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Research on Static Fracturing Roof Caving Technology for Hard Immediate Roof at the Open-off Cut of 15221 Fully Mechanized Mining Face in Hongliulin Coal Mine

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Abstract

Aiming at the engineering challenge that the hard immediate roof at the open-off cut of the 15221 fully mechanized mining face in Hongliulin Coal Mine is extremely prone to forming a large-area suspended roof and inducing dynamic strata pressure disasters during the initial mining period, this paper conducted an engineering experimental study on the static fracturing roof caving technology for hard immediate roofs. By drilling pre-splitting boreholes in the open-off cut and two gateways of the 15221 working face and injecting expansive cartridges, the roof caving characteristics, working resistance of supports, wind speed, and dust concentration changes before and after fracturing were analyzed. The results show that the static fracturing technology effectively severed the integrity of the hard roof, and the initial weighting step was controlled at 43.5 m. The over-limit ratio of support pressure dropped to 0.5%, effectively avoiding the risk of support crushing, and the average dust concentration in the working face was significantly reduced, achieving safe, efficient, and green roof caving.

Keywords

Static fracturing; Hard immediate roof; Open-off cut; Strata pressure control; Initial roof caving

1. Introduction

In coal resource mining, the control of hard roofs composed of thick sandstone layers has become increasingly prominent[1-2]. During the initial mining and initial caving stage at the open-off cut of a fully mechanized mining face, because the hard immediate roof is difficult to cave naturally, it is extremely easy to evolve into a large-area suspended roof structure[3-4]. When the accumulated elastic energy breaks through the limit, it will induce instantaneous large-area roof fracture, which in turn triggers severe dynamic load impacts and airblast disasters[5-6]. Traditional

deep-hole pre-splitting blasting technology has safety hazards such as vibration damage, dust, and sparks, while high-pressure hydraulic fracturing has problems such as high water consumption[7]. Static expansion fracturing technology utilizes the expansion pressure generated by the hydration reaction of soundless cracking agents to drive the slow initiation and propagation of cracks in hard rock masses, which is an inherently safe roof caving technology[8]. Taking the 15221 fully mechanized mining face of Hongliulin Coal Mine as the engineering background, this paper conducts an engineering experimental study on the static fracturing roof caving technology for the hard immediate roof at the open-off cut.

2. Engineering Overview and Construction Technology

2.1. Working Face Overview

The Shanxi 5^{-2} coal seam is the primary minable coal seam in Hongliulin Coal Mine. The 15221 working face is adjacent to the completed 15220 working face; they are the 21st and 20th working faces of the 5^{-2} coal seam in the South No. 1 panel, respectively. The geological conditions and mining technology of the two working faces are basically identical. To the north is the 5^{-2} coal auxiliary transportation main roadway, and to the south is the solid coal seam. The thickness of the overlying strata is 90~113 m, the thickness of the overlying bedrock is 73~95 m, and the thickness of the unconsolidated layers is 18~44 m. Above it is the completed and sealed 4^{-2} coal seam, with an interval of 75 m from the 5^{-2} coal seam. The 5^{-2} coal is a spontaneous combustion coal seam with simple hydrogeological conditions. The occurrence status of roof and floor rock layers of the 5^{-2} coal seam is shown in Table 1.

Table 1. Conditions of coal seam roof and floor

Strata Name	Lithology	Thickness (m)	Lithological Characteristics
Main Roof	Fine sandstone	19.6-29.1 (24.47)	Light gray, mainly composed of quartz and feldspar, poorly sorted, sub-angular, calcareous-argillaceous cementation, uniform bedding
Immediate Roof	Sandy mudstone	0.00-2.66 (0.83)	Light gray, with sandstone bands, containing a large amount of mica fragments, small cross-bedding
Coal Seam	5^{-2} Coal	5.42-7.75 (6.85)	Black, massive, pitch luster, uneven and angular fracture, banded structure, developed endogenous fissures, filled with calcite and pyrite, belongs to semi-bright coal
Immediate Floor	Siltstone	5.1-11.61 (6.78)	Gray, dark gray, with wavy cross-bedding, containing plant root fossil fragments, with two thin coal seams of 0.3~0.5m in the middle of the rock layer
Main Floor	Medium sandstone	4.4-6.93 (5.69)	Light gray, mainly composed of quartz and feldspar, containing a small amount of dark minerals, poorly sorted, angular, argillaceous cementation

2.2. Static Fracturing Scheme for Hard Immediate Roof at Open-off Cut

Based on the actual engineering conditions, the construction scheme was designed. After the open-off cut of the 15221 fully mechanized mining face is formed, static expansive agents are used in the pre-splitting boreholes to weaken the roof.

2.2.1. Determination of borehole fracturing height

According to the borehole columnar section near the open-off cut of the 15221 working face, the lithological thickness of the overlying strata of the working face open-off cut includes 5.6 m siltstone, 2.3 m fine sandstone, 2.5 m siltstone, 13.07 m fine sandstone, 8.85 m medium sandstone, 5.85 m fine sandstone, and 1.1 m siltstone, etc. According to the thickness of 5-2 coal and the designed mining height of the 15221 working face, combined with the stratification characteristics of the overlying strata, the maximum static fracturing height is controlled at about 10 m. Targeted tests can be carried out during specific implementation to achieve the best initial roof caving effect. The maximum fracturing height in the open-off cut is 10 m, exceeding the length of the anchor cables.

2.2.2. Determination of borehole parameters

Based on the static fracturing and strata pressure theory, the maximum tensile stress criterion, and the roof strata structure, strata thickness, lithology, and mining height of the 15221 working face open-off cut. Combined with previous test experience of static fracturing at the face ends, the static fracturing method with expansive cartridges is adopted, that is, putting the expansive cartridges into the boreholes, sealing the holes, and injecting water to make the cartridges absorb water and wait for the reaction to fracture.

To ensure the fracturing effect, engineering tests are carried out in the open-off cut and the initial mining section of the two gateways, and the test range is within 80 m of the two ends of the open-off cut. The specific layout parameters of the static fracturing boreholes are as follows:

Borehole-S: Arranged within the 80 m range at both ends of the open-off cut. There are 4 boreholes per row, and 8 rows at each of the two ends of the open-off cut, with a row spacing of 10 m. The hole depth is 20 m, the inclination angle is 30°, the vertical depth is 10 m, and the diameter is Φ75 mm. The opening position of the first borehole in each row is 0.5~0.8 m away from the tail beam line of the support, the hole spacing is 0.5 m, and the deflection angles of the boreholes in each row are 20°, 16°, 15°, and 10°, respectively, deflected towards the coal wall of the mining rib in the open-off cut.

Borehole-T: Arranged in the belt transportation gateway and the return air gateway, with 4 boreholes per row. The opening position of the first row is on the extension line of the non-mining rib coal wall in the open-off cut. There are 4 rows arranged in each of the two gateways, with a row spacing of 6 m. The hole depth is 15 m, the inclination angle is 30°, the vertical depth is 7.5 m, and the diameter is Φ75 mm. The

opening position of the first borehole in each row is 0.5~0.8 m away from the non-mining rib coal wall of the gateway, the hole spacing is 1 m, and the borehole direction is parallel to the axial direction of the roadway.

For detailed parameters of all boreholes, please refer to Figure 1 and Figure 2.

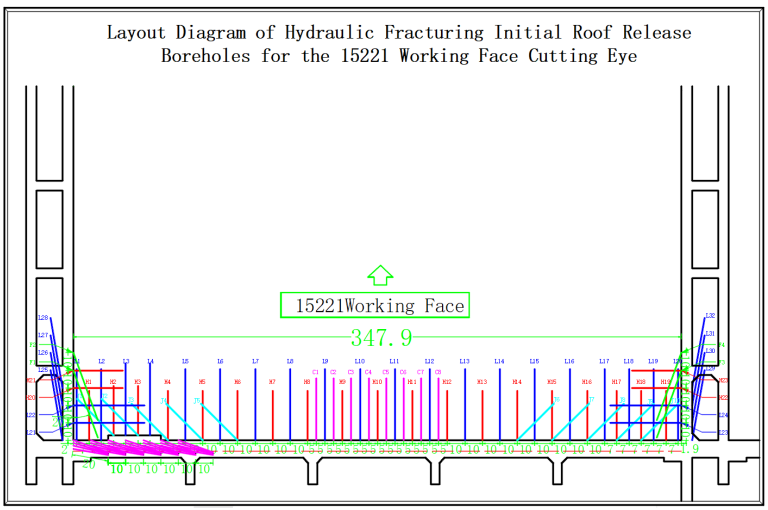


Figure 1. Layout plan of static fracturing roof caving boreholes in 15221 working face open-off cut

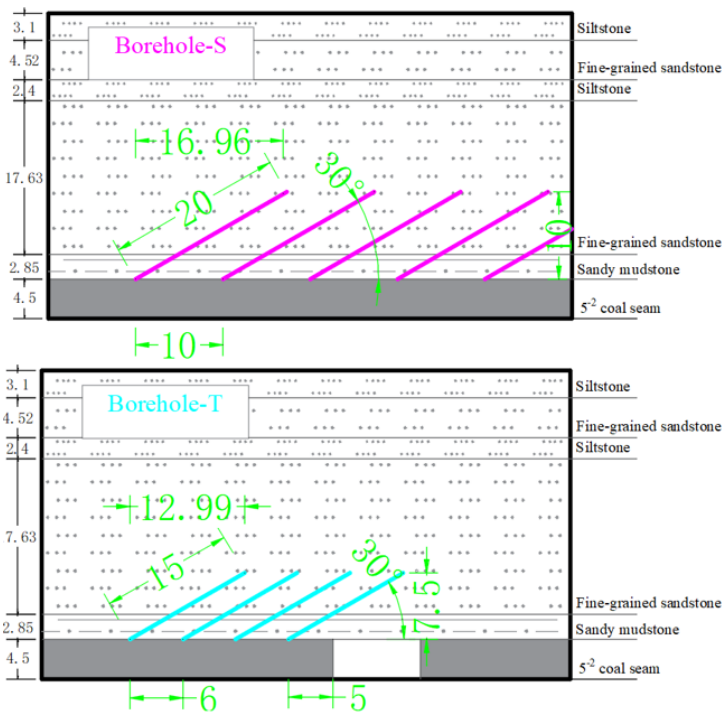


Figure 2. Enlarged views of static fracturing boreholes at the gateway ends of 15221 working face open-off cut

2.3. On-site Construction Technology

To solve the problem of untimely caving of the hard immediate roof during the initial mining period of the 15221 working face, the wrapped expansive agent (expansive cartridge) is adopted in this governance project to implement the static fracturing technology.

When the working face formally advances from the open-off cut and the cumulative advance reaches 8 meters, the water injection work for all pre-embedded expansive cartridge boreholes at both ends in the open-off cut is uniformly started, and the static fracturing roof caving project in the two gateways is carried out with the advancement of the working face.

This arrangement is based on the following considerations: when advancing 8 meters, the roof strata begin to move, but a large-area suspended roof has not yet formed. At this time, injecting water into the expansive cartridges pre-embedded in the boreholes in advance can reserve about 12~24 hours of reaction and effective time for them, ensuring that the fracturing effect begins to manifest within the critical range of 10~15 meters of working face advancement, and the roof can cave along with the mining.

The specific technological process is: borehole drilling → using a rod to clear the borehole → putting cartridges into the hole one by one → hole sealing → fixing the water injection pipe and return water pipe in the borehole to both sides of the roadway or other positions convenient for operation → injecting clean water into the borehole → cartridges absorbing water and reacting to fracture the roof.

3. Analysis of Engineering Application Effects

3.1. Advance Degree and Goaf Caving Conditions

The 15221 fully mechanized mining face formally started mining in the 4:00 PM shift on May 16, 2025. Starting from the midnight shift on May 19, the immediate roof of the working face caved locally and sporadically. At 1:00 in the midnight shift on May 25, the initial weighting ended. The initial weighting step of the 15221 working face this time was 43.5 m, which lasted for 8 days, 1 sub-shift, and 1 hour. The advancement progress of the 15221 fully mechanized mining face during the initial mining and initial caving period is shown in Table 2

Table 2. Statistics of advance degree during the initial mining and caving period of 15221 working face

Date	Single-day Advance Degree	Average Cumulative Advance Degree	Goaf Caving Conditions
May 17	Head: 2m,Tail: 1.6m	1.8m	Un-injected for fracturing
May 19	Head: 10m,Tail: 5.8m	7.9m	Un-injected for fracturing
May 19	Head: 18m,Tail: 14m	16m	Un-injected for fracturing
May 20(Water injection for fracturing)	Head: 25m,Tail: 20m	22.5m	Cartridge injected with water, roof not caved

May 21	Head: 30m,Tail: 28.5m	9.25m	Cartridge reacted to fracture after water injection, local caving in the fractured area roof
May 22	Head: 39.2m,Tail: 38m	38.6m	Cartridge reached maximum expansion force, immediate roof near the two ends fully caved
May 24	Head: 45m,Tail: 42m	43.5m	Immediate roof near the two ends fully caved, main roof initial weighting
May 25	Head: 52.2m,Tail: 49.2m	50.7m	Immediate roof periodic caving

3.2. Analysis of Hydraulic Support Pressure in Working Face

To study the influence of static fracturing technology on the manifestation of roof strata pressure during the initial mining period of the fully mechanized mining face, the 15221 working face and the adjacent 15220 working face were selected for comparative analysis. The geological conditions and mining technology of the two working faces are basically identical. Among them, the 15220 working face did not adopt static fracturing measures, while the 15221 working face used static expansive fracturing agents in the open-off cut and initial mining stage to perform fracturing pretreatment on the hard roof. A systematic comparison was made through data such as pressure variations, bearing characteristics, and state distribution of hydraulic supports in the two working faces.

3.2.1. Support pressure comparative analysis

As shown in Figure 3, it is the comparison of the support groups with the maximum bearing pressure in the 15220 and 15221 fully mechanized mining faces. For the 15220 working face, the pressure curve of its maximum bearing support group presents characteristics of severe jumps, sharp mutations, and frequent unloading and reloading during the advancement process, with the pressure reaching above 45 MPa multiple times. The 82#, 83#, and 84# supports showed high-intensity bearing and unloading responses almost simultaneously, demonstrating strong concentrated load transfer and large-scale roof caving characteristics. This pressure manifestation phenomenon indicates that the roof has strong integrity and did not cave during initial mining, forming a large-span suspended roof structure, which eventually collapsed violently after delayed advancement, inducing concentrated strata pressure manifestation.

In contrast, the maximum bearing 133# support in the 15221 working face had several local pressure increases near the advance of 22.5 m and 29.25 m, but the overall pressure level remained between 25~35 MPa for most of the time, only approaching 45 MPa at individual moments, and there was no continuous high-intensity sudden pressure like that in 15220. The trend of its pressure curve is relatively gentle with obvious fluctuation rhythm, indicating that the fragmentation of the roof was enhanced after static cracking agent fracturing, and the stress release process of the rock mass was more buffering and dispersive, effectively avoiding strong pressure manifestation and sudden pressure loads.

The comparison of the maximum bearing support groups further shows that the static expansive agent fracturing technology can effectively weaken the strong strata pressure manifestation caused by concentrated caving. In the 15221 working face, the roof caving process showed advance, fragmentation, and segmentation, and the bearing process was more stable; while in the 15220 working face, due to the strong integrity of the roof and the large range of the suspended roof, sudden concentrated strata pressure manifestation appeared after advancing to a certain step, causing severe impact on the supports. It can be seen that the static fracturing measures have significant application value in controlling the caving method of the hard roof during the initial mining period, reducing the burden on the hydraulic supports, and improving the safety of the mining face.

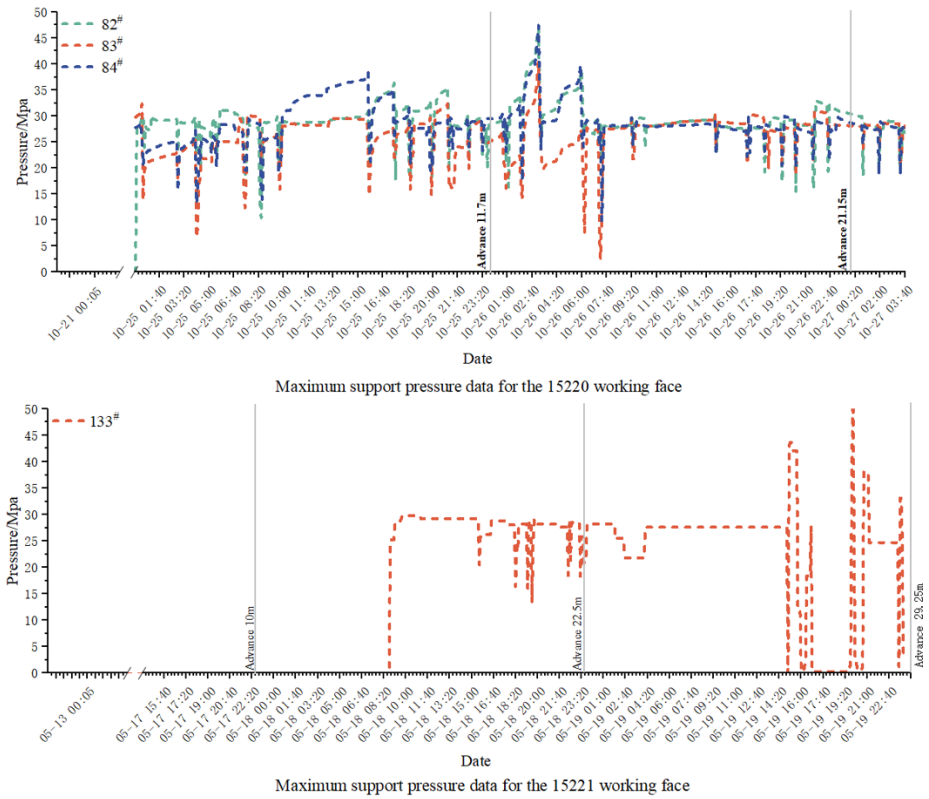


Figure 3. Schematic diagram of the arrangement of expansive cartridges and water injection pipelines

3.2.2. Statistics of hydraulic support working status

Figure 4 shows the statistical comparison of hydraulic support states in the 15220 and 15221 fully mechanized mining faces. From the statistical results, it can be seen that the overall bearing state of the supports has changed significantly before and after using the static expansive agent. In the 15220 working face, the proportion of time the hydraulic supports were in a normal working state was 80.3%, under-pressure proportion was 15%, and the over-limit state was as high as 4.7%.

This result shows that although the supports run normally most of the time, the concentrated roof caving at some stages causes the supports to bear instantaneous high loads, resulting in over-limit pressure conditions.

In contrast, after the 15221 working face used the static expansive agent to fracture the roof, the proportion of the over-limit state of the hydraulic supports dropped to only 0.5%, which is almost negligible; the proportion of the under-pressure state was 30.5%, and although it increased, the normal state proportion still reached 69%. This state distribution indicates that although the enhanced roof fragmentation after fracturing and incomplete contact may cause some under-pressure phenomena, the over-load risk is greatly reduced because the roof caves more timely and the load distribution is more uniform. The statistical results of the hydraulic support status further confirm the positive effect of static expansion fracturing technology on roof control. The 15221 working face effectively avoided high-intensity concentrated strata pressure manifestations, significantly reduced the risk of support over-load and over-limit, and guaranteed the safety of working face advancement.

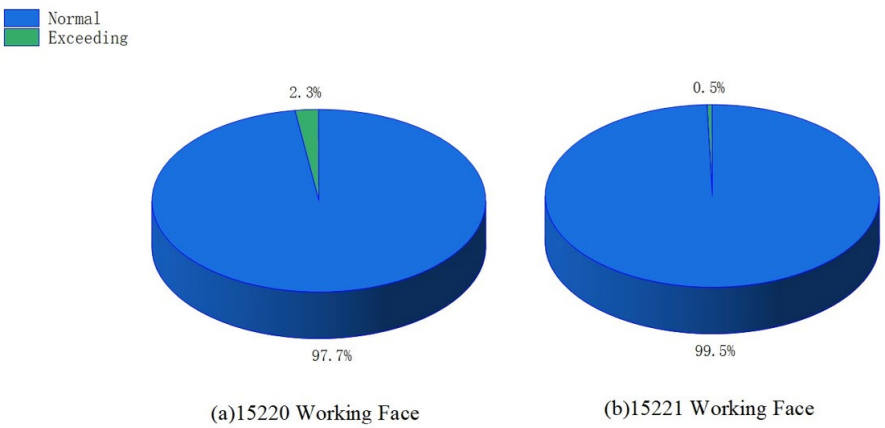


Figure 4. Statistics of hydraulic support status in 15220 and 15221 fully mechanized mining faces

3.3. Wind Speed Monitoring in Working Face

The wind speeds before and after the static fracturing of the immediate roof at the open-off cut of the working face were tested respectively. Measuring point layout: According to the large suspended roof distance of the immediate roof during the initial mining of the fully mechanized mining face in the past and the existing air leakage problems, the wind speed during the initial mining period was tested to understand the improvement of static fracturing on air leakage in the fully mechanized mining face during the initial mining period. Among them, 7 wind speed measuring points were arranged, and the cross-sectional area was based on on-site measured data.The specific layout of measuring points is as follows:

Cross-section wind speed points: Located in the working face, corresponding to the

vicinity of the 6# support, 90# support, and 166# support. Measure the average wind speed of the cross-section passage.

Key position points: Intake air end, return air end, shearer head, shearer tai.

The wind speed in the belt transportation gateway increased from 0.39~0.43 m/s to 0.69~0.85 m/s; the wind speeds at the 6#, 90#, and 166# supports in the working face increased from 0.54~0.68 m/s, 0.28~0.47 m/s, and 0.40~0.59 m/s to 0.76~0.87 m/s, 0.52~0.65 m/s, and 0.74~0.88 m/s, respectively; the wind speed in the return air gateway increased from 1.32~1.35 m/s to 1.61~1.65 m/s. In terms of air volume, the air volume in the belt transportation gateway increased from 613~676 m^3/min to 1060~1312 m^3/min, and the total return air volume increased from 1980~2025 m^3/min to 2463~2525 m^3/min.

In terms of air volume parameters, the air volume in the auxiliary transportation gateway decreased slightly after fracturing, and the average air volume of the 3 measuring points dropped from 1340 m^3/min to 1270 m^3/min. The air volume in the belt transportation gateway increased significantly, with the average air volume increasing from 645 m^3/min before fracturing to 1171 m^3/min, an increase of 81.55%. The air volume in the return air gateway was greatly improved, with the average air volume increasing from 2005 m^3/min before fracturing to 2489 m^3/min, an increase of 24.14%.As shown in Figure 5.

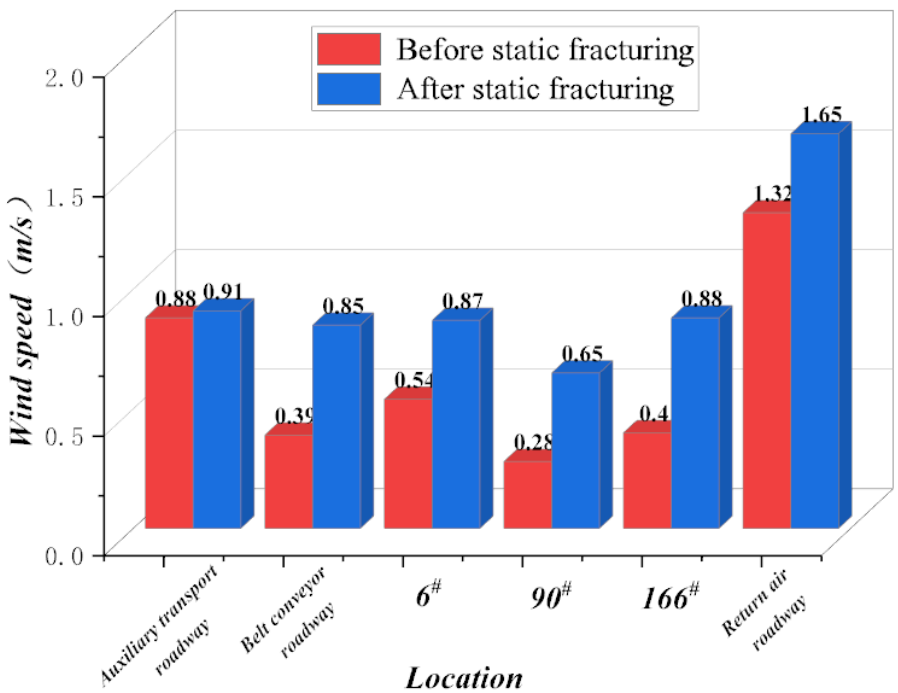


Figure 5. Comparison of air leakage before and after adopting static fracturing during the initial mining period of 15221 fully mechanized mining face

4. Conclusion

Through the engineering test of static fracturing roof caving technology on the hard immediate roof at the open-off cut of the 15221 fully mechanized mining face in Hongliulin Coal Mine, and comparative analysis with the adjacent 15220 working face, the following main conclusions are drawn:

(1) Effectively improved the caving characteristics of the hard roof. The static fracturing technology uses expansion pressure to drive the initiation and penetration of cracks in the rock mass, effectively cutting off the integrity of the roof. Tests show that the initial weighting step of the 15221 working face was successfully controlled at 43.5 m, realizing roof caving along with mining, and effectively solving the difficult problem of large-area suspended roofs.

（2）Significantly reduced the manifestation intensity of strata pressure in the working face. Comparative analysis shows that after implementing fracturing, the hydraulic support pressure curve of the 15221 working face fluctuates gently, and there is no continuous high-intensity sudden pressure phenomenon commonly seen in the 15220 working face. The over-limit proportion of support working pressure dropped from 4.7% to 0.5%, which greatly reduced the risk of support crushing and ensured the stability of the mining face support system.

（3）Optimized the mine ventilation quality and reduced air leakage. Static fracturing promotes timely roof caving to fill the goaf, significantly improving the air leakage problem during the initial mining period. Monitoring data show that the average air volume in the belt transportation gateway increased by 81.55%, and the total return air volume increased by 24.14%, effectively improving the stability of the working face airflow.

（4）Realized safe, efficient, and green mining. Compared with traditional blasting technology, static fracturing has no vibration, no dust, and no sparks, and is an inherently safe technology. At the same time, the average dust concentration in the working face after fracturing is greatly reduced, providing a green and efficient new technical path for the control of hard roofs under similar geological conditions.

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