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Geomechanical and water vapor absorption characteristics of clay-bearing soft rocks at great depth

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ABSTRACT

The geological and physico-mechanical properties characterization of deep soft rocks is one of the critical scientific issues for deep soft rock engineering. In the present study, X-ray diffraction (XRD) analysis, scanning electron microscope (SEM), and mercury intrusion porosimetry experiments were carried out to investigate the mineral compositions, microstructure and porosity characteristics of the 13 clay-bearing soft rock samples collected from a deep coal mine in China. Water vapor absorption and uniaxial compressive experiments were also performed to examine water absorption characteristics and water-induced strength degradation effect of the investigated deep soft rock samples. The results show that the dominant mineral components in mudstone, coarse sandstone and fine sandstone samples were calcite, quartz and clay respectively. The contents of clay minerals in all samples were relatively high and ranged from 12.3% (N-4) to 56.5% (XS-1). Water vapor absorption processes of all the soft rock samples follow an exponential law which is very similar to the water vapor absorption behavior of conglomerate samples reported in our earlier study. Correlation analyses also suggested that there were good positive correlation relationships between water absorptivity and clay minerals for both mudstone and sandstone samples. Furthermore, it was found that vapor absorption was not correlated with the porosity for mudstone, however, positive correlation relationship was found between them for sandstone. Correlation analysis between UCS, modulus of elasticity and water content demonstrated that both of them tend to decrease with the increase of their water content due to water absorption.

1. Introduction

With the dwindling of shallow resources, deep mining has become the inexorable trend of the mineral resource exploitation worldwide. In China, deep coal resources are the main body energy reserves in the 21st century, so it is imperative to carry out basic theory research on the deep mining engineering rock mechanics [1]. Among them, the geological and physico-mechanical property (including water absorption and its mechanical effect) characterization of deep soft rocks is one of the critical scientific issues for deep soft rock engineering.

It is well known that for clay-bearing soft rock, whether it is shallow rock or deep rock, physicochemical and mechanical effects of rock–water interaction are important causes for deformation and deterioration of rocks [2–12]. Thus, a better understanding of water absorption and its geomechanical effects on rocks is of great importance to the stability and durability of related soft rock engineering projects. So far, extensive researches [13–17] have been carried out in order to thoroughly explore geomechanical and water absorption characteristics of the shallow soft rocks. But for deep soft rocks at the depth of 1000–1500 m, the relative researches are rather rare.

In the present study, X-ray diffraction (XRD) analysis, scanning electron microscope (SEM), and mercury intrusion porosimetry experiments were carried out to investigate the mineral compositions, microstructure and porosity characteristics of the 13 clay-bearing soft rock samples at the depth interval of 1283–1359 m. Water vapor absorption and uniaxial compressive experiments were also performed to examine water absorption characteristics and water-induced strength degradation effect of the investigated deep soft rock samples.

2. Sampling and geological characterization of soft rock samples

2.1. Sampling and preparation of soft rock samples

The soft rock samples used in this study were collected from Daqiang coal mine which is located in Kangping county of

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Shenyang city, Liaoning province of China. All samples were located at the depth interval of 1283–1359 m. Investigated samples included five mudstones, four coarse sandstones and four fine sandstones.

Collected specimens were wrapped with ziplock bags and then sealed immediately with wax after transported to the ground to maintain their original state. After carried to the laboratory, all samples were processed into cylindrical cores with a uniform size of $\Phi 55 \times 110$ mm using rock drilling, cutting and grinding machines. Numbered samples were then dried in a vacuum drying oven for 1–2 days until their weights had little changes. Finally, all the dried soft rock samples were kept in desiccators before using. Table 1 lists the basic geological parameters of the thirteen clay-bearing soft rock samples investigated in this study.

2.2. Geological characteristics

2.2.1. Mineralogical composition

Mineral compositions of the soft rock samples were quantitatively determined by XRD analysis using a Rigaku Electric Co. (Rigaku) D/MAX250 analyzer. *The Quantitative Analysis of Total Contents of Clay Minerals and Common Non-Clay Minerals in Sedimentary Rocks by X-ray Diffraction* (SY/T 6210-1996) [18] were employed for the determination of relative mineral contents of the soft rock samples during the X-ray analysis.

Table 2 lists the mineralogical composition of the soft rock samples determined by X-ray diffraction. As Table 2 displays, the dominant mineral components in mudstone, coarse sandstone and fine sandstone samples were calcite, quartz and clay respectively. The contents of clay minerals in all samples were relatively high and ranged from 12.3% (N-4) to 56.5% (XS-1). And, the average values of clay minerals in mudstone, coarse sandstone and fine sandstone samples were 19.8%, 33.4% and 46.7% respectively. In addition, the dominant clay components were illite/smectite, illite and kaolinite, accounting for the highest among all clay mineral components.

2.2.2. Microstructure

Micro-structural features of clay minerals contained in rock samples, including the type of clay minerals, crystal morphology and its occurrence features were observed by scanning electron microscope (SEM) method (LEO435VP, Cambridge, UK) according to *Analytical Method of Rock Sample by Scanning Electron Microscope* (SY/T 5162-1997) [19]. Micro-structural images of mudstone, coarse sandstone and fine sandstone samples determined by SEM are shown in Figs. 1–3 respectively.

2.2.2.1. Mudstone. It was observed from Fig. 1 that the mudstone samples had compact structure and a few micro-pores (Fig. 1a). Intergranular dissolved pores with diameter of 2–13 μm distributed among clay particles; the pores were mainly ankerite intragranular dissolved pores with diameter of 10–25 μm, calcite intragranular dissolved pores with diameter of 2–30 μm (Fig. 1b) and feldspar leaching micro-pores with diameter of 2–6 μm (Fig. 1c). Cube-like dolomite, quartz and albite between the argillaceous are shown in Fig. 1d. Mildew spherical pyrite and calcite between the argillaceous are shown in Fig. 1e. Grain surface flaky kaolinite and ankerite are shown in Fig. 1f. Piece of flocculent illite/smectite mixture, the massive calcite and quartz are shown

Table 1
Geological description of the investigated deep soft rock samples selected from Daqiang coal mine in northeastern China.

No.	Lithology	Depth (m)	Geological description
N-1	Mudstone	1304	Gray brown, dense, obvious bedding
N-2	Mudstone	1284	Gray brown, dense, obvious bedding
N-3	Mudstone	1283	Gray brown, dense, obvious bedding, with brown filler
N-4	Mudstone	1304	Gray brown, dense, obvious bedding, with white filler
N-5	Mudstone	1305	Gray brown, dense, obvious bedding, with white filler
CS-1	Coarse sandstone	1354	Gray, dense
CS-2	Coarse sandstone	1354	Gray, dense, less obvious joint
CS-3	Coarse sandstone	1354	Gray, dense, less obvious joint
CS-4	Coarse sandstone	1354	Gray, dense
XS-1	Fine sandstone	1359	Gray brown, dense
XS-2	Fine sandstone	1359	Gray brown, dense
XS-3	Fine sandstone	1355	Dark gray, dense, with few red-brown filler
XS-4	Fine sandstone	1355	Brown, dense

Table 2
Mineralogical composition determined by X-ray diffraction analysis for the investigated deep soft rock samples (%).

No.	All minerals									Clay minerals				
	Quartz	Potash feldspar	Plagioclase	Calcite	Dolomite	Pyrite	Siderite	Analcite	Clay mineral	Illite/smectite	Illite	Kaolinite	Chlorite	Chlorite/smectite
N-1	22.4	1.1	5.0	39.1	6.5	5.5	/	/	20.4	60	15	11	14	/
N-2	24.0	1.5	7.2	25.3	15.0	5.6	/	/	21.4	70	18	5	7	/
N-3	23.6	1.4	6.4	26.4	12.7	/	/	/	29.5	71	10	10	9	/
N-4	11.4	1.6	6.9	56.5	7.1	2.9	/	1.3	12.3	50	36	7	7	/
N-5	16.5	1.3	10.4	9.9	46.3	/	/	/	15.6	36	24	11	13	16
CS-1	33.8	/	18.9	17.2	/		/		30.1	16	52	27	5	/
CS-2	36.3	/	19.2	15.1	/		/		29.4	20	58	18	4	/
CS-3	37.2	/	20.6	14.5	/		/		27.7	18	50	27	5	/
CS-4	38.8	/	14.3	0.7	/		/		46.2	24	46	26	4	/
XS-1	28.4	/	15.1	/	/		/		56.5	16	24	54	6	/
XS-2	36.8	/	17.0	5.2	/		/		41.0	15	24	55	6	/
XS-3	32.7	/	12.6	/	/		/		54.7	39	33	24	4	/
XS-4	17.9	/	9.2	8.6	/		29.6		34.7	30	26	40	4	/