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Zhaoping Meng
Jincai Zhang
Suping Peng

Influence of sedimentary environments on mechanical properties of clastic rocks

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Z. Meng · S. Peng
Department of Resources and Geosciences, China University of Mining and Technology at Beijing, Beijing 10008, People's Republic China
E-mail: mzp@cumtb.edu.cn

J. Zhang (✉)
Knowledge Systems, Inc., 1 Sugar creek center Blvd. Ste.1100, Sugar Land, TX 77478, USA
E-mail: zhang@knowsys.com
Tel.: +1-281-2434382
Fax: +1-281-2434399

Abstract The sedimentary environments are the intrinsic factor controlling the mechanical properties of clastic rocks. Examining the relationship between rock sedimentary environments and rock mechanical properties gives a better understanding of rock deformation and failure mechanisms. In this study, more than 55 samples in coal measures were taken from seven different lithologic formations in eastern China. Using the optical microscope the sedimentary characteristics, such as components of clastic rocks and sizes of clastic grains were quantitatively tested and analyzed. The corresponding mechanical parameters were tested using the servo-controlled testing system. Different lithologic attributes in the sedimentary rocks sampled different stress–strain behaviors and failure characteristics under different confining pressures, mainly due to different compositions and textures. Results demonstrate that clastic rocks have the linear best-fit for Mohr-Coulomb failure criterion. The elastic moduli in clastic rocks are highly dependent upon confining pressures, unlike hard rocks. The envelope lines of the mechanical properties versus the contents of quartz, detritus of the grain diameter of more than 0.03 mm, and grain size in clastic rocks are given. The compressive strength or elastic modulus and the grain diameter have a non-monotonic relation and demonstrate the "grain-diameter softening" effect.

Keywords Clastic rock · Mechanical property · Lithology · Content of clasts · Grain size · China

Introduction

The mechanical properties of clastic rocks are not only influenced by external factors, such as stress and surrounding geological environment, but also strongly dependent on the depositional and sedimentary environments, including components, textures, and structures of the rocks. The mechanical properties of clastic formations are important for the energy industry (Zhang and Peng 2005). The relationship of strength and grain size of clastic rocks has been preliminarily investigated (Robertson 1995; Paterson 1958; Dreyer 1973; Fahy and Guccione 1979). Some researchers concluded that peak strength and inverse of the square root of grain size in clastic rocks had a linear relation (Olsson 1974; Haney and Shakoor 1994; Wong et al. 1996; Hatzor and Palchik 1997; Fredrich et al. 1990). As porosity increases, the rock compressive strength decreases (Farmer 1982; Brace 1961). Sandstone with a smaller gain size had a higher strength (Brace 1961). The relationship between the texture and mechanical properties of carbonate rocks and some crystal rocks were also investigated (Hugman and Friedman 1979; Onodera and Asoka 1980). Prikryl conducted research on the microstructure of granite and its strength, and concluded that grain size is the main microstructure factor controlling the rock strength (Prikryl 2001). Eberhardt et al. (1999) tested the effect of grain sizes on samples of granodiorite, granite, and pegmatite. The relation between the fabric characteristics of carbonate reservoir and its physical properties was investigated by Diirrast and Siegesmund (1999). Sedimentary characteristics of mudstone and its mechanical properties were tested for the purpose of tunnel stability (He et al. 1996; Zhou 1996) because mudstone can be a problematic layer in rock engineering. Until now, most research on the microstructure of rock and its deformation and strength behaviors mainly focuses on granites and other hard rocks. Relationship between sedimentary characteristics and mechanical properties of clastic rocks need to be more thoroughly addressed.

The formations of the China coal measures are primarily composed of clastic rocks and coal seams. The rocks in coal measures are primarily sandstones, siltstones, and mudstones. For example, coal measures of the Permian period in the Huainan coalfield in China were formed from a delta plain environment (Meng et al. 2003; Peng and Meng 2002), which contains 33.66% of sandstones, 8.7% of siltstones, 50.38% of mudstones, and 7.23% of coal seams. Sedimentary rocks in coal measures originated in shallow crust. Because of their lithological characteristics, complex components, and textures, clastic rocks differ considerably from other rocks in mechanical properties (Xiao and Yang 1987; Yang et al. 1999).

Sample preparation and test methods

The rock samples were obtained from the roof and floor strata of the primary coal seam in the Permian coal measures in the Xinji coal mine in the Huainan coalfield. To make the testing results conform as much as possible to the natural status, the rock samples were promptly packaged and fully waxed after collection. Quantitatively statistical analyses were conducted. Table 1 lists the rock samples with different lithologies.

The mechanical properties were tested in the servo-controlled testing system (MTS 815.02). Using the optical microscope, sedimentary parameters such as component, grain size, intersertal material, cementation type, and structural support type were observed and analyzed statistically.

The following expression is used to calculate the standard grain-size scale (phi scale, Tucker 2001):

$$\phi = -\log_2 D, \quad (1)$$

where ϕ is the grain-size phi scale; D is the diameter of the grain in millimeter. The larger diameter of the grain size has a smaller ϕ scale.

The average grain size in the ϕ scale can be calculated by the following equation:

$$\Phi = \frac{(\phi_{16} + \phi_{50} + \phi_{84})}{3}, \quad (2)$$

where Φ is the average grain-size ϕ scale, which reflects the hydrodynamic performance during deposition of terrigenous clasts; $\phi16$, $\phi50$ and $\phi84$ are the corresponding grain sizes of the cumulative contents of 16, 50, and 84% in the cumulative curve of the clastic grains, respectively.

The contents and grain size of clastic rocks versus rock mechanical properties

The effect of the contents of clastic rocks

In the experiments, the mechanical parameters (uniaxial compressive strength and elastic modulus etc.) were tested, and the contents were analyzed. Statistical analyses show that the mechanical properties are highly related to the content of the clastic grains and quartz in clastic rocks. It should be noted that rocks in this research were situated in a similar cementation environment. The clasts whose grain diameters were more than 0.03 mm (ϕ scale < 5) called contents of detritus. Table 2 lists the mechanical properties of sedimentary rocks with different content of detritus. There is wide variation; however, the general trend is that average uniaxial compressive strength and elastic modulus increase as the contents of detritus increase.

Figures 1, 2, 3 and 4 show the uniaxial compressive strength and elastic modulus of rocks versus the contents of detritus and quartz. The contents of detritus and quartz have profound effects on the strength and elastic modulus. In each figure, the maximal uniaxial compressive strength or elastic modulus for various percentages of detritus or quartz is connected to form an envelope of the maximum strength or modulus. There

Table 1 Rock types in the experiments

Rock	Coarse-grained sandstone	Medium-grained sandstone	Fine grained sandstone	Ultra-fine-grained sandstone	Siltstone	Sandy mudstone	Mudstone
Numbers of sample	2	9	12	7	14	5	6

Table 2 The mechanical properties of sedimentary rocks with different detritus contents

Detritus content (%)	Compressive strength (MPa)	Elastic modulus (GPa)
< 25	(35.5 − 56.47)/51.45	(24 − 27)/25.5
25–50	(28.81 − 77.01)/49.25	(18 − 31)/24.5
50–75	(54.59 − 110.93)/92.64	(9.58 − 54)/35.82
> 75	(30.5 − 176)/107.67	(12.97 − 86.44)/41.1

Note, (Min − Max)/Ave

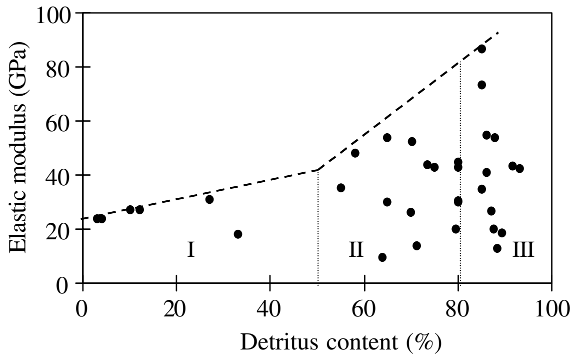

Fig. 3 The relationship between the content of detritus and the elastic modulus

are two obvious turning points in each envelope showing two jumps in the compressive strength or elastic modulus of clastic rocks.

The first jump takes place at a content of detritus of 50% or the content of quartz of 40%. In this interval (area I in Figs.1, 2, 3, 4) the uniaxial compressive strength and elastic modulus of clastic rocks are small. As the percentage of detritus increases, the enveloping lines slowly climb, i.e., the uniaxial compressive strength increases from 54 to 70 MPa in Fig. 1, and the elastic modulus from 24 to 35 GPa in Fig. 2. The dispersion in the uniaxial compressive strength or elastic modulus in this interval is small because rocks in this interval are mainly fine-grained siltstones, sandy mudstones, and mudstones with smaller grain sizes (grain scale $\phi > 5$). Because the content of detritus is small and the mutual connection of the grains of detritus is quite weak, the change in the amount of detritus is not large enough to cause significant changes. The mechanical strength in this case is mainly dependent on the cementation of clay minerals. The rocks behave as if they were elasto-plastic, plastic, or visco-elastoplastic deformations.

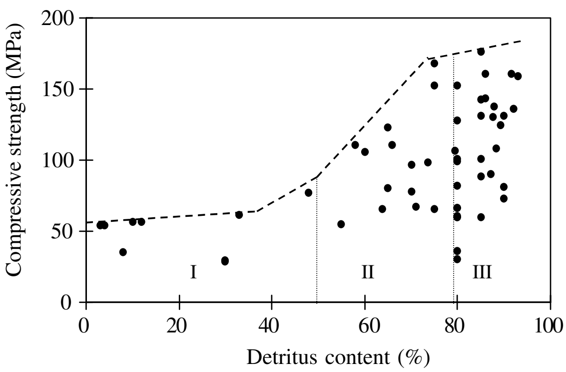

Fig. 1 The relationship between the content of detritus and the compressive strength

In area II in Figs. 1, 2, 3 and 4, each envelope has a steep slope, showing that the uniaxial compressive strength or the elastic modulus increases significantly as the content of the detritus or quartz increases. For example, the uniaxial compressive strength increases from 70 to 176 MPa in Fig. 1, and the elastic modulus from 35 to 86 GPa in Fig. 3. The dispersion of the uniaxial compressive strength or elastic modulus also increases. The large size detritus are the main constitutional element in the sandstones and siltstones of various grades. In this

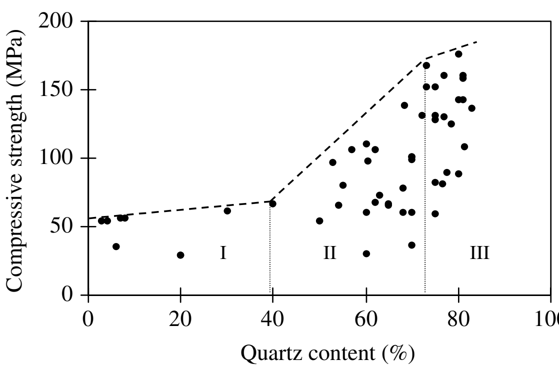

Fig. 2 The relationship between the content of quartz and the compressive strength

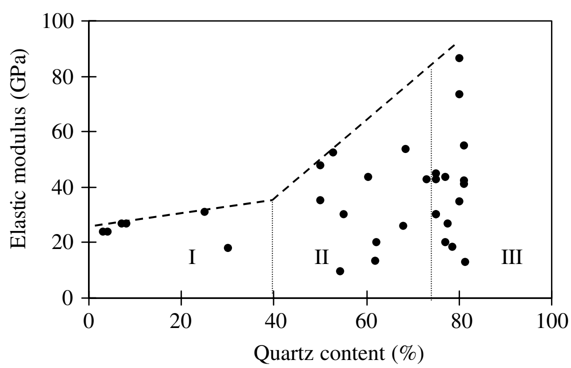

Fig. 4 The relationship between the content of quartz and the elastic modulus

case the contacts between grains gradually become rigid. The internal cementation of clastic rocks transitions from basal cementation to porous cementation, osculant cementation, and inserted cementation. The dispersion of the uniaxial compressive strength obviously increases.

The second jump happens at about 80% of detritus content or 75% of quartz content, as shown in area III in Figs. 1, 2, 3 and 4. The slope of each envelope in the compressive strength or elastic modulus of clastic rocks increases slightly as the contents of detritus or quartz increases. When the content of detritus is greater than 80% or the content of quartz more than 75%, the rocks have very high compressive strength and elastic modulus. These rocks are mainly quartzy sandstones, feldspathic-quartzy sandstones, and debris-quartzy sandstones. For clastic sedimentary rocks, particularly sandstones, the main composition of clastic grains is quartz, which accounts for up to 80–90% of the clast. Quartz is a rigid mineral with a higher strength, hence under a similar cementation clastic rock with higher content of quartz has high compressive strength and elastic modulus.

The effect of the grain size of clastic rocks

Results show that the mechanical properties of clastic rocks are highly related to their textures. The texture parameters that considerably affect the mechanical properties are the grain size, cementation between grains, and cementation type in the clast. Table 3 lists the experimental results of rock mechanical properties for various clastic rocks with different grain sizes. Dispersion is large between the mechanical properties and grain sizes. Figures 5 and 6 plot the uniaxial compressive strength and elastic modulus versus the Φ scale (i.e., average grain-size ϕ scale obtained from Eq. 1). The envelope lines for the maximal uniaxial compressive strength and elastic modulus are closely related to the grain sizes of the rocks (Figs. 5, 6).

When the grain-size scale Φ is small, or when the grain diameter is large (coarse-grained sandstones and medium-grained sandstones), the maximum mechanical values on the envelopes increase gradually as the grain size decreases. When the scale of grain diameter is 2.5Φ (fine-grained sandstone), the maximum compressive strength reaches its peak value of 176 MPa. The "grain-scale softening" then appears on the envelopes in Fig. 5 or 6. In other words, the uniaxial compressive strength and elastic modulus decrease dramatically as the Φ scale increases after the peak values. In this stage, the lithology transitions from fine-grained sandstone to siltstone and mudstone. When the Φ scale increases to 5 (equivalent of fine siltstone), the compressive strength or elastic modulus reaches a low value and keeps approximately constant thereafter. The "grain-scale softening" in the envelope of the uniaxial compressive strength or the elastic modulus is reflected to the strain softening in the stress–strain relationship. Change of the grain diameter denotes the change of the rock types. As the grain Φ scale increases, the clastic rock gradually changes from the coarse-grained sandstone to fine-grained sandstone, then to mudstone.

The envelopes of the mechanical properties versus the grain size of clasts are non-monotonic. The grain sizes in clastic rocks are determined by the internal components and structures of clasts. As the Φ scale increases, the internal components of clastic rocks change gradually from detritus, polycrystalline quartz, feldspar, single-crystal quartz into clay and mica. In general, the strength and rigidity of single-crystal quartz are greater than those of polycrystalline quartz. From the sedimentological theory, the distribution of the grain sizes has a certain regularity. The detritus and polycrystalline quartz mostly exist in conglomerate and coarse-grained sandstone, and the single-crystal quartz mainly exists in fine-grained sandstone. Therefore, the mechanical properties for the largest grain size are not the highest. However, the mechanical properties in the fine-grained sandstone ($\Phi = 2.5$) are the highest (Figs. 5, 6). As the Φ scale increases (the grains in clasts become finer), the content of clay and mica minerals increases, the structure of clastic rocks changes, and the mechanical properties of the rocks decrease. However, the mechanical properties of clastic rocks are also influenced by other factors such as the cementation.

Mechanical properties of rocks with lithology

The mechanical properties under the uniaxial compression test

The uniaxial compression results (Table 4) show that the mechanical properties differ in various type of clastic

Table 3 The influence of the grain sizes on rock mechanical properties

Lithology	Grain size (φ)	Compression strength (MPa)	Elastic modulus (GPa)
Coarse-grained sandstone	0–1.0	(97.55 − 136.05)/116.8	(32 − 32)/32
Medium-grained sandstone	1.0–2.0	(54.59 − 160.26)/124.7	(35.1 − 55)/45.68
Fine-grained sandstone	2.0–3.3	(59.44 − 176.14)/116.99	(18.69 − 79.89)/40.68
Siltstone	3.3–6.67	(60.02 − 130.56)/84.36	(9.58 − 52.47)/23.87
Mudstone	> 6.67	(28.81 − 56.47)/45.1	(24 − 27)/25.5

Note, (Min − Max)/Ave

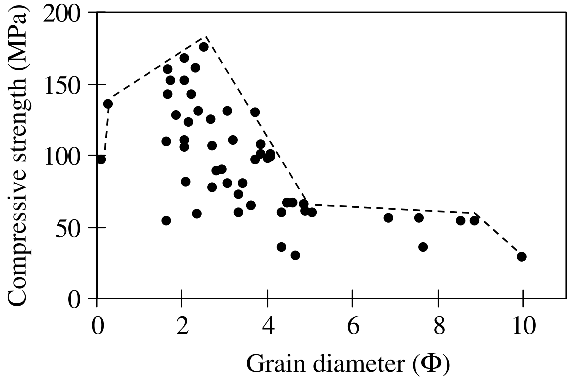

Fig. 5 The relationship between the scale of grain diameter and the compressive strength

sandstone, siltstone, sandy mudstone and mudstone. The average values of the compressive and tensile strength are the largest in sandstone, 111.50 and 6.66 MPa, respectively. The values in mudstone are the least, 42.75 and 1.91 MPa, respectively (Fig. 7). Strength and other mechanical properties of the rocks strongly depend upon lithology.

Stress–strain curves for different lithologies have obvious differences, particularly after the peak value (Fig. 8). For sandstone, in the stress–strain curve the stress drops sharply down with a very steep slope after the peak strength, and the residual strength is only 1/10–1/20 of its peak value. For mudstone, which has the lowest strength, after the peak load the stress–strain curve has a gentle slope and the mudstone retains more of its strength. The residual strength in the mudstone is about 1/3 of the peak value. The stress–strain curve for sandy mudstone lies in between sandstone and mudstone and residual strength is about 1/4–1/8 of peak value.

The complete stress–strain curves under confining pressures

Triaxial compression tests demonstrate that the deformations and strength of clastic rocks are closely related

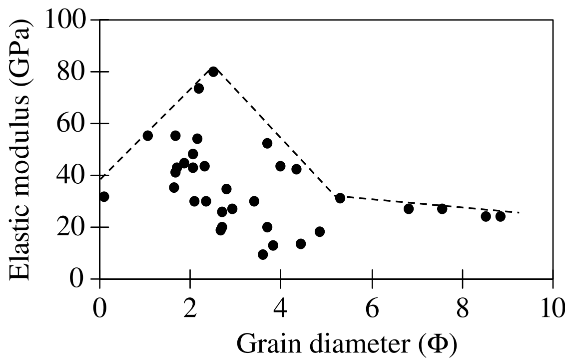

Fig. 6 The relationship between the scale of grain diameter and the elastic modulus

to confining pressures (Figs. 9, 10, 11). The slopes of the stress–strain curves obviously become steep, and the strength increases as confining pressures increase for all rock types (Fig. 12). Confining stress is an important aspect of rock engineering stability.

The elastic modulus is not a constant, but increases as confining pressures increase (Fig. 12). Statistics of experimental results indicate that the elastic modulus and confining pressure have a non-linear relationship for each lithology. It can be expressed as follows:

$$E = b_2\sigma_3^2 + b_1\sigma_3 + b_0, \quad (3)$$

where E is the rock elastic modulus (GPa); σ_3 is the confining pressure (MPa); b_0, b_1 and b_2 are the parameters dependent on lithology.

For different lithologies, the parameters in Eq. 3 differ (Table 5). The correlation coefficients are very high. Therefore, the elastic modulus and confining pressure in clastic rocks in the Huainan coalfield in eastern China have a pronounced power relation, which best fits the following relation proposed by Brown et al. (1989), with the exponent $c = 2$:

$$E = (a\sigma_3 + b)^c, \quad (4)$$

where a, b and c are the parameters.

The compressive strength increases as confining pressures increase. However, variations are controlled by lithology. Figure 13 plots the compression experimental results in maximum principal stress (σ_1) versus minimum principal stress (σ_3) domain. The following relationship between the principal stresses and uniaxial compressive strength is obtained from the experimental results (Fig. 13):

$$\sigma_1 = \sigma_c + k\sigma_3, \quad (5)$$

where σ_1 is the maximum principal stress (MPa); σ_3 is the confining pressure (MPa); σ_c is the unixial compressive strength (MPa); k is the parameter dependent upon lithology (refer to Table 6).

Based on Eq. 5 and Table 6 data, clastic rocks have the linear best-fit for Mohr-Coulomb failure criterion. For the soft formations, such as mudstone and coal, there is perfect fit to linear Mohr-Coulomb strength criterion (Fig. 13), and the correlation coefficient R^2 is over 0.99. This is important for choosing a correct strength criterion in modeling of rock engineering in such rocks.

Conclusions

The sedimentary characteristics of clastic rocks, such as components, textures, and structures, strongly affect mechanical properties. The following conclusions are drawn from the lab experiments for these rocks.

Table 4 Lab test results of the mechanical properties in clastic rocks

Mechanical properties	Sandstone	Siltstone	Sandy mudstone	Mudstone
Density ρ (g/cm^3)	(2.47–3.47)/2.76	(2.43–2.63)/2.56	(2.64–2.98)/2.72	(2.05–2.97)/2.68
Compressive strength Rc (MPa)	(50.60–281.30)/111.50	(67.2828–130.09)/94.54	(13.50–112.10)/53.46	(9.81–81.50)/42.75
Tensile strength Rt (MPa)	(1.77–10.67)/6.66	(1.20–9.20)/5.20	(0.70–8.70)/4.39	(0.30–7.29)/1.91
Cohesion C (MPa)	(1.91–13.07)/6.30	(1.25–2.40)/2.33	(4.00–11.90)/6.22	(0.14–8.40)/3.95
Internal friction angle φ (°)	(33.41–39.15)/36.49	(39.00–40.03)/39.52	(31.90–38.39)/34.14	(31.80–41.52)/36.72
Elastic modulus E_{50} (GPa)	(16.13–86.44)/59.54	(30.00–34.00)/32.00	(7.60–44.00)/22.96	(2.01–19.71)/10.35
Poisson's ratio v	(0.11–0.33)/0.20	(0.28–0.33)/0.30	(0.10–0.30)/0.22	(0.15–0.34)/0.24

(Min – Max)/Ave

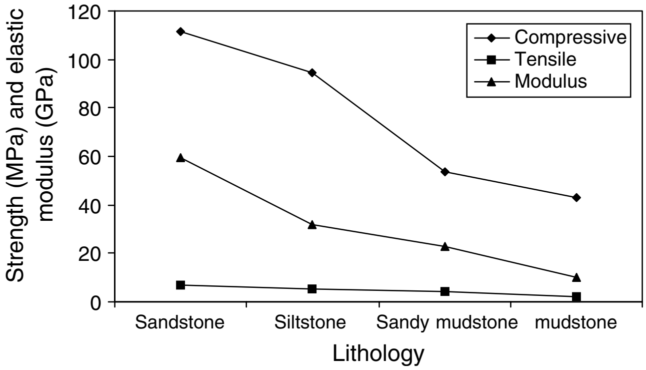

Fig. 7 The comparison of the compressive and tensile strength and elastic modulus for different lithologic samples under the uniaxial tests

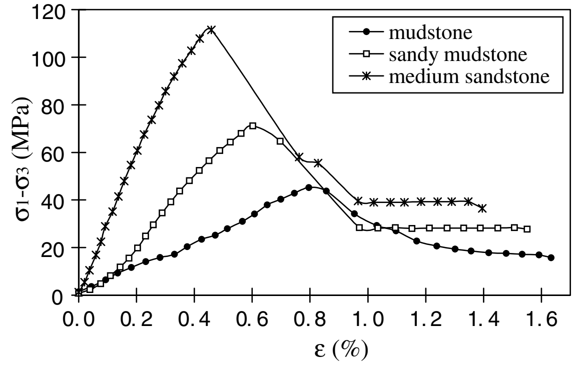

Fig. 9 Complete stress–strain curves for different rock samples under the triaxial tests with confining pressure of 5 MPa

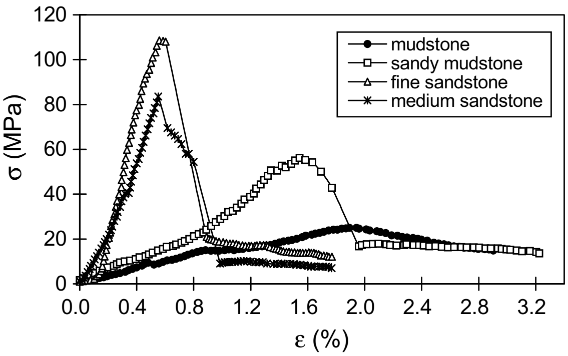

Fig. 8 Complete stress–strain curves for different rock samples under the uniaxial tests

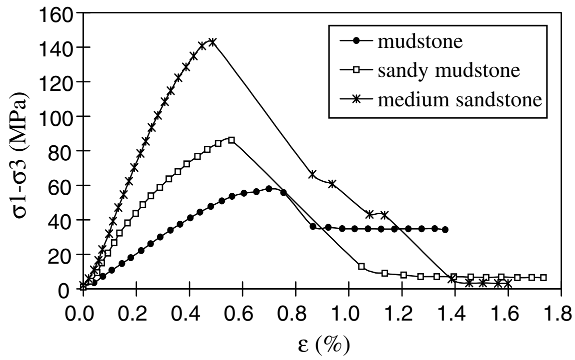

Fig. 10 Complete stress–strain curves for different rock samples under the triaxial tests with confining pressure of 10 MPa

1. Under a similar cementation condition, the contents of detritus and quartz have profound effects on the uniaxial compressive strength and elastic modulus of rocks. The envelope obtained by connecting the maximal uniaxial compressive strength or elastic modulus in various contents of detritus or quartz shows that the maximum uniaxial compressive strength or elastic modulus increases as the content of detritus or quartz increases. When the content of detritus exceeds 50% or the content of quartz exceeds 40%, the value of the uniaxial compressive strength or the elastic modulus of clastic rocks has a dramatic increase.
2. As the grain scale increases (grain diameter decreases), envelope lines of the compressive strength and elastic modulus increase. After reaching peak values, the strength and modulus reduce dramatically as grain diameter decreases, demonstrating the "grain-diameter softening" effect.

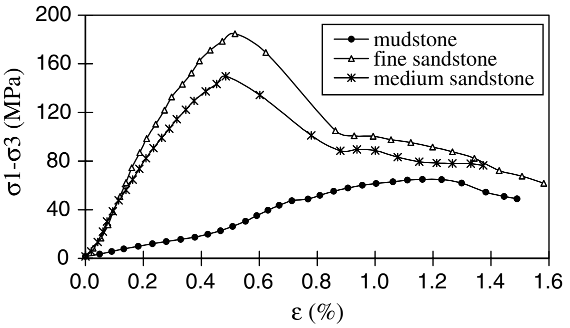

Fig. 11 Complete stress–strain curves for different rock samples under the triaxial tests with confining pressure of 15 MPa

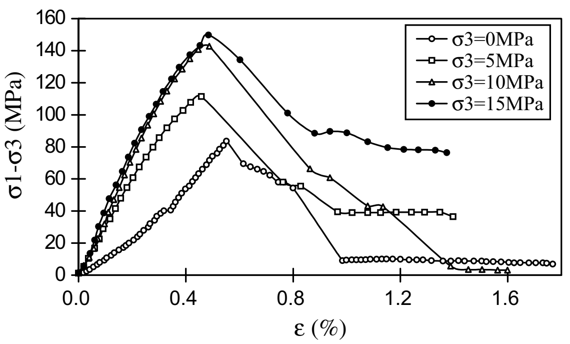

Fig. 12 Complete stress–strain curves for different confining pressures under the triaxial tests in medium-grained sandstone

Table 5 The parameters for different lithologies in Eq. 3

Lithology	b_2	b_1	b_0	σ_3 (MPa)	Correlation coefficients
Medium-, fine-grained sandstone	0.016	−0.121	38.113	≤ 50	0.97
Sandy mudstone	0.040	−0.678	26.909	≤ 40	0.94
Mudstone	0.006	0.254	28.876	≤ 50	0.99

3. There is a non-monotonic relation between grain diameter and the compressive strength or elastic modulus.
4. Of different clastic rocks, fine-grained sandstone usually has the highest uniaxial compressive strength and elastic modulus. The strength and modulus decrease gradually in the following sequence; i.e., from sandstone, to siltstone, to sandy mudstone, to mudstone.

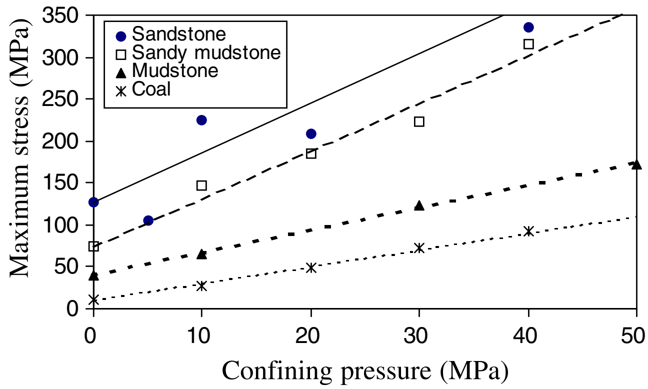

Fig. 13 Experimental results showing that clastic rocks fit the linear Mohr-Coulomb strength criterion in terms of the maximum and minimum principal stresses for fine- and medium-grained sandstone, sandy mudstone, mudstone and coal obtained from the triaxial compression tests. Note that the *symbols* are the experimental results and the *lines* represent linear regressions for the different rocks

Table 6 The parameters in different lithologies in Eq. 5

Lithology	σ_c (MPa)	k	σ_3 (MPa)	Correlation coefficients (R^2)
Medium-, fine-grained sandstone	127.83	5.89	≤ 40	0.822
Sandy mudstone	73.85	5.72	≤ 40	0.972
Mudstone	40.15	2.66	≤ 50	0.998
Coal	11.23	1.99	≤ 30	0.993

5. Results followed the linear Mohr-Coulomb strength criterion. The elastic modulus strongly depends on confining pressures and has a power relation with confining pressure.

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