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Latest progress of soft rock mechanics and engineering in China

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ABSTRACT

The progress of soft rock mechanics and associated technology in China is basically accompanied by the development of mining engineering and the increasing disasters of large rock deformation during construction of underground engineering. In this regard, Chinese scholars proposed various concepts and classification methods for soft rocks in terms of engineering practices. The large deformation mechanism of engineering soft rocks is to be understood through numerous experiments; and thus a coupled support theory for soft rock roadways is established, followed by the development of a new support material, i.e. the constant resistance and large deformation bolt/anchor with negative Poisson's ratio effect, and associated control technology. Field results show that large deformation problems related to numbers of engineering cases can be well addressed with this new technology, an effective way for similar soft rock deformation control.

1. Introduction

With the increasing shortage of resources worldwide in shallow depth, the deep resources exploitation has been becoming a good alternative. At the same time, the underground space has already been considered as a new growth of land resources in the development of deep geotechnical exploitation, including the fields of the nuclear industry, defense industry, transportation, water conservancy and other industries in the world. In recent years, large-scale and deep underground projects are planned to be built, where the difficulties caused by the requirements associated with the quantity and quality have been rising with increasing depth. For example, the metal mining reached a depth of 4 km, and the coal mine depth has reached 1.5 km, while hydroelectric engineering, traffic engineering, and other civil works have exceeded the depth of 2.5 km. Core scientific issues arising in deep underground projects are encountered with the conditions of "three-high and one-disturbance", i.e. high stress, high temperature, high seepage pressure and a strong mining disturbance, which form a complex geomechanical environment for deep engineering. In addition, the changes in deep rock structure, basic physico-mechanical behaviors and responses due to engineering disturbance present the weakness of the mechanical properties of soft rocks in the form of a significantly large deformation. As a result, the disasters caused by large deformation of deep soft rocks have been increasingly developed, a serious threat to the safety of deep resources mining and the efficient development of underground space (He et al., 2005; He and Qian, 2010).

In the 1950s, Chinese scholars began to focus on the issues of the large deformation and failure of soft rocks, and launched a series of research projects. In the 1980s, with the increasing depth of coal mining, the engineering problems caused by high in situ stress promoted the study of soft rocks in deep coal mining, followed by the initial concepts of "changing axis theory", "combined support technology", "anchor-arc board support measures", "excavation damaged zone", "primary and secondary loading zones", as well as other supporting theories and techniques (Yu and Qiao, 1981; Lu, 1986; Zheng et al., 1993; Dong et al., 1994; Fang, 1996). After the 1990s, regarding the problems of soft rock large deformation, Chinese scholars in the fields of rock mechanics and mining engineering started to conduct researches on systems theory, experimental and technological innovations, soft rocks landslide, tunnel excavation, and other issues, with fruitful achievements observed. For example, the State Key Laboratory of Geomechanics and Deep Underground Engineering (SKLGDUE) in Beijing has conducted integrated studies on modern mechanics and engineering geology with great progress in the concept and classification of soft rocks, in establishing a mechanism for transforming complex deformation, and in soft rock mechanics theory and technology systems, for which the core idea of energy security release was proposed (He et al., 1993, 2002). These results

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are attributed to the promotion and developments of China's soft rock engineering science.

This paper summarizes the proposed concepts and classification of soft rocks, and introduces the concept of engineering soft rock. With various experimental results, the large deformation mechanism is revealed, and subsequently the coupled supporting technology is developed for large rock deformation control. In this regard, we also developed a new support material with negative Poisson's ratio effect, i.e. the constant resistance and large deformation (CRLD) bolts and anchors.

2. Classification of soft rocks

2.1. Concepts of soft rock

International Society for Rock Mechanics (ISRM) raised the definition of soft rock in 1981: "*the International Society for Rock Mechanics (ISRM) describes rock with an UCS (uniaxial/compressive strength) in the range of 0.25 MPa to 25 MPa as 'extremely weak' to 'weak'*" (ISRM, 1981). However, Chinese scholars present a different definition of soft rock in view of rock mass characteristics, deformation and failure behaviors, where the engineering responses of rocks, such as the strength index, should be considered when defining soft rocks.

Since the definition of soft rock is not commonly acknowledged, a potential impediment will be encountered in further academic exchanges and researches of soft rocks. Thus in theoretical research and engineering application of soft rocks, the concept should indeed cover a variety of definitions of common laws and the essential characteristics of soft rocks, and reflect the basic performances of soft rocks. On the basis of previous studies on soft rock concept, it was proposed a new concept in association with geological soft rock and engineering soft rock (He, 1992a; He et al., 1993, 2002).

Geological soft rock refers to the rocks characterized by low stress, large porosity, poor cementation, broken surface and strong weathering-dependence, which basically contain swelling and loose clayey minerals and/or loose, soft, weak layers. The concept proposed by ISRM is within the scope of geological soft rock.

Engineering soft rock refers to the rocks that can produce significant plastic deformation under engineering forces. The concept of engineering soft rock emphasizes the importance of strength characteristics and the engineering forces, using the following conditions:

$$\left.\begin{array}{l}\sigma \geq [\sigma] \\ U \geq [U]\end{array}\right\} \tag{1}$$

where σ is the engineering stress (MPa), $[\sigma]$ is the strength of engineering rock mass (MPa), U is the rock deformation (mm), and $[U]$ is the deformation allowance (mm).

Engineering rock mass is the main object of soft rock engineering, covering all the rock mass disturbed by an eventual excavation. The key of this concept is the engineering force, significant plastic deformation for rock engineering.

Engineering force is the sum of all kinds of forces acting on rock mass, including gravity force, swelling force (when exposed to water), and other forces induced by engineering disturbances.

Significant plastic deformation is mainly of plastic deformation that is beyond deformation allowance in engineering design. It can reflect the normal operation of the project. It is noted that plastic deformation contains significant elastoplastic deformation, viscoelastoplastic deformation, and continuous and discontinuous deformations.

The definition of soft rock reveals its dependence on the relationship between engineering force and rock strength. Thus if the rock strength is higher than engineering force, the rock is regarded as hard rock; if less than engineering force, it may show the mechanical characteristics of soft rock. Even for the same kind of rock, if under low engineering force, it behaves as hard rock with small deformation, but on the contrary, it may be regarded as soft rock under high engineering force, showing large deformation properties (He et al., 2008a; Zhang et al., 2012).

The relationship between the geological soft rock and engineering soft rock is: when the load is smaller than the strength of geological soft rock (e.g. mud, shale), there is no significant plastic deformation of geological soft rock, so it is geological but not engineering soft rock. When the geological soft rock, e.g. shale and cemented sandstone, is under a condition of critical depth associated with high in situ stress, it would also undergo a significantly large deformation and displays soft rock characteristics. In such a case, it can be regarded as hard rock in terms of geology and/or soft rock in terms of engineering.

2.2. Basic mechanical properties of soft rock

There are two basic indices associated with the mechanical properties of soft rock: the critical load and the critical depth for softening (He et al., 1993).

(1) Critical load for softening

When the external load applied on rocks is greater than a threshold value, the plastic deformation of the rocks will show an evident acceleration phase, and thus form an unstable deformation. The threshold value of applied load is called the critical load for softening, under which a significant rock deformation can be produced. When the stress imposed on rocks is higher than the critical load for softening, the rock would display the typical properties of soft rock in terms of large deformation, and subsequently is called soft rock.

(2) Critical depth for softening

Critical depth for softening has a close relation with the critical load for softening. When an excavation reaches a position greater than a critical depth, rock shows significant plastic deformation, suggesting high ground pressure and supporting difficulties. This depth is called the critical depth for rock softening, at which the engineering force is roughly equal to the critical load for softening applied.

Table 1
Soft rock classification.

Class of soft rock	Conditions	Plastic deformation characteristics
Expansive soft rock (low-intensity)	Shale content >25%	Under external loads applied, it slips along the clay mineral pieces of silicate, significant expansion under action of water, etc.
High-stress soft rock	$\sigma_c < 25$ MPa	A little inflation under action of water, it slips along the flaky clay minerals under high stress condition.
Jointed soft rock	$\sigma_c \geq 25$ MPa	Plastic deformations such as slip and expansion are produced along the jointed structure surface.
Combined soft rock	Shale content ≤25%	Complex mechanism with combination of the above-mentioned characteristics.

Note: σ_c is the uniaxial compressive strength (UCS).

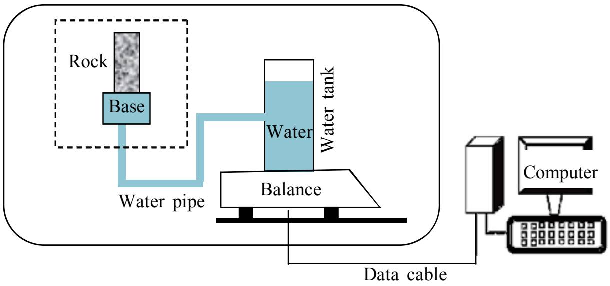


Fig. 1. Schematic diagram of the computer-automated water absorption tester for soft rock.

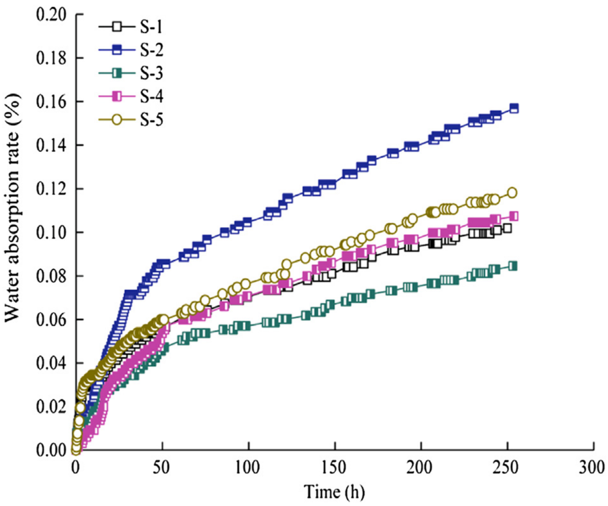


Fig. 2. Changes of the water absorption with time for the shale samples.

2.3. Classification of soft rock

According to the strength characteristics, such as rock type, shale content, rock structure, surface characteristics and other mechanical characteristics associated with plastic deformation, soft rock can be divided into four categories, namely expansive soft rock (also called low-intensity soft rock), high-stress soft rock, jointed soft rock and combined soft rock, as shown in Table 1.

The four types of soft rock mentioned above can be called as HS, HJ, HJS and CSR (combined soft rocks), respectively, i.e. the high stress–strong expansion combined soft rock, the high stress-jointed and the high stress-jointed–strong expansion combined soft rock.

3. Experimental study of water and soft rock interaction

3.1. Experimental study of water absorption on shale at great depth

In this study, water absorption experiments without hydraulic pressure were carried out on shale samples collected from a deep coal mine in China in order to investigate the processes of water absorption and hydrophilic characteristics of deep clay-bearing surrounding rocks after excavation. The major factors that determine the hydrophilic characteristics of soft rock including mineralogical composition and pore texture were also investigated using X-ray diffraction analysis (XRD), mercury porosimetry analysis and scanning electron microscope technique.

Shale samples were collected from Daqiang coal mine at Shenyang, Liaoning Province, China, at the depths of 1283 m–1305 m. All shale samples were obtained into a uniform size of ϕ55 mm × 110 mm. Basic physical parameters were determined according to *Standard for Tests Method of Engineering Rock Masses* (GB/T50266-1999). In deep mining engineering, the confining pressure is changed in association with hydrogeological environment of surrounding rocks after excavation. The possibilities of water absorption from moist environment by soft surrounding rocks increase and consequently a marked decrease in strength and deformability can occur. A computer-automated water absorption tester (Fig. 1) was specially designed to investigate water absorption performance of rock samples by simulating one kind of water absorption process of surrounding rocks in real environments, i.e. water absorption only by the exposed surface under no hydraulic pressure.

Changes of water absorption with time for the shale specimens are presented in Fig. 2. It can be seen that the amount of water absorbed by each sample increases with time. Moreover, despite keeping a same trend, the water absorption curves varied significantly among samples. The variance of water absorptivity of shale samples can be attributed to their difference in physico-chemical parameters which are analyzed in the following chapters.

Clay mineral percentage presented in rock is one of the most important parameters affecting water absorption performances (e.g. water absorption capacity and rate) of clay-bearing soft rocks. Clay minerals have a strong adsorption capacity because of the extra electric charges formed on their surface by isomorphous substitution. Mineral compositions of the rock samples were quantitatively determined by XRD 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)* was employed for the determination of relative mineral contents in X-ray analyses. The results of XRD for all minerals and clay minerals in all samples are listed in Table 2. It shows that the contents of clay minerals in all shale samples are relatively low and range from 7.2% (S-1) to 17.0% (S-4). In addition, illite is the dominant clay mineral component in all samples.

Pore texture is another important parameter influencing water absorption of rocks, such as the amount and the structure of micropores in rocks. The cumulative distribution curves of pore size for the shale samples are shown in Fig. 3. It can be seen that the curves of pore size distribution for the shale samples have similar pattern while the total number and size distribution of micro-pores differ slightly among them. It is evident that rock heterogeneity is resultant from different micro-pore structures in the shale samples that are from the same rock stratum with the same lithology.

Table 2
Analytical results of X-ray diffraction for shale specimens.

Sample No.	Quartz (%)	Potash feldspar (%)	Plagioclase (%)	Calcite (%)	Dolomite (%)	Pyrite (%)	Analcite (%)	Illite (%)	Kaolinite (%)
S-1	13.7	2.9	9	–	67.2	–	–	7.1	0.1
S-2	10.6	7.2	15	25.4	24	3.2	–	14.6	–
S-3	19.1	14	16.8	1.6	27.5	7.1	–	13.6	0.3
S-4	15.2	8.1	5.9	–	53.8	–	–	16.3	0.7
S-5	14.1	4.3	10	–	53.8	2.8	–	15	–

3.2. *Water vapor sorption and its mechanical effect on conglomerate rocks*

Clay-bearing conglomerate rocks sampled from Daqiang coal mine in Northeast China were used to investigate water vapor sorption and its effects on rock mechanical properties. Dynamic changes of water vapor sorption with elapsed time for conglomerate rocks were observed through laboratory experiment conducted on a novel computer-automated testing apparatus. Meanwhile, uniaxial compression tests, XRDs, mercury porosimetry analyses were performed on rock samples to determine their mechanical, physico-chemical and micro-structural properties. The effects of parameters such as mineral components and pore texture on water vapor sorption were discussed. Water vapor-induced strength softening effect was analyzed based on correlation between water content and rock mechanical properties including UCS and modulus of elasticity (van Olphen, 1965; Zielinski et al., 1982; Shang et al., 1994; Vásárhelyi and Ván, 2006; Taibi et al., 2009; Yilmaz, 2010; Zhang et al., 2012). Furthermore, microstructure changes after vapor sorption were observed by scanning electron microscope images.

Rock samples were also processed to a dimension of ϕ55 mm × 110 mm in laboratory, using rock drilling, cutting and grinding machines. An experimental system was specially developed to measure water vapor sorption of rock samples. The schematic diagram of the apparatus is shown in Fig. 4. Conglomerate rock samples were placed in the testing chamber of the experimental system under relative humidity of 97% at room temperature (about 24 °C) and atmospheric pressure for 905 h to observe weight changes of rocks due to vapor sorption.

Dynamic changes of water vapor sorption with time for conglomerate specimens are presented in Fig. 5. While remaining a same trend, the vapor sorption curves varied significantly among samples, with C-1 and C-2, and C-5 and C-6 being the largest and the least vapor sorption respectively. As shown in Fig. 5, the amount of water vapor absorbed by each conglomerate rock sample kept increasing with time until it finally reached a plateau. It is thus inferred that vapor sorption for each sample achieved equilibrium state at the end of sorption experiment.

The results of XRDs (X-ray diffraction) for conglomerate rock samples are listed in Table 3. Clay minerals were most abundant in C-2 (47.1%) and least in C-6 (20%). In addition, the dominant clay component was smectite in all samples, accounting for the highest among all clay mineral components. Correlation analyses have shown positive correlations between absorbed water content and clay mineral content as well as smectite content (Fig. 6).

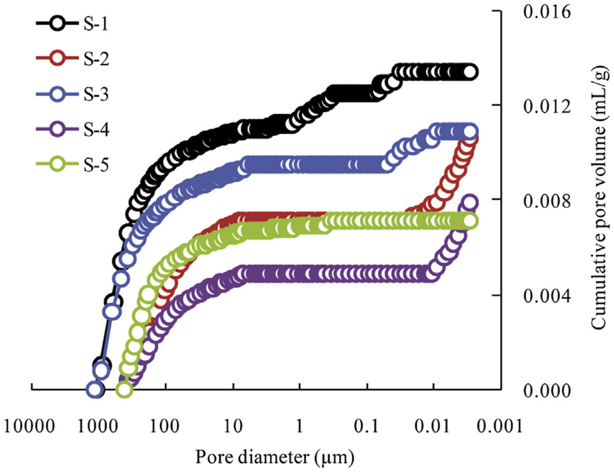


Fig. 3. Cumulative distribution curves of pore size for the shale samples (Zhang et al., 2012).

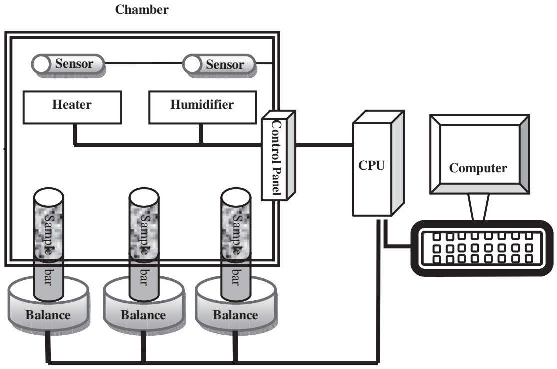


Fig. 4. Schematic diagram of the experimental system for water vapor sorption of deep soft rocks (Zhang et al., 2012).

The results of uniaxial compression tests for dry and vapor wetted conglomerate rock samples are shown in Table 4. The results suggested that with increasing water content induced by vapor sorption, conglomerate rock strength tended to decrease, meanwhile it was more prone to deformation. Consequently, it is evident that vapor sorption leads to reduced rock strength and increased vulnerability to deformation.

4. Large deformation mechanisms of soft rocks

Specific large deformation at rock failure is frequently reported in soft rock engineering, which is related to the characteristics of complex geomechanical environment, the unique physico-chemical composition of rocks, and the structure of rock mass. Thus, a comprehensive understanding of large deformation mechanism of soft rock is of great importance for further soft rock engineering design.

4.1. *Swelling mechanism of clayey minerals in soft rocks*

Clayey minerals in soft rock would swell when exposed to water, causing large-deformation disasters, such as landslide. Research team of the author developed a series of experiment systems for rock–water coupling analysis (Fig. 7). The analyses of interaction between soft rock and absorbed water are conducted using the intelligent test system, with which the mechanism of landslides with the increasing water quantity and strength degradation in

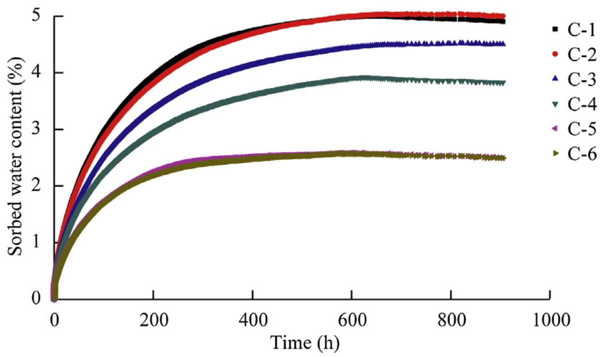
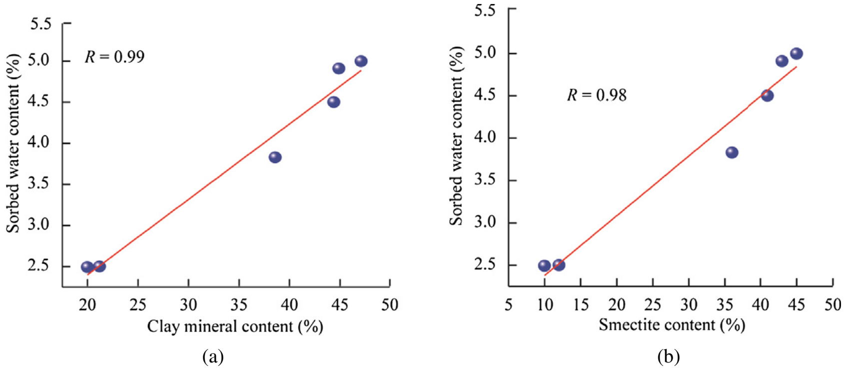


Fig. 5. Dynamic changes of the vapor sorption with time for conglomerate rock samples (Zhang et al., 2012).

Table 3
Analytical results of X-ray diffraction for conglomerate rock specimens.

Sample No.	Mineral contents (%)							Clay mineral contents (%)		
	Quartz	Potash feldspar	Plagioclase	Calcite	Dolomite	Pyrite	Clay mineral	Smectite	Illite	Kaolinite
C-1	15.1	1.8	17.4	3.2	7.3	10.3	44.9	95	–	5
C-2	13.3	1.2	17.2	2.1	6.6	12.5	47.1	96	–	4
C-3	14.3	2.3	22.2	3	5.7	8.1	44.4	93	–	7
C-4	18.9	2.4	23.5	1.4	6.8	8.4	38.6	92	–	8
C-5	14.8	2.6	28.1	15.4	3.9	14	21.2	58	–	25
C-6	10.7	3.1	28.6	21.1	5.5	11	20	49	3	23



(a) (b)

Fig. 6. Correlations between absorbed water and (a) clay mineral content, and (b) smectite content (Zhang et al., 2012).

rock mass with elapsed time can be well captured. It also provides a basis for support design of soft rock tunnel excavation.

On the basis of experimental results, soft rock adsorption mechanism was studied by soft rock adsorption supercomputing system (He et al., 2009a,b, 2011; He and Zhao, 2012). It shows that the adsorption characteristics of soft rocks depend on ion-exchanges, which make the clay mineral inside the soft rock be negatively charged, and thus large adsorption energy for water molecules was induced (Figs. 8 and 9). During tunnel excavation, huge internal energy induced by soft rock expansion was generated under the varying physico-mechanical conditions, which is the fundamental factor to cause rock failure.

In addition, Zhou et al. (2005, 2010) analyzed layered red soft rock softening when subjected to widely distributed water in South China. Accordingly, “self-organized criticality” concept was adopted on the basis of water softening tests, in combination with soft rock physico-mechanical properties, microstructure, and the test results of aqueous solution concentration. The phenomena are highlighted with two significant characteristics: self-organization and criticality. In the perspective of system evolution, the properties variation under the action of water in soft rock engineering is given to determine the stable critical instant (Zhou et al., 2005, 2010; Liu et al., 2011). Based on this, the combination of soft rock microstructure elements is proposed, as shown in Fig. 10, with the construction of two typical microstructure units. The natural structure considering granular microstructure and dense block structure of soft rock (Figs. 11 and 12) presented a critical criterion for the microstructure evolution of softening process, and the quantitative relationship describing the microstructure of soft rock and its mechanical properties can be built subsequently.

Table 4
Values of uniaxial compressive strength and modulus of elasticity of conglomerate rock specimens with different water contents.

Specimen No.	Water content (%)	Uniaxial compressive strength (MPa)	Modulus of elasticity (GPa)
C-1	7.21	51.45	5.7
C-2	6.88	54.55	5
C-3	6.65	31.57	5.3
C-4	5.7	50.1	6.8
C-5	3.96	79.5	7.9
C-6	4.26	51.5	3.9
C-7	0	70.1	8.7

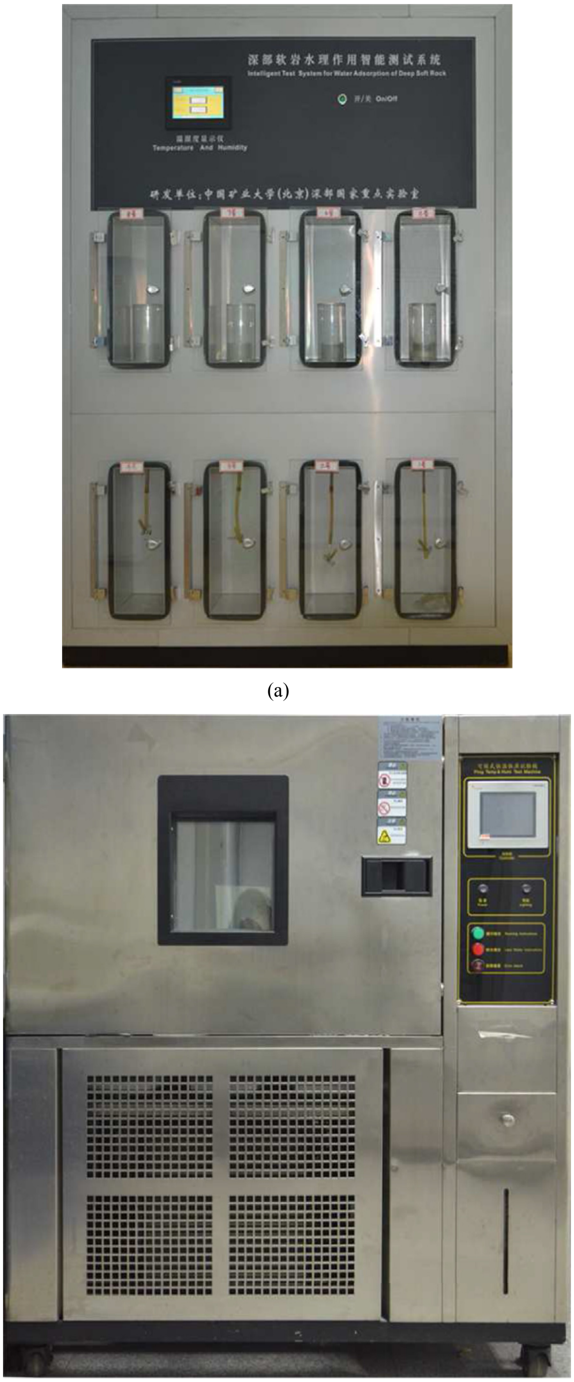
Other scholars have also carried out studies on the characteristics of soft rocks, such as the expansion, collapse, and crack propagation (Liu et al., 2006; Guo et al., 2007; Kang et al., 2009; Wang et al., 2011).

4.2. *Asymmetric large deformation mechanism of layered deep rock mass*

Landslides and other disasters basically have a close relation with large deformation of layered rocks in a roadway. To solve these problems, a physical model has been developed using this experimental system, with which the structural effect of soft rock roadway can be considered (Fig. 13). The roadway excavation at failure process under different engineering geological conditions can also be realized with this experimental system (Fig. 14). Experimental results show that rock structural plane can lead to decreasing strength and the asymmetric large deformation of surrounding rocks in the failure. Asymmetric supporting design for rock structure becomes a key issue to control deformation of structural planes. It can be noted that this system can provide a basis for large deformation control design in soft rock roadways (He et al., 2008b, 2010a,b; He, 2011; Sun et al., 2009a).

4.3. *Large deformation mechanism of deep soft rock softening under high temperature*

Large deformation and failure of rocks caused by high temperature and high humidity environments in deep soft rock



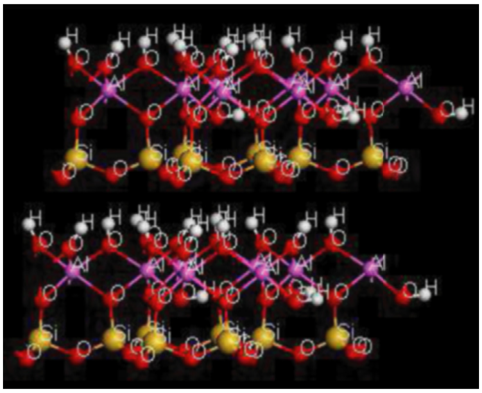
(a)

(b)

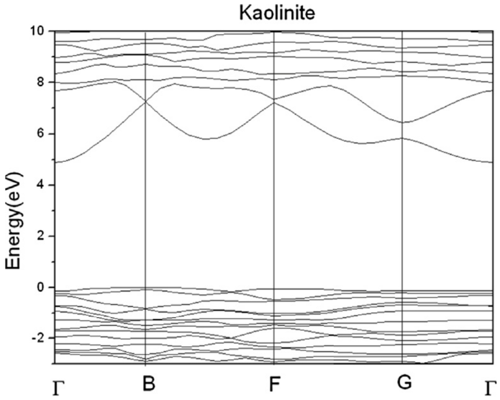
Fig. 7. Test system for water adsorption of deep soft rock (He et al., 2009a,b,c, 2011).

engineering are the hot issues in recent years in deep mining. Researches on mechanical properties of carbonate formation for disposal of high radioactive waste and associated geological conditions at different temperatures were conducted by Gao et al. (2005). Their results show that the influence of temperature on the formation mechanical behaviors is significant with increasing temperature and the degradation of formation mechanical strengths. The peak stress and the elastic modulus also decreased significantly but peak strain increased drastically with the increase of temperature, indicating that deformation characteristics of carbonate rocks are more pronounced (Figs. 15–18).

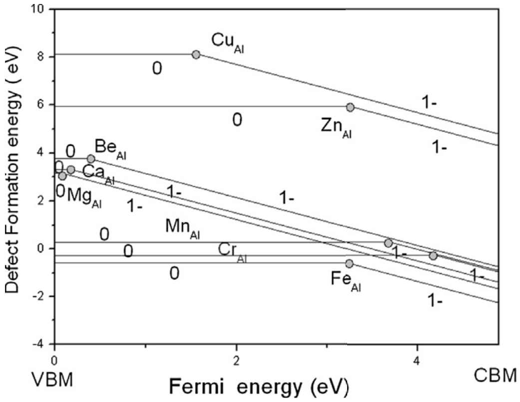
Aiming at the variations of mechanical properties of sedimentary rocks during deep coal mining, we developed an experimental system in order to analyze the mechanical properties of deep rocks under high temperature (Figs. 19 and 20). The mechanical properties of rocks under room and high temperatures in association with humidity environments have been tested by this system, indicating that high temperature and high humidity environments can also lead to surrounding rock softening with major strength degradation, which is the main reason for rock large deformation and failure. It is thus believed that adequate control of high temperature and high humidity environments is the key to controlling large deformation of soft rocks.



(a) Crystal 1: 1 layer structure.

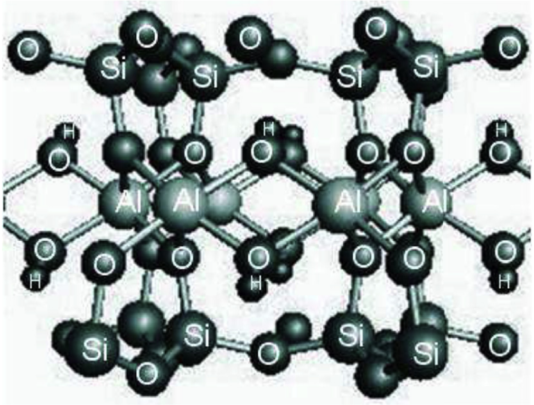


(b) Energy curves.

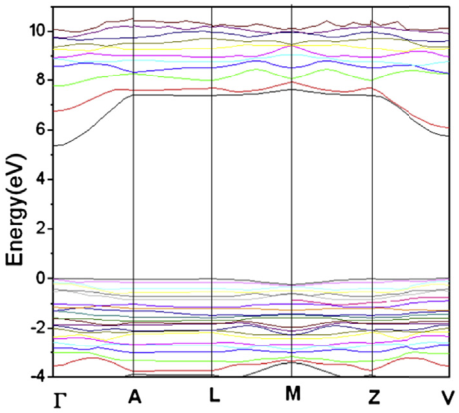


(c) Impurities formation energy.

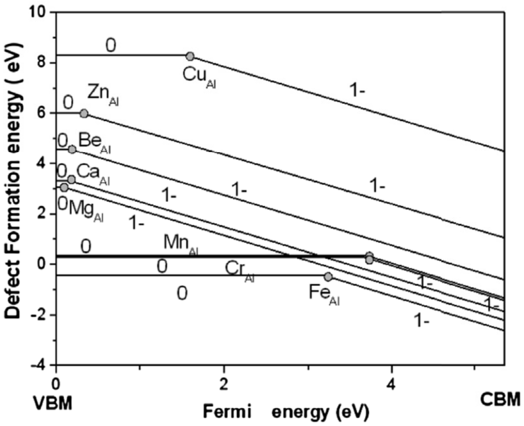
Fig. 8. First principles study of kaolinite.



(a) Crystal 2: 1 layer structure.



(b) Energy curves.



(c) Impurities formation energy.

Fig. 9. First principles study of smectite.

4.4. Large deformation mechanism of soft rock rheology

Rheological property of soft rocks is a key factor to induce large deformation of soft rocks, leading to failure of rock engineering. In recent years, the concepts of damage and hardening variable functions are introduced and the axial and transverse nonlinear creep model of soft rock is established (Fan and Gao, 2007). According to the analysis of soft rock characteristics under uniaxial compression conditions, this model can be used to compare the test results of mudstone and red sandstone with field results, and a good agreement can be obtained. Zhao et al. (2008) used multi-step loading and unloading methods to conduct a series of creep tests on rocks with weak joints sampled from Jinchuan mine in Gansu Province, China. According to the instantaneous elastic strain, lagging viscoelastic strain, instantaneous plastic strain and sticky plastic strain theories, the sticky elastoplastic deformation characteristics of rock with weak joints are also discussed. Chen et al. (2009) also performed a series of uniaxial compression creep tests on layered red soft rock using Burgers model, and the creep parameters under different stresses were also determined.

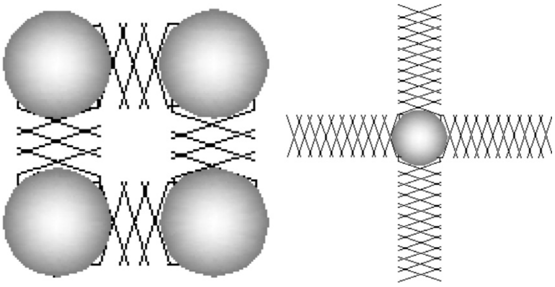


Fig. 10. Typical microstructure unit of soft rock in natural state (Liu et al., 2011).

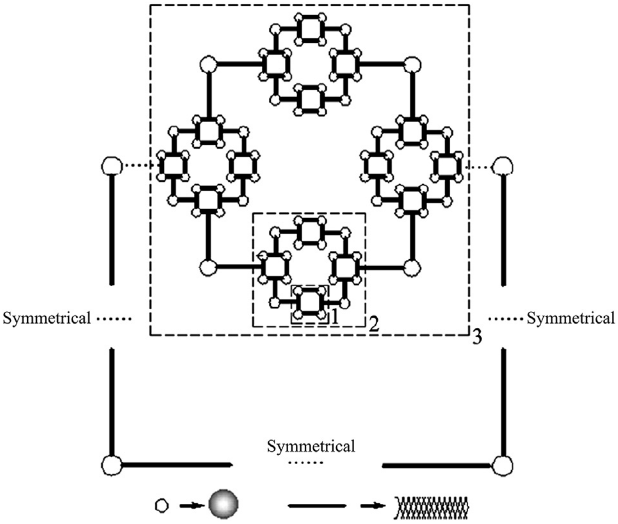


Fig. 11. Two-dimensional (2D) isotropic model of soft rock with granular structure (Liu et al., 2011).

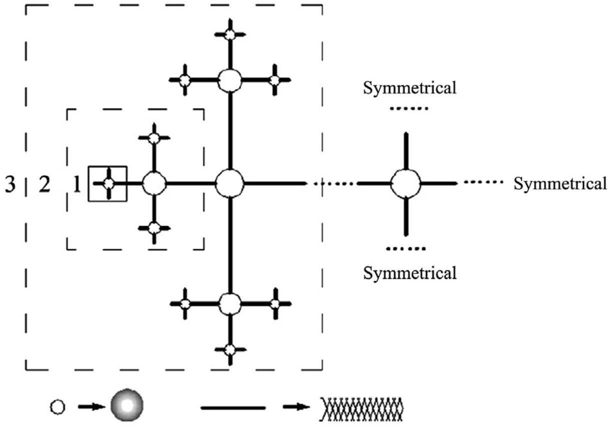


Fig. 12. 2D isotropic model of soft rocks with dense stripy structure (Liu et al., 2011).

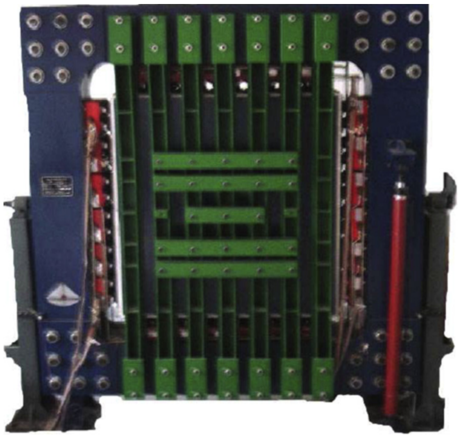


Fig. 13. Physical model of experimental system that can consider structural effect of soft rock roadway (He et al., 2010a).

Fig. 14. Results of one physical model experiment (He et al., 2010a).

Liang et al. (2010) studied the rate effect of layered salt rock and thenardite salt rocks on UCS and deformation. Within the scope of the strain rate, they concluded that the UCS and elastic modulus of salt and thenardite rocks do not change with loading strain rate. Li et al. (2011) described nonlinear creep constitutive model of rocks according to the results of triaxial shear creep tests on deep soft rocks. Tian et al. (2012, 2013) established creep damage evolution equations with introduction of creep damage factor imbedded in ABAQUS software, in combination with the self-correction nonlinear creep damage model and rheological test analysis. The development of the relaxation damage in the process of the relaxation is believed to be nonlinear.

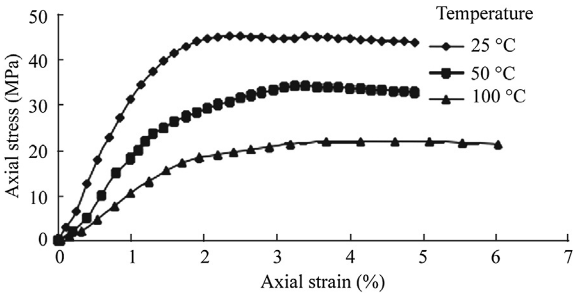


Fig. 15. Triaxial stress–strain curves of post-high-temperature rock salt (Gao et al., 2005).

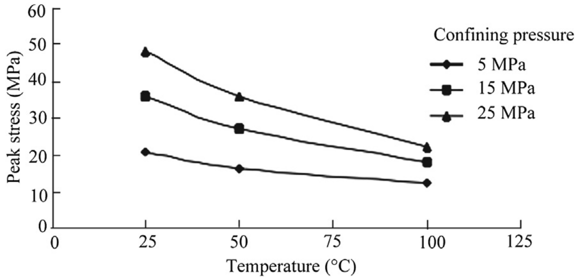


Fig. 16. Relationship between peak stress and temperature of rock salt (Gao et al., 2005).

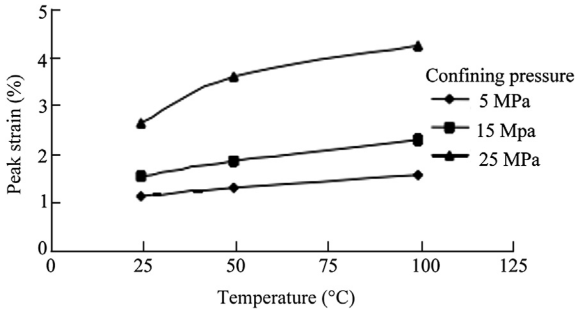


Fig. 17. Relationship between peak strain and temperature of rock salt (Gao et al., 2005).

Sun (2007) summarized the research results of rheological mechanical properties of rock mass in China and pointed out that "*The nonlinear rheology of rock mass is a complicated problem, and many important features of nonlinear rheology have not been fully understood yet. The study of nonlinear rheology of rock mass is even more difficult, because the research methods are limited.*" In order to solve the problem of soft rock rheological experiments, the author's group developed *the Deep Soft Rock Immovable High-temperature Rheological Mechanics Experiment System* (Fig. 21), in an attempt to provide an effective method for nonlinear rheological mechanics experiments.

4.5. Large deformation mechanism of soft rock rockburst

In view of rockburst phenomenon in argillaceous sandstone and coal under high stress, we developed the rockburst mechanics experiment systems (see Figs. 22 and 23). Different types of rockburst experiments are designed, in order to represent the whole rockburst process and understand the complex mechanical phenomenon in laboratory for the first time.

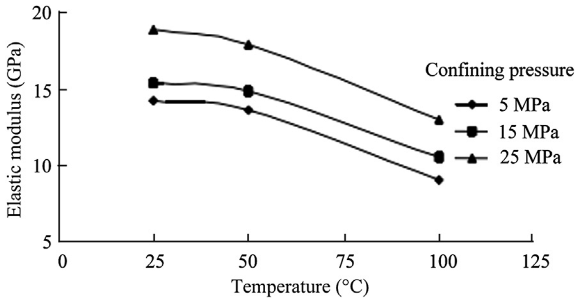


Fig. 18. Relationship between Young's modulus and temperature of rock salt (Gao et al., 2005).

Fig. 19. Experimental system for mechanical properties of deep rocks under high temperature.

The development of crack propagation and energy variation during rockburst can be understood through experiments. It shows that the intensity of rockburst in coal mine is controlled by clay mineral content (Table 5), while the type of rockburst is governed by the bedding plane occurrence (He et al., 2010c, 2012a,b, 2013; He and Zhao, 2013) (Fig. 24). To date, more than 300 rockburst tests were commissioned and conducted on behalf of 7 foreign countries, such as Canada and Italy.

5. Coupling control theory of soft rock roadway

5.1. Deformation mechanism of soft rock excavations

The reasons for rock deformation and instability vary in soft rock engineering, but the dominant factor is basically considered as the complex deformation mechanism of soft rocks. According to the theoretical analysis and various engineering practices, the deformation mechanism of soft rocks can be classified into 3 categories, i.e. physical expansion type, stress dilatancy type and structure deformation type (He, 1992b,c,d,e, 1997, 2011; He et al., 2002). On the basis of rockburst intensity caused by rock deformation, it can be divided into five levels of A, B, C, D and E, a total of thirteen subcategories, as shown in Fig. 25.

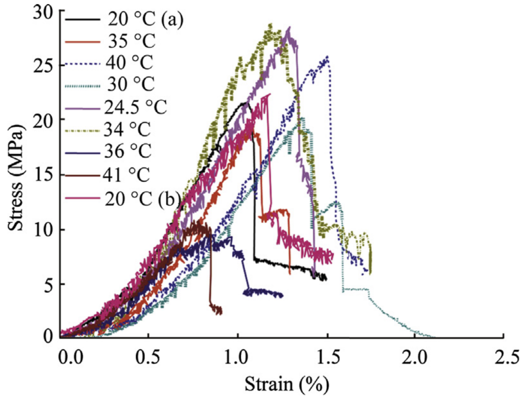
Type I is related to the chemical properties of soft rock and the molecular structure, type II to the forces applied and type III to the combination characteristic of roadway structure and rock mass. Each deformation mechanism has its own characteristics in terms of mineral content, mechanical behavior and structure of rocks. In this regard, the failure characteristics of soft rock roadway are also varied, as shown in Table 6. By field investigation of geological setting in association with laboratory test analysis and theoretical analysis, the type of deformation mechanism can be accurately determined. Deformation mechanism type I is determined by the mineral characteristics and the development of microcracks. Type II is mainly controlled by stress characteristics and site-specific roadway characteristics. Type III is the asymmetric mechanism that is mainly governed by structure plane. Then, it is necessary to identify the mechanical properties of structural plane and/or structural system, and the relationship between occurrence and strike of roadway should also be determined.

5.2. The key technology to soft rock supports in excavations

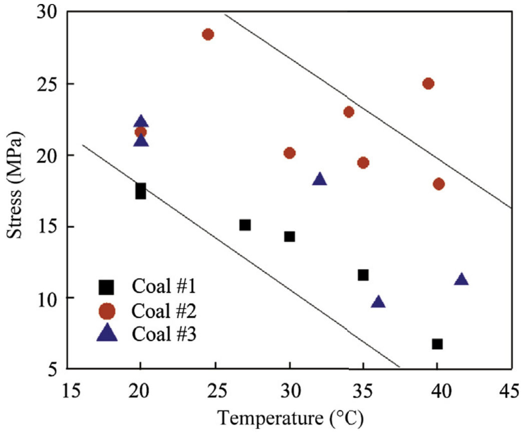
Studies show that deformation mechanism of soft rock tunnels and roadway in mines is usually complex, basically the combination type of more or less of the three types. Therefore, if we can successfully support the soft rock roadway, three key technologies are needed: (1) adequate determination of composite deformation mechanism of soft rocks. (2) Effective transfer of complex deformation mechanism to a single type. (3) Effective use of the conversion technology of complex deformation mechanism.

5.3. The coupling support theory for soft rock roadway

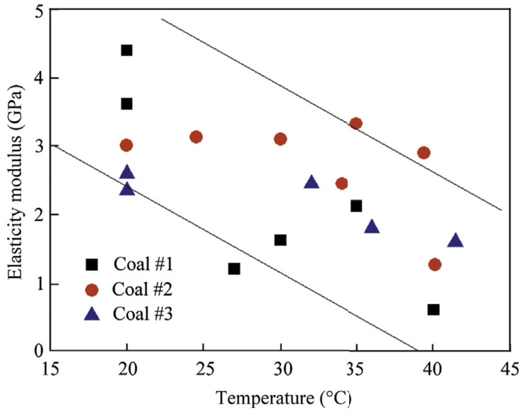
Practice of soft rock roadway engineering shows that, due to the complexity of deformation mechanism of soft rock roadway, the



(a) Stress-strain curves.



(b) Stress-temperature.



(c) Elasticity modulus-temperature.

Fig. 20. Rock mass strength and deformation characteristics under different temperatures.

Fig. 21. High-temperature rheological mechanics experiment system.

first supporting theory formed by the passive support can be represented by steel frame support. It should be noted that steel frame support can only be applied to small deformation ($\varepsilon < 3\%$) of rocks. While the second supporting theory is realized by the active supporting ideas represented by the bolt (cable) supporting, which can be applied at moderate deformation ($\varepsilon = 3\%$–5%). As for the high in situ stress and the mining-induced stress in depth, the stiffness, strength and structure are not well coupled between supporting system and surrounding rocks, so the supporting is always considered to be ineffective. Therefore, the author proposed the theory of coupling support in soft rock roadway in 1997 (He and Gao, 1997), and presented a systematic coupling support theory for soft rock roadway through years of engineering practices and theoretical researches (He and Sun, 2004).

(1) The concept of soft rock roadway coupling support

For the uncoordinated parts with large plastic deformation in deep surrounding rocks, we adopt the coupling between support system and surrounding rocks to limit the deformation of surrounding rocks at failure. At the same time, we can maximize surrounding rocks' bearing capacity to achieve the support integration and load uniformity, and to realize the purpose of the stability of roadway (He and Sun, 2004).

(2) The mechanical effect of coupling support

In order to solve the coupling problem between the various supporting materials and supporting types in the deep roadway, systematic analysis has been performed with the spatio-temporal evolution of interaction between the supporting system and surrounding rocks (He and Sun, 2004; Sun et al., 2007). It should be noted that on the basis of strength improvement of surrounding rocks by bolt supporting, the coupling effect between anchor-mesh and surrounding rock can maximize the bearing capacity of surrounding rocks. When higher stiffness metal-mesh and composite trays are adopted, the effect of coupled anchor-mesh–tray support can be realized, which can fully transform the swelling plasticity and maximize the bearing capacity of surrounding rocks. Applying anchor support to key parts at optimal supporting time can achieve coupling effect of prestressed anchor, and can fully mobilize the strength of surrounding rocks so as to achieve the supporting effect on shallow roadway. According to the different types of soft rocks, passive support of steel frame can be realized by reserving the corresponding deformation space, with the full development of active support using anchor. The targeted coupling effect is to achieve the transformation of high stress in surrounding rocks, namely transfer of the high stress area to low stress area, and to achieve the homogenization of the supporting stress and deformation of surrounding rocks.

Fig. 22. Strain rockburst experiment system (He et al., 2012a,b).

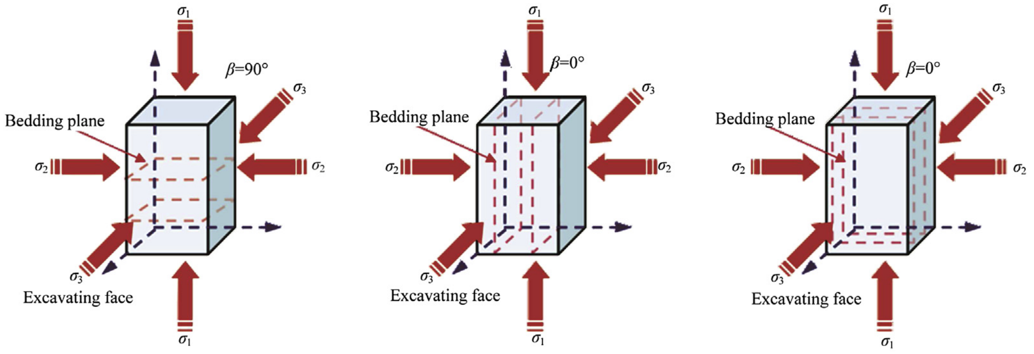
Fig. 23. Impact rockburst experiment system (He et al., 2013).

5.4. *Support design for nonlinear large deformation control in soft rock roadway*

Large deformation in soft rock engineering is the occurrence of significant plastic deformation. The deformation control cannot only rely on parameters selection, but also on the nonlinear large deformation theory (He et al., 2002; Sun et al., 2007). The roadway design for soft rock large deformation must use the method based on soft rock nonlinear mechanics. The mechanical process of large deformation doesn't obey the commonly used superposition principle any longer, and the mechanical equilibrium relationship is closely related to the various load characteristics and the loading

Table 5
Rockburst possibility predicted by clay mineral content.

Clay content (%)	Rockburst tendency	Type of failure
<5	Very high	Rockburst
5–10	High	Rockburst
10–15	Low	Rockburst or extrusion
>15	Very low	Extrusion



(a) Horizontal bedding (low). (b) Vertical bedding (medium). (c) Side of vertical bedding (high).

Fig. 24. Relationship between rockburst and bedding (He et al., 2012a,b).

processes. Therefore, the design cannot merely depend on parameters design, suggesting that the nonlinear mechanical design is much more complex and various factors should be considered. The design process is basically described as follows:

(1) Strategy design: carefully analyze and confirm various load characteristics on rock and soil.
(2) Process optimization design: focus on mechanical countermeasures and process of application. Practices in soft rock engineering prove that the same mechanical measures associated with different loading processes would gain different effects, so optimization design is necessary.
(3) Parameter design: based on the steps mentioned above, an optimal parameter design is needed for the optimum process.

6. Control technology considering coupling effect of constant resistance and large deformation

Aiming at the problem of large deformation control in deep soft rock engineering, the theories of high prestressed, high toughness and strong supporting technologies for different rock projects are proposed (Sun et al., 2006, 2009a). The representative systems are the classical bolt support system (Kang et al., 2010a,b), floor grouting anchor support system (Kan et al., 2011), the coupled dynamic support system (Niu et al., 2011) and the net shell bolting system (Su et al., 2011), and others (Liu et al., 2010; Zhang et al., 2010). In addition, the author's research team self-developed support systems, including the asymmetric coupling support technology (He et al., 2008b, 2009c; Sun et al., 2009b), the floor heave control technology, intersection controlling technology with anchor for large cross-sectional roadway (Li et al., 2010), and series technologies of deep pump station group design (Sun et al., 2010). These technologies are all proposed based on years of practices on stability control in different deep soft rock projects. Engineering practices show that the disasters would occur when rock deformation exceeds the limits of designed support system in the project, therefore the engineering forces, including the forces at failure and the driving forces for development of surrounding rock deformation, must be considered in order to control induced deformation and rock failure, and to avoid disasters that may occur. In this regard, the author's research team has developed a new material, the

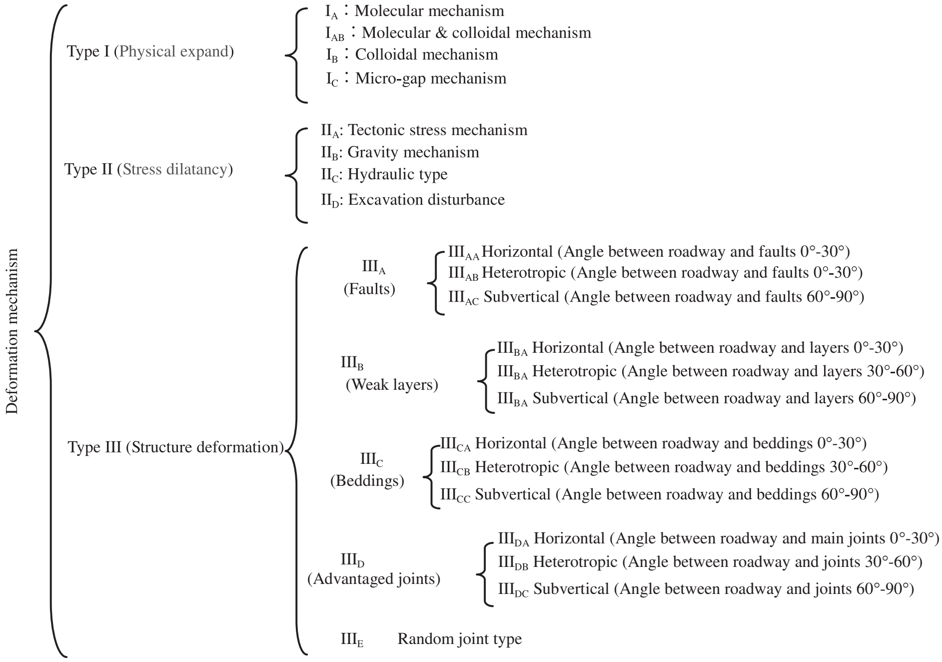


Fig. 25. Deformation mechanism and its classification (He et al., 2002).

Table 6
The deformation mechanism and failure characteristics (He et al., 2002).

Type	Subtype	Controlling factors	Characteristics	Failure characteristics
I	I_A	Molecular mechanism of water absorption, strong absorption ability	Smectite	Weathering, softening, fissure after exposure; causing floor heave, both sides of roadway broken, bring problems in supporting. I_A is the most serious, I_C depends on the distribution.
	I_{AB}	I_A and I_B	I/S type	
	I_B	Colloidal mechanism of water absorption, forming clay surface adsorption layer not in the molecule	Kaolinite	
	I_C	Micro gap – capillary suction mechanism	Micro gap	
II	II_A	Residual tectonic stress	Tectonic stress	Related with trend of roadway
	II_B	Gravity stress	Gravity	Related with depth
	II_C	Underground water	Hydraulic	Related with underground water
	II_D	Engineering excavation disturbance	Disturbance	Designed intensive roadways
III	III_A	Fault, fault zones	Fault type	Collapse, roof caving
	III_B	Weak intercalated layer	Weak layer	Overbreak, flat roof
	III_C	Bedding	Bedding type	Inerratic serrated
	III_D	Advanced joints	Joint type	Irregular serrated
	III_E	Random joints	Random joint	Chipping

constant resistance and large deformation (CRLD) bolt/anchor, for rock supporting, followed by corresponding coupling support technologies.

6.1. New material with negative Poisson's ratio effect for support engineering

In order to avoid the misfits in traditional support materials for rock large deformation and failure, the CRLD bolt/anchor with special structural function is developed (Fig. 26). This new material shows a negative Poisson's ratio effect during supporting when using the CRLD device. The CRLD bolt/anchor can resist large deformation under constant resistance conditions, and it has the capacity to endure impact resistance and to absorb large deformation energy.

Laboratory results of tensile tests show that the CRLD material can elongate with large tensile deformation under constant support resistance, which is adapted to the slowly increasing large deformation and can effectively control the stability of roadways. The CRLD device becomes thicker after tensile tests, suggesting the negative Poisson's ratio effect of this material (Figs. 27 and 28).

(a) Constant resistance of 200 kN, and the maximum deformation of 1000 mm.

(b) Constant resistance of 350 kN, and the maximum deformation of 1000 mm.

Fig. 26. The developed CRLD bolts/anchors (He et al., 2009c).

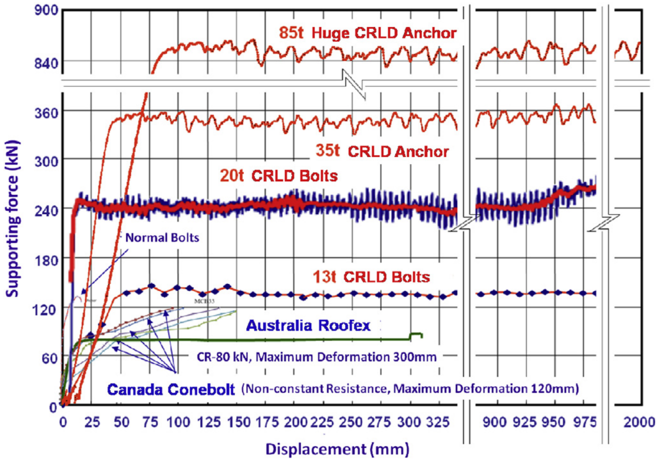


Fig. 27. Mechanics performance comparison (He et al., 2012a,b).

The results of dynamic impact loading experiment show that the CRLD anchor can keep constant under the action of repeated impact loading (Fig. 29), and can absorb impact energy during rock mass deformation. Accordingly, the energy balance equations between CRLD bolts and surrounding rocks have been established.

6.2. CRLD supporting technology for soft rock engineering

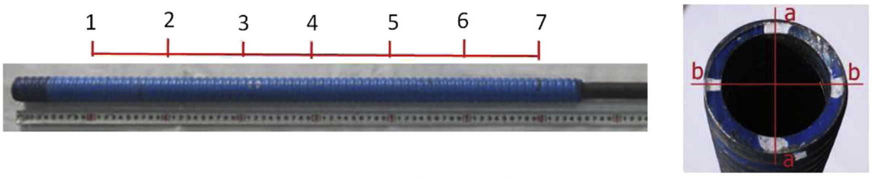
Combined with the development of CRLD bolt/anchor, a new concept regarding safe energy release by CRLD material is put forward, with which the mechanical properties of protecting structure should be rigid and flexible, i.e. the structure with enough deformability for energy release and enough constant resistance to control the deformation of surrounding rocks.

On this basis, the concept of "large deformation resistance + high prestressed anchor supporting" is also proposed, which can be used for large deformation control of soft rocks and the landslide control.

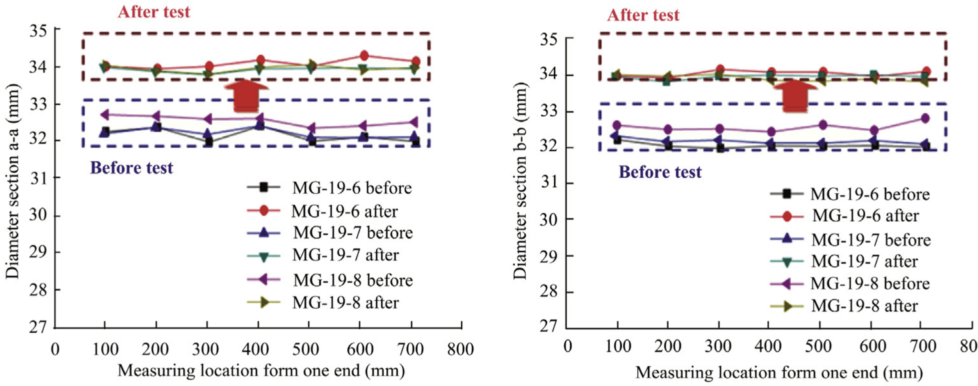
The CRLD supporting mechanism has been revealed through the underground in situ test. The advanced slitting of roof energy release, mining without coal pillars, stress concentration and tectonic stress release can be adequately controlled, with which the comprehensive countermeasures of rockburst are developed (Fig. 30). The technology has been successfully applied to many projects in China, where the mining areas suffer from disasters of rock large deformation.

6.3. Engineering application

CRLD coupled supporting technology for soft rock engineering has been applied to various coal mines, such as Shajihai coal mine (Xinjiang Uygur Autonomous Region), Longkou mine (Shandong Province), Shenyang Coal Group (Liaoning Province), Furong mine (Sichuan Province), Pingliang deep coal mine (Gansu Province). A total length of 49,735 m construction roadways that suffer soft rock large deformation disaster during the last 10 years was reinforced with CRLD bolt/anchor, and direct economic benefits reach RMB 641.81 million compared to typical applications, as shown in Table 7.



(a) Bolt sample for tensile tests.



(b) Diameter variation at section a-a.

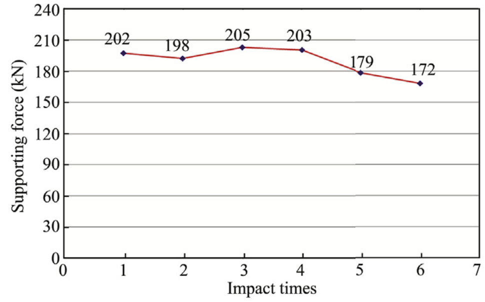
(c) Diameter variation at section b-b.

Fig. 28. Negative Poisson's ratio effect of CRLD bolt/anchor (He et al., 2012a,b).

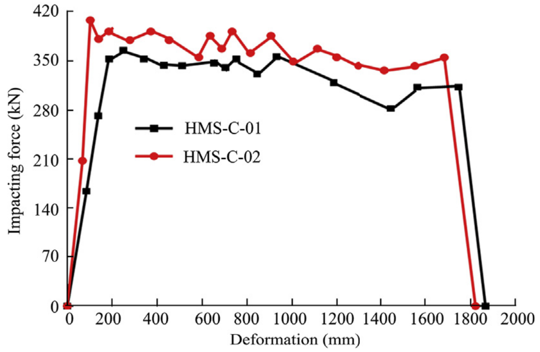
7. Conclusions

Researches on soft rock mechanics and technology are associated with development of resources exploration and disasters controlling, especially the control of soft rocks' large deformation. For more than half a century, Chinese scholars and engineers of rock mechanics and mining have made great efforts to the development of theories and technologies of soft rock controlling in terms of engineering practices. Accordingly, fruitful researches in concept and classification of soft rocks, deformation mechanisms, supporting technologies and other technical countermeasures are achieved, which are an important contribution to safe and efficient development of mineral resources and rational and efficient use of underground space in China.

With the further explorations of geotechnical engineering, there will be more new scientific and technical issues about the disaster control of soft rock large deformation. With the efforts of experts and scholars in the field of soft rock mechanics across the world, more new theories, technologies, materials, and design methods would be observed in the near future.

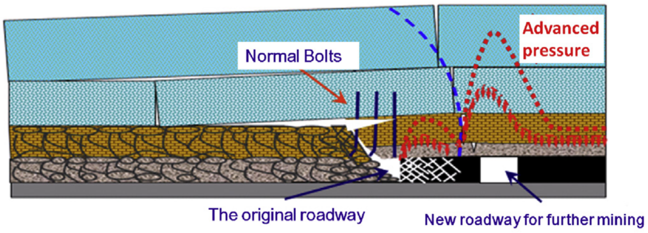


(a) Impact experiment curve of CRLD bolt.

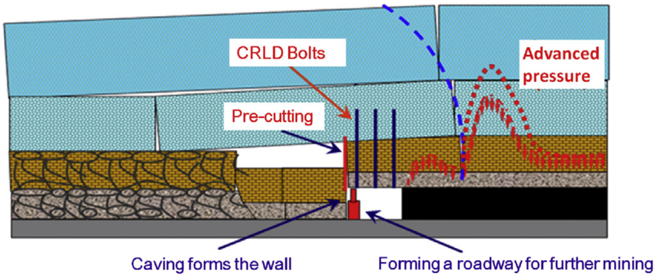


(b) Impact experimental curves of CRLD anchor.

Fig. 29. The impact dynamics features of CRLD bolt/anchor (He et al., 2012a,b).



(a) Conventional coal pillar mining.



(b) Top pressure relief mining without coal pillar.

Fig. 30. Mining technologies comparison.

Table 7
The engineering application of soft rock supporting technology in China.

No.	Location	Projects	Year	Length (m)	Benefits ($\times 10^6$ RMB)
1	Shajihai coal mine	Large section roadways, crossheading	2009–2014	13,000	140.23
2	Xuzhou Coal Mine Group	Large section roadways, crossheading	2004–2008	8756	275.62
3	Datun Coal and Electricity Company	Large section roadways, crossheading	2004–2010	2183	31.47
4	Hegang coal mine	Large section roadways, crossheading	2005–2007	1580	5.87
5	Hebi coal mine	Large section roadways, crossheading	2005–2009	960	3.20
6	Shenyang Coal Group	Crossheading	2009–2014	420	1.50
7	Tiefa Energy Group	Large section roadways, crossheading	2009–2013	12,120	130.85
8	Yanzhou, Shandong	Roadways, crossheading	2002–2010	820	7.51
9	Longkou coal mine, Shandong	Crossheading	2011–2014	410	1.20
10	Liuhai coal mine, Shandong	Ingate, roadways	2004–2007	3470	14.56
11	Furong coal mine, Sichuan	Crossheading	2008–2014	3420	10.44
12	Jiayang coal mine, Sichuan	Crossheading	2013–2014	1296	8.90
13	Dazhu coal mine, Sichuan	Crossheading	2011–2013	980	7.68
14	Xin'an coal mine	Large section roadways	2010–2012	320	2.78
Total				49,735	641.81

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