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Mechanical Properties and Deformation Failure Characteristics of Anthracite under the Conditions of Loading-Unloading

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Abstract: Based on the conventional triaxial and loading-unloading mechanical experiments, the strength characteristics, the deformation and failure characteristics and shear parameters of the anthracite under two kinds of stress path were analyzed. With the increase of initial confining pressure, anthracite peak strength increase under two kinds of stress path. Compared with the conventional triaxial experiment, internal friction angle increases, the cohesion decreases under loading-unloading conditions; under the same initial confining pressure, the compressive strength is reduced, thus easier to failure. In loading-unloading experiments, unloading confining pressure rate slower, the greater the degree of deformation and failure of coal specimen; the faster the rate of unloading confining pressure, the smaller the coal specimen fracture strength, and the shorter the time required, , the coal specimen more easy to failure. In the process of unloading confining pressure, the deformation modulus of coal increased first and then decreased, the Poisson's ratio continued to increase. Compared with the conventional three axis experiment, under the loading-unloading experimental conditions, the difference deformation modulus E_{50}-E_c and the difference Poisson's ratio μ_c-μ_{50} have a larger increase, and it demonstrated a greater degree of deformation and failure in loading-unloading experiments.

Keywords: *Anthracite; Loading-unloading; Mechanical Properties; Deformation and Failure*

1. Introduction

The excavation of coal rock mass of underground coal mine caused the stress redistribution surrounding coal rock mass, for the performance of the loading and unloading of coal rock mass [1]. With the increase of buried depth of coal rock, geostress increases, performance for different state of hydrostatic pressure. Study of coal rock mechanical characteristics of different confining pressure under the conditions of loading-unloading, to grasp the change rule of coal rock mass mechanical coal mining process, have practical significance for guiding engineering design.

Due to the limitation of complexity and conditions of coal mine underground, often through the experimental study of mechanical characteristics of coal rock mass of loading and unloading process. In the current study, mainly on uniaxial and conventional triaxial experiment, but in the process of coal mining, axial pressure and confining pressure is constantly changing, should be simulated according to the actual circumstance of the coal mine. Unloading confining pressure in the process of axial compression is different with the results of conventional triaxial experiment, through dynamic loading and unloading process is more realistic.

2. State of the art:

Coal and rock damage both may be caused by the axial stress increases can also be caused by unloading confining pressure. In the present study, conventional triaxial to be studied more. Robinson [2] thought the rock strength increased and the mode of failure changed as the confining pressure increase by triaxial compression experiment. Serdengectip [3] studied triaxial stress-strain characteristics under the influence of strain rate and temperature of rock. Brace [4] studied dilatancy phenomenon during granite triaxial experiments, found that the specimen crack initiation direction parallel to the direction of maximum compression. Hobbs [5] measurement stress and strain characteristics of rock specimen under the influence of confining pressure, gives the corresponding failure eoretical models. Logan [6] found that rock limited bearing load increase with the increase of confining pressure, the limited bearing loads is proportional to the strain rate. With the increase of confining pressure, give priority to with brittle deformation. Mogi K [7] through the triaxial stress experiment, and compared with General Von Mises criterion, when the strain energy deformation reaches a critical value, the rock will fracture yield, and increases with the increase of average effective stress.

Horizontal stress increase and vertical stress decrease surrounding roadway caused by excavation. Strength criterion, roadway deformation, disturbed zone and excavation rate were studied about the roadway excavation [8, 9, 10, 11]. Usually triaxial experiments are adopted to simulate the roadway excavation process. Loading-unloading Triaxial experiment research coal and rock mechanics properties under the influence of different initial confining pressure, loading-unloading rate and loading-unloading path [12, 13, 14]. And experiments have many observation methods, such as HS(high speed) camera, computed tomography (CT), scanning electron microscopy (SEM), nuclear magnetic resonance (NMR) and acoustic emission, etc. [15,16,17,18]. And in coal triaxial mechanics experiment, Xu [19] studied mechanical properties and seepage characteristics of coal under loading-unloading conditions. Yin [20] studied the mechanical properties of coal and seepage characteristics under loading-unloading conditions consider gas pressure ground stress and stress path factors.

Unlike conventional triaxial experiment, loading-unloading experiment is in axial compression and unloading confining pressure at the same time, this is consistent with the stress variation ahead of mining face, can reflect the real situation. Because of mechanical characteristics of conventional triaxial experiment and loading-unloading experiment is different, so loading-unloading experiment need to be designed and studied. In view of the problem that the mechanical property is not clear in the process of loading-unloading, the mechanical properties of coal is analyzed by loading-unloading experiment in this paper.

3. Methodology:

3.1. Experiment apparatus:

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The experiment uses the TAW-2000 experimental rock mechanics machine. The experimental apparatus is shown in Figure 1. The maximum axial force: 2000kN; Experimental force accuracy: ± 1%; Effective measuring range: 0-2000kN; Maximum axial displacement: 50mm; Displacement accuracy: ± 0.5%; Axial deformation measuring range: 0-10mm; Lateral deformation measurements range: 0-5mm; Deformation measurement accuracy: ± 1%.

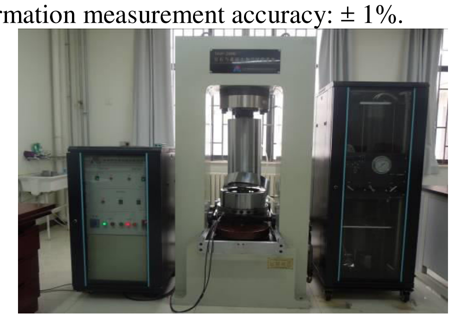


Fig.1. *TAW-2000 rock mechanics experimenting machine*

3.2. Specimens making:

Coal density between 1.43-1.46 g-cm^3. Due to the dense hard and coal seam structure simple, combined with field in simple structure, and shear force is small, block rate is high.

Specimen making steps is shown in Figure2.

(1) First, take a rectangular shape, a certain thickness of a number of coal blocks in the coal mine.

(2) Use the rock drilling machine drill the coal core.

(3) The use of double-face millstone get coal core drilling machine for grinding.

(4) Polished Φ50mm × 100mm standard specimen, specimen height and flatness of the end face of rock mechanics testing to meet the requirements.

Fig.2. *Specimen making*

3.3. Experiment program:

(1) Program 1: conventional triaxial experiment. Experiments were performed on a TAW-2000 experimental rock mechanics machine. Conventional triaxial experiments under different confining pressure, confining pressure are respectively 2MPa, 4MPa, 6MPa, 8MPa, and loading rate of 0.5MPa-s. Add axial pressure and confining pressure to the hydrostatic pressure ($\sigma_1 = \sigma_3$) state, constant confining pressure; continues to add axial pressure to coal specimen failure.

(2) Program 2: Loading - unloading experiment. This paper refers to the loading-unloading conditions mean that load axial pressure and unload confining pressure meantime. Loading - unloading triaxial experiments under different initial confining pressure and unloading rate, initial confining pressure are respectively 4MPa, 6MPa, 8MPa, loading-unloading rate and experiment program as shown in Table 1. Axial pressure and confining pressure to the hydrostatic pressure ($\sigma_1 = \sigma_3$) state, add axial pressure and unloading confining pressure meantime to coal specimen failure. In this experiment, in order to reduce the effects of discreteness, select surface intact specimens, and accordance with the rules in the operation. Stress path as shown in figure 3.

Table 1: *Experiment program*

Experiment program	Serial number	Confining pressure (MPa)	Loading rate (MPa-s)	Unloading rate (MPa-s)
Program 1	CSZ-1	2	0.5	-
	CSZ-2	4	0.5	-
	CSZ-3	6	0.5	-
	CSZ-4	8	0.5	-
Program 2	JXZ-1	4	0.192	0.024
	JXZ-2	6	0.192	0.024
	JXZ-3	8	0.192	0.024
	JXZ-4	8	0.192	0.012

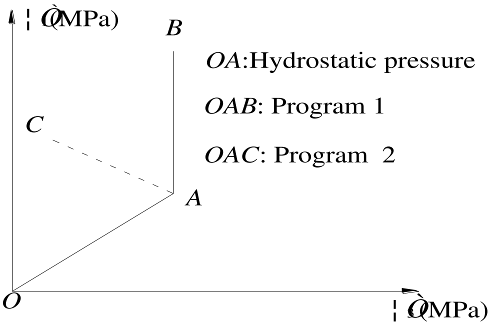


Fig.3. *Stress path*

4. Methodology:

4.1. Experiment apparatus:

Under the condition of conventional triaxial compression, triaxial compression strength of coal samples with a linear relationship with confining pressure (not including uniaxial compression), coal and rock failure in accordance with Coulomb strength criterion.

$$\tau = C + \sigma \tan\varphi \tag{1}$$

Where, τ the shear is stress; σ is the normal stress; C *is* the cohesion of the material and φ is the angle of internal friction of the material

According to the experiment results, get the anthracite strength curves; adopt pair of straight line type curve of strength, strength curve as shown in Fig.4.

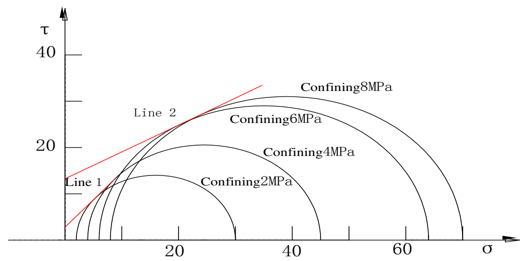


Fig.4. *Strength curves of anthracite*

Firgure4 shows, when the confining pressure is low (confining pressure 2MPa, 4MPa), line 1 is used to describe the relationship between shear stress and normal stress. The cohesion is 2.62MPa, Angle of internal friction of 50 °; When the confining pressure is high(6MPa, 8MPa), line 2 is used to describe the relationship between shear stress and normal stress, the cohesion is 13.26MPa, internal friction angle is 30 °.

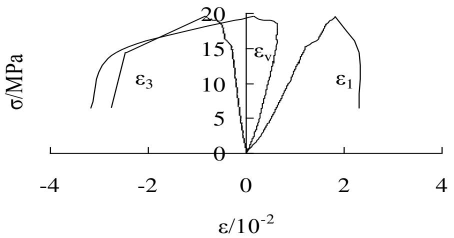
When confining pressure is low, shear stress and normal stress relational expression is:

$$\tau = 2.62 + \sigma \tan 50° \tag{2}$$

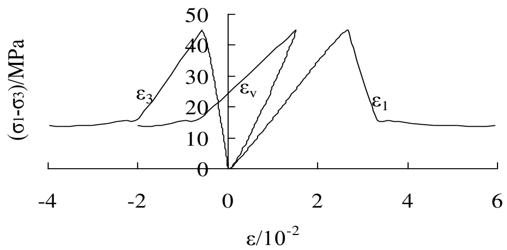
When confining pressure is high, shear stress and normal stress relational expression is:

$$\tau = 13.26 + \sigma \tan 30° \tag{3}$$

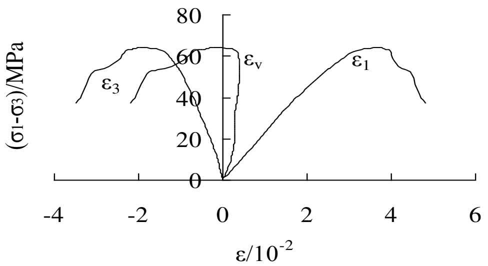
The analysis results show that anthracite at low confining pressure and high confining pressure exhibit different strength characteristics. High confining pressure makes the peak strength increases, the cohesion increases, and the internal friction angle decreases. By slope angle $\theta = \frac{\pi}{4} + \frac{\varphi}{2}$, slope angle decreases with the angle of internal friction decreases. Coal specimen deformation failure through three stages: elastic stage, plastic yielding stage and failure stage. In the elastic stage, specimen axial linear compression, after plastic deformation and yielding, the specimen fracture later. In the conventional triaxial experiments, the peak strength of CSZ-1～CSZ-4 was 30.1 MPa, 44.9 MPa, 64.0 MPa, 70.2 MPa. The peak strength increases with the increase of confining pressure. With the increase of confining pressure, Coal specimen brittleness decrease, plasticity increase. Stress-strain curves of conventional triaxial under different confining pressure as shown in Figure5.



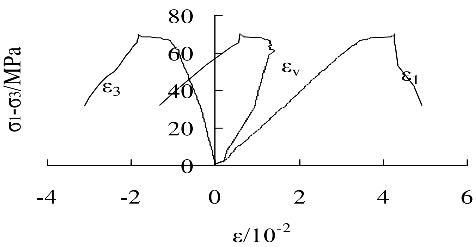
(a) CSZ-1



(b) CSZ-2



(c) CSZ-3



(d) CSZ-4

Fig.5.*Stress-strain curves of conventional triaxial experiment*

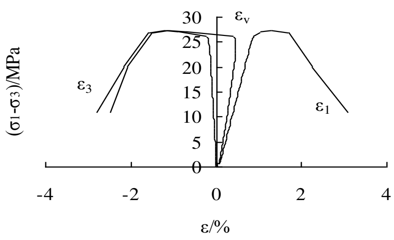
In conventional triaxial experiments, confining pressure has greater impact on coal specimen. With the increase of confining pressure, the elastic compressive deformation of coal specimen increases, and the axial deformation increases. When confining pressure is 2MPa, coal specimen is given priority to shear failure, has obvious shear failure surface. When the confining pressure is 4MPa, there is more than one failure surface, and have tensile crack and shear crack at the same time. With the increase of confining pressure (6MPa), show conjugate shear failure. Along with the confining pressure continues to increase (8MPa), specimen has no obvious failure surface, but showing the bulging phenomenon. As can be seen from the deformation and failure characteristics of the confining pressure, the greater the confining pressure, the more intense the failure. Coal specimens' failure photos of uniaxial and triaxial compression are shown in Figure6.

(a) CSZ-1 *(b) CSZ-2* *(c) CSZ-3* *(d) CSZ-4*

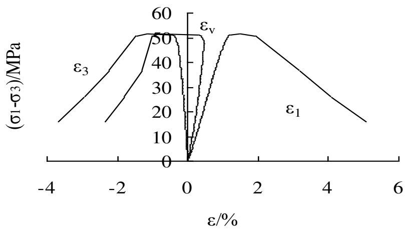
Fig.6. *Coal specimen failure photos of conventional triaxial experiment*

4.2. Stress-strain analysis of loading-unloading experiment:

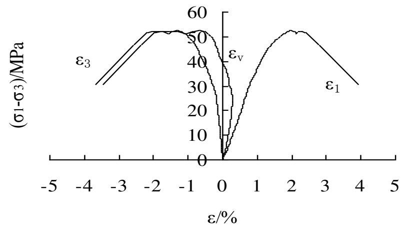
Loading-unloading experiment is that load axial pressure while unload confining pressure under the certain state of hydrostatic pressure in the process of triaxial compression experiment. In the initial stage of the experiment, the axial deformation increases linearly; when the confining pressure is reduced to a certain value, the coal specimens close to failure. When coal specimen close to failure, there is a vibration platform stage, and axial deformation increases approximately level. Then confining pressure continues to decline, coal specimens rapidly failure, and the stress-strain curves can show the coal specimens with sudden failure. Loading-unloading stress-strain curves as shown in Figure 7.



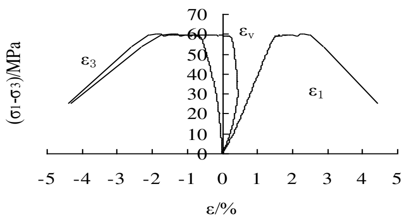
(a) CSZ-1



(b) CSZ-2



(c) CSZ-3



(d) CSZ-4

Fig.7. *Stress-strain curves of loading-unloading triaxial experiment*

Compressive strength of anthracite increases with the increase of initial confining pressure under loading-unloading conditions, while the larger the initial confining pressure, the more axial deformation of coal specimen. From stress- axial deformation curve in Figure 6, the slope of the curve increases with the initial confining pressure increasing, the deformation modulus increases with the increase of initial confining pressure. Compared with the conventional triaxial experiment, the same initial confining pressure conditions, coal specimen deformation is greater in loading-unloading experiment, and coal specimen showed strong expansion characteristics.

Coal specimen's failure photos under loading-unloading conditions as shown in Figure 8. Compared with the conventional three axis experiment, under the condition of unloading coal specimen is given priority to with tensile damage, no obvious smooth fracture surface. Due to large deformation, coal specimen is more broken. With the increase of initial confining pressure, coal specimen deformation is large. When the initial confining pressure are 8MPa, unloading confining pressure rates were 0.024MPa - s and 0.012MPa - s, contrast JXZ -3 and JXZ -4, JXZ -4 failure more intense. Therefore, the slower rate of unloading confining pressure, the greater the degree of coal deformation and failure of the specimens.

(a) JXZ-1 (b) JXZ -2 (c) JXZ -3 (d) JXZ -4

Fig.8. *Coal specimen failure photos of loading-unloading triaxial experiment*

4.3. The mechanical properties of anthracite under two kinds of stress path:

In order to study of mechanical characteristics of anthracite, deformation modulus and Poisson's ratio to be used to describe the stress strain state of the specimens. Strictly speaking, Poisson's ratio is the ratio of the lateral strain and axial strain and usually used to describe the elastic stage. Poisson's ratio is called a lateral expansion coefficient more accurate in plastic stage. Poisson's ratio can be calculated by

$$\mu = \varepsilon_3 / \varepsilon_1 \quad (4)$$

Where μ is the Poisson's ratio; ε_1 is the lateral deformation; ε_3 is the axial deformation.

$$E = (\sigma_1 - 2\mu\sigma_3) / \varepsilon_1 \quad (5)$$

Where E is the deformation modulus; σ_1 is the axial stress; σ_3 is the lateral stress.

In Table 2, respectively, E_{50} and μ_{50} is the deformation modulus and Poisson's ratio as the peak strength of 50%; E_c and μ_c is the deformation modulus and Poisson's ratio when the coal specimen failure. In the elastic stage, deformation modulus and Poisson's ratio were similar under the two kinds of program, and deformation modulus of program 2 is slightly lower than program 1. And under the same initial confining pressure, and deformation modulus E_c of program 2 have larger decline than program 1 and lateral expansion coefficient is 2-3 times program 1.

Compared with the conventional triaxial experiment, in the loading-unloading experiment, due to the specimen damage has experienced a long process, deformation modulus continue decrease, so the deformation modulus difference E_{50} - E_c is larger. Compared with Program 1, the Poisson's ratio difference Poisson μ_c - μ_{50} increases obviously of Program 2, and about 2-10 times Program 1. It shows that the lateral deformation of the specimen dominant than axial deformation in loading-unloading experiment, compared to axial deformation, lateral deformation of coal specimens changes larger and therefore the Poisson's ratio up sharply when the specimen failure.

Table 2: *Comparison of mechanical properties of anthracite under two kinds of stress path*

Stress path	Serial number	$\sigma_1-\sigma_3$ (MPa)	E_{50} (GPa)	μ_{50}	E_c (GPa)	μ_c	E_{50} - E_c (GPa)	μ_c - μ_{50}
Program 1	CSZ-1	30.1	3.74	0.26	2.30	0.54	1.44	0.28
	CSZ-2	44.9	3.38	0.17	3.37	0.22	0.06	0.05
	CSZ-3	64.0	4.42	0.34	3.25	0.41	1.17	0.07
	CSZ-4	70.2	4.10	0.24	3.45	0.45	0.65	0.21
Program 2	JXZ-1	27.3	2.90	0.18	1.58	0.94	1.33	0.77
	JXZ-2	39.5	3.54	0.23	2.01	0.76	1.54	0.53
	JXZ-3	52.6	3.91	0.30	2.26	0.89	1.65	0.59
	JXZ-4	60.2	3.80	0.22	1.86	0.90	1.95	0.68

By the axial stress σ_1 and lateral stress σ_3, Mohr-Coulomb criterion is expressed as [21]

$$\sigma_1 = b + k\sigma_3 \quad (6)$$

Where, *b*, *k* is the strength coefficient, available cohesion and internal friction angle to represent. The slope *k* and intercept *b* are used to calculate internal friction Angle and cohesive. Internal friction Angle ϕ and cohesive C can be calculated as

$$\phi = \arcsin \frac{k-1}{k+1} \quad (7)$$

$$C = \frac{b(1-\sin\phi)}{2\cos\phi} \quad (8)$$

The relationship between the axial stress and confining pressure curve in conventional triaxial and loading-unloading experiment when the coal specimen failure as shown in figure 8 and figure 9.

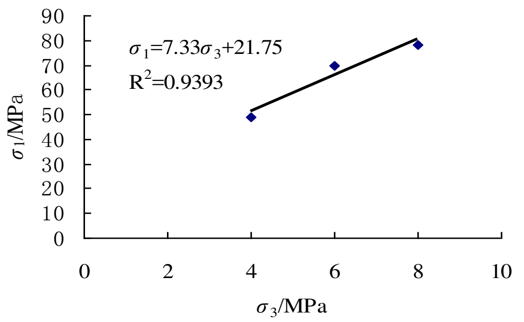


Fig.8. *Experiment axial stress and confining pressure curve of conventional triaxial experiment*

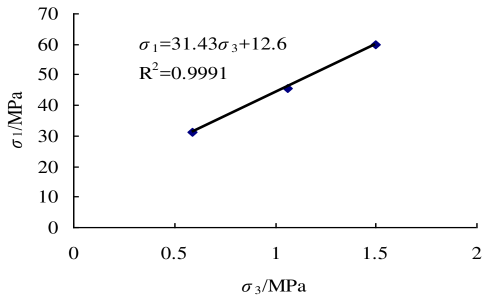


Fig.9. *Experiment axial stress and confining pressure curve of loading-unloading triaxial experiment*

***Table 3**: The shear parameters of anthracite under two kind of stress path*

Experiment program	*k*	*b*	ϕ-°	C-MPa
Program 1	7.33	21.75	49.45	16.38
Program 2	31.43	12.60	69.78	10.56

Compared with the conventional triaxial experiments, under conditions of loading-unloading, internal friction angle increases, the cohesive reduction, which the internal friction Angle increased by 29.1%, and cohesive force is reduced by 35.5% (as shown in table 3). And failure surface show the complicated and rough, broken characteristics, it can be seen from the failure photos. The greater the internal friction angle, the greater the friction between the particles inside the coal specimens, and the more prone to large deformation at failure. Cohesion is the attraction between the molecules within the material, the smaller the cohesion, the material more easily damaged.

4.4. The deformation modulus and Poisson's ratio changes with confining pressure unloading:

In the process of loading and unloading experiments, unloading confining pressure cause deformation modulus and Poisson's ratio change (Figure 10, Figure 11). Different initial confining pressure and discharge rate, the confining pressure and deformation modulus curve, confining pressure and Poisson's ratio curve are also different.

Initial stage of unloading confining pressure, confining pressure and deformation modulus of the approximate linear relationship, the deformation modulus increases with the decreasing of confining pressure, with the confining pressure continues to decrease, the specimen began expansion, deformation modulus started to decrease after reaching the peak; the higher the initial confining pressure, the deformation modulus of the more obvious changes, that is, the difference of deformation modulus is greater. The faster unloading confining pressure, deformation modulus and modulus difference is smaller and the shorter the time required to failure. Loading-unloading conditions, the initial confining pressure 8MPa; unloading rate was 0.012MPa - s and 0.024MPa - s, the specimen failure time are respectively 314s, 271s.

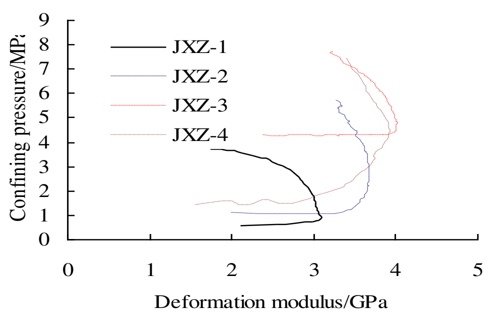


***Fig.10.** The change of deformation modulus of unloading confining pressure process*

The initial stage of loading-unloading, the relationship between Poisson's ratio and confining pressure also exist a linear stage. Poisson's ratio decrease with confining pressure increases, with the continued decrease of confining pressure than non-linear increase when the specimen near failure. Poisson's ratio in oscillation platform period is nearly level increased, and Poisson's ratio changes greatly. And the higher the initial confining pressure, curve at the initial stage of the more obvious nonlinear characteristics. Unloading confining pressure faster, slower Poisson's ratio increases.

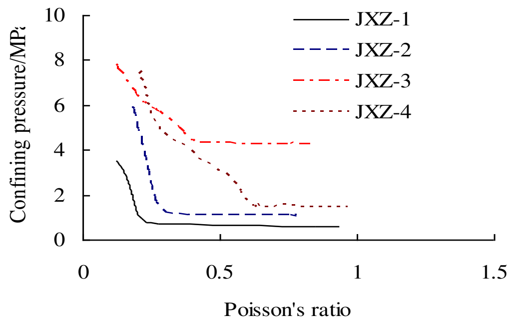


***Fig.11.** The change of Poisson's ratio of unloading confining pressure process*

5. Conclusions:

This paper firstly studied the conventional triaxial and loading-unloading mechanical experiments, then analyzed the strength characteristics, the deformation and failure characteristics and shear parameters of the anthracite under two kinds of stress path are, the main conclusions are drawn as follows:

(1) With the increase of initial confining pressure, anthracite peak strength increase under two kinds of stress path. In conventional triaxial experiments, under low confining pressure, the coal specimen is given priority to with shear failure, and there are obvious shear failure surface. With the increase of confining pressure, failure characteristics appeared tensional failure, "X" type conjugate failure, bulging failure. Compared with the conventional triaxial experiment, in the laoding-unloading experiments, coal specimen damage is more severe, broken degree is bigger, and the deformation increases with the increase of initial confining pressure.

(2) Compared with the conventional triaxial experiment, under the same initial confining pressure, the compressive strength is reduced of loading-unloading conditions, thus easier to failure; and internal friction angle increases, the cohesion decreases at the same time. Unloading confining pressure rate slower, the greater the degree of deformation and failure of coal specimen; the faster the rate of unloading confining pressure, the smaller the coal specimen fracture strength, and the shorter the time required, , the coal specimen more easy to failure.

(3) In the process of unloading confining pressure, the deformation modulus of coal increased first and then decreased, the Poisson's ratio continued to increase. Compared with the conventional three axis experiment, under the loading-unloading experimental conditions, the difference deformation modulus E_{50} - E_c and the difference Poisson's ratio μ_c - μ_{50} have a larger increase, and it demonstrated a greater degree of deformation and failure in loading-unloading experiments.

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