Timeliness Analysis of Coalbed Methane Workover for Reducing Damage to Coal Reservoirs
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ABSTRACT: The workover operations are related to the efficiency of coalbed methane (CBM) and directly decide whether the CBM production target can be achieved. To reduce the damage to the coal reservoir caused by the workover duration, a series of experiments related to the damage to the coal seam by the workover duration, such as permeability experiment, stress–strain experiment, velocity sensitivity experiment, and stress sensitivity experiment, was carried out. The results show that the permeability of the coal sample increases first and then declines with the increase of the immersion time and the changed rate of coal samples is unbalanced. The permeability of the coal sample begins to decrease after 384 h of immersion. The mechanical properties of the coal sample did not change much when the water immersion time was short, but it showed a zigzag change when the water immersion time increased, and the stress–strain peak appeared earlier after 384 h of water immersion, and the elastic modulus became smaller. The consequences of stress sensitivity experiments show that the longer the immersion time, the weaker the recovery of permeability after pressure relief; especially after 384 h, the recovery of permeability is even weaker. Speed sensitivity test results show that the degree of damage to the sensitivity of the coal sample is moderate, but when the coal sample is immersed in water for more than 96 h, the permeability damage is generally greater than that of the dry coal sample. The experimental results prove that the effect of the workover duration has a significant impact on coal reservoir damage, and the workover duration is reasonably arranged. If we can make use of the phase characteristics of physical property changes of coal samples under different immersion times and complete the workover operation in the most appropriate time, then the coal reservoir can be well transformed, and it is possible to obtain good results. Both the production efficiency and production volume of CBM wells will increase.

1. INTRODUCTION
As of 2020, the number of existing coalbed methane (CBM) surface wells in China has been close to 20,000, but the CBM production in 2020 is only 5.767 billion cubic meters, and the production capacity does not match the number of CBM wells. The complexity of the geological structure and various engineering factors are the two most important factors that affect CBM production. Among many engineering factors, reservoir damage caused by workover operations occupies an important position. The workover operation process may reduce the permeability of the coal seam or affect the normal diffusion of the pressure drop area; especially, the damage to the coal seam permeability is irreversible. Especially, the opening and closing of the well in the process of CBM workover will cause the liquid flow rate to rise and fall rapidly, causing stress-sensitive damage and velocity-sensitive damage to the coal reservoir. For example, the increase in flow velocity caused by workover operations may increase the liquid carrying capacity, and the pulverized coal may be dragged out by the liquid to block the CBM migration channel, thereby reducing the permeability. In addition, workover operations cause changes in the water content of coal reservoirs. As the water saturation of coal reservoirs is different, its mechanical properties and reservoir permeability will show different changes. In the CBM production block of the Qinshui Basin in Shanxi, China, it was found that both CBM production and water production decreased after unreasonable workover operations, and the longer the time spent, the more serious the reservoir damage. However, there are not many scholars concerned about the research on the duration effect of CBM workover operations on reservoir damage. Based on the characteristics of CBM workover operations that will cause discontinuous drainage or repeated flooding, this paper uses different experimental methods to study the phase changes of the
physical characteristics of coal reservoirs under different flooding times. It is found that the duration of workover operations affects the physical characteristics of coal reservoirs. This research has important guiding significance for reducing or avoiding damage to coal reservoirs caused by workover.

2. BACKGROUND IN THE STUDY AREA

Qinshui Basin is one of the hot spots for CBM exploration and development in China. The main coal seams for CBM development are 3# and 15#. The 3# coal seam is the Shanxi formation of the Lower Permian System, with a thickness between 3.50 and 7.70 m and an average thickness of 5.63 m. The formation water salinity in the Carboniferous-Permian coal seams in this mine field in the southern Qinshui Basin of Shanxi Province, China. All coal samples were from coal seam No. 3 in the Sihe coal mine in the southern Qinshui Basin of Shanxi Province, China. All coal samples were fresh coal samples. In order to avoid excessive differences in the properties of the coal samples, the sampling points of the coal samples are required to be located on the gentle folds of the wing, where the structural influence is weak and the agglomeration is better. It can be ensured that the individual coal samples obtained are not less than 300 mm × 300 mm × 200 mm, and according to GB474-2008 "Coal Sample Preparation Method", multiple coal pillars of 25 mm × 50 mm are drilled on a single large coal block. A total of 36 coal samples were prepared this time.

3. EXPERIMENTAL METHOD

Unreasonable workover duration has obvious damage to coal reservoirs, especially its permeability, and permeability changes are closely related to the physical characteristics of coal reservoirs. Therefore, four experiments with coal samples under different immersion duration are designed. Coal sample permeability changes the experiment, and coal skeleton mechanical property changes the experiment, velocity sensitivity experiment, and stress sensitivity experiment.

3.1. Sample Preparation. The coal samples were taken from coal seam No. 3 in the Sihe coal mine in the southern Qinshui Basin of Shanxi Province, China. All coal samples were fresh coal samples. In order to avoid excessive differences in the properties of the coal samples, the sampling points of the coal samples are required to be located on the gentle folds of the wing, where the structural influence is weak and the agglomeration is better. It can be ensured that the individual coal samples obtained are not less than 300 mm × 300 mm × 200 mm, and according to GB474-2008 "Coal Sample Preparation Method", multiple coal pillars of 25 mm × 50 mm are drilled on a single large coal block. A total of 36 coal samples were prepared this time.

3.2. Experiments. 3.2.1. Experiments on Permeability Changes. According to the standard GB19560-2008 "High-pressure isothermal adsorption test method for coal", the experimental device is configured. The experimental equipment includes a gas permeability tester, a core holder, a pressure control system, a pipeline flow system, a temperature control system, and a data acquisition system. The specific experimental steps are as follows:

1. The drilled coal sample is placed in a dry box for drying, and the combined drying device is a sub-heat precision drying box (Dongfang-D) and a blower box. Considering that the coal sample is easy to oxidize and deteriorate and is flammable, the temperature is controlled at about 52 °C through the blower box, and the drying time is not less than 10 h, until it reaches the air-dry state.
2. After the coal column is dried and cooled, the permeability is tested. The test conditions are as follows: The test gas is nitrogen, the purity is 99.9%, the confining pressure is 2.5 MPa, and the inlet air pressure is 0.2 MPa.
3. After the permeability test, the coal sample was placed in the produced water of a CBM well with a water pressure of 9.3 MPa (water composition distribution is given in Table 1) and kept for 1 h.

Table 1. Relative Content of Clay Minerals in Coal in the Study Area

| item          | montmorillonite/% | kaolinite/% | illite/% | chlorite/% | mixed illite and montmorillonite/% |
|---------------|-------------------|-------------|----------|------------|-----------------------------------|
| KF1           | 44.2              | 14.3        | 18.7     | 11.9       | 10.9                              |
| KF2           | 55.3              | 12.2        | 9.8      | 19.2       | 13.5                              |
| KF3           | 45.1              | 6.3         | 16.4     | 9.2        | 13                                |
| KF4           | 49.2              | 14.5        | 20.2     | 14.2       | 13.5                              |
| KF5           | 50.6              | 10.3        | 12.1     | 15.7       | 11.3                              |
| KF6           | 47.2              | 11.2        | 14.5     | 13.6       | 13.5                              |
| average       | 48.6              | 11.5        | 15.3     | 14         | 9                                 |

Table 2. Data of Chemical Properties of Water in Coal Seams in the Study Area (Unit in mg/L)

| sampling location | burial depth of coal seam m | pH | Na⁺ + K⁺ | Mg²⁺ | Ca²⁺ | Cl⁻ | SO₄²⁻ | HCO₃⁻ | CO₂⁻ | TDS | water type |
|-------------------|-----------------------------|----|----------|------|------|-----|-------|-------|------|-----|-------------|
| S1 well 3# coal seam | 352                         | 8.3 | 560      | 7    | 10   | 123 | 43    | 1412  | 63   | 2512 | NaHCO₃      |
| S3 well 3# coal seam | 445                         | 8.5 | 567      | 7.5  | 12   | 122 | 45    | 14323 | 62   | 2523 | NaHCO₃      |
| S2 well 3# coal seam | 596                         | 7.4 | 977      | 7    | 13   | 192 | 430   | 1783  | 4    | 3403 | NaHCO₃      |
In the sensitivity test, the stress of the stress sensitivity experiment was set to 2, 3, 4, 5, 6, 7 MPa, where the displacement medium was nitrogen, and the displacement pressure is set to 0, 1, 2, 3, 4, 5, and 6 MPa in order. In step 3, 3 h is adjusted to 6, 12, 24, 48, 96, 192, 384, 768, and 1536 h in order.

3.2.3. Speed Sensitivity and Stress Sensitivity Experiment

Damage of coal skeleton under different water immersion times is reflected in the change of internal physical properties, which can be characterized by the stress sensitivity test and speed sensitivity test. According to the national standard SY/T5336-2006 core analysis method and SY/T5338-2010 reservoir sensitivity experimental evaluation method, the test is carried out. Experimental instruments include a gas permeability tester, core holder, high-pressure methane gas cylinder, pressure regulating valve, constant-speed and constant-pressure pump, and so forth.

The experiment was carried out at room temperature (20 °C), where the displacement medium was nitrogen, and the effective stress of the stress sensitivity experiment was set to 2, 3, 4, 5, 6, 7, 8, 9, and 10 MPa. In the sensitivity test, the flow rate setting test is carried out by changing the displacement pressure. The displacement pressure is set to 0, 1, 2, 3, 4, 5, and 6 MPa in sequence, the displacement medium is standard brine, and the measurement is carried out under the corresponding stable displacement pressure.

4. RESULTS

4.1. Permeability Changes

Permeability test results of coal samples under different immersion times are shown in Table 3 and Figure 1. It can be seen from the test results that the permeability of the coal sample exhibits significant changes at different immersion times such as 3, 6, and 12 h, until the geometric sequence increases to 1536 h.

When the coal sample is immersed in water for a period of time between 0 and 384 h, the permeability tends to increase. Among them, from 0 to 96 h, the permeability increases slowly; from 96 to 384 h, the permeability of the coal sample shows a stable and stable change. However, the permeability of 384–768 h tends to decrease rapidly.

4.2. Characteristics of the Stress—Strain Curve of the Coal Sample

Figure 2 shows that the stress—strain curve of the test samples is basically similar, but there is little change with the difference in water immersion time. On the whole, as the immersion time increases, the slope of the stress—strain curve in

| Item     | 0 h | 3 h | 6 h | 12 h | 24 h | 48 h | 96 h | 192 h | 384 h | 768 h | 1536 h |
|----------|-----|-----|-----|------|------|------|------|-------|------|-------|-------|
| MY01     | 1.29| 1.50| 1.50| 1.51 | 1.59 | 1.73 | 2.00 | 2.12  | 2.10 | 1.73  | 1.58  |
| MY02     | 1.69| 1.85| 1.92| 2.04 | 2.10 | 2.11 | 2.12 | 2.10  | 2.19 |      |       |
| MY03     | 1.58| 1.61| 1.65| 1.67 | 1.70 | 1.74 | 1.94 | 1.97  | 1.95 | 1.73  | 1.57  |
| MY04     | 0.47| 0.67| 0.87| 0.91 | 1.04 | 1.11 | 1.30 | 1.31  | 1.23 | 1.18  |       |
| MY05     | 0.55| 0.72| 0.87| 1.04 | 1.05 | 1.11 | 1.16 | 1.28  | 1.17 | 1.07  | 0.89  |
| MY06     | 0.48| 0.71| 0.83| 0.90 | 1.01 | 1.08 | 1.27 |       |      |       |       |
the straight phase gradually decreases, indicating that the elastic modulus decreases. The longer the coal sample is immersed in water, the lower the compressive strength of the coal sample, and the increase of the peak strain, that is, the coal sample’s plasticity increases and the brittleness decreases.

Coal samples that have not been immersed in water and the coal samples that have been immersed in water for less than 48 h show a stable stress–strain curve under compression, showing high brittleness, and the stress–strain peak appears later than the coal sample that has been immersed in water for a longer time. When the water immersion time is between 48 and 384 h, the coal sample exhibits a canine-like stress–strain under the compressive stress; when the water immersion time is longer than 384 h, the peak of the stress–strain curve of the coal sample under compression appears earlier. It is shown that the peak strength of the coal sample has a negative linear relationship with the water immersion time, and the peak strain has a positive linear relationship with the water immersion time.

4.3. Stress Sensitivity Experiment of Coal Samples under Different Immersion Times. The experimental results of stress sensitivity (Figure 3) show that the permeability of the four coal samples shows a downward trend as the confining pressure increases. The increase in confining pressure is in the range of 2–4 MPa, and the permeability of unsoaked coal samples decreases in a curve, while the permeability of water-immersed coal samples decreases linearly; when the confining pressure increases in the range of 5–7 MPa, the permeability of the water-soaked coal sample shows a curve decline, while the unsoaked coal sample shows a linear decline. The permeability of the four coal samples decreased linearly when the confining pressure increased to 7–10 MPa. When the confining pressure reaches 9–10 MPa, the permeability damage rate of the coal sample reaches more than 83%, and the permeability damage rate of coal samples increases with the immersion time (after 96 h). When the confining pressure drops gradually, from 10 to 7 MPa, the permeability value shows a slow linear increase and recovery; when 7 MPa drops to 3 MPa, the permeability value shows a curve increase and recovery; when 3 MPa drops to 2 MPa, the permeability value shows a linear growth recovery, but the damage to the permeability value is still above 42%. The entire stress sensitivity experiment cycle shows that the permeability value is still damaged by more than 42%, and the longer the immersion time, the greater the permeability damage. It shows that even if the confining pressure is reduced, the elastic deformation of the coal sample will recover, and the total pore volume will also recover to a certain extent. However, the plastic damage and brittle damage of the coal sample cannot be repaired, which is the result of the stress sensitivity of the coal seam.

4.4. Speed Sensitivity Experiment of Coal Samples under Different Immersion Times. The experimental results of the velocity sensitivity effect (Figure 4) show that with the increase of the fluid flow rate, the five coal samples show varying degrees of permeability reduction. However, the permeability change trajectories of the five coal samples show two types. The permeability change trajectory of the coal samples whose immersion time is shorter than 96 (0, 96 h) is first linearly decreased and then the curve decreases. For coal samples immersed in water for 192 and 384 h, with the increase of flow velocity, the permeability showed a nearly linear drop. For coal samples that have been immersed in water for less than 192 h, when the flow velocity is between 0 and 0.25 m/s, the permeability changes linearly; when the flow velocity is between 0.25 and 0.95 m/s, the permeability value shows a decrease in the curve. Figure 6 shows that whether it is a water-immersed coal sample or a non-water-immersed coal sample, the permeability decreases with the increase of the flow rate, and the difference between the results is not obvious. The damage rate of unsoaked coal samples due to flow velocity changes was 47%, and the highest damage rate of water-immersed coal samples was 55% and the lowest was 40.5%. However, the permeability damage of coal samples with a water immersion longer than 96 h is greater than 47% of that of unsoaked coal samples, indicating that too fast or uneven changes in the flow rate will cause damage to the permeability. Among them, the permeability of coal samples with a water immersion longer than 96 h is more severely damaged by the flow velocity, which means that the immersion time to a certain extent will cause changes in the microstructure and composition of the coal, and thus the stress sensitivity will be more obvious. Multiple openings and shut-ins in the process of CBM workover will cause acceleration or unbalanced changes in the flow rate and will cause damage to coal reservoirs. In the actual production of CBM wells, a reasonable flow rate must be controlled to avoid speed-sensitive damage.

5. DISCUSSION

5.1. Impact of CBM Workover on the Reservoir. CBM is an unconventional natural gas that is self-generated and self-stored. To extract it, it needs to be drained and decompressed and desorbed. With the continuation of drainage, a stable production process will form a pressure drop funnel around the CBM well, and this pressure drop funnel will gradually expand.

Figure 4. Test results of the rate sensitivity experiment.
However, when a production failure occurs during the production of a CBM well, workover operations are required to resume production. Workover operations must suspend pumping, and the production pressure (bottom hole pressure) in the reservoir will gradually return to the initial stage after pumping is stopped. The area of the funnel formed by the pressure drop is gradually occupied by water as the liquid level in the wellbore rises, and the coal reservoir that was originally exposed above the liquid level will be infiltrated by water. In the preceding normal production process, the coal matrix shrinks or expands due to drainage and pressure reduction, resulting in more new cracks and more exposure of inorganic minerals in the coal. After being soaked in water again, it is destined to have a chemical reaction with water (Figure 5).

As a mixture of organic macromolecules and inorganic minerals, the coal itself is more sensitive to stress. The stress sensitivity of coal reservoirs during well workover is obviously more fragile than coal that is not infiltrated by water. The pore structure and mineral composition of coal reservoirs will inevitably be affected by changes in the environment, which will cause damage to the reservoir, that is, a decrease in permeability. The production practice data of CBM wells show that after the workover, the permeability will indeed decrease. Figure 6 shows that under the same pump efficiency after the workover, the average daily water production is significantly lower than before at the same liquid rate, indicating that the reservoir is damaged after the workover. Moreover, comparing the duration of the first workover with the duration of the second workover, it is found that the longer the workover duration, the more the permeability decreases, indicating that the reservoir damage is too strong.

5.2. Time Effect of Workover. 5.2.1. Influence of Immersion Time on Permeability. The fracture system of coal reservoirs is a direct factor affecting permeability. The experimental results (Figure 2) show that the water immersion of the coal sample has indeed caused changes in the internal fracture system of the coal reservoir. At the initial stage of coal immersion (less than 384 h under water immersion), the number of micropores in the coal sample increases due to water infiltration. The cumulative pore volume of the coal is greater than that before the water immersion, and the increase of micropores and the combination of adjacent micropores can form mesopores or even large pores, so the permeability increases significantly during a period of time of immersion in water. For this result, Yang et al. and Gu also tested the pore structure characteristics of water-immersed coal samples, concluding that the pore volume and porosity of coal after water immersion leads to significant pore expansion.

However, as the immersion time increases (more than 384 h), the permeability starts to decrease. From the increase in the permeability of the coal sample in the early stage to the decrease in the later period, the reason is that the coal sample is immersed in water for a long time, and the cracks or joints in the coal begin to change, and the surface is gradually rough. The coal in the Panzhuang block contains inorganic minerals such as kaolinite, montmorillonite, and so forth (Table 1), which also reacted with water and increased in volume, resulting in a decrease in the permeability of the coal reservoir. Here, only the montmorillonite mineral is taken as an example. Both sides of the montmorillonite unit crystal layer are composed of oxygen atoms. The force between the crystal layers is intermolecular force (there is no hydrogen bond), and water molecules are easy to enter; after the water molecules enter, a large number of crystal lattices in the montmorillonite are replaced. Because

![Figure 5. Changes in the reservoir environment before and after the workover of a coalbed methane well.](https://pubs.acs.org/doi/abs/10.1021/acsomega.1c06644)

![Figure 6. Workover operations of a CBM well lead to reduced permeability.](https://pubs.acs.org/doi/abs/10.1021/acsomega.1c06644)
there are a large number of exchangeable ions on the crystal surface; these cations dissociate in the water to form a diffuse electric double layer, which makes the surface of the crystal layer negatively charged and repels each other, resulting in the usual clay swelling, which increases the volume of minerals swelled with water. It occupies a certain flow micropore channel, which eventually leads to a decrease in permeability. Li also used scanning electron microscopy and a specific surface analyzer to test the pore volume and specific surface of coal samples after water immersion with different times and found that the pore volume and specific surface first grow and drop down over time. Therefore, the control of the duration of CBM workover operations is related to the permeability of the coal reservoir, and it is more related to the efficiency of CBM production. The results of the permeability change of the coal sample during immersion in water show that the coal sample’s immersion time is controlled reasonably and the permeability of the coal reservoir will increase. The consequences of the permeability change of the coal sample during the immersion time show that the coal sample immersion time is controlled reasonably and the permeability of the coal reservoir will increase. If a reasonable workover time can be controlled and combined with the operating characteristics of the workover process, for example, there will be a certain degree of pressure fluctuations in the pipe string during the workover process, which is combined with the penetration under the control of the workover time. The increase in the rate can achieve resonance. If it can communicate with the high gas-bearing area, the original low-yield well can be transformed into a high-yield well.

In the process of drainage and production, it is possible to achieve good results by consciously arranging some workover operations with a reasonable duration.

5.2.2. Changes of Coal Mechanical Properties with Water Immersion Time. Previous studies have also shown that the mechanical properties of coal samples will change significantly after being immersed in water for a period of time. It is estimated that water will reduce the mechanical strength of coal and is more prone to deformation and damage. The reason for the ruin is that some substances in the coal are dissolved by water to form pores, and the increase of pores reduces the density and strength of the coal. According to Table 1, the main mineral components in coal are clay minerals, and the clay minerals are mostly montmorillonite and illite. Once the immersion time reaches a certain level (more than 196 h), montmorillonite and illite can dissolve and react with water, resulting in poor connectivity between coal particles. After the clay minerals in the coal react with water, new pores and fractures are generated; moreover, part of the mineral components in the coal are also lost with the water, and the loss of the minerals in the coal as a cement will inevitably cause the mechanical properties of the coal skeleton to change. Therefore, it is not hard to explain that the mechanical properties of the coal sample in Figure 2 change with the duration of water immersion. A series of experimental studies have shown that the reason for the increase in plastic deformation of the coal body skeleton with the immersion time is that the addition of water increases the activity of some molecules in the coal, and the liquid or gas in the pores and cracks of the coal will generate pore pressure, which offset part of the total stress acting on any cross section of the coal and rock, so that the elastic yield limit of the coal is reduced, and it is easy to be plastically deformed. At the same time, it will also decrease the shear strength of the coal. The changes in the mechanical properties of the coal body skeleton are the manifestations of the changes in the internal structure of the coal body. Under different immersion times, due to the reaction of water and minerals in the coal, the internal structure of the coal body, such as the coal matrix, also changes. In the process of normal drainage and extraction, the steady shrinkage of the coal matrix can ensure the stability of permeability, but the workover operation caused the interruption of the coal matrix shrinkage process, and the coal matrix that was originally exposed to the liquid surface was immersed again, and previous studies also showed that the coal after mechanical modification is more susceptible to matrix shrinkage than the primary structure coal. Therefore, the results of stress damage and velocity-sensitive ruin of coal samples with water immersion time are shown in Figures 3 and 4. If the rearrangement system is not properly selected after the workover, the blind pursuit of the rate of liquid drop is likely to cause a pressure-sensitive effect. At this time, even if you continue to enhance the horsepower, no more water can be discharged. Moreover, the damage to the permeability of the coal seam cannot be fully recovered at this time. The abovementioned research results show that the duration of workover operation affects the mechanical properties of the coal skeleton to a certain extent, as well as the physical properties of the coal reservoir.

6. CONCLUSIONS

(1) The degree of change in permeability of coal reservoirs varies with the duration of water immersion. It first increases and then decreases, and the rate of changing is unbalanced. The permeability of the coal sample begins to decrease after 384 h of immersion in water.

(2) The mechanical properties of coal reservoirs will also show varying degrees of change with the duration of water immersion. When the immersion time is less than 384 h, the mechanical properties do not vary much, but the stress peak appears early after 384 h. It means that the modulus of elasticity decreases as the immersion time increases.

(3) The stress sensitivity experiment shows that the longer the immersion time, the weaker the permeability recovery after pressure relief, and especially after 384 h, the performance is more obvious; the speed sensitivity experiment shows that the sensitivity of the coal sample is moderate to weak. However, once the immersion time is longer than 96 h, the permeability damage is generally greater than that of dry coal samples.

Therefore, the duration of CBM workover will have an impact on coal reservoirs. If a reasonable workover time can be controlled during the drainage process, and combined with the operation characteristics of the workover process, it will be possible to carry out benign reforms to low-production CBM wells, thereby avoiding reservoir damage caused by workover operations.

However, under different geological conditions and coal body structure characteristics, the time limit of coal seam permeability may be different under different immersion durations. Therefore, when using the abovementioned results for workover operations, specific analysis needs to be combined with specific issues.

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Notes
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