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International Journal of Mining Science and Technology xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

International Journal of Mining Science and Technology

journal homepage: www.elsevier.com/locate/ijmst

Effect of rock composition microstructure and pore characteristics on its rock mechanics properties

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ARTICLE INFO

Article history:
Received 25 May 2017
Received in revised form 28 August 2017
Accepted 10 October 2017
Available online xxxx

Keywords:
Mechanical characteristics
Pore characteristics
Microstructure
Composition
Scanning electron microscope

ABSTRACT

This paper is to study the influence of composition, microstructure and pore characteristics on the rock mechanical properties. Five kinds of sandstone compositions were analyzed by using X-ray diffraction instrument. And the microstructure was observed by using scanning electron microscope. Then the pore distribution characteristic was investigated by using the low field nuclear magnetic resonance equipment. Finally, the uniaxial compression test was carried out to investigate the mechanical characteristics by using RMT150C mechanics experimental system and the uniaxial compressive strength, Poisson's ratio and elastic modulus were obtained. Compared to the analysis of the composition, structure and pore distribution and mechanical properties of the five kinds of sandstones, the relationship among composition, structure, pore distribution and mechanical properties was obtained. The results show that the composition, microstructure, pore distribution and mechanical properties of sandstone are closely related. With the decrease of feldspar and quartz particles, the compressive strength and elastic modulus increase, while the porosity decreases.

1. Introduction

Abundant high quality coal resources exist in the Ordos and Yulin coal fields, China, which have developed into an important modern coal production bases. However, the bedrock is relatively thin with low shear bond strength. This specific roof strata structure, as well as the high mining dynamic stress caused by the high strength mining. Severe dynamic disasters, such as large area roof falls and shield damaged were occurred by the high ground pressure. The specific physical and mechanical properties of the overlying strata are the internal factors causing the dynamic disasters. Therefore, the study of the physical properties of the overburden strata under this mining conditions is the fundamental research for the prevention of the dynamic disasters.

In recent years, many scholars have researched in this area with great success. Many valuable achievements on strata movement and control, and the microstructures of the shallow buried have been produced [1–12]. For micro-structure research, the relationship between micro-structure and rock mechanics properties has been analyzed [13–15]. Lindqvist et al. studied the effects of mineral composition, grain size, porosity and micro-fissures on rock mechanics properties [16]. Johansson confirmed that mineral composition, micropore porosity, grain size and shape as well as lamination are the most important factors influencing rock mechanics properties, He also summarized the different characteristics of various mineral composition and structure porosity as well as their effects on rock mechanics properties [17]. Tuğrul et al. recognized that the physical and mechanics properties of rock are functions of mineral composition and structure [18]. Přikryl concluded that the uniaxial compressive strength (UCS) of granite is closely related to its grain size [19]. Although many significant results have been obtained by numerous researchers in the past, there exist many problems in theoretical research and production process. Therefore the research on rock's mineral composition, structure and rock mechanics, especially the relationships among them are needed.

In order to study the effect of rock composition, micro structure and porosity on rock mechanics properties, five kinds of sandstones located at different depths were selected for this research. Their compositions were analyzed by X-ray diffraction instrument. The semi quantitative analysis of the components was carried out by using the Jade 6.0 analysis software. The microstructure characteristics were observed by using the scanning electron microscope of SM-6390LV. The pore distribution characteristics were investigated by using the low field nuclear magnetic resonance

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https://doi.org/10.1016/j.ijmst.2017.12.008
2095-2686/

Please cite this article in press as: Li H et al. Effect of rock composition microstructure and pore characteristics on its rock mechanics properties. Int J Min Sci Technol (2018), https://doi.org/10.1016/j.ijmst.2017.12.008

equipment. The uniaxial compression test was carried out to investigate the mechanical characteristics by using RMT-150C rock mechanics experimental testing system to obtain the uniaxial compressive strength, Poisson's ratio and elastic modulus. The compositions, structure, porosity distribution and rock mechanics properties of those five kinds of sandstones were systematically analyzed.

2. Laboratory facilities and test methods

2.1. Laboratory facilities

Composition analysis employed the X-ray diffractometer manufactured by Bruker Co. of Germany. For micro-structure analysis, model JSM-6930 all digital system with high resolution and high precision in variable focusing lens system made by Electronic Co. Ltd of was used. The low field nuclear magnetic resonance device made by Newman Electronic Scientific Co. Ltd was employed for analyzing the porosity distribution. The Model RMT-150 Crock Mechanics Testing system made by Wuhan Institute of Soil Mechanics was employed. All tests were performed with displacement-controlled at 0.002 mm/s.

Table 1
The stratigraphic column.

Number	Lithology	Buried depth (m)	Thickness (m)
A	Fine sandstone	143.70–146.10	2.40
B	Fine sandstone	314.10–320.00	5.90
C	Fine sandstone	345.50–347.60	2.10
D	Fine sandstone	200.60–201.70	1.10
E	Siltstone	119.50–122.20	2.70

2.2. Sample collection and preparation

Five kinds of sandstones, *A*, *B*, *C*, *D*, and *E*, located at different depths were selected for this research, The five groups of samples collected from the mine site were first divided into two parts. One part is for composition and SEM analyses, while the other for nuclear magnetic resonant analysis and rock mechanics testing. One sample from each kind of sandstone was made for composition and SEM analyses. The sample for composition analysis was ground to powder, while the SEM sample was made to a disk with a size of 0.5 cm × 0.5 cm × 0.5 cm. Samples for rock mechanic property and nuclear magnetic resonant tests were finished to standard cylinder test size with 50 mm in diameter by 100 mm

Table 2
Component analysis.

Sample	Mineral components (%)										
	Quartz	Feldspar	Kaolinite	Dolomite	Calcite	Gypsum	Micas	Pyrite	Chlorite	Clinochlore	Analcime
A	24.4	42.8		4.9	4.5			10.6			12.8
B	36.0	42.9	0.1				7.8	4.7		6.3	2.2
C	21.7	44.5	5.4				6.0	7.1	13.5	1.8	
D	47.2	27.8		0.2	7.5	17.3					
E	23.7	32.8		35.6			4.7				3.2

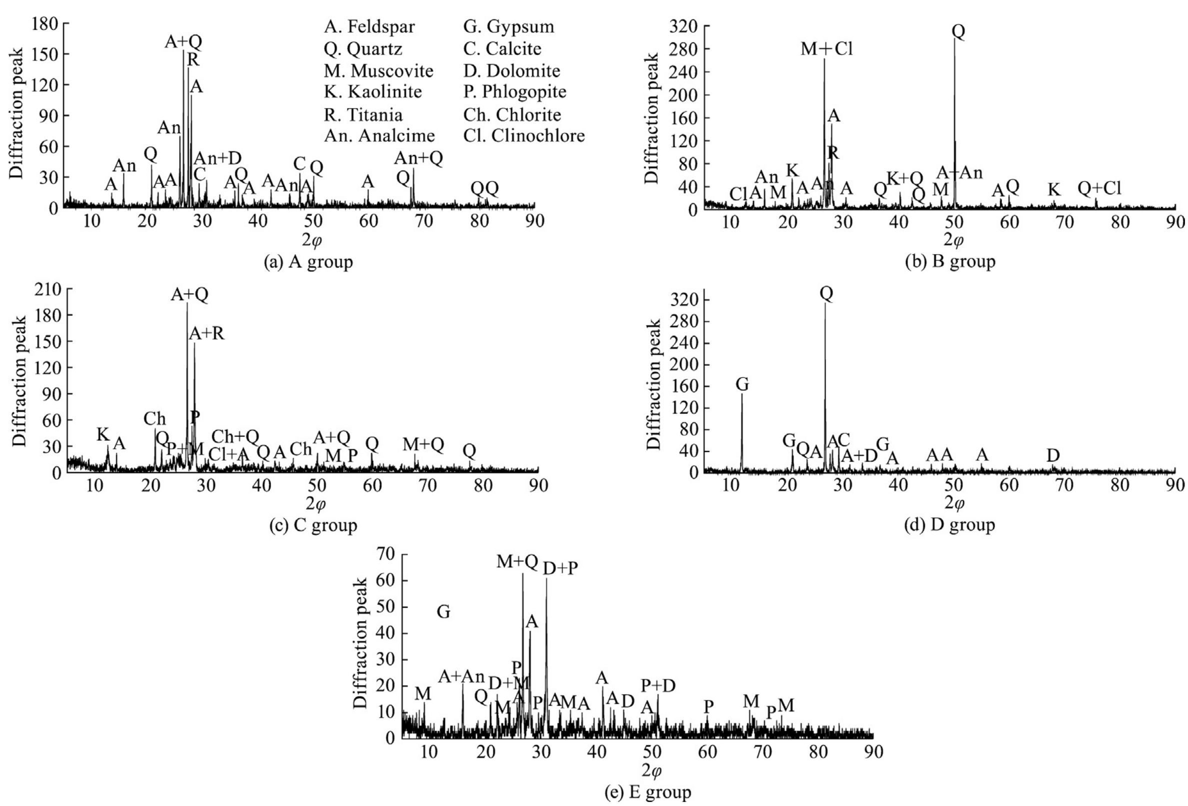

Fig. 1. X-ray diffraction analysis of sandstones.

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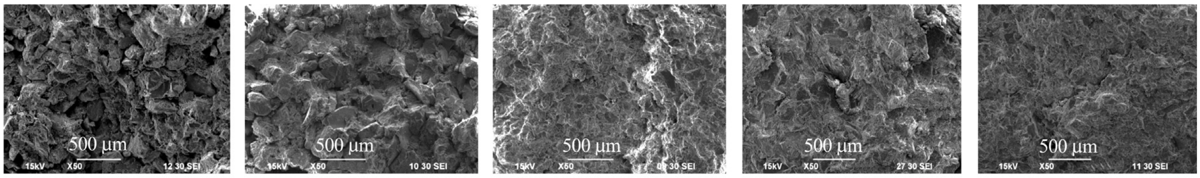

(a) A group (b) B group (c) C group (d) D group (e) E group

Fig. 2. Scanning electron microscope results of sandstones at different buried depth.

Table 3
Pore characteristics.

Sample	Porosity (%)		First peak		Second peak		Third peak	
	Value	Mean	Peak area	Peak time (ms)	Peak area	Peak time (ms)	Peak area	Peak time (ms)
*A*1 (6152-1)	7.5	7.6	21,400	2.31	20	613.59		
*A*2 (6152-3)	7.7		22,083	2.66	15	811.13		
*A*3 (6153-2)	7.6		21,354	2.31	33	811.13		
*B*1 (1301-1)	5.9	5.9	19,380	16.30	182	351.12		
*B*2 (1302-2)	6.3		19,280	21.54	169	464.16		
*B*3 (1303-2)	5.4		18,749	12.33				
*C*1 (6501-1)	4.5	4.4	15,063	2.01	552	57.22	5.2	1233
*C*2 (6501-2)	4.7		16,414	2.01	736	49.77		
*C*3 (6502-3)	4.0		14,229	2.31	601	57.22		
*D*1 (6271-1)	3.3	3.0	9026	0.76	1422	28.48	53	403.70
*D*2 (6271-2)	2.7		6082	0.87	1878	24.77	34	403.70
*D*3 (6273-1)	2.9		7006	0.87	2162	28.48	36	464.16
*E*1 (691-1)	1.2	1.6	4395	0.87	824	21.54	38	464.16
*E*2 (692-1)	2.0		5673	0.87	744	24.8	42	403.70
*E*3 (693-1)	1.5		6102	1.00	394	32.75	23	533.67

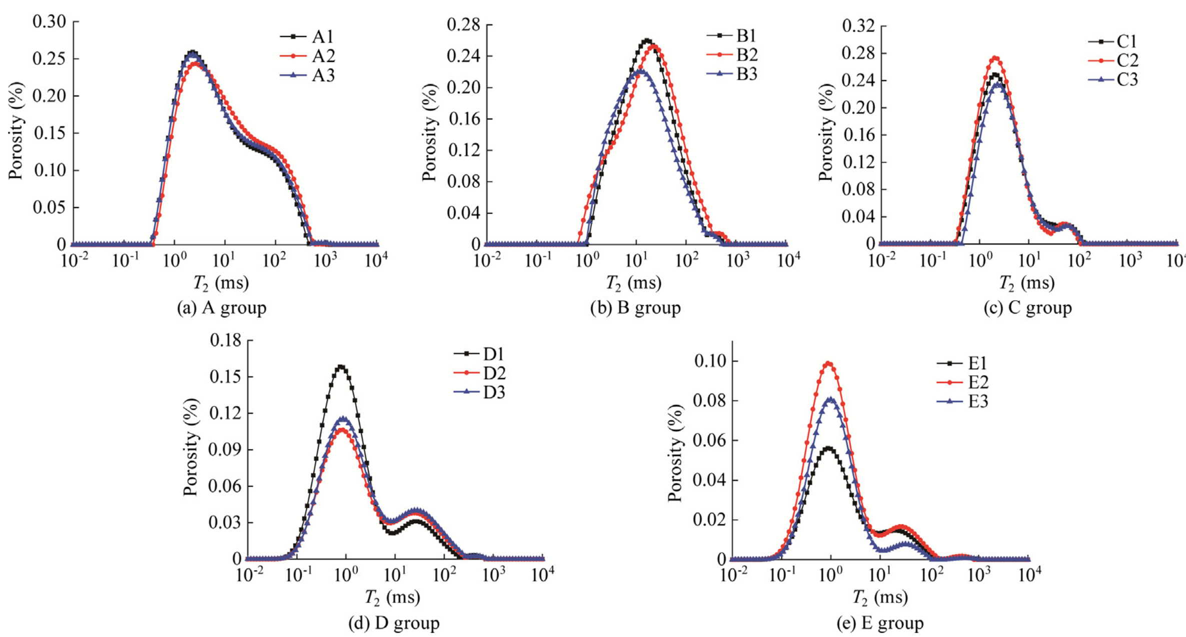

Fig. 3. Pore characteristics of sandstones.

high. Table 1 shows the stratigraphic column of the five kinds of sandstones.

3. Results

3.1. Composition

Table 2 shows the results of composition analysis for the five kinds of sandstones, and Fig. 1 is the X-ray histograms. It can be seen from Table 2 and Fig. 1 that the main components of the five sandstones are quartz and feldspar, and the content is more than 50%. Other major minerals include kaolinite, dolomite, calcite, gypsum, mica, pyrite, chlorite, clinochlore and analcime. The cement materials for *A* group are mainly carbonate (9.4%), ironic (10.6%) and analcime (12.8%); For *B* group, the major cementing materials are clay minerals (14.2%), ironic (4.7%) and analcime (2.2%); For *C* group, the major cementing materials are clay minerals (26.7%) and ironic (7.1%); For *D* group, the major cementing materials are

Table 4
Rock mechanics properties.

Sample	Loading rate (mm/s)	Compressive strength (MPa)	Mean value (MPa)	Elasticity modulus (GPa)	Mean value (GPa)	Poisson's ratio	Mean value	Axial deformation (mm)
A1 (6152-1)	0.002	27.9	27.2	6.4	6.2	0.36	0.36	0.68
A2 (6152-3)	0.002	25.8		5.8		0.36		0.84
A3 (6153-2)	0.002	28.0		6.5		0.36		0.72
B1 (1292-1)	0.002	42.9	41.8	10.1	9.6	0.30	0.30	0.67
B2 (1292-2)	0.002	41.1		8.2		0.32		0.89
B3 (1293-2)	0.002	41.4		10.4		0.29		0.66
C1 (6501-1)	0.002	46.2	49.6	9.9	9.1	0.22	0.24	0.72
C2 (6501-2)	0.002	52.0		8.0		0.26		1.20
C3 (6502-3)	0.002	50.6		9.3		0.24		0.81
D1 (6271-1)	0.002	78.7	87.6	20.6	23.3	0.30	0.32	0.64
D2 (6271-2)	0.002	96.8		29.2		0.34		0.50
D3 (6273-1)	0.002	87.2		20.0		0.33		0.77
E1 (691-1)	0.002	128.2	115.9	24.6	23.8	0.26	0.27	0.96
E2 (692-1)	0.002	101.0		20.5		0.26		0.76
E3 (693-1)	0.002	118.5		26.3		0.30		0.68

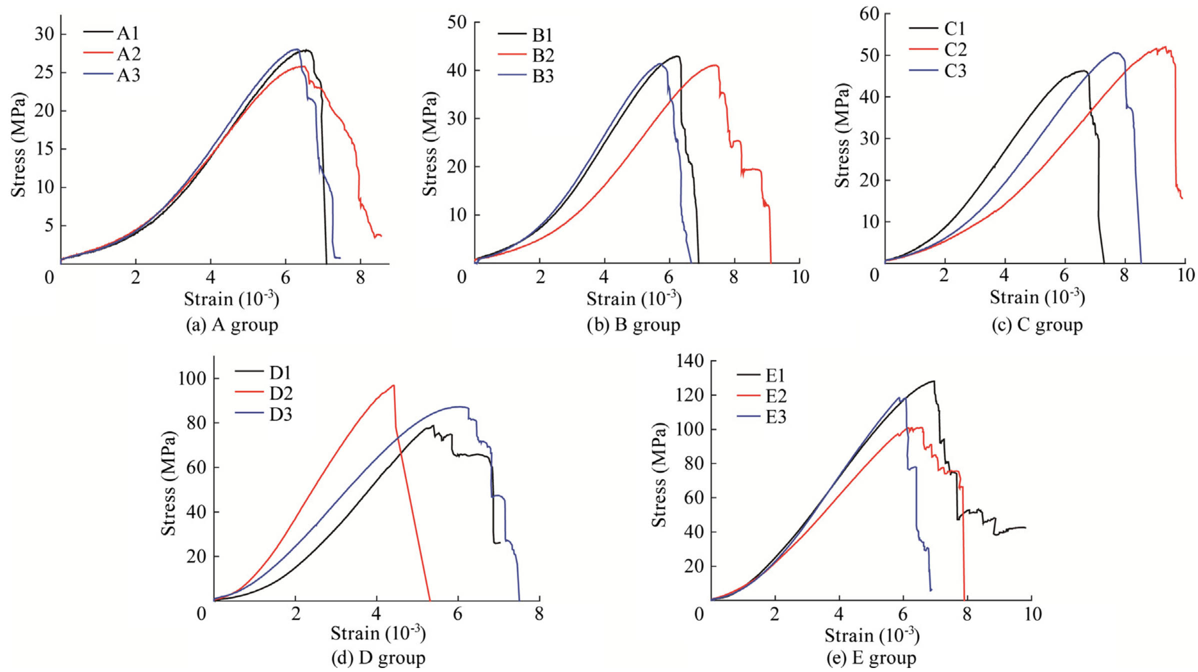

Fig. 4. Stress-strain curves of five different groups of sandstones (each group has three samples).

carbonates (7.7%) and sulfate (17.3%); and for *E* group, the major cementing materials are carbonate (35.6%), clay minerals (4.7%) and analcime (3.2%).

3.2. Micro structure

Fig. 2 shows the SEM photos for the five sandstones. It can be seen that there exist cement materials in all five kinds of sandstones with different bonding characteristics. The cementing strength increases from *A* to *E* groups. Mineral grains are more visible in groups *A* and *B*, not obvious in *C*, *D* or *E* groups. A large amount of pores can be found in groups *A* and *B*. Large pores could not be detected in groups *C*, *D* or *E*, and only a few small pores can be found.

3.3. Pore characteristics

Table 3 shows the results of analysis of pore characteristics, and Fig. 3 is the porosity distribution for the 5 kinds of sandstones. It can be seen that group *A* has the largest porosity, 7.6%. The porosities of groups *B*, *C*, *D* and *E* are 5.9%, 4.4%, 3.0% and 1.6%, respectively. There are two peaks in porosity distribution for group *A*. In group *B*, two samples have two peaks, while one sample has only one peak. In group *C*, one sample has three peaks, while two samples have two peaks; both *D* and *E* groups have three peaks. The first wave range of group *A*, group *B*, group *C*, group *D* and group *E* are 2.31–2.66 ms, 12.33–21.54 ms, 2.01–2.31 ms, 0.76–0.87 ms, 0.87–1.00 ms respectively. The second wave range are 613.59–811.13 ms, 35 1.12–464.16 ms, 49.77–57.22 ms, 24.77–28.88 ms, 21.54–32.75 ms, respectively. In groups *C-E*, the third peaks are at 1233 ms, 403.7–464.16 ms, 403.7–533.67 ms, respectively. According to Yao et al., the peaks for micropores are mainly found between $T_2 = 0.5–2.5$ ms; mid and large pores are found between $T_2 = 2$ 0–50 ms; fissures lies mainly $T_2 > 1000$ ms [12]. Therefore, the five kinds of sandstones have micropores, mid- and large-pores, but no fissure. Groups *A* and *B* mainly have mid- and large-pores, while groups *C-E* have mainly micropores.

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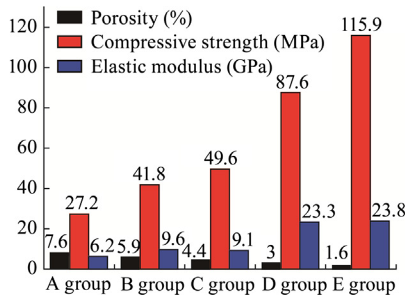

Fig. 5. Relationship between porosity and rock mechanical properties of sandstone.

3.4. Rock mechanics properties

Table 4 shows the results of UCS, Young's Modulus, Poisson's ratio and axial maximum deformation. Fig. 4 presents the complete stress-strain curves for the five kinds of sandstones. It can be seen from Table 4 that there are difference in rock mechanics properties among the five kinds of sandstones. The UCS increases from group *A* to group *E*. The average UCS for groups *A*, *B*, *C*, *D* and *E* are 27.2 MPa, 41.8 MPa, 49.6 MPa, 87.6 MPa and 115.9 MPa, respectively. Although they are different in Young's Modulus, Poisson's ratio and axial maximum deformation among the five sandstones, no obvious trends exist. The Young's Modulus for groups *A*, *B*, *C*, *D* and *E* are 6.2 GPa, 9.6 GPa, 9.1 GPa, 23.3 GPa and 23.8 GPa, respectively, while the Poisson's ratio are 0.36, 0.30, 0.24, 0.32 and 0.27, respectively. It can be seen from Fig. 5 that the complete stress-strain curves of the five sandstones can all be divided into the following four sections: initial compressed, linear elastic, plastic deformation failure and residual strength. In the initial compressed section, all five curves are in concave shape; in the linear elastic section, all five curves are basically straight lines; in the plastic deformation section, all five curves exhibit elastic-plastic and plastic deformations; in the residual strength section, the residual strength for all five kinds of sandstones are very low.

4. Discussion

4.1. Composition versus rock mechanics properties

Many factors play a role in rock mechanics properties. In addition to stress and natural environments, the internal factors such as composition, structure and porosity do have positive effect on its rock mechanics properties. The effect of rock composition on rock mechanics properties is mainly expressed in terms of the type and amount of major composition and cementing materials. Table 5 shows the results of composition and rock mechanics properties. It can be seen that quartz and feldspar have a positive effect on rock mechanics properties, but it is not linearly proportional to UCS; the UCS and Young's Modulus of rocks are not only affected by quartz and feldspar, but also decisively by the type and amount of cementing materials.

4.2. Micro structure versus rock mechanics properties

In addition to mineral composition, microstructure also positively affects the rock mechanics properties. It can be seen from Fig. 2 and Table 4, the bonding of cementing materials, grain size and pore size all have effect on rock mechanics properties. The stronger the bonding of cementing materials, the larger is the UCS. There is no clear relationship between Young's Modulus and cement. The smaller the grain size, the larger the UCS. The less the pores, the larger the UCS.

4.3. Porosity versus rock mechanics properties

Fig. 5 shows the relationship among porosity, UCS and Young's Modulus. It can be seen that the UCS increases with decreasing porosity. The porosity for group *A* is 7.6%, its UCS is 27.2 MPa; the porosity for group *B* is 5.9%, and its UCS is 41.8 MPa. Compared to group *A*, the porosity for group *B* is 22.4% less, but its UCS is 53.7% larger. The porosity for group *C* is 4.4%, its UCS is 49.6 MPa. Compared to group *B*, its porosity is 25.4% less, but its UCS is 18.7% larger. The porosity for group *D* is 3%, its UCS is 87.6 MPa. Compared to group *C*, its porosity is 31.8% less, but its UCS is 76.6% larger. The porosity for group *E* is 1.6%, its UCS is 115.9 MPa. Compared to group *D*, its porosity is 46.7% less, but its UCS is 32.3% larger. Although the Young's Modulus of sandstone does not exhibit positive relationship, it shows increasing trend, as the porosity decreases.

5. Conclusions

(1) The major component minerals of five kinds of sandstones are quartz and feldspar. Major cement materials are clay minerals, carbonate, ironic, analcime, and sulfate; analcime dominates group *A*, clay minerals dominate groups *B* and *C*, sulfate dominates group *D*, and carbonate dominates group *E*.
(2) There are difference in cementing quality among the five kinds of sandstones. From group *A* to group *E*, cementing quality increases, but the particle diameter and pore diameter are getting smaller and smaller, and the number of pores is less and less.
(3) The porosity decreases from group *A* to group *E*. The porosities for group *A*, group *B*, group *C*, group *D*, and group *E* are.7.6%, 5.9%, 4.4%, 3.0%, 1.6%, respectively.
(4) The composition of sandstone is closely related to its rock mechanics properties. Quartz and feldspar are important factors affecting the rock mechanics properties. However, the cement content of sandstone and the type of cement also play a decisive role in its mechanical characteristics.
(5) The cementing quality, grain size, and quantity and size of pores all affect the rock mechanics properties of sandstone. The better the cementing quality, the larger the UCS. The smaller the grain size, the higher the UCS. The smaller and the less the number of pore, the higher the UCS.

Table 5
Comparison of mineral components and rock mechanics characteristics.

Sample	Mineral components (%)							Compressive strength (MPa)	Young's modulus (GPa)
	Quartz	Feldspar	Carbonate cement	Ferruginous cement	Zeolite cement	Clay minerals	Sulfate cement		
A (6151)	24.4	42.8	9.4	10.6	12.8	0	0	27.2	6.2
B (1301)	36.0	42.9	0	4.7	2.2	14.2	0	41.8	9.6
C (6501)	21.7	44.5	0	7.1	0	26.7	0	49.6	9.1
D (6271)	47.2	27.8	7.7	0	0	0	17.3	87.6	23.3
E (691)	23.7	32.8	35.6	0	3.2	4.7	0	115.9	23.8

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(6) Porosity is closely related to the rock mechanics properties of sandstone. Decreasing porosity will increase UCS. There is a trend of negative relationship between Young's Modulus and porosity.

Acknowledgments

Financial support for this work, provided by the National Natural Science Foundation of China (No. U1261207), is gratefully acknowledged.

References

[1] Ren YF, Ning Y, Qi QX. Physical analogous simulation on the characteristics of overburden breakage at shallow longwall coalface. J Chin Coal Soc 2013;38(1):61–6.
[2] Wang FT, Tu SH, Zhang YW, Song Q, Yan RL, Duan CH. Ground pressure rules and roof control technology for the longwall mining of shallow seam beneath the gully topography. J Min Saf Eng 2015;32(6):877–82.
[3] Li G, Liang B, Li FY. Cover-rock movement law for Daliuta mine 12305 working face by similar simulation test. J Heilongjiang Inst Sci Technol 2015;15(5):295–8.
[4] Xuan YQ. Research on movement and evolution law of breaking of overlying strata in shallow coal seam with a thin bedrock. Rock Soil Mech 2008;29(2):512–6.
[5] Huang QX. Impermeability of overburden rock in shallow buried coal seam and classification of water conservation mining. Chin J Rock Mech Eng 2010;29(Suppl 2):3622–7.
[6] Fan GW, Zhang DS, Ma LQ. Overburden movement and fracture distribution induced by longwall mining of the shallow coal seam in the Shendong coal field. J Chin Univ Min Technol 2011;40(2):196–201.
[7] Li HM, Syd P, Li HG, Xu YX, Yuan RF, Yue SS, et al. Trial of small gateroad pillar in top coal caving longwall mining of large mining height. Int J Min Sci Technol 2016;26(1):139–47.
[8] Ju F, Huang P, Guo S, Xiao M, Lan LX. A roof model and its application in solid backfilling mining. Int J Min Sci Technol 2017;27(1):139–43.
[9] Xue HQ, Xu RN, Jiang PX, Zhou SW. Characterization of rock microstructure using 3D X-ray computed tomography. Chin J Theor Appl Mech 2015;47(6):1073–8.
[10] Deng JX, Wang H, Zhou H, Liu ZH, Song LT, Wang XB. Microtexture, seismic rock physical properties and modeling of Longmaxi formation shale. Chin J Geophys 2015;58(6):2123–36.
[11] Zhao K, Zhao HY, Jia QY. An analysis of rockburst fracture micromorphology and study of its mechanism. Explos Shock Waves 2015;35(6):913–8.
[12] Yao J, Zhao XC, Yi YJ, Tao J. Analysis methods for reservoir rock's microstructure. J Chin Univ Petrol 2007;31(1):80–6.
[13] Yang CH, Mao HJ, Wang XC, Li XH, Chen JW. Study on variation of microstructure and mechanical properties of water-weakening slates. Rock Soil Mech 2006;27(6):2090–8.
[14] Li SB, Chen J, Yi GD. Experimental study on the relationship between micro-characteristics and compressive strength of the red bed rock. Geotech Invest Surv 2013;41(3):1–5.
[15] Shi X, Cheng YF, Jiang S, Cai DS, Zhang T. Experimental study of microstructure and rock properties of shale samples. Chin J Rock Mech Eng 2014;33(Suppl 2):3439–45.
[16] Lindqvist JE, Åkesson U, Malaga K. Microstructure and functional properties of rock materials. Mater Charact 2007;58(11–12):1183–8.
[17] Johansson E. Technological properties of rock aggregates. Luleå: Luleå University of Technology; 2011.
[18] Tugrul A, Zarif IH. Correlation of mineralogical and textural characteristics with engineering properties of selected granitic rocks from Turkey. Eng Geol 1999;51(4):303–17.
[19] Prikryl R. Some microstructural aspects of strength variation in rocks. Int J Rock Mech Min Sci 2001;38(5):671–82.