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Experimental Study on the Rupture Process and Hydraulic Pressure Critical Condition about Two Kinds of Typical Raw Coal Sample Loaded by High Pressure Water

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Abstract: Hard and soft coal raw samples of the same coal mine are manufactured successfully with "twice moulding", The rupture process of two typical raw coal sample are studied with self-designed "simulation experiment device about the rupture process of raw coal samples containing gas loaded by high pressure water". Research results show that under the action of high pressure water, brittle deformation appears to the hard raw coal samples, destruction process of "crack initiation-multiple fracturing-completely broken" occurs. Finally samples are broken absolutely, internal cracks is expanded and derived fully, extended fracture network forms, to the soft raw coal samples, plastic deformation appears internally, destruction process of "crack initiation-compaction-occlusion" occurs, samples are compacted absolutely, cracks can not be fully penetrated and extended. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Twice moulding, Hard coal, Soft coal, Loaded by high pressure water, Rupture process, Critical condition.

1. Introduction

The hydraulic fracturing for coal body is a gas control technical measure that is feasible theoretically and can be operated in practice, the effect about the gas pressure relief and the coal seam permeability improvement is associated with the physical and mechanical characteristics of coal body closely under high pressure water [1-5]. Vast theoretical research and field practice have proved that the effect of hydraulic fracturing for coal body is not only associated with the process and way of fracturing but also with the fracturing features of coal seam to a great degree, that is to say, the coal body whether or not can generate deformation and fracture that is conducive to the increase of the gas permeability under high pressure water [6-8]. At present, the reason why hydraulic fracturing technology did not obtain ideal effect in many mines is that the fracturing feature of objects is not clear [9-10]. If just follow the measures and experience of successful case not considering the actual condition about coal seam, the effect of hydraulic fracturing will be severely affected, even the final failure will appear.

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The simulation experiment about rupture process of raw coal samples loaded by high pressure water has certain theoretical value for reducing unnecessary engineering investment and the blindness in the process of technology implementation, improving the success probability of hydraulic fracturing measure and the coal seam gas extraction effect effectively, lowering the gas pressure and gas content of coal seam, ensuring the longevity and continuity of coal mine safety production.

2. The Production of Raw Coal Samples

Experimental coal sample can be divided into type coal sample and raw coal sample. Type coal sample can be made by grinding raw coal into small particles and adding a certain amount of bonding material, raw coal sample is got by drilling with core drill or mechanical processing [11]. Generally, type coal sample is made with core drill directly, but the making of soft raw coal sample is difficult by this way because of the strong geological structure in the process of its formation. Therefore, type coal sample is universal used to the study of the soft coal. However, there exist certain differences differences between type coal samples and raw coal samples in structure characteristics, it is difficult to reflect the actual characteristics of soft coal [13-15]. It is necessary to take raw coal sample as the research object that can more reflect the characteristics of the coal body itself. In this experiment, for the comparability of experimental results, hard and soft raw coal samples are collected from Daning coal mine.

2.1. Specimens Manufacture and Raw Coal Samples Collection of Soft and Easy Broken Coal (Soft Coal)

Because the vibration of the core drill during sampling, moreover the soft coal is floppy and fragile, the samples will rupture even crush, integrated raw coal samples can not be obtained. Therefore, the raw sample of soft coal is hard to get with core drill [16]. It can be make with “twice moulding” method like this: collect large raw coal with regular shape underground and carry it to the ground, at last, process the coal into the designed size.

1. Collection of big size coal. Firstly, cut out a regular coal cube approximately, afterwards, cover the cube with the processed tin box (the specification is 200 mm × 200 mm × 200 mm, as shown in Fig. 1), the gap between coal body and tin box is filled with polyurethane, in the end, cut off the bottom of the coal cube with hand saw. Carry the coal cube (as shown in Fig. 2.) to the ground and seal it with wax.

2. Mechanical processing of coal body.

1) Drill a hole in the polyurethane layer with drilling tool close to the tin box, make saw blade through the hole and fixe it on the saw bow. Cut along the polyurethane layer slowly, take out the polyurethane between coal body and tin box.

2) Remove the tin box, cut the coal body into cuboid (the specification is 120 mm × 120 mm × 150 mm), smooth the two ends. In order to prevent the coal sample rupture, sawing and grinding operation process should be steady as much as possible.

Fig. 1. The processed tin box.

(a) soft coal body (b) hard coal body

Fig. 2. The large degree raw coal.

3) Cut off the four sides of the cuboid coal body, making it into a kind of analogous cylindrical, polish highlight edges on the analogous cylindrical, making it as smooth as possible. After these two steps, the coal sample is basically close to the cylinder. The size of polished raw coal samples will be smaller due to grinding friction. With stainless steel, process a cylinder grinding apparatus that the inside diameter is 50 mm, the height is 100 mm, both the above and below are open, as shown in Fig. 3. Put the coal samples into the cylinder, replenishing it into standard coal samples(the specification is Φ50 mm × 100 mm) with silicate glass glue.

4) Put grinding apparatus in a cool and dry room, after the silicate glass glue becoming solidification (general 2 to 3 days), remove the top and bottom cover, push out the coal samples from the grinding apparatus with great care, polish away the residue colloid in the samples with rough type gauze, the standard soft coal samples are successful to be made, as shown in Fig. 4.

2.2. Specimens Manufacture and Raw Coal Samples Collection of Hard Coal

Although the hard raw coal sample is relatively easy to obtain by core drilling method, for comparison with the soft raw coal samples, both of the two type samples are gained adopting “twice moulding” method, as shown in Fig. 4.

Fig. 3. The stainless steel cylinder.

(a) soft coal samples.

(b) hard coal samples.

Fig. 4. Raw coal samples.

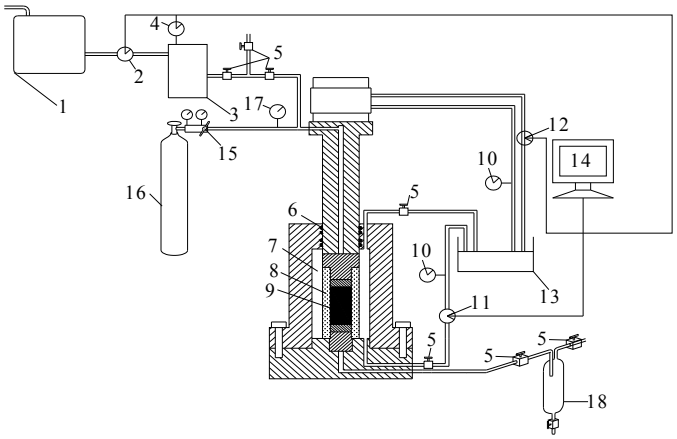
3. Simulation Experiment Device about the Rupture Process of Raw Coal Samples Containing Gas Loaded by High Pressure Water

3.1. Introduction to Main Part of the Experimental Equipment

The self-designed "simulation experiment device about the rupture process of raw coal samples containing gas loaded by high pressure water" mainly consists of six parts, that is the high pressure water connection and control system, the gas connection system, the stress loading system, the coal sample sealing system, the experimental data collection and analysis system, the water storage system, as shown in Fig. 5.

The high pressure water connection and control system is responsible for the control of high pressure water switch, and can control the water pressure and flow. The gas connection system mainly supplies high purity CH4 (99.99 % or higher), and adjusts the gas pressure according to the actual need. The stress loading system is responsible for loading axial pressure and confining pressure to coal samples.

The coal sample sealing system is a closed space, ensuring the loaded pressure to the coal samples during experiment process.



1-Water tank, 2-Water flow meter, 3-Metering pump, 4-Water pressure gauge, 5-The valve, 6-O-ring seal, 7-Pressure chamber, 8-Confining pressure booster aprons, 9-Coal test specimen, 10-Oil pressure gauge, 11-Confining pressure control valve, 12-Axial pressure control valve, 13-Fuel tank, 14-Computer, 15-Pressure release valve, 16-High pressure gas, 17-Gas Pressure gauge, 18-Gas-water separator.

Fig. 5. The sketch map of simulation experiment device about the rupture process of raw coal samples containing gas loaded by high pressure water.

The experimental data collection and analysis system collects experimental data including axial compression, confining pressure and water pump injection pressure, the information acquisition frequency can be set by computer program. The water storage system mainly stores the water percolating from coal samples in the process of fracturing.

The main parameters about each attachment of the experimental system as follows:

1) JW-2/20 mini type experiment metering pump, the largest rated flow: 5 L/h, the largest outlet pressure: 16 MPa.

2) Gas pressure range: 0-10 MPa, precision: 0.1 MPa,

3) Axial compression: 0-30 MPa, precision: 0.1 MPa,

4) Confining pressure: 0-20 MPa, precision: 0.1 MPa.

3.2. Coal Samples Seal System

In order to simulate the experiment site, drill an appropriate drilling hole along the coal samples' axial with borer. Place a steel pipe in the drilling hole to avoid drilling hole damage when confining pressure load, which diameter is a little thinner than the drilling hole.

The gaps between the steel pipe and coal borehole wall is blocked off with special A/B chemicals, these two kinds of liquid mixture has a good bonding effect, can be fully integrated with the surrounding coal body, have strong ability to resist rupture, as shown in Fig. 6.

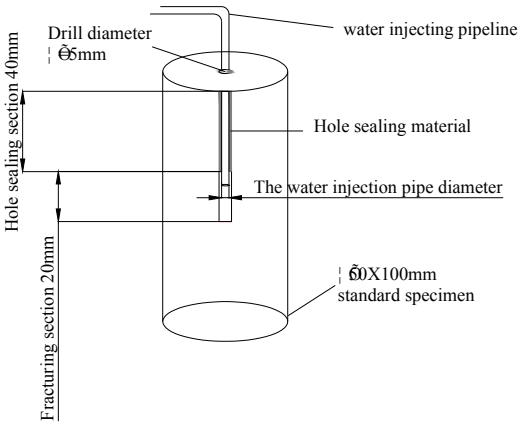


Fig. 6. Stress and drill of specimen.

4. The Experimental Scheme

Theoretical analysis and numerical simulation have shown that fissures always stretch along the direction perpendicular to the minimum principal stress when adopting the hydraulic fracturing measure [16]. Fracture pressure depends on the minimum principal stress. In this experiment, loaded axial compression is always equal to the loaded confining pressure, fracture pressure depends on the confining pressure, the coal samples rupture when P(water) overcome the sum of samples' confining pressure and tensile strength, that is P(water) ≥P(confining pressure) +σ(tensile strength).

Once the coal sample rupture, for coal sample that can be completely fracturing, due to the expansion and extension of the internal crack, the injected water flow will percolate along the generated fracture, the water injection pressure is difficult to be raised. Meanwhile, for coal sample that can not be completely fracturing, fracture network can not generate within the coal sample, the injection water has no room to percolate, the water injection pressure ascend climb constantly.

In this experiment, loaded axial compression is always equal to the loaded confining pressure, that is 3 MPa and 4 MPa respectively, the gas pressure is 0.4 MPa and 0.6 MPa respectively. Raw coal samples are 8 groups (Hard coal and soft coal samples is 4 groups respectively). The experimental scheme is shown in Table 1.

Table 1. The combination of experimental scheme.

Source of coal samples	Hardness of coal samples	Gas pressure (MPa)	Confining pressure=axial pressure $\sigma_3=\sigma_1$ (MPa)
NO.3 coal seam of Daning coal mine (soft)	Hard coal (f < 0.5)	0.4/0.6	3/4
NO.3 coal seam of Daning coal mine (hard)	Soft coal (f > 0.5)	0.4/0.6	3/4

5. The Experimental Results

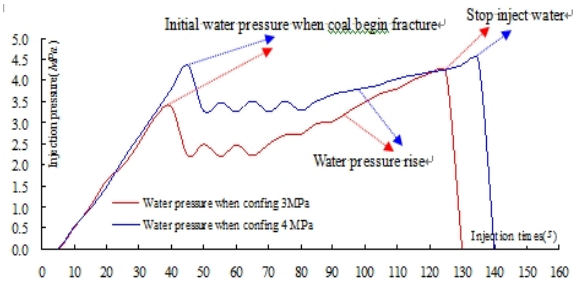
5.1. The Fracture Process of Different Kinds of Coal Loaded by High Pressure Water

1. The high pressure water loading dynamic variation rule about soft raw samples

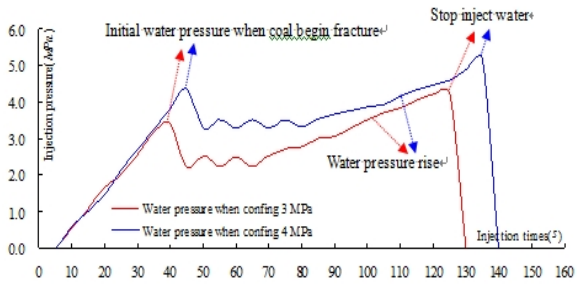
According to the experiment scheme in Table 1, load high pressure water to the four soft samples under the combination condition of constant gas pressure and confining pressure respectively. Control the water injection flow rate at approximate 1.0 mL/s (3.6 L/h) adjusting the control valve of metering pump, set the sampling frequency for water injection pressure at time/5seconds through the computer software. The high pressure water loading dynamic graphs about soft coal samples under the condition of constant gas pressure (0.4 MPa, 0.6 MPa) are shown as Fig. 7.

We can see from the figure above, the four soft coal samples' loading curves about water injection pressure with time are basically consistent, the four curves are roughly divided into six phases, that is the water injection pressure stranded phase (the pressure is 0), pressure sharp rise phase, pressure instant decline phase, close-fracturing alternating phase, gradually compaction phase, stop pump injection water phase.

1) There exists micro pore, small pore, medium pore, or large pore even fracture within the coal, in the initial period of pump injection water, the filtration out water from internal fissure is much greater than the injection water. Therefore, although the pump injection has started, pump injection pressure does not rise. It can been seen from the figures above this phase lasts not long, usually from 3 to 5 seconds.



(a) Gas pressure P=0.4 MPa



(b) Gas pressure P=0.6 MPa

Fig. 7. The high pressure loading dynamic graph of soft raw coal samples from Daning coal mine under the condition of constant gas pressure.

2) With the ceaselessly increasing of injection water, the pore and fracture interspace within the coal is gradually filled by the injection water. When the injection water is greater than the filtration out water from pore and fissure, water injection pressure rises with time.

3) When the pump injection water pressure reach a certain value, coal begins fracture under the effect of high pressure water, the initial cracks generate, injection water fills the cracks, water pressure drops suddenly.

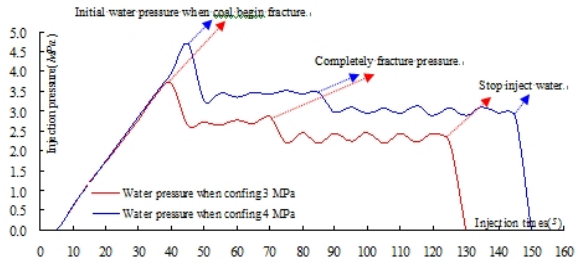
4) As a result of sudden drop of the pump injection pressure, crack propagation behavior stops. With the continuous injection of high pressure water which gradually accumulates in the cracks, water pressure increases again. When the pump injection water pressure reaches fracture pressure once again, secondary crack initiation begins to form. With the increase of injection time, multiple crack initiation comes one after another, crack develops forward circularly.

5) Plastic deformation appears under the high pressure water because coal is soft and broken. High pressure water and coal combine with each other forming coal slime, coal is compacted by high pressure water thoroughly. Crack extension stops, the cracks that generated due to the hydraulic fracturing and the internal pore of the coal itself are blocked off by coal slime, leading to pump injection pressure rises ceaselessly.

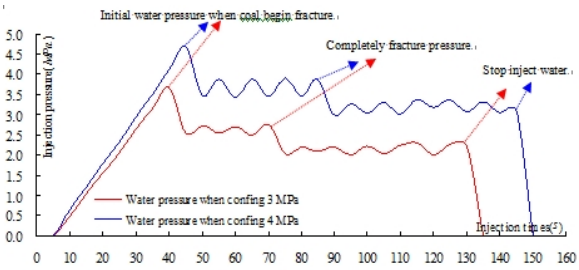
6) After the high pressure water injection lasting a period of time (about 60 seconds), the injection water pressure of four coal samples climbs to 4.55 MPa, 4.55 MPa, 5.24 MPa and 5.26 MPa respectively. The pump injection pressure is far more than the fracture pressure of coal, the coal has been fully compacted, close the high-pressure pump, hydraulic fracturing is finished.

2. The high pressure water loading dynamic variation rule about hard raw samples

Same as above, set the sampling frequency for water injection pressure at time/5seconds through the computer software. The high pressure water loading dynamic graphs about soft coal samples under the condition of constant gas pressure (0.4 MPa, 0.6 MPa) are shown as Fig. 8.



(a) Gas pressure P=0.4 MPa



(b) Gas pressure P=0.6 MPa

Fig. 8. The high pressure loading dynamic graph of hard raw coal samples from Daning coal mine under the condition of constant gas pressure.

We can see from the figure above, the four hard coal samples' loading curves about water injection pressure with time are basically consistent, the four curves are roughly divided into six stages, that is the water injection pressure stranded phase (the pressure is 0), pressure sharp rise phase, begin fracturing phase, close-fracturing alternating phase, completely broken phase, stop pump injection water phase.

1) In the initial period of pump injection water, the filtration out water from internal fissure is much greater than the water injection. Therefore, although the pump injection has started, pump injection pressure does not rise. It can be seen from the figures above this phase lasts not long, usually about 5 seconds.

2) With the ceaselessly increasing of injection water, the pore and fracture interspace within the coal is gradually filled by injection water. When the injection water is greater than the filtration out water

from pore and fissure, water injection pressure rises with time.

3) When the pump injection water pressure reaches a certain value, coal begins fracture under the effect of high pressure water, the initial cracks generate, injection water fills the cracks, water pressure drops suddenly.

4) As a result of sudden drop of the pump injection pressure, crack propagation behavior stops. With the continuous injection of high pressure water which gradually accumulates in the cracks, water pressure increases again. When the pump injection water pressure reaches fracture pressure once again, secondary crack initiation begin to form. With the increase of injection time, multiple crack initiation comes one after another, crack develops forward circularly.

5) A period of time after the water injection, filtration out water is basically equal to the pump injection water, the injection water pressure maintains at a constant value. At this time, the object within the influence scope of high pressure water was completely fractured, this value is called completely fracture pressure.

6) Maintain complete rupture pressure about 60 seconds, close the metering pump, hydraulic fracturing is finished.

5.2. The Water Pressure Critical Condition When Coal Fracture

The initial water pressure when coal begins fracture and the completely fracture pressure of hard coal samples can be observed according to the dynamic graphs about high pressure water combining with the exported computer data.

1) The initial fracture critical condition of the soft coal samples from Daning coal mine.

Under the condition that gas pressure is 0.4 MPa, confining pressure is 3 MPa, 4 MPa, the initial fracture pressure of the two soft samples are 3.37 MPa and 4.35 MPa, under the condition that gas pressure is 0.6 MPa, confining pressure are 3 MPa, 4 MPa, the initial fracture pressure of the two soft samples is 3.40 MPa and 4.37 MPa. After the process of "crack initiation- compaction-occlusion", samples are compacted absolutely.

According to the formula P(water)=P(initial fracture)=P(confining pressure)+б(tensile strength), the tensile strength of the four soft coal samples are 0.37 MPa, 0.35 MPa, 0.40 MPa and 0.37 MPa respectively.

2) The initial fracture critical condition of the hard coal samples from Daning coal mine.

Under the condition that gas pressure is 0.4 MPa, confining pressure is 3 MPa, 4 MPa, the initial fracture pressure of the two samples is 3.68 MPa and 4.70 MPa, under the condition that gas pressure is 0.6 MPa, confining pressure is 3 MPa, 4 MPa, the initial fracture pressure of the two samples is 3.67 MPa and 4.68 MPa. Therefore, the tensile strength of the four hard coal samples are 0.68 MPa, 0.70 MPa, 0.67 MPa and 0.68 MPa respectively.

3) The completely fracture critical condition of the hard coal samples from Daning coal mine.

Under the condition that gas pressure is 0.4 MPa, confining pressure is 3 MPa, 4 MPa, the two coal samples' duration times is 35 s and 40 s respectively during "closed-fracturing" alternant phase, under the condition that gas pressure is 0.6 MPa, confining pressure is 3 MPa, 4 MPa, the two coal samples' duration times is also 35 s and 40 s respectively during "closed-fracturing" alternant phase. According to the data exported from the computer, the completely fracture pressure of the four hard samples are 2.18 MPa, 2.98 MPa, 2.02 MPa and 3.0 MPa respectively. The completely fracture pressure is less than its corresponding initial fracture pressure.

6. Conclusion

1) Raw coal sample can reveal the gas seepage law of coal itself more than type coal sample, although the fabrication of soft coal is difficult, "twice moulding" method can accomplish successfully.

2) The conclusion can be obtained from the dynamic graphs about high pressure water injection: under the high pressure water injection, the hard coal samples through the process of "fracturing-multiple fracturing", internal fracture network fully develop eventually, dissimilarly, the soft coal samples through the process of "fracturing-compaction-closed", the internal fracture network can not fully develop in the end.

Hydraulic fracturing technical measure is not applicable to all coal seams. The effect that increase the permeability of coal seam is closely related to the physical and mechanical characteristics of coal seam itself, at present, the reason why this measure has not obtained the ideal effect in many mining area and coal seam lies in here.

Under the action of high pressure water, brittle deformation appears to the hard coal, internal cracks is expanded and derived, extended fracture network forms, effective porosity increase, the permeability of coal greatly increases. Hydraulic fracturing technical measure can improve the permeability coefficient of coal seam so as to improve the effect of gas drainage. However, under the action of confining pressure, at what time fracture will close again, how long the fracturing effect lasts has yet to be further studied.

Acknowledgements

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