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Experimental Research on Coal-Gas Outburst Prevention by Injection Liquid Freezing during Uncovering Coal Seam in Rock Crosscut

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Abstract: According to the existing problems of the control measures of uncovering coal seams in rock crosscut, such as long time of uncovering coal, poor construction safety, etc., the main effect factors of coal–gas outburst of uncovering coal seams in rock crosscut are analyzed, the existing hypotheses and the process of coal–gas outburst are described, and then the feasibility of the injection liquid freezing to prevent the coal–gas outburst is analyzed. It is concluded that the measure of the injection liquid freezing has the following functions: ① changing the physical properties of coal, ② improving the integrity of the surrounding rocks of the coal–rock interface, ③ enhancing coal strength, ④ effectively avoiding the discontinuous deformation of coal and rock under the action of gas pressure, ⑤ strengthening the block action of the external coal, ⑥ changing the stress distribution of coal near rock crosscut. The freezing makes the freezing ring in the roadway surroundings become a relatively stable flexible combination, which has a better stability. The experiment device of injection liquid freezing is designed, and the coal samples are analyzed before and after the freezing. The experiment results show that the indexes of coal–gas outburst are greatly dropped after adopting the measure of the injection liquid freezing, which can effectively control the coal–gas outburst. The experiments also show that it is feasible to prevent coal–gas outburst by the technology of the injection liquid freezing. The study results provide a new way to prevent the coal–gas outburst in uncovering coal seams in rock crosscut.

Keywords: uncovering coal seam; rock crosscut; coal–gas outburst; stress distribution; injection liquid freezing; mechanical properties of coal

Citation: Jia, Z.; Tao, F.; Ye, Q. Experimental Research on Coal-Gas Outburst Prevention by Injection Liquid Freezing during Uncovering Coal Seam in Rock Crosscut. *Sustainability* **2023**, *15*, 1788. https://doi.org/10.3390/su15031788

Academic Editors: Wei Yang, Xu Yu and Chunchen Wei

Received: 13 December 2022
Revised: 11 January 2023
Accepted: 11 January 2023
Published: 17 January 2023

1. Introduction

In the mine with a coal–gas outburst risk, the occurrence and development of the outburst in uncovering coal seams is easier than those in a horizontal roadway, upward roadway, downward roadway, and the coal mining working face, which causes serious damages, especially, the coal–gas delay outburst in rock crosscut results in the long time of uncovering coal and high cost, therefore the outbursts seriously affect the smooth replacement and bring threats to the safety production in the coal mine [1,2]. According to the statistics of domestic and foreign outburst data, most of the outbursts of morethan1000 t appear in uncovering coal seams in rock crosscuts. The average intensity of the outbursts in uncovering coal seams is more than six times larger than those of other kind of outbursts. For example, the Daping coal mine accident in 2004 was caused by a coal–gas outburst of uncovering coal seams in rock crosscut, which caused a gas explosion accident, resulting in 148 deaths. In 2006, a coal outburst accident occurred in Fenggang coal mine, resulting in 12 deaths. The release of the gas potential energy and the coal strength of determining the outburst have not been taken into consideration in the conventional outburst prevention measures in uncovering coal seams in rock crosscut. Because of the high intensity and delay characteristics of coal–gas delay outburst in uncovering coal seams in rock crosscut, a lot of researches on the outburst mechanism and control technology of uncovering coal seams in rock crosscut were carried out by many scholars at home and abroad [3–6]. Main existing outburst prevention measures of uncovering coal seams in rock crosscut are borehole gas drainage [7], freezing based on metal skeleton [8], progressive tunneling technology [9], advance grouting reinforcement technology [10], etc. However, due to the complexity of the outburst mechanism and the limitation of the prevention and control technology, the methods and measures of effectively preventing the outburst in process of uncovering coal seams in rock crosscut have not yet been found [11,12]. Based on the researches and analyses on the outburst prevention measure, it is found that some technical measures of prevention and control are insufficient [13], for example, the implement of the solidification measure is difficult, the solidifying liquid(curing agent) is difficult to be penetrated into the coal body, the metal framework is generally used in thin coal seams, it is difficult to play the role of "shield", the solidification measures are easy to destroy the coal stability, the grouting pressure is bound to cause the stress deflection in the coal body. Therefore, combining the advantages and disadvantages of each technology, the injection liquid freezing technology of preventing outburst in uncovering coal seams in rock crosscut is put forward, and the feasibility of the technology is determined through experimental research in this paper.

2. Main Influence Factors and Hypotheses of Coal–Gas Outburst

The influence factors of coal–gas outbursts are very complex and include various geological factors, but they also include a lot of non-geological factors. In general, the influence factors mainly include four aspects [11,14]. ① The geological structure of coal seams: the geological structure is the dominant factor of controlling coal–gas outbursts. The geological structure type, size, characteristics, density, and arrangement of structural parts have different effects on coal–gas outbursts. ② The coal seam factors and gas parameters: the coal seam factors include the thickness of the coal seam, the dip angle of the coal seam, the thickness of the soft layer, and the buried depth of the coal seam. The gas parameters include the gas content, gas pressure, initial speed of gas diffusion, gas gradient, and gas emission quantity. ③ Stress conditions in the mining area or coal seams: the ground stress is composed of stratum self-weight stress and tectonic stress. ④ Engineering factors of mining: the factors include blasting, mining, external disturbance excitation, supporting method, etc. In the above four factors, the geological structure is the geological background of coal–gas outbursts; coal and gas are the material bases of the outburst; the ground stress state is the dynamic condition of coal–gas outburst; some engineering factors such as blasting and external disturbance are the inducing conditions of coal–gas outburst, however some engineering factors such as roadway support are the restraining conditions of coal–gas outburst. Obviously, the coal–gas outburst is the result of the comprehensive function of various factors [11,13]. If the geological factor is the inevitable condition of coal–gas outburst, the non-geological factor is the sufficient condition. Therefore the risk of coal–gas outburst can be reduced by controlling the non-geological factors.

The mechanism of coal–gas outbursts has been studied since the world's first outburst in France in 1834. Especially from the last century, a lot of careful observations in the outburst field and laboratory were carried out; thousands of outburst records were gained; the successful experiences and the failure lessons of years were summarized [12]. The hypothesis of gas leading role, hypothesis of the ground stress leading role, hypothesis of the coal structure leading role, and hypothesis of the comprehensive effect, etc., were put forward [15]. The gas function hypothesis holds that the high-pressure gas stored in the coal is the main factor of the outburst; its representative content concludes the "gas bag hypothesis", "the powder coal belt hypothesis", "coal pore structure uneven hypothesis", etc. The ground stress hypothesis believes that the outburst is the result of the high ground stress, its representative content concludes "rock deformation potential theory", "stress concentration theory", "stress superposition theory", etc. The hypothesis of the coal structure leading role is the hypothesis of chemistry essence, which holds that the coal structure plays a leading role in the process of the outburst. The hypothesis of the comprehensive effects highlights that the outburst is result of the comprehensive effects of ground stress, gas pressure, the mechanical property of coal, and other factors. There also is not a unified understanding that how the process is happening and developing; the various hypotheses only can explain some of the individual phenomena in the field. Therefore, if the coal–gas outburst needs be effectively prevented and controlled, the measures should be adopted by changing the stress distribution of coal body, reducing the gas pressure, increasing the strength of coal, etc.

3. Analyses on Coal–Gas Outburst Process

As shown in Figure 1, when the roadway working face is pushed a distance D, the stress state of the coal body in front of the roadway working face will be suddenly changed. The stresses on the coal body in the pressure relief zone and the concentrated stress zone must be transferred to the deeper coal body, namely, the pressure relief zone and the concentrated stress zone are pushed forward a distance D with advance of roadway working face, the peak value of the concentrated stress is also pushed forward a distance D. Therefore, in terms of the coal body in the front of the roadway working face, there is a process from the original stress state to the concentrated stress state, which makes the coal (containing gas) produce the stress concentration in a short time, a pressure relief zone with rupture belt will be formed in front of the new exposed area; the lower the coal strength, the larger the rupture zone [16]. When the coal (containing gas) begins to enter the instantaneous and stable rheology, the deformation and destruction of the coal is accelerated under the action of a sharp increase in the concentrated stress, which makes coals in the last rheological stage produce further fractures. If the accumulated intrinsic gas energy does work, it can brake coal, shatter and throw the broken coals, namely, the instantaneous coal–gas outburst appears. Before the coal seam in rock crosscut is uncovered, if the gas in the coal seam is not drained, or the coal seam still maintains gas with high pressure after drainage at the moment of the uncovering the coal seam by blasting, the stress state of the coal seam with the outburst danger is destroyed. Due to the high gas pressure gradient inside and outside, the coal body destroyed by the ground stress is thrown into the roadway space under the action of high gas pressure, at the same time, which makes the internal coal body expose, the exposed coal body is again destroyed under the action of the ground stress. After the destruction, the destroyed coal body is thrown into the roadway space under the action of high gas pressure. So the continuous fracture and coal throwing make the outburst extend to the deeper coal body and form a continuous outburst [17]. However, before the coals are uncovered, the gas drainage and other measures generally have been adopted, which can drain a lot of the gases in coals in the surrounding roadway, the outburst risk is lost. So the gas energy (pressure) is not enough to shatter the destroyed coals and induce the outburst.

After uncovering the coal seam in rock crosscut, due to the block and the support of the pressure relief zone, the coals with outburst danger in the pressure relief zone cannot be exposed, so the outburst will not happen. When the coals with outburst danger are in the concentrated stress zone or in the original stress zone, because the ground stress is large, gases are not easily leaked [15–17]. After the coal seam in rock crosscut is uncovered, if the roadway support is not in time, the fracture belt surrounding the roadway will be destroyed under the action of the ground stress, the support action will be loss, and then the sudden fall will be produced. If the sudden fall can result that the coals with outburst danger are suddenly exposed, the coal–gas delay outburst will appear [17]. It can be seen that the delay is formed by failure of the rock (or coal) stopping the rheology, or the coal block layer of the pressure relief zone gradually losing the support force.

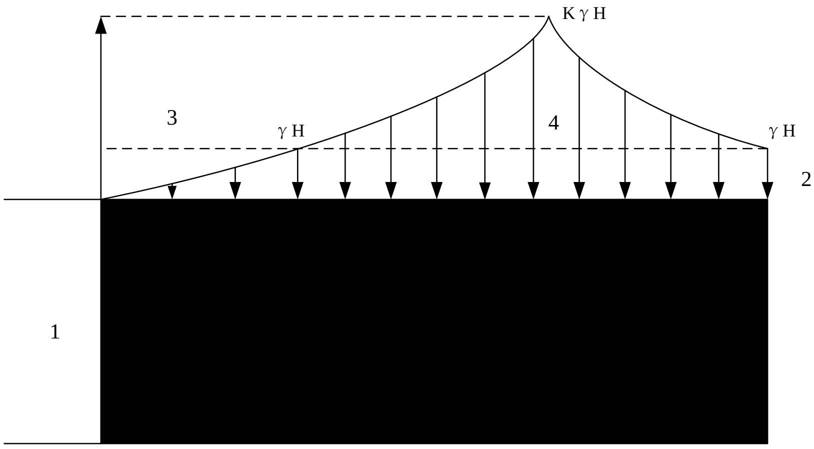

Figure 1. Stress distribution of coal and rock in front of roadway working face. 1—Roadway working face; 2—Original stress zone; 3—Pressure relief zone; 4—Concentrated stress zone.

According to the references [18] and the above analyses, there is a direct relationship between the size of pressure relief zone near the roadway working face and the coal–gas outburst, the size of pressure relief zone determines whether the elastic potential energy and intrinsic gas energy can be released or not, and whether the outburst can be formed or not. When the pressure relief zone is large enough, even if there is the high-pressure gas and sharp stress concentration in front of the roadway working face, the outburst is not possible to be formed. Conversely, the smaller the pressure relief zone, the thinner the protective barrier, and therefore it is easier for the outburst to be formed. At present, the common outburst prevention measures are the conventional measures, such as protection layer mining, advance pressure relief drilling hole, pre-gas drainage, hydraulic flushing, loose blasting, etc. [11]. Although these measures have certain prevention function on the outburst, they only focus on the release of elastic energy and gas potential energy, and ignore the bearing capacity of coal and its effect on the outburst [16,17]. So the conventional outburst prevention measures generally have different degree damages to the coal body structure, which reduces the coal body's resistance against the outburst. For the soft coal seam or failure zone of the geological structure, the effect is more serious. However, the injection liquid freezing technology of the drainage borehole can overcome the shortcomings of the conventional measures; it not only releases the gas pressure and transfers the ground stress, but also releases the elastic energy and the intrinsic gas energy, and strengthens the capacity of the coal and the outburst resistance. So before the coal seam in the rock crosscut is uncovered, the gas drainage borehole can drain the gases, release gas pressure, and transfer ground stress, then the injection liquid freezing technology can increase the scope of the pressure relief zone and the strength of the coals in the pressure relief zone, change the stress distribution, and prevent the coal–gas outburst.

4. Research Methods on Injection Liquid Freezing

In 1883, the artificial freezing method was applied for the first times and succeeded in the shaft construction in Alred coal mine in Germany. In the coal mining industry, the artificial freezing method was mainly used in the shaft construction of the mine with the water flow and sediment, which can freeze the stratum and form the frozen wall to resist the ground stress, and isolate from the ground water, under the protection of the frozen wall, the excavation can be smoothly carried out [19].

From the process of coal–gas outburst in uncovering coal seams in rock crosscuts and its effect factors, it can be obtained that when the coal seam with the outburst danger is uncovered and the coal body is destroyed, the coal strength and the whole stability will be lowered, the ability of preventing the internal coal–gas outburst also will decrease, which easily make a lot of adsorption gases instantaneously desorb into the free gases, so a lot of gases will be suddenly emitted and the coal–gas outburst will be formed. At the same time, when the coal seam with coal–gas outburst danger in rock crosscut is uncovered, the mechanical properties of rock and coal in both sides of the coal–rock interface are different; this difference is easy to produce deformation of the space mutation (stress discontinuity). Adopting appropriate measures of improving the coal strength can make coal strength be in a dominant position, and can effectively resist the action of the high stress and the expansion of the high-pressure gas. So it can effectively prevent coal–gas outburst, and realize safe production. The injection liquid freezing is that a lot of waters are injected into the coal seam near rock crosscut and penetrated into the cracks and pores under a certain pressure, and then the waters are cooled and frozen, so the coals and waters form a larger freezing body. The compressive strength, elastic modulus and Poisson's ratio are the main parameters to measure the mechanical properties of coal seams [20], the parameters are easily affected by coal structure, moisture, temperature, and other factors. The physical-mechanical properties of coal–rock body can be artificially improved by freezing [21], which can change the coal heterogeneity, improve the strength and self bearing capacity of coal, reduce the differences of the mechanical properties of coal–rock body, enhance the integrity of surrounding rock in the vicinity of coal–rock interface, and increase the resistance against coal–gas outburst. When the coal seam in rock crosscut is uncovered, the coal body freezing can avoid the deformation in interface between coal and rock, and stress discontinuity of surrounding rocks. At the same time, the filled liquid can jam the cracks and pores in closed coal seams, block the flow channel of gas desorption, so the adsorption gases are not easy to form the free gases, which reduce the gas desorption velocity and desorption quantity, decrease the adsorption capacity of coal [15]. When the coal– gas balance system is suddenly destroyed, it can reduce or prevent the compressed gas potential energy transfer into kinetic energy, and weaken gas potential energy, so the outburst prevention goal can be obtained.

Theoretically speaking, the injection liquid freezing can change the physical properties of coals and the stress distribution around the coals in rock crosscut, which can effectively prevent the coal–gas outburst. At the same time, the injection liquid freezing makes the freezing loop of the roadway surroundings become a relatively stable flexible combination, which has better stability. The roof will not immediately collapse in process of construction, which has obtained a valuable time to support the roof. Plus compared to other conventional methods, the injection liquid freezing method can significantly shorten the time of uncovering coal seams in rock crosscut.

5. Injection Liquid Freezing Experiment

According to the results of theoretical analysis, several experiments and measurements were carried out in the early stage, and it was finally determined that these equipment and materials were needed in the experiment: the coal samples of coal mine with the coal–gas outburst danger, cement tank-coal body freezing model, temperature sensor, freezing pipe, low temperature brine unit and heat preservation material, etc.

5.1. Sampling Survey

The gas level identification in the Tanshan coal mine is that the absolute gas emission is 5.7 m^3/min, relative gas emission is 21 m^3/t. The Tanshan coal mine is a mine with the coal–gas outburst danger, the outbursts have occurred more than 30 times. In order to determine the physical-mechanical properties of coal after adopting the measure of the injection liquid freezing, the coal samples from Tanshan coal mine are obtained to determinate porosity, the initial speed of gas diffusion, gas adsorption capacity, and compressive capacity before and after freezing.

5.2. Experiment Equipment

According to the section size of roadway working face in rock crosscut in coal mine, the requirements and operation characteristics of the outburst prevention, the indoor model of cement tank is established to implement the freezing experiment of coal body. The temperature change in the coal in the cement tank during freezing are recorded, and the change relation of physical-mechanical properties of the coal with the freezing time is analyzed.

The cement tank model is structured. The freezing pipes with a diameter of 80 mm are set in the centre of the cement tank. The shape and size of the cement tank model is that length, width, height, and wall thickness are 4000 mm, 1000 mm, 1000 mm, and100 mm, respectively, which is shown in Figure 2. Two layers of foam insulation materials with thicknesses of 50 mm are set in inner wall (Figure 2). The coals in the cement tank are compressed. Temperature sensors are arranged in different sections to record the temperature changes of each measuring point in the coal body. The insulation materials are set in section center position and the cement tank wall to reduce the heat exchange between coals in the cement tank and the outside environment.

Figure 2. Top view of cement tank model.

The cooling exchange is carried out between the low temperature $CaCl_2$ brine of the circulating flow in the freezing pipes and the coals in the cement tank. The coals are gradually frozen into structural morphology of the solid-fluid coupling structure of three phases. In this experiment, the YSLGF120A low temperature brine unit is adopted, the automatic temperature control system is set for cooling and freezing. All the freezing pipes are wrapped with insulation materials to reduce the influence of environment temperature on the cooling system. The $CaCl_2$ brine is used as refrigerant water, the water temperature can be controlled by the operation screen, and the temperature data are collected in the experiment process.

5.3. Experiment Procedure

According to the experimental requirements and experimental design, the following eight experimental procedures are developed: (1) Two layers of insulation materials with thickness of 50 mm are set in the bottom and the inner walls of the cement tank, the total thickness of the insulation materials inside the tank is 100 mm. (2) In the cement tank, the filled coals are compressed; when the coal height arrives at +300 mm (height in the bottom of cement tank is 0 mm), the coals are compressed by the I-beam counterforce device. (3) The freezing pipes are layout and installed, and the coals are filled, when the height of the coal arrives at +600 mm, the coals are compressed by the I-beam counterforce device. (4) The temperature sensors are arranged and laid. (5) The coals are filled continuously, until the height arrives at +1000 mm, the coals are compressed by the I-beam counterforce device, two layers of insulation materials with thickness of 50 mm are set on the top. (6)

The temperature sensors are connected to the data acquisition system. (7) Launching the cooling water pump and cooling tower fan. (8) When the coal temperature in the cement tank reaches the needed freezing temperature, the cooling water pump and cooling tower fan should be stopped, then the experiment data are processed and analyzed.

6. Results and Discussion

After the freezing unit is turned on, the coal temperature in the cement tank model begins to decline. The STI-AS-DA-C16-X100T intelligent multi-path inspection instrument displays the temperatures of 12 temperature sensors, each channel corresponds to a temperature sensor; the temperature data are recorded every 5 h. After freezing, the porosity and initial speed of gas diffusion, compressive capacity, and mechanic performance of the coal body are analyzed, and the following data are obtained.

6.1. Relationship between Temperature and Freezing Time

After the coals in the cement tank are frozen, the heat is exchanged between the low-temperature brine of circulating flow in the freezing pipes and the surrounding coals. The frozen coal pillar with radius of *R* is formed in the vicinity of the freezing pipe, and extends with time along the radial direction. With the continuous supply of the cooling through the freezing pipes, the diameter of the coal pillar increases and the temperature of the frozen coals gradually decrease. The three-phase body of the coal, gas, and water eventually becomes a hard freezing body, which greatly improves the mechanical properties, such as the compressive strength and elastic modulus. At the same freezing time, the closer the distance from the freezing pipe is, the more the cooling of the coal is, the lower the temperature of the coal body is.

Figures 3 and 4 show the relationship curve of temperature and freezing time. It can be seen from the curves that the coal temperature decreases with increase in the freezing time, the final temperature dropped to 0 °C, the three-phase body of the coal, gas, and water eventually becomes a hard freezing body. On the circumference of same radius, the coal temperature decreases rapidly with increase in the freezing time. After 15 h of freezing, the coal body temperature also is high; after155 h of freezing, the part of the coal temperature decreases rapidly, parts of the coal body are frozen and the freezing situation is shown in Figures 5 and 6.

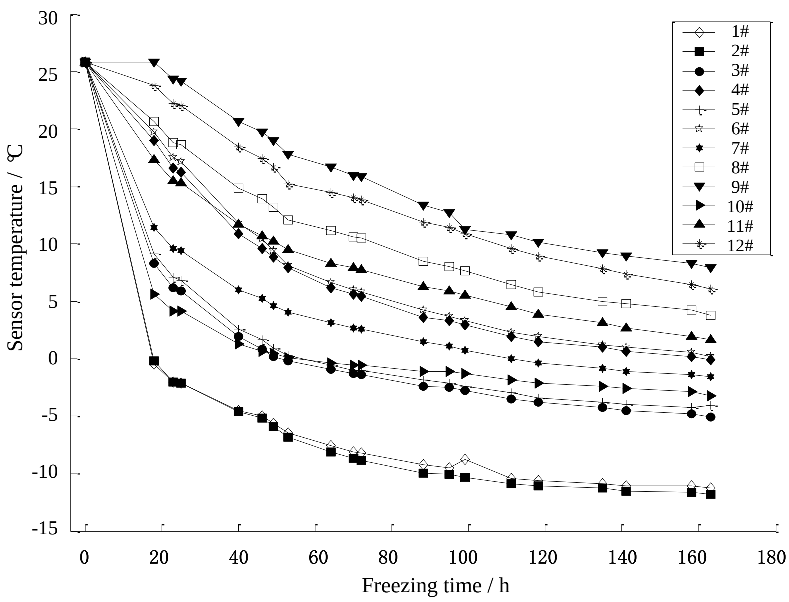

Figure 3. Relationship between sensor temperature and freezing time.

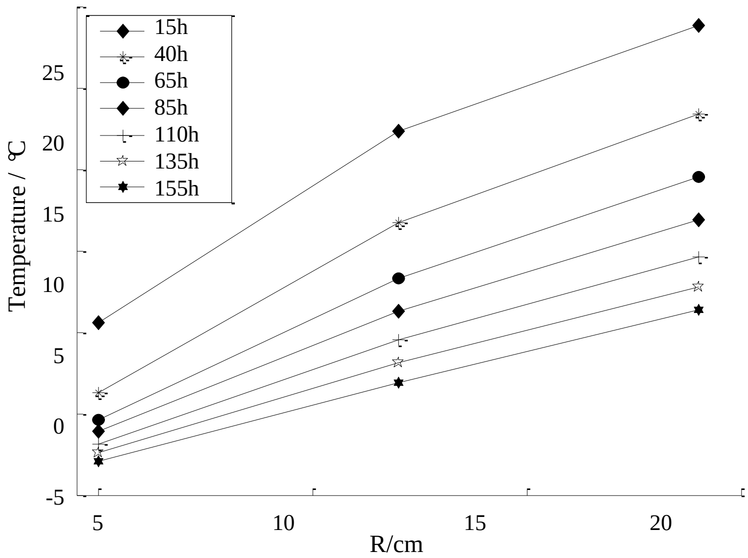

Figure 4. Relationship between temperature and freezing time in freezing pipe center.

Figure 5. Freezing effect around freezing pipe.

6.2. Porosity and the Initial Speed of Gas Diffusion

The initial speed of gas diffusion (ΔP) and porosity (n) of raw coal samples in the laboratory determination and of coal samples processed by liquid freezing with different moistures are obtained as shown in Table 1. From Table 1, the porosity of raw coal samples is 12.6 (11.8), and the porosity of coal samples processed by liquid freezing is 8.14 (8.06), so the porosity is lower about 36.4% (31.7%) than the porosity of raw coal sample. The initial speed of gas diffusion (ΔP) of raw coal samples is 35.5 (36.2); the initial speed of gas diffusion (ΔP) of coal samples processed by liquid freezing is 4 (5), so the initial speed of gas diffusion (ΔP) of coal samples processed by liquid freezing is lower about 88.7% (86.2%) than the initial speed of gas diffusion (ΔP) of raw coal samples. The similar conclusion also was obtained in the literature [22]. Thus it may be known that the injection liquid freezing can seal the fractures and pores, the initial speed of gas diffusion(ΔP) is greatly reduced, which can effectively suppress the release of the gas potential energy and reduce the gas quantity of outburst.

Figure 6. Freezing effect of cement tank overall.

Table 1. Initial speed of gas diffusion (ΔP) and porosity (n) in different conditions.

Coal Sample Number	Test Index	Before Freezing	After Freezing	Ratio
1	n	12.6	8.14	64.6%
2	n	11.8	8.06	68.3%
1#	ΔP	35.5	4	11.3%
2#	ΔP	36.2	5	13.8%

6.3. Effect of Temperature on CH_4 Adsorption of Coal

The WY-98A adsorption constant measurement instrument is mainly used to determine the gas adsorption constant of coal in the process of gas content determination (a, b).The CH_4 adsorption constants (a, b) of coal are obtained by the instrument at a low temperature ($T \leq 0$ °C). When the temperature T is less than or equal to 0 °C, the isotherm adsorption curve still belongs to the isotherm adsorption of type I, which can describe the CH_4 adsorption model of coal by the Langmuir equation [14]. The CH_4 adsorption of coal is mainly physical adsorption, the temperature is activated to adsorption, the higher the temperature is, the more the free gases are, the less the adsorption gases are. From the experiment results, it can be found that at different temperatures and the same pressure, there is approximately linear negative correlation between the temperature and adsorption quantity of same coal samples, with the decrease in temperature, the CH_4 adsorption capacity of coal is increased, as shown in Figure 7. Under the pressure of 6 MPa, when the adsorption temperature decreases from 30 °C to −10 °C, the adsorption quantity of coal sample increases from 34 cm^3/g to 73 cm^3/g. The lower the pressure is, the better the correlation is. When the pressures are different, the linear relationships are different. The similar conclusion also was obtained in the literature [23].

According to the above conclusion, before the outburst coal seam in rock crosscut is exposed, the coals in the front of the roadway working face should be frozen by the measure of the injection liquid freezing to increase the gas adsorption quantity of coal, reduce the free gas quantity, and decline the gas pressure of outburst coal seams, so the measure of the injection liquid freezing can prevent coal–gas outburst in uncovering coal seams in rock crosscut.

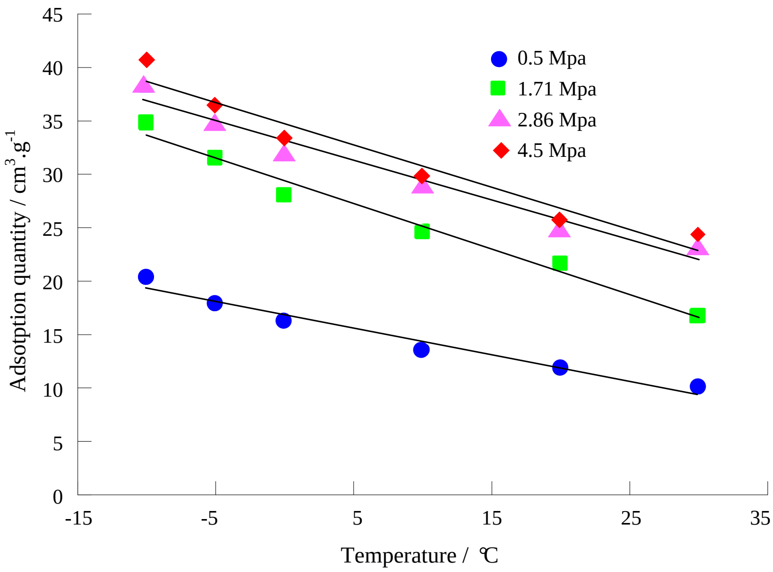

Figure 7. Relationship between temperature and the adsorption quantity of samples under different pressures.

6.4. The Changes inMechanical Properties of Coal

Because the coal strength of the outburst coal seam is often very low, and the coal is easy to break, in the process of drilling and sampling, it is easy to produce the accidents, such as drilling tool jamming, pump suffocation, jet orifice, etc., which result that the sampling is very difficult. In the experiment, the molding coal sample is relatively simple; it can avoid the different experiment results due to the heterogeneity of raw coal. Based on the above reasons, the molding coal samples from the outburst coal seams in Tanshan coal mine are frozen by liquid injection freezing.

The coal samples are crushed into the coal particles with very small size, the molding pressure is 15 MPa, 25 MPa, 35 MPa, and 42 MPa, respectively. The standard molding coal samples with the diameters of 50 mm and height of 100 mm are formed by universal hydraulic testing machine with pressure of 10 tons, which is shown in Figure 8. The standard molding coal samples are put in the freezing device, the freezing temperature is −5 °C, −10 °C, −15 °C, and −20 °C, respectively. The freezing time is 48 h, the samples are taken out for the experiment of uniaxial compressive strength. The equipments are three axis rock mechanical testing machine of RMT-150 type and homemade environment box. In this experiment, the stroke control is adopted and the loading speed is 0.5 mm/s.

Figure 8. Molding coal samples from the outburst coal seam.

The outburst coal seam belongs to IV and V type of the high destruction type, at room temperature, the coals can be twisted into pieces by hand, so the strength is very low. After the injection liquid freezing, the mechanical properties of the molding coal sample change greatly, the mechanical properties of the different freezing temperatures are shown in Table 2.

Table 2. Mechanical parameters of the molding coal sample in different freezing temperatures.

Freezing Temperature (°C)	Average Compressive Strength (MPa)	Average Axial Strain (10^{-3})	Average Transverse Strain (10^{-3})	Average Elastic Modulus (GPa)	Average Poisson Ratio
−5	1.36	59.16	35.10	0.028	0.48
−10	2.17	55.91	30.64	0.046	0.39
−15	3.03	61.02	61.02	0.061	0.41
−20	3.82	67.13	67.13	0.066	0.35

As can be seen from Table 2, after the injection liquid freezing, the average compressive strength, the average axial strain, the average transverse strain, and the average elastic modulus are greatly improved. With the decrease in temperature, the values of mechanical properties increase.

It can also be seen from Table 2 that with the decrease in the freezing temperature, the compressive strength of the molding coal sample (no consideration of the effect of compression molding) increases significantly. When the freezing temperature is −20 °C, the compressive strength of the molding coal sample is largest. The fitting formula (1) of uniaxial compressive strength of molding coal sample under different freezing temperatures is obtained by fitting the experiment data.

The fitting formula:

$$\sigma = -0.1702T + 0.4365 \tag{1}$$

where T—freezing temperature, °C; σ—uniaxial compressive strength, MPa.

It can be seen from Table 2 that with the decrease in the freezing temperature, the elastic modulus of the molding coal sample (no consideration of the effect of compression molding) increases significantly. When the freezing temperature is −20 °C, the elastic modulus of the molding coal sample is largest. The fitting formula (2) of elastic modulus of molding coal sample under different freezing temperatures is obtained by fitting the experiment data.

The fitting formula:

$$E = -0.0001352T^2 - 0.005965T + 0.001044 \tag{2}$$

where T—freezing temperature, °C; E—elastic modulus, GPa.

6.5. The Changes of the Coal Structure

It can be seen from the Figures 9 and 10 that the original coals are loose, but after freezing, the coals are solidified into a hard structure, their integrity is obviously strengthened, and the hard structure is difficult crush by a hammer and other tools. As a result, the mechanical properties, such as compressive strength and elastic modulus, are greatly increased; the whole structure of coal is changed.

6.6. Effect Evaluation of Freezing Measures for Injection Liquid Freezing

According to the requirements of "*prevention and control of coal and gas outburst*", it is necessary to take the effect evaluation for the prevention measure. After all the work is conducted by 4 h, the method of drilling chip index is used to evaluate the effect of the coal body in the frozen area. If the indexes in the evaluation results are below the critical danger value, the prevention and control measures can be confirmed effectively. Otherwise it is necessary to take remedial measures until the danger of the roadway working face is eliminated. According to the results of effect evaluation, it is found that all the indexes are below the critical value after the injection liquid freezing, therefore the control effect is achieved.

Figure 9. Frozen effect diagram of section center.

Figure 10. Frozen coal sample of section center.

7. Conclusions

Aiming at the existing problems of the control measures of uncovering coal seams in rock crosscut, in this paper, the process and main influencing factors of coal–gas outburst in rock crosscut are analyzed. The injection liquid freezing method for uncovering coal seams in a rock crosscut is put forward and the theoretical analysis is carried out. Finally, the freezing experiment device is designed and the coal samples before and after the injection liquid freezing are experimentally analyzed in the laboratory. The following results are concluded.

(1) There is a direct relationship between the scope of the pressure relief zone near the roadway working face and coal–gas outburst. Before the coal seam in a rock crosscut is uncovered, if the technology of the injection liquid freezing is adopted, it can increase the

scope of the pressure relief zone and the strength of the coal body in the pressure relief zone, change the stress distribution of coal body, and prevent the coal–gas outburst.

(2) The injection liquid freezing in outburst coal seams can improve the coal strength, enhance the coal ability to resist outburst. After freezing, the loose original coals are solidified into a hard structure; their integrity is obviously strengthened.

(3) The injection liquid freezing can fill and freeze the cracks and pores of the coal body, reduce the porosity of coal seams, slow down the transformation of adsorption gas to the free gas, and reduce the gas quantity involved in the outburst, so the release of the gas potential energy is fundamentally weakened.

(4) The injection liquid freezing can seal the fractures and pores, greatly reduce the initial speed of gas diffusion (ΔP). The temperature decrease can increase the gas adsorption capacity of coal, reduce the amount of free gases, and reduce gas pressure of outburst coal seams.

(5) When the freezing temperature drops to a certain value, the corresponding width and strength of the pressure relief zone will be enough to resist the outburst energy, such as intrinsic gas energy and the elastic potential energy accumulated in the internal coal.

Author Contributions: Conceptualization, F.T. and Q.Y.; methodology, Z.J. and F.T.; software, Z.J. and Q.Y.; investigation, F.T.; writing—original draft preparation, Q.Y.; writing—review and editing, Q.Y. and Z.J. All authors have read and agreed to the published version of the manuscript.

Funding: The National Natural Science Foundation Project of China (52174177, 52174178) and project supported by Scientific Research Fund of Hunan Provincial Education Department (20B240).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

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