically assess linear and nonlinear relationships between the true mean of the response and the collection of available predictors. The additive regression model (GAM) has the form of Equation (1) where $f(x_i, \beta)$ is replaced by

$$f(x_i) = \alpha + s_1(x_{1i}) + \dots + s_p(x_{pi}) \quad (5)$$

where x_{ki} denotes predictor variable k , α denotes the intercept, s_k denotes the corresponding smoothing spline for predictor variable k , and $k = 1, 2, \dots, p$ [23]. The additive models are fitted using the GAM function in the GAM package available in the R Program [24]. Hypothesis tests are conducted on the linear trend and the nonlinear trend associated with x_{ki} on the true mean of the response Y_i .

3. Unconfined Compressive Strength (UCS)

3.1. Sample Preparation and Test Equipment

An experimental study is carried out on 13 sandstone formations from Wyoming, USA, to examine the effect of physical properties and confining stress on mechanical behaviors. Rotary drilling of rock cores and boulders is used to extract testing specimens. The rock specimen length is cut to obtain a length-to-diameter ratio (L/D) of two according to the ASTM standards, and both ends of the rock specimens are trimmed and polished.

The effect of the specimen size has been investigated by several researchers with most of them focusing on UC tests. A study by Hoek and Brown [25] conducted on specimens with a diameter range from 15 to 200 mm showed that UCS increases progressively as the sample diameter decreases. Other studies, such as Li et al. [26], found that the scale effect proposed by Hoek and Brown (1980) did not hold for sandstone in which there is an increase in UCS with specimen diameter based on a study conducted on specimens with a diameter range of 12.7 to 101.6 mm. Compression tests in this study are conducted on 25- and 50 mm diameter sandstone specimens in addition to other diameters for sandstones collected from the literature that are presented in Tables 1–3. The sample size effect is ignored due to the narrow range of test sample diameters ranging from 20 to 50 mm.

Table 1. Summary of the UC test results of sandstone formations in Wyoming.

Sample ID	Formation	Geological Age	Depth, m	Size Classification	D, mm	<i>n</i> , %	<i>w</i> , %	UCS, MPa	<i>E</i> , GPa
16	Flathead	Cambrian	6.04	Medium	50	3.06	0	20.31	2.60
17	Cloverly	Cretaceous	30.34	Medium	50	21.20	0	11.61	1.51
18	Sundance	Jurassic	6.49	Fine	50	23.20	0	13.88	24.08
19	Aspen	Cretaceous	6.19	Medium	50	3.69	0	22.59	NA

Table 1. Cont.

Sample ID	Formation	Geological Age	Depth, m	Size Classification	D, mm	<i>n</i> , %	<i>w</i> , %	UCS, MPa	<i>E</i> , GPa
23	Lance	Cretaceous	Surface	Fine	50	13.82	0	2.47	3.067
31	Tensleep	Pennsylvanian	Surface	Fine	50	12.80	0	55.90	12.79
32	Arikaree	Lower Miocene	Surface	Coarse	50	10.90	0	12.18	4.39
33					50	12.10	0	17.00	4.44
39	Hanna	Paleogene	43.96	Fine	25	13.80	0	9.39	2.21
41			23.26	Coarse	25	15.40	0	9.65	1.91
43	Wind River	Eocene	Surface	Medium	25	13.60	0	47.59	7.64
49	Bridger	Eocene	Surface	Medium	25	26.20	0	13.91	6.83
50	Fort Union	Paleocene	Surface	Medium	25	13.80	0	6.00	1.15
51					25	3.92	0	26.08	2.75
56	Casper	Permian	Surface	Medium	25	9.37	0	39.00	9.54

D—Specimen diameter in mm, *n*—Porosity in percentage, *w*—water content in percentage, UCS—Uniaxial Compressive Strength in MPa, *E*—Young’s modulus in GPa.

Table 2. A summary of UC test data from historical WYDOT database.

Formation	Geological Age	Size Classification	D, mm	<i>n</i> , %	Number of UC test	<i>w</i> , %	UCS, MPa
Flathead	Cambrian	Fine	50	2.10	12	4.49–8.88	1.86–12.79
Cloverly	Cretaceous	Medium	50	18.00	10	0.27–5.33	10.56–61.21
Sundance	Jurassic	Fine	50	23.00	5	3.44–5.74	14.38–38.62
Aspen	Cretaceous	Medium	50	3.40	9	0.51–3.19	11.43–161.43

D—Specimen diameter in mm, *n*—Porosity in percentage, *w*—water content in percentage, UCS—Uniaxial Compressive Strength in MPa.

Table 3. Summary of UC test results of sandstones from the literature.

The Formation, (Location)	Size Classification	D, mm	<i>n</i> , %	<i>w</i> , %	UCS, MPa	<i>E</i> , GPa	Reference
NA, (France, Germany, USA, UK)	Medium	20	6.50–28.00	0	161.40–30.10	NA	Baud et al. (2014) [27]
NA, (Chuxiong)	Fine	50	8.50	0–2.29	71.91–50.48	7.05–5.52	Cai et al. (2019) [28]
NA, (Cauvery basin)	Medium-Coarse	28	3.00–25.00	0	48.00–10.60	30.00–8.50	Chatterjee and Mukhopadhyay. (2002) [12]
NA, (Hongliulin coal mine)	Fine	50	4.70	0–3.63	111.12–76.47	18.84–15.15	Chen et al. (2021) [5]
Buntsandstein, (Pfinztal)	Fine	40	8.00	0	114.00–142.00	16.70–26.40	Egert et al. (2018) [29]
Buntsandstein, (Tennenbach)	Fine	40	9.00	0	42.00–47.00	11.60–11.50	
NA, (Linyi)	Coarse	50	6.00	0–5.13	60.85–29.11	NA	Geng and Cao. (2020) [6]
Buntsandstein, (France)	Medium	20	3.40–18.50	0	242.70–58.20	39.60–16.10	Heap et al. (2019) [30]
Red sandstone, (Yichang)	Medium	50	12.69	0–6.25	32.00–19.00	5.00–2.30	Huang et al. (2021) [1]
Red, Berea, and Buff sandstone, (Utah and Ohio)	Fine	55	5.60–23.00	0	183.00–75.00	25.00–11.60	Kim et al. (2017) [31]
Red sandstone, (Yunnan)	Fine	50	8.50	0, 3.3	147.3, 112	NA	Li et al. (2019) [7]

Table 3. Cont.

The Formation, (Location)	Size Classification	D, mm	<i>n</i> , %	<i>w</i> , %	UCS, MPa	<i>E</i> , GPa	Reference
NA, (NA)	Fine	50	3.00–7.60	0	87.20–27.90	20.00–6.40	Huamin et al. (2018) [14]
Red sandstone, (Hunan)	Medium	50	5.20–5.30	0	60.73–64.62	10.53–10.36	Lin et al. (2020) [32]
Shanxi, (Huaibei and Xuzhou mining areas)	Fine	25	7.90	0–2.96	66.45–40.62	10.17–5.24	Lu et al. (2017) [33]
NA, (Atovgvia da Baleia)	Fine	50	3.60–18.60	0	135.70–17.60	NA	Ludovico- Marques et al. (2012) [15]
Gosford, (Sydney basin)	Coarse	42	18.00	0–6.90	43.98–11.69	6.58–1.98	Masoumi et al. (2017) [8]
Hawkesbury sandstone (Australia)	Medium	42	12.50	0	38.81–77.22	8.00–11.60	Roshan et al. (2018) [34]
NA, (Dholpur)	Fine	50	21.00	0	31.14–37.68	11.98–7.48	Sirdesai et al. (2018) [35]
Red sandstone, (Hunan)	Fine	50	11.60	0–3.40	108.00–55.50	16.80–11.30	Tang et al. (2018) [9]
NA, (Longchang)	Fine	50	4.70	0–1.61	127.45–61.17	20.98–12.34	Shibin Tang. (2018) [10]
NA, (Perth and Sydney basin)	Fine	38	13.00–16.00	0	65.01–32.37	13.34	Wasantha et al. (2018) [11]
Jiaozuo, (Henan)	Fine	50	5.30–16.00	0.38	140.00–54.00	34.50–6.25	Wu et al. (2013) [36]
Red sandstone, (Hongyang)	Fine	50	6.48	0	101.28–107.38	NA	Wu et al. (2018) [19]
NA, (Chongqing)	Coarse	25	8.10	0	42.40	7.23	Xu et al. (2017) [37]
NA, (Rizhao)	Fine-Medium	50	6.88	0	134.45–137.99	28.78–27.16	Sheng-Qi Yang. (2016) [38]
Red sandstone, (Hunan)	Fine	50	12.60	0–4.70	75.00–48.00	10.95–7.70	Yu et al. (2019) [4]
Red sandstone, (Ganzhou)	Fine	50	2.80	0–2.77	96.58–53.07	16.00–10.60	Zhao et al. (2021) [39]
Black sandstone, (NA)	Medium	50	1.50	0	93.64	19.47	Zhou et al. (2018) [20]
Red sandstone, (NA)	Medium	50	2.00	0	43.32	8.52	

NA—Not Available, D—Specimen diameter in mm, *n*—Porosity in percentage, *w*—water content in percentage, UCS—Uniaxial Compressive Strength in MPa, *E*—Young's modulus in GPa.

ASTM recommends using samples of 2:1 (height: diameter) ratio for testing. The advisability of using cores of 2:1 factor is indicated by John (1972) [40]. He demonstrated that for dry sandstone, the compressive strengths obtained are approximately the same for cores of a height/diameter ratio of 2:1 or greater, but for a smaller ratio, there is a notable increase in strength. In this study, all our tested sandstones and the sandstones collected in the literature have a height/diameter ratio of 2:1, as shown in Figure 1.

All specimens are oven-dried for 24 h to assure that they are completely dry before testing. No macroscale defects are observed in any of the specimens before testing. The porosity (*n*) of each sandstone specimen is calculated using the gravimetric method by determining the specific gravity and moisture content. The specific gravity is determined using the AASHTO-100 standard [41] test method. Then, the porosity is calculated by:

$$\text{Porosity (\%)} = \frac{1 - \text{dry bulk density}}{\text{specific gravity}} \times 100 \quad (6)$$

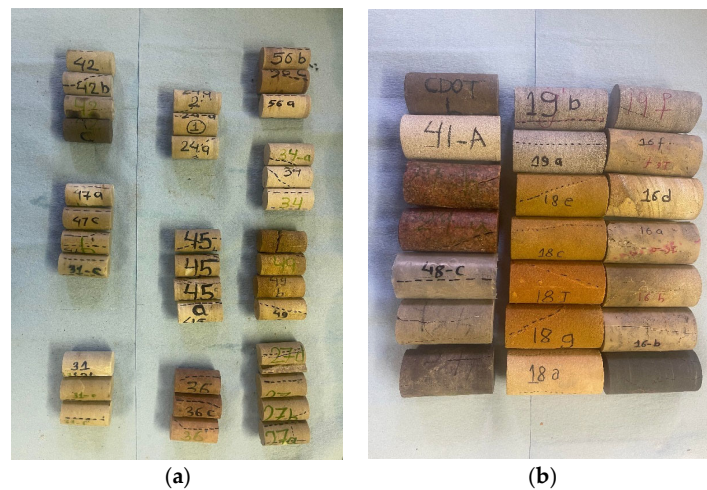


Figure 1. Tested sandstone specimens from Wyoming showing (a) 25 mm in diameter and (b) 50 mm in diameter.

Average porosity values range from 3.43% to 31.2% with an average dry density of 2.406 g/cm^3 . Mean grain sizes are examined using a glass magnifier with high-power magnification from which the grain size is estimated based on the size scale of sandstone. The data of grain size obtained from the size scale of the magnifier are subdivided into three categories: fine, medium, and coarse-grained according to the USGS classification scheme for sandstone [42].

The UC and triaxial tests are conducted at room temperature using the testing system (GCTS RTR-1500) at the University of Wyoming in accordance with ASTM D7012 (2014) [43], as shown in Figure 2a. This loading system has a maximum compression load of 1500 kN, and a tension load of 818 kN and can test most rock types using a controlled axial strain setup at a constant strain rate of 0.1% per minute for hard rocks and 0.05% per minute for softer rocks. Each rock specimen is instrumented with three Linear Variable Differential Transformers (LVDTs) to measure two axial strains and a radial strain, as shown in Figure 2b. The load and deformation responses of each test are recorded simultaneously at a data collection interval of 0.5 s.

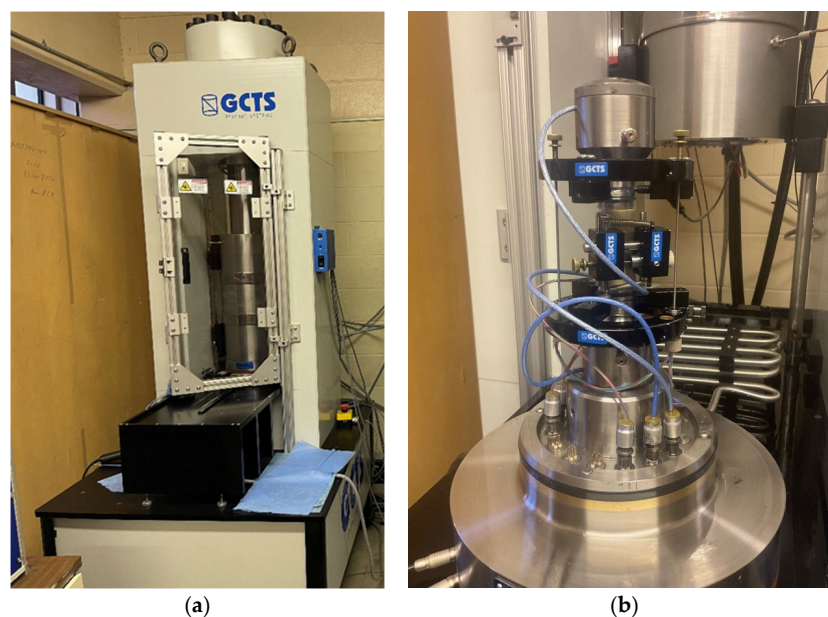


Figure 2. (a) GCTS RTR-1500 uniaxial and triaxial testing equipment, (b) Triaxial setup with three LVDT sensors.

Young's modulus was determined based on axial stress–strain data using a moving average regression analysis method [44]. A linear part of the stress–strain plot was determined for a range of stress–strain data that yields the highest coefficient of determination (R^2) closer to 1. Young's modulus was calculated as the slope or gradient of the best linear stress–strain curve.

3.2. Uniaxial Compression Testing

A total of twelve sandstone samples of different formations and porosities are tested under a UC condition and at room temperature. A summary of the UC test results is given in Table 1.

Rocks with higher porosities tend to have lower UCS and E values. For example, Flathead Sandstone with a porosity of 3.06% exhibits higher UCS and E values by 43% and 66%, respectively, than that of Cloverly Sandstone with a porosity of 21.2%.

3.3. Historical Sandstone Data from WYDOT Database

Additional test results of four different sandstone formations are collected from a historical rock database developed by the Wyoming Department of Transportation (WYDOT). The laboratory tests were conducted in the WYDOT's certified laboratory and conducted by trained laboratory engineers. These sandstones are tested under different water contents and porosities. Table 2 summarizes 36 UC test results of the four sandstone formations.

Sandstones with the lowest water content and porosity have the highest UCS values. For example, Aspen Sandstone with the lowest water content ranging from 0.51 to 3.19% and a relatively low porosity of 3.4% exhibits the highest UCS ranging from 11.43 to 161.34 MPa.

3.4. Experimental Sandstone Data from the Literature

Experimental data compiled from the literature are utilized to better understand the mechanical behaviors of sandstone from different regions of the world. Sixty-one sandstone formations collected from the literature, in addition to sixteen formations from Wyoming, USA, were tested under UC. However, other sandstone formations such as Bentheim and Fontainebleau sandstones were not included in this study due to relatively different testing conditions such as specimen shape (i.e., prismatic), drainage condition during compression (i.e., deformation is fully drained), and principal stresses condition (i.e., biaxial) [45,46]. Sandstone formations and properties are summarized in Table 3.

3.5. Relationship between UCS, Water Content, Mean Grain Size and Porosity

UCS is one of the most commonly measured rock parameters in rock engineering [47]. Compressive strength generally decreases with the increase in water content, porosity, and mean grain size. Various models are evaluated to the mean UCS based on the predictor's mean grain size, porosity, and water content after the exclusion of one outlier. The GAM is only able to provide marginal evidence against claims of linear trends in the predictors on the true mean UCS, as shown in Figure 3 where the black squares represent experimental data points of the training dataset, and the red lines represent the trend of the response variable and the predictors. While it might be possible to identify complex nonlinear trends in these predictors, such models are not pursued here for the sake of simplicity and to prevent overfitting. Thus, the recommended model for the true mean UCS is linear in the predictors mean grain size (d_m in mm), porosity (n in %), and water content (w in %), as shown in Figure 3 and given by Equation (7) based on the training dataset that contains 193 data points with 31 formations from the literature and four formations from Wyoming.

Since some sandstones from the literature, in addition to our tested sandstones, only have size classification and no exact grain size, the USGS classification scheme for sandstone [42] assumes a specific grain diameter for each size classification (i.e., for fine sandstone, the upper and lower grain diameter is 250 and 125 μm , respectively). Several data points are clustered at the same grain size and have different UCS values since they

have the same size classification but different water contents and porosities. Also, some sandstones are tested under dry condition, which explains the large amount of data at $w = 0$ in the scatterplot of UCS versus w (Figure 3).

$$\hat{UCS} \text{ (MPa)} = 108.46 - 2.23 n - 8.78 w - 38.77 d_m \quad (7)$$

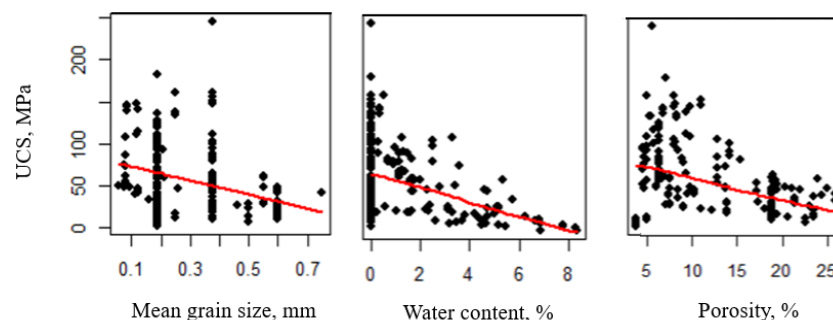


Figure 3. Linear trend associated with the predictor variables on the true mean of the response UCS.

It is desirable to test porous rocks such as sandstone under moist and saturated conditions so that a comparison can be made under dry and saturated levels, and an estimate for the lower bound of design parameters can be used [48]. The negative linear trend in water content on predicting UCS from Equation (7) is consistent with past findings that explain the water weakening effect as a combination of mechanical and chemical processes that occur at a microscopic scale [49].

The water weakening effect includes the dissolution of cement inside the rock that leads to the loosening of the internal microstructure [6]. Furthermore, the increase in water saturation means more voids are occupied with water and increases the likelihood of slippage between solid particles. For example, the UCS of Shanxi Sandstone in Table 3 with a porosity of 7.90% decreases from 66.45 to 40.62 MPa or 39% when the water content increases from 0 to 2.96%, emphasizing the weakening effect of saturation [33]. Similarly, an increase in porosity reduces the predicted UCS values of both dry and saturated sandstones because pores are considered weak points within a rock matrix that induces stress concentration. Hence, more porous sandstones have more voids and higher porosity, reducing the strength of the rock skeleton [15]. The negative linear trend of the mean grain size on the predicted UCS from Equation (7) is consistent with the past findings on artificial sandstones [50]. This observation can be explained by the fact that larger grains have longer grain boundaries, which provide more flaws for the nucleation of cracks and stress concentration [51].

Table 4 summarizes several relationships for predicting the UCS of specific sandstone formations reported in the literature.

Table 4. Assessment of prediction equations for UCS based on the testing dataset.

Sandstone Formation	Sandstone Location	Equation	RMSE	MAD	Reference
Tables 1–3	Wyoming and literature data	$\hat{UCS} = 108.46 - 2.23 n\% - 8.78 w\% - 38.77 d_m$	31.60	22.13	This study
NA	Krishna-Godavari Basin, India	$\hat{UCS} = -2.16 n\% + 52.84$	50.91	38.72	Chatterjee and Mukhopadhyay (2002) [12]
NA	Cauvery Basin, India	$\hat{UCS} = -0.79 n\% + 30.88$	58.31	45.55	Chatterjee and Mukhopadhyay (2002) [12]
NA	Shanxi Province, China	$\hat{UCS} = 44.6 e^{-0.399w\%} + 66.60$	46.80	37.24	Chen et al. (2021) [5]
NA	Atouguia da Baleia, Portugal	$\hat{UCS} = 206.7 e^{-0.129 n\%}$	50.55	38.64	Ludovico-Marques et al. (2012) [15]
Gosford sandstone	Sydney Basin, Australia	$\hat{UCS} = 43.63 e^{-0.20w\%}$	48.50	36.60	Masoumi et al. (2017) [8]

Table 4. Cont.

Sandstone Formation	Sandstone Location	Equation	RMSE	MAD	Reference
Red sandstone	Hunan Province, China	$\text{UCS} = 55.21 e^{-0.7502w\%} + 51.6$	40.63	29.82	Tang et al. (2018) [9]
Black sandstone	Sichuan Province, China	$\text{UCS} = 80.604 e^{-0.9044w\%} + 43.17$	46.44	34.11	Shibin Tang. (2018) [10]
Red sandstone	Jiangxi Province, China	$\text{UCS} = 70.8734 e^{-0.3188 w\%} + 26.84$	37.01	26.59	Zhao et al. (2021) [39]

NA—Not available, UCS—Uniaxial compressive strength in MPa; w —water content in percentage, and n —rock porosity in percentage, RMSE—Root Mean Square Error, MAD—Mean Absolute Deviation.

These relationships are developed based on a single predictor variable of either water content (w) or porosity (n) in percentage. According to the independent testing dataset that contains 78 data points of 19 sandstone formations from the literature and four sandstone formations from Wyoming, RMSE values ranging from 31.6 to 58.31 and MAD values ranging from 22.13 to 45.55 are calculated for the comparison of the different equations. The proposed Equation (7) for UCS prediction fits the testing dataset better than other equations according to the lowest RMSE of 31.6 and MAD of 22.13 summarized in Table 4.

4. Triaxial Compressive Strength

4.1. Conventional Triaxial Compression Testing

Conventional triaxial compression tests are conducted on 17 samples from 13 sandstone formations. GCTS RTR-1500 equipment has rapid, easy, and safe operation with automated cell assembly and meets the specifications of the ISRM and ASTM standards for triaxial testing of the rock samples. The axial load actuator has a capacity ranging up to 1500 kN and the triaxial cell can apply a maximum confining pressure of 140 MPa. The confinement is applied using an oil-filled stainless-steel chamber inside the frame. The initial seating pressure of 0.345 MPa is applied before the shearing stage. A summary of the triaxial compression test results is given in Table 5.

Table 5. Summary of triaxial compression test results of dried sandstones from Wyoming.

Sample ID	Formation	Geological Age	Depth m	D, mm	n , %	σ_3 , MPa	σ_1 , MPa	E , GPa	c_r , MPa	ϕ , Degree
16	Flathead	Cambrian	4.76	50	2.20	4	95.59	61.33	20.34	37
			5.85	50	5.35	10	120.12	41.027		
17	Cloverly	Cretaceous	30.18	50	17.80	4	15.89	36.57	3.45	22
			30.03	50	19.50	10	31.90	27.34		
18	Sundance	Jurassic	3.35	50	22.50	8	38.58	13.91	6.07	18
19	Aspen	Cretaceous	6.10	50	3.43	10	98.89	34.31	5.38	49
			11.52	50	5.62	4	45.85	53.52		
20	Aspen	Cretaceous	11.65	50	7.18	10	99.53	1.41	5.52	49
				50	30.40	1	8.71	0.097		
21	Denver and Arapahoe	NA	NA	50	30.00	4	15.57	1.095	2.62	18
				50	31.20	10	25.92	0.21		
23	Lance	Cretaceous	Surface	50	9.31	2	5.07	1.72	11	8
				50	12.18	4	36.50	4.64		
31	Tensleep	Pennsylvanian	Surface	50	13.00	1	70.24	18.67	13.1	48
				50	13.20	4	59.88	17.25		
32	Arikaree	Lower Miocene	Surface	50	13.11	8	120.39	8.48	2.76	51
				50	11.70	4	45.86	33.99		
33	Arikaree	Lower Miocene	Surface	50	14.00	10	93.80	NA	3.1	54
				50	12.20	4	46.49	8.95		
39	Hanna	Paleocene	Surface	44.15	11.10	10	111.03	0.34	2.48	46
				25	13.10	4	33.19	3.14		
41	Hanna	Paleocene	Surface	44.60	15.20	10	70.72	5.82	2.34	44
				25	14.80	4	31.47	4.09		
43	Wind River	Eocene	Surface	23.32	16.80	6	42.96	4.17	8.96	56
				24.09	14.50	4	14.00	17.90		
				25	14.00	10	21.11	7.70		

Table 5. Cont.

Sample ID	Formation	Geological Age	Depth m	D, mm	<i>n</i> , %	σ_3 , MPa	σ_1 , MPa	<i>E</i> , GPa	<i>c</i> , MPa	ϕ , Degree
49	Bridger	Eocene	Surface	25	27.20	4	34.68	29.59	4.48	29
50	Fort Union	Paleocene	Surface	25	24.20	10	42.44	4.40	1.38	47
51	Fort Union	Paleocene	Surface	25	12.20	4	31.48	3.52	5.52	55
				25	5.92	6	89.69	5.03		
				25	3.92	8	147.00	7.70		
				25	11.10	4	72.56	14.38		
56	Casper	Permian	Surface	25	10.20	10	132.23	16.99	7.93	53
				25	14.00	10	21.11	7.70		

NA—Not Available, D—Specimen diameter in mm, *n*—Porosity in percentage, σ_3 —Confining stress in MPa, σ_1 —Peak Compressive Strength in MPa, *E*—Young's modulus in GPa, *c*—cohesion in MPa, ϕ —Internal friction angle.

4.2. Experimental Sandstone Data from the Literature

Thirty sandstone formations collected from the literature and thirteen formations from Wyoming, USA, were tested under triaxial compression under confining stresses ranging from 1 to 90 MPa. These formations, with a porosity of 1.5 to 21%, are summarized in Table 6.

Table 6. Summary of triaxial compression test results of sandstones from the literature.

Formation, (Location)	Size Classification	D, mm	<i>n</i> , %	<i>w</i> , %	σ_3 , MPa	σ_1 , MPa	<i>E</i> , GPa	<i>c</i> , MPa	ϕ , Degree	Reference
Vosges sandstone (France)	Medium	50	22.00	0	0.1–60	32.10–175.00	NA	NA	NA	Bésuelle et al. (2000) [52]
Buntsandstein, (Pfinztal)	Fine	40	8.00	0	50–90	337.00–471.00	11.80–13.00	40	35	Egert et al. (2018) [29]
Buntsandstein, (Tennenbach)	Fine	40	9.00	0	50–90	251.00–358.00	10.90–10.20	24	31	
Red sandstone, (Yichang)	Medium	50	12.69	0–6.25	10	121.00–86.00	12.00–8.45	NA	NA	Huang et al. (2021) [1]
Yellow sandstone, (Meishan)	Medium	50	21.00	0	2–8	106.12–164.23	NA	NA	NA	Huang et al. (2021) [1]
NA, (Yunnan)	Fine	50	8.50	0	2–10	110.02–185.97	26.71–30.97	13.86	56.29	Kegang et al. (2016) [53]
Red sandstone, (Yunnan)	Fine	50	8.50	0	10–40	147.00–245.00	19.00–17.00	28.07	38.38	Li et al. (2019) [7]
NA, (Qinghai)	Fine	50	1.63	0	1–3	120.00–127.60	NA	27.74	38.32	Liping et al. (2019) [54]
	Coarse	50	1.92	0	1–3	109.30–122.30	NA	20.74	46.32	
Hawkesbury, (Sydney basin)	Medium	50	16.00	0	10–30	109.90–172.40	NA	22.6	31.5	Roshan et al. (2017) [34]
NA, (Xiangjiaba)	Fine	50	2.64	0	3–20	144.81–266.08	27.18–31.12	32	44	Wang et al. (2020) [55]
Shanxi, (Henan)	Fine-Coarse	50	6.53	0	10–50	187.81–283.93	NA	40	32	Wang and Cui. (2018) [56]
Hawkesbury, (Sydney)	Medium	54	13.00	0	4–25	58.00–116.00	NA	16.5	28	Wasantha and Ranjith. (2014) [57]
NA, (Chongqing)	Coarse	25	8.10	0	5–40	77.00–219.09	8.03–16.07	30.16	38.4	Xu et al. (2017) [37]
NA, (Rizhaou)	Fine-Medium	50	6.88	0	8–35	198.92–316.38	29.03–33.69	30.58	45.7	Sheng-Qi Yang. (2016) [38]
Red sandstone, (Shandong)	Fine-Medium	55	6.48	0	5–35	115.10–242.90	18.81–23.80	22.42	37.8	Yang and Jing. (2013) [58]
Black sandstone, (NA)	Medium	50	1.50	0	10–60	131.86–241.81	19.89–21.71	22.5	33.5	Zhou et al. (2018) [20]
Red sandstone, (NA)	Medium	50	2.00	0	10–60	93.40–131.49	10.76–9.90	13	23	

NA—Not Available, D—Specimen diameter in mm, *n*—Porosity in percentage, *w*—water content in percentage, σ_3 —Confining stress in MPa, σ_1 —Compressive Strength in MPa, *E*—Young's modulus in GPa, *c*—cohesion in MPa, ϕ —Internal friction angle in degree.

4.3. Effect of Porosity and Confining Stress

The effect of porosity on rock strength is further demonstrated with a comparison of porosity and the failure parameters, cohesion (c), and internal friction angle (ϕ) separately, derived for the Mohr–Coulomb criterion as shown in Figure 4. Figure 4a shows the relationship between porosity and the internal friction angle, whereas Figure 4b shows the relationship between porosity and cohesion. The blue squares represent experimental data of cohesion and internal friction angle resulting from triaxial compression tests of tested sandstone fitted by linear black lines to check the significance of porosity on the response variables (i.e., c and ϕ).

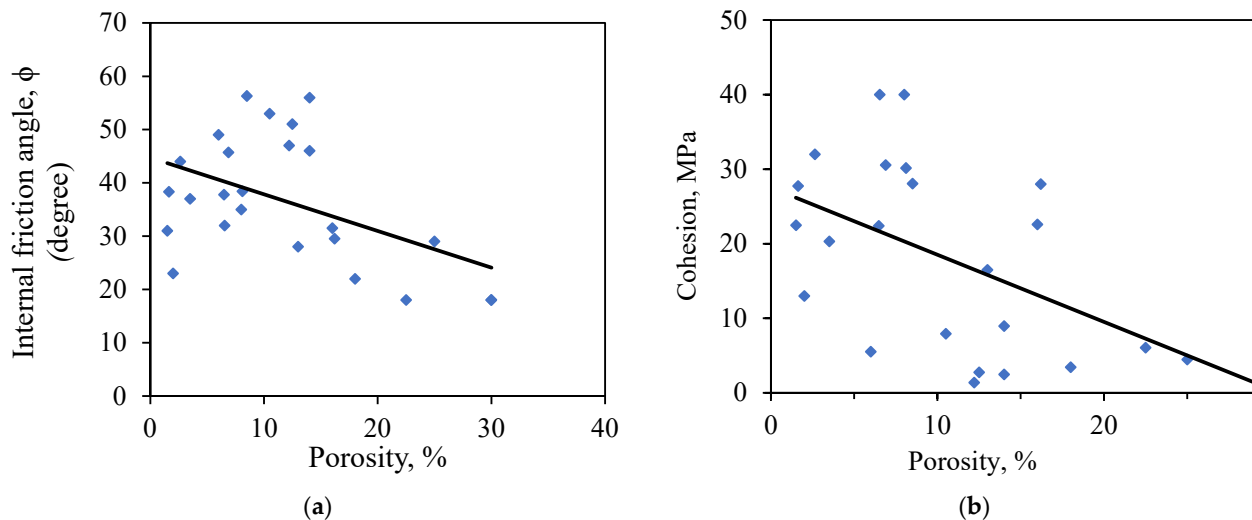


Figure 4. Comparison of the internal friction angle and porosity based on the training dataset.

The ϕ decreases with increasing porosity indicating that the porosity has a significant effect on the rock failure, as shown in Figure 4a. A similar decreasing trend is observed between porosity and cohesion. However, since cohesion depends on other factors that are not available in this study, such as mineralogy, geological process (cementation), and compaction, a weak relationship and large variation is observed between porosity and cohesion, as shown in Figure 4b, compared to the relationship between the internal friction angle and porosity.

The peak compressive strength σ_1 decreases with the increase in n . An increase in the internal surface area per unit rock volume resulting from a higher n decreases the predicted integrity of the rock and hence reduces its strength [16]. Compressive strength decreases as the porosity increases. This observation is explained by the weakening effect of higher porosity on the rock strength since a higher volume of voids induces stress concentrations inside the rock matrix. On the other hand, the mean σ_1 generally increases with an increase in the confining stress (σ_3) due to the strengthening effect of confinement on compressive strength.

The test results from the GAM indicate that both n and σ_3 are important predictors of mean σ_1 . The GAM test results do not indicate evidence against a simple linear trend of σ_3 on the true mean σ_1 , but do provide evidence against a simple linear trend of n on the true mean σ_1 . As a result, the proposed Equation (8) contains a polynomial of order two to capture the nonlinear relationship between n in %, σ_3 in MPa and the true mean σ_1 in MPa based on the training dataset that contains 61 data points represented by the black circles in Figure 5 with 17 sandstone formations from the literature and the 13 sandstone formations from Wyoming, as shown in Figure 5.

$$\hat{\sigma}_1 = 90.68 + 1.63 n\% + 2.9 \sigma_3 - 0.12 n\%^2 + 0.0042 \sigma_3^2 \quad (8)$$

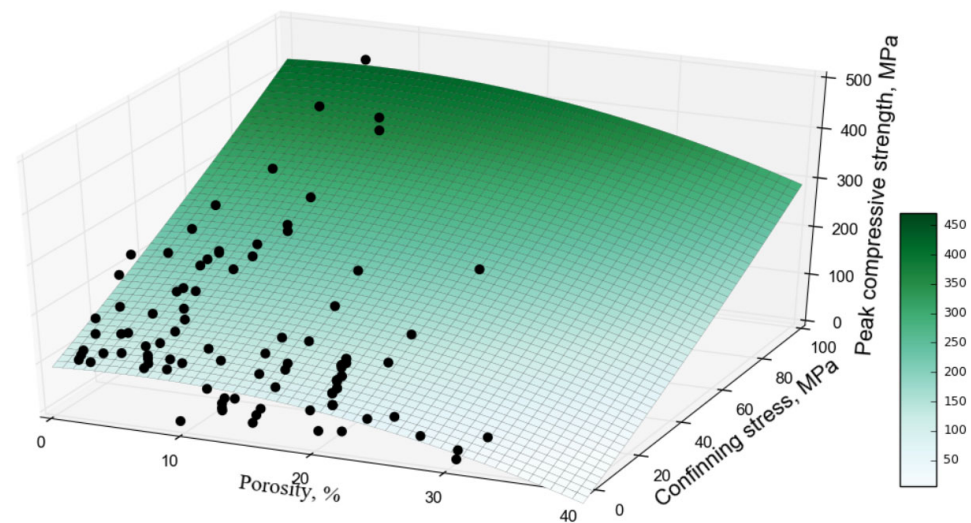


Figure 5. Relationship between the peak compressive strength and the rock porosity in % and confining stress in MPa (Edited).

Previously published relationships related σ_1 to σ_3 without considering the effect of porosity. Table 7 summarizes several relationships for predicting the σ_1 of specific sandstone formations reported in the literature.

Table 7. Assessment of prediction equations based on the testing dataset.

Sandstone Formation	Sandstone Location	Equation	Reference	RMSE	MAD
Tables 5 and 6	Wyoming and literature data	$\hat{\sigma}_1 = 90.68 + 1.63 n\% + 2.9 \sigma_3 - 0.12 n\%^2 + 0.0042 \sigma_3^2$	This study	50.19	40.60
General	General	$\hat{\sigma}_1 = \sigma_3 + \sigma_c \sqrt{m_i \times \frac{\sigma_3}{\sigma_c} + 1}$	Generalized Hoek and Brown criterion, 1980 [25]	62.62	41.64
NA	Linyi	$\hat{\sigma}_1 = 9.008 \sigma_3 + 83.56$	Gong et al., 2019 [59]	169.05	119.59
Red Sandstone	Shandong	$\hat{\sigma}_1 = 3.9766 \sigma_3 + 109.1850$	Wu et al., 2018 [19]	62.15	45.51
Yellow Sandstone	Zunyi	$\hat{\sigma}_1 = 4.36 \sigma_3 + 77.33$	Yang et al., 2020 [60]	57.18	44.40

NA—Not Available, σ_1 —Compressive strength in MPa, σ_3 —Confining stress in MPa, n —Porosity in percentage, σ_c —Unconfined compressive strength, m_i —Material constant, RMSE—Root mean square error, MAD—Mean Absolute Deviation.

According to the independent testing dataset that contains 43 data points of 15 sandstone formations from the literature and three sandstone formations from Wyoming, RMSE values ranging from 57.18 to 169.05 and MAD values ranging from 44.40 to 119.59 are calculated for comparing the different equations. The proposed Equation (8) for σ_1 prediction fits the testing dataset better than other equations according to the lowest RMSE of 50.19 and MAD of 40.60 summarized in Table 7.

5. Young's Modulus

Beside the compressive strength of sandstone, it is important to understand the deformation behavior of sandstone characterized by Young's modulus. The data presented in Tables 1–3 is split randomly into training and testing datasets. The training dataset contains 90 UC data points with 16 sandstone formations from the literature and 12 sandstone formations from Wyoming (mentioned in Table 1), whereas the testing dataset contains 39 data points represented by the black squares in Figure 6 for 13 sandstone formations from the literature and 1 sandstone formation from Wyoming. The relationship between Young's modulus (E) and UCS according to the training dataset is shown in Figure 6 represented by the black linear fit. The plot illustrates a linear increase in mean E as UCS increases with a statistical measure R-squared of 0.80.

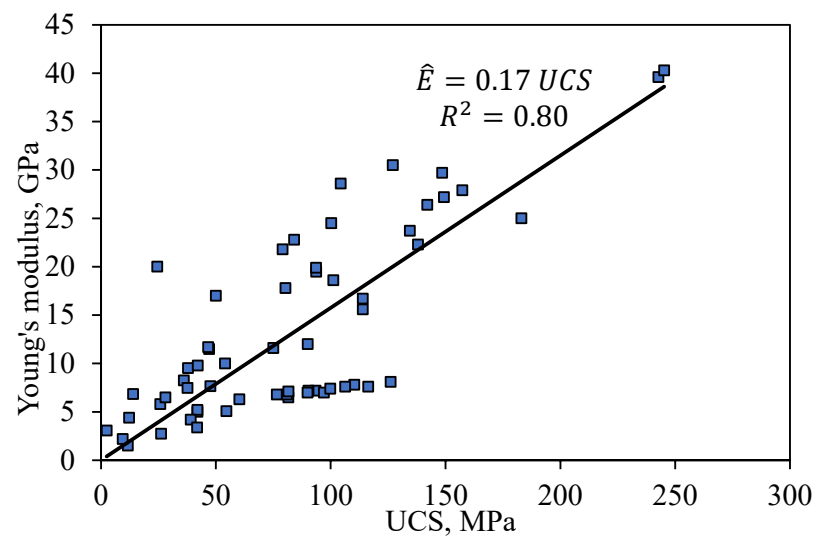


Figure 6. Relationship between UCS and Young's modulus E of the training dataset.

The prediction equation given by Equation (9) describes a linear increase in the predicted Young's modulus ($\hat{E}$) with an increase in UCS. Other related studies predicted UCS linearly to E , as summarized in Table 8 [12,61,62]

$$\hat{E}(\text{GPa}) = 0.17 \times \text{UCS}(\text{MPa}) \quad (9)$$

Table 8. Assessment of prediction equations based on the testing dataset.

Sandstone Formation	Sandstone Location	Equation	Reference	RMSE	MAD
Tables 1 and 4	Wyoming and literature data	$\hat{E} = 0.17 \text{ UCS}$	This study	9.79	7.05
Krishna-Godavari and Cauvery basin	India	$\hat{E} = 0.73 \text{ UCS} + 0.17$	Chatterjee and Mukhopadhyay. (2002) [12]	33.35	26.90
Upper Silesia Basin	Poland	$\hat{E} = 0.17 \text{ UCS} + 2.907$	Malkowski et al. (2018) [61]	9.81	8.13
Island Creek	US Bureau of mines	$\hat{E} = 0.05 \text{ UCS} + 20.6$	Rohde and Feng. (1990) [62]	12.17	10.59

RMSE—Root mean square error, MAD—Mean Absolute Deviation, UCS—Uniaxial compressive strength in MPa, E —Young's modulus in GPa.

A comparison of the proposed Equation (9) with other relationships reported in the literature is presented in Table 8.

According to the testing dataset, the proposed Equation (9) has the lowest RMSE of 9.79 and MAD of 7.05 compared to those from the literature, indicating a better prediction of the Young's modulus.

6. Conclusions

A series of uniaxial and triaxial compression tests are carried out in addition to experimental data collected from the literature to study the effects of physical properties and environmental conditions on the mechanical behaviors of sandstone under different loading conditions. The main findings drawn from this study are as follows:

1. The uniaxial compressive strength of both dry and saturated sandstones is linearly related to water content, porosity, and mean grain size.

2. For the triaxial compression condition, the internal friction angle is influenced by porosity. The internal friction angle decreases with the increase in porosity. A similar negative trend is observed between porosity and cohesion.
3. A significant effect of the porosity and confining stress on the triaxial compressive strength was observed on dry sandstones. The results of this study offer insights into how commonly measured properties can be utilized to improve the engineering design of sandstone structures.
4. Particularly, the research findings from this study are established based on different sandstone formations from all over the world. Hence, the proposed empirical equations provide a better prediction of sandstone mechanical properties.

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References

1. Huang, Z.; Gu, Q.; Wu, Y.; Li, S.; Zhao, K.; Zhang, R. Effects of Confining Pressure on Acoustic Emission and Failure Characteristics of Sandstone. *Int. J. Min. Sci. Technol.* **2021**, *31*, 963–974. [\[CrossRef\]](#)
2. Li, J.; Zhang, X.; Tian, J.; Liang, Q.; Cao, T. Effects of deposition and diagenesis on sandstone reservoir quality: A case study of Permian sandstones formed in a braided river sedimentary system, northern Ordos Basin, Northern China. *J. Asian Earth Sci.* **2021**, *213*, 104745. [\[CrossRef\]](#)
3. Medici, G.; West, L.J. Review of groundwater flow and contaminant transport modelling approaches for the Sherwood Sandstone aquifer, UK; insights from analogous successions worldwide. *Q. J. Eng. Geol. Hydrogeol.* **2022**, *55*, qjeh2021-176. [\[CrossRef\]](#)
4. Yu-hang, G.; Bao-zhi, P.; Li-hua, Z.; Chuan-hui, F. Research and application of the relationship between transverse relaxation time and resistivity index in tight sandstone reservoir. *J. Pet. Sci. Eng.* **2018**, *160*, 597–604. [\[CrossRef\]](#)
5. Chen, P.; Tang, S.; Liang, X.; Zhang, Y.; Tang, C. The influence of immersed water level on the short-and long-term mechanical behavior of sandstone. *Int. J. Rock Mech. Min. Sci.* **2021**, *138*, 104631. [\[CrossRef\]](#)
6. Geng, J.; Cao, L. Failure Analysis of Water-Bearing Sandstone Using Acoustic Emission and Energy Dissipation. *Eng. Fract. Mech.* **2020**, *231*, 107021. [\[CrossRef\]](#)
7. Li, D.; Sun, Z.; Zhu, Q.; Peng, K. Triaxial Loading and Unloading Tests on Dry and Saturated Sandstone Specimens. *Appl. Sci.* **2019**, *9*, 1689. [\[CrossRef\]](#)
8. Masoumi, H.; Horne, J.; Timms, W. Establishing Empirical Relationships for the Effects of Water Content on the Mechanical Behavior of Gosford Sandstone. *Rock Mech. Rock Eng.* **2017**, *50*, 2235–2242. [\[CrossRef\]](#)
9. Tang, S.B.; Yu, C.Y.; Heap, M.J.; Chen, P.Z.; Ren, Y.G. The Influence of Water Saturation on the Short- and Long-Term Mechanical Behavior of Red Sandstone. *Rock Mech. Rock Eng.* **2018**, *51*, 2669–2687. [\[CrossRef\]](#)
10. Tang, S. The Effects of Water on the Strength of Black Sandstone in a Brittle Regime. *Eng. Geol.* **2018**, *239*, 167–178. [\[CrossRef\]](#)

11. Wasantha, P.; Ranjith, P.; Permata, G.; Bing, D. Damage Evolution and Deformation Behaviour of Dry and Saturated Sandstones: Insights Gleaned from Optical Measurements. *Measurement* **2018**, *130*, 8–17. [CrossRef]
12. Chatterjee, R.; Mukhopadhyay, M. Petrophysical and Geomechanical Properties of Rocks from the Oilfields of the Krishna-Godavari and Cauvery Basins, India. *Bull. Eng. Geol. Environ.* **2002**, *61*, 169–178. [CrossRef]
13. Heidari, M.; Momeni, A.A.; Rafiei, B.; Khodabakhsh, S.; Torabi-Kaveh, M. Relationship Between Petrographic Characteristics and the Engineering Properties of Jurassic Sandstones, Hamedan, Iran. *Rock Mech. Rock Eng.* **2012**, *46*, 1091–1101. [CrossRef]
14. Li, H.; Li, H.; Wang, K.; Liu, C. Effect of Rock Composition Microstructure and Pore Characteristics on Its Rock Mechanics Properties. *Int. J. Min. Sci. Technol.* **2018**, *28*, 303–308. [CrossRef]
15. Ludovico-Marques, M.; Chastre, C.; Vasconcelos, G. Modelling the Compressive Mechanical Behaviour of Granite and Sandstone Historical Building Stones. *Constr. Build. Mater.* **2012**, *28*, 372–381. [CrossRef]
16. Atapour, H.; Mortazavi, A. The Influence of Mean Grain Size on Unconfined Compressive Strength of Weakly Consolidated Reservoir Sandstones. *J. Pet. Sci. Eng.* **2018**, *171*, 63–70. [CrossRef]
17. Hill, S.; Villeneuve, M.C.; McNamara, D. Physical and Mechanical Characteristic Relationships of Late-Cretaceous to Eocene Reservoir Rocks in the Maui, Maari and Manaia Fields, New Zealand. *J. Pet. Sci. Eng.* **2022**, *213*, 110375. [CrossRef]
18. Wasantha, P.L.P.; Ranjith, P.G.; Viète, D.R.; Haque, A.; Bouazza, A. Crack Initiation Stress for Saturated Sandstone in Triaxial Compression. In *46th U.S. Rock Mechanics/Geomechanics Symposium*; Bobet, A., Ed.; American Rock Mechanics Association: Alexandria, VA, USA, 2012; pp. 573–579. Available online: <https://www.onepetro.org/conference-paper/ARMA-2012-228> (accessed on 17 June 2023).
19. Wu, J.; Feng, M.; Yu, B.; Zhang, W.; Ni, X.; Han, G. Experimental Investigation on Dilatancy Behavior of Water-Saturated Sandstone. *Int. J. Min. Sci. Technol.* **2018**, *28*, 323–329. [CrossRef]
20. Zhou, H.; Chen, J.; Lu, J.; Jiang, Y.; Meng, F. A New Rock Brittleness Evaluation Index Based on the Internal Friction Angle and Class I Stress–Strain Curve. *Rock Mech. Rock Eng.* **2018**, *51*, 2309–2316. [CrossRef]
21. Kutner, M.H. (Ed.) *Applied Linear Statistical Models*, 5th ed.; The McGraw-Hill/Irwin Series Operations and Decision Sciences; McGraw-Hill Irwin: Boston, MA, USA, 2005.
22. Cleveland, W.S. Robust Locally Weighted Regression and Smoothing Scatterplots. *J. Am. Stat. Assoc.* **1979**, *74*, 829–836. [CrossRef]
23. Chambers, J.M.; Trevor, H. *Statistical Models in S*. Pacific Grove, Calif.: Wadsworth & Brooks/Cole Advanced Books & Software, 1992. Available online: <http://archive.org/details/statisticalmodel00john> (accessed on 17 June 2023).
24. Hastie, T. Gam: Generalized Additive Models. Available online: <https://CRAN.R-project.org/package=gam> (accessed on 17 June 2023).
25. Brown, E.T.; Hoek, E. *Underground Excavations in Rock*; CRC Press: Boca Raton, FL, USA, 1980.
26. Li, H.; Song, K.; Tang, M.; Qin, M.; Liu, Z.; Qu, M.; Li, B.; Li, Y. Determination of Scale Effects on Mechanical Properties of Berea Sandstone. *Geofluids* **2021**, *2021*, 6637371. [CrossRef]
27. Baud, P.; Wong, T.-F.; Zhu, W. Effects of Porosity and Crack Density on the Compressive Strength of Rocks. *Int. J. Rock Mech. Min. Sci.* **2013**, *67*, 202–211. [CrossRef]
28. Cai, X.; Zhou, Z.; Liu, K.; Du, X.; Zang, H. Water-weakening effects on the mechanical behavior of different rock types: Phenomena and mechanisms. *Appl. Sci.* **2019**, *9*, 4450. [CrossRef]
29. Egert, R.; Seithel, R.; Kohl, T.; Stober, I. Triaxial Testing and Hydraulic–Mechanical Modeling of Sandstone Reservoir Rock in the Upper Rhine Graben. *Geotherm. Energy* **2018**, *6*, 23. [CrossRef]
30. Heap, M.J.; Villeneuve, M.; Kushnir, A.R.; Farquharson, J.I.; Baud, P.; Reuschlé, T. Rock Mass Strength and Elastic Modulus of the Buntsandstein: An Important Lithostratigraphic Unit for Geothermal Exploitation in the Upper Rhine Graben. *Geothermics* **2018**, *77*, 236–256. [CrossRef]
31. Kim, E.; Stine, M.A.; de Oliveira, D.B.M.; Changani, H. Correlations between the Physical and Mechanical Properties of Sandstones with Changes of Water Content and Loading Rates. *Int. J. Rock Mech. Min. Sci.* **2017**, *100*, 255–262. [CrossRef]
32. Lin, Y.; Zhou, K.; Li, J.; Ke, B.; Gao, R. Weakening Laws of Mechanical Properties of Sandstone Under the Effect of Chemical Corrosion. *Rock Mech. Rock Eng.* **2019**, *53*, 1857–1877. [CrossRef]
33. Lu, Y.; Wang, L.; Sun, X.; Wang, J. Experimental Study of the Influence of Water and Temperature on the Mechanical Behavior of Mudstone and Sandstone. *Bull. Eng. Geol. Environ.* **2016**, *76*, 645–660. [CrossRef]
34. Roshan, H.; Masoumi, H.; Regenauer-Lieb, K. Frictional Behaviour of Sandstone: A Sample-Size Dependent Triaxial Investigation. *J. Struct. Geol.* **2017**, *94*, 154–165. [CrossRef]
35. Sirdesai, N.; Gupta, T.; Singh, T.; Ranjith, P. Studying the Acoustic Emission Response of an Indian Monumental Sandstone under Varying Temperatures and Strains. *Constr. Build. Mater.* **2018**, *168*, 346–361. [CrossRef]
36. Wu, G.; Wang, Y.; Swift, G.; Chen, J. Laboratory Investigation of the Effects of Temperature on the Mechanical Properties of Sandstone. *Geotech. Geol. Eng.* **2013**, *31*, 809–816. [CrossRef]
37. Xu, F.; Yang, C.; Guo, Y.; Wang, T.; Wang, L.; Zhang, P. Effect of Confining Pressure on the Mechanical Properties of Thermally Treated Sandstone. *Curr. Sci.* **2017**, *112*, 6.
38. Yang, S.-Q. Experimental Study on Deformation, Peak Strength and Crack Damage Behavior of Hollow Sandstone under Conventional Triaxial Compression. *Eng. Geol.* **2016**, *213*, 11–24. [CrossRef]
39. Zhao, K.; Yang, D.; Zeng, P.; Huang, Z.; Wu, W.; Li, B.; Teng, T. Effect of Water Content on the Failure Pattern and Acoustic Emission Characteristics of Red Sandstone. *Int. J. Rock Mech. Min. Sci.* **2021**, *142*, 104709. [CrossRef]

40. John, M. *The Influence of Length to Diameter Ratio on Rock Properties in Uniaxial Compression: A Contribution to Standardization in Rock Mechanics Testing*; Report South African CSIR No ME1083/5; Council for Scientific and Industrial Research: Pretoria, South Africa, 1972.
41. AASHTO-100; Standard Method for Specific Gravity of Soils. American Association of State Highway and Transportation Officials: Washington, DC, USA, 2017.
42. Pettijohn, F.J.; Potter, P.E.; Siever, R.; Pettijohn, F.J.; Potter, P.E.; Siever, R. Sand and Sandstone. *J. Geol.* **1974**, *82*, 396–397. [[CrossRef](#)]
43. ASTM D7012; Standard Test Methods for Compressive Strength and Elastic Moduli of Intact Rock Core Specimens under Varying States of Stress and Temperature. American Society for Testing and Materials: West Conshohocken, PA, USA, 2014.
44. Yu, H.; Ng, K. New Systematic Method to Determine Elastic Constants and Crack Propagation Thresholds of Brittle Rocks Under Triaxial Compression. *Geotech. Geol. Eng.* **2021**, *39*, 3931–3945. [[CrossRef](#)]
45. Haied, A.; Kondo, D. Strain Localization in Fontainebleau Sandstone: Macroscopic and Microscopic Investigations. *Int. J. Rock Mech. Min. Sci.* **1997**, *34*, 161.e1–161.e13. [[CrossRef](#)]
46. Maso, J.C.; Lerau, J. Mechanical Behaviour of Darney Sandstone (Vosges, France) in Biaxial Compression. *Int. J. Rock Mech. Min. Sci. Geomech. Abstr.* **1980**, *17*, 109–115. [[CrossRef](#)]
47. Yagiz, S. Assessment of Brittleness Using Rock Strength and Density with Punch Penetration Test. *Tunn. Undergr. Space Technol.* **2009**, *24*, 66–74. [[CrossRef](#)]
48. Yates, P.G.J. The material strength of sandstones of the Sherwood Sandstone Group of north Staffordshire with reference to microfabric. *Q. J. Eng. Geol.* **1992**, *25*, 107–113. [[CrossRef](#)]
49. Noël, C.; Baud, P.; Violay, M. Effect of Water on Sandstone's Fracture Toughness and Frictional Parameters: Brittle Strength Constraints. *Int. J. Rock Mech. Min. Sci.* **2021**, *147*, 104916. [[CrossRef](#)]
50. Fattahpour, V.; Baudet, B.A.; Moosavi, M.; Mehranpour, M.; Ashkezari, A. Effect of Grain Characteristics and Cement Content on the Unconfined Compressive Strength of Artificial Sandstones. *Int. J. Rock Mech. Min. Sci.* **2014**, *72*, 109–116. [[CrossRef](#)]
51. Qi, Y.; Ju, Y.; Yu, K.; Meng, S.; Qiao, P. The Effect of Grain Size, Porosity and Mineralogy on the Compressive Strength of Tight Sandstones: A Case Study from the Eastern Ordos Basin, China. *J. Pet. Sci. Eng.* **2022**, *208*, 109461. [[CrossRef](#)]
52. Bésuelle, P.; Desrues, J.; Raynaud, S. Experimental characterisation of the localisation phenomenon inside a Vosges sandstone in a triaxial cell. *Int. J. Rock Mech. Min. Sci.* **2000**, *37*, 1223–1237. [[CrossRef](#)]
53. Kegang, L.; Lin, M.; Xiangxing, L.; Shoujian, P. Effect of Drying-Wetting Cycles on Triaxial Compression Mechanical Properties of Sandstone. *J. Eng. Sci. Technol. Rev.* **2016**, *9*, 66–73. [[CrossRef](#)]
54. Liping, W.; Ning, L.; Jilin, Q.; Yanzhe, T.; Shuanhai, X. A Study on the Physical Index Change and Triaxial Compression Test of Intact Hard Rock Subjected to Freeze-Thaw Cycles. *Cold Reg. Sci. Technol.* **2019**, *160*, 39–47. [[CrossRef](#)]
55. Wang, S.; Xu, W.; Wang, W. Experimental and Numerical Investigations on Hydro-Mechanical Properties of Saturated Fine-Grained Sandstone. *Int. J. Rock Mech. Min. Sci.* **2020**, *127*, 104222. [[CrossRef](#)]
56. Wang, Y.; Cui, F. Energy Evolution Mechanism in Process of Sandstone Failure and Energy Strength Criterion. *J. Appl. Geophys.* **2018**, *154*, 21–28. [[CrossRef](#)]
57. Wasantha, P.; Ranjith, P. Water-Weakening Behavior of Hawkesbury Sandstone in Brittle Regime. *Eng. Geol.* **2014**, *178*, 91–101. [[CrossRef](#)]
58. Yang, S.-Q.; Jing, H.-W. Evaluation on Strength and Deformation Behavior of Red Sandstone under Simple and Complex Loading Paths. *Eng. Geol.* **2013**, *164*, 1–17. [[CrossRef](#)]
59. Gong, F.; Si, X.-F.; Li, X.-B.; Wang, S.-Y. Dynamic triaxial compression tests on sandstone at high strain rates and low confining pressures with split Hopkinson pressure bar. *Int. J. Rock Mech. Min. Sci.* **2019**, *113*, 211–219. [[CrossRef](#)]
60. Yang, S.-Q.; Huang, Y.-H.; Tang, J.-Z. Mechanical, Acoustic, and Fracture Behaviors of Yellow Sandstone Specimens under Triaxial Monotonic and Cyclic Loading. *Int. J. Rock Mech. Min. Sci.* **2020**, *130*, 104268. [[CrossRef](#)]
61. Małkowski, P.; Ostrowski, L.; Brodny, J. Analysis of Young's Modulus for Carboniferous Sedimentary Rocks and Its Relationship with Uniaxial Compressive Strength Using Different Methods of Modulus Determination. *J. Sustain. Min.* **2018**, *17*, 145–157. [[CrossRef](#)]
62. Rohde, J.; Feng, H. Analysis of the Variability of Unconfined Compression Tests of Rock. *Rock Mech. Rock Eng.* **1990**, *23*, 231–236. [[CrossRef](#)]

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