


Article

Borehole Protection Technology of Screen Pipes for Gas Drainage Boreholes in Soft Coal Seams

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Abstract: In this paper, research was carried out on borehole protection technology using screen pipes, aiming to address the problems of gas drainage borehole collapse and low gas drainage efficiency in soft coal seams, which have low gas permeability and high gas content. An experiment was conducted to study the compressive resistance and borehole protection effects of polyvinylchloride (PVC), polypropylene (PP), and acrylonitrile–butadiene–styrene (ABS) screen pipes with different sieve opening spacings. The optimal screen pipe material and sieve opening spacing were determined. The borehole protection effect and gas drainage efficiency using three borehole protection methods, namely, bare boreholes, traditional PVC screen pipes, and new ABS screen pipes, were compared and studied on site, and the influence of pipe diameter on borehole protection efficiency was revealed. The results show that the compressive resistance and borehole protection effects of the three types of screen pipes are in the following order: PVC < PP < ABS. ABS screen pipes can more effectively inhibit boreholes from collapse, and the best borehole protection is achieved with a sieve opening spacing of 50 mm. The field tests showed that the gas drainage concentration of the bare borehole in the creep deceleration stage was 113% higher than that of the borehole protected by the ABS screen pipe and 255% higher than that of the borehole with the PVC screen pipe. The screen pipe began to play a role in borehole protection at the beginning of the stable working stage, as the borehole wall began to deform and collapse. On the 30th day of gas drainage, the gas drainage concentration of the borehole installed with the ABS screen pipe was about 9 times that of the bare borehole due to the collapse and blockage of the bare borehole. The new ABS screen pipe with an outer diameter of 40 mm and a sieve opening spacing of 50 mm had a better borehole protection effect and gas drainage efficiency than the traditional PVC pipe. Proper sizing of the screen pipe diameter can improve borehole service life and gas drainage efficiency. The research results are of great significance for solving the problem of gas drainage borehole instability and for improving gas drainage efficiency in soft coal seams.



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1. Introduction

Soft coal seams with low gas permeability and high gas content are often accompanied by serious hazards, namely, coal and gas outbursts [1]. The pre-drainage of gas through boreholes is a fundamental measure used to prevent and control gas accidents in coal mines [2–5]. Highly gassy coal seams are widely distributed in major coal-producing countries. Gas drainage boreholes in soft coal seams are prone to deformation, instability, and even collapse, owing to low coal strength and permeability, a high gas concentration, gas pressure, and other factors, which can cause the partial or overall blockage of

boreholes [6,7]. This problem affects the long-term service of boreholes and reduces gas drainage efficiency. Researchers from various countries have carried out extensive studies on the collapse problem of gas drainage boreholes in soft coal seams [8–13]. Improvements in drilling technology can effectively enhance the probability of borehole formation and the depth of gas drainage boreholes in soft coal seams [2,14–16]. Ji [17] proposed a combined auger–air drilling technique; a specially designed blade in the drill rod can stir up large particles of coal so that the large particles can be brought to the ground smoothly using compressed air. This drilling technique is efficient in preventing borehole collapse. In order to improve the gas drainage efficiency of soft coal seams, Li et al. [14,16] proposed new drilling technology, wherein boreholes are protected by spraying foamed concrete slurry onto the surfaces of the borehole walls during drilling to prevent borehole collapse in the seam. However, due to the poor stability of borehole walls in soft coal seams, the stability of boreholes after their formation and the removal of the drill is still problematic [18]. The screen pipe borehole protection method uses screen pipes as gas drainage channels and provides support for borehole walls. This method avoids the blockage of borehole channels due to collapse. The screen pipe parameters are determined mainly depending on the compressive resistance and drainage efficiency of the screen pipe [19,20]. Ji [17] used flame-retardant and anti-static polyvinylchloride (PVC) materials to make screen pipes in order to solve the problem of borehole collapse in gas drainage boreholes in soft coal seams. Zhu et al. [21] used borehole-protecting screen pipes with different diameters for field comparison experiments, and they determined the influence of the screen pipes on the gas drainage of long boreholes with large diameters. Zhai et al. [22] studied the stability and acoustic emission characteristics of bare boreholes and boreholes protected by a 40 mm-diameter PVC screen pipe using experiments, and they concluded that a screen pipe can improve a borehole's resistance to interference by at least 40%. Li et al. [16] found that a PVC plastic pipe with a sieve opening diameter of 10 mm and a screen pipe diameter of 32 mm or 50 mm can inhibit the collapse of boreholes. Zhao et al. [23] conducted a field experiment to study the impact of the diameter and wall thickness of a polyethylene (PE) screen pipe on the borehole protection effect on site in the Chengzhuang coal mine, China. They finally determined the optimal screen pipe outer diameter (50.8 mm) and wall thickness (4.6 mm). Xue et al. [24] proposed the use of an assembly of various casing pipes in boreholes to improve gas drainage stability. A monitored trial was carried out at the Zhuji coal mine in China, and the gas production rate increased 16 times after installing the developed pipe. Peng et al. [25] studied the crushing strength of screen pipes under different arrangements of sieve openings using a numerical simulation based on ABAQUS to optimize the diameter and spacing of the sieve openings.

Huang et al. [26] compared and analyzed the collapsing strength and bending strength of steel and PVC screen pipes using compressive testing. They found that increasing the sieve opening density can weaken the compressive resistance of steel screen pipes more than that of PVC screen pipes. The compression resistance of steel pipes is indeed good, but, usually, the drilling trajectory changes, and the drilled borehole is generally not straight. Steel pipes cannot be bent, and they are inconvenient to install. Zhang et al. [18] established a particle flow model of coal particles passing through screen pipes based on the discrete element method, and they analyzed the impacts of the screen pipe diameter, sieve opening diameter, and slotting area on the ability of coal particles to passing through screen pipes and on gas drainage efficiency. Liu et al. [27] compared the mechanical properties of PVC, polypropylene (PP), and PE screen pipes based on experiments, and they concluded that PP pipes provide better borehole support and that sieve opening density can affect the tensile strength of screens. The above studies show that borehole protection efficiency is directly affected by screen pipe parameters, including screen pipe material, sieve opening diameter, sieve opening spacing, and pipe wall thickness. Field applications show that the compressive strength of traditional PVC, PP, and PE screen pipes is relatively poor, so screen pipes are prone to damage during borehole collapse. Additionally, existing studies

have not been able to properly select a screen pipe with the consideration of both the borehole protection effect and gas drainage efficiency.

Considering the abovementioned problems, this paper proposes a laboratory method to compare the compressive resistance and borehole protection effect of PVC, acrylonitrile–butadiene–styrene (ABS), and PP screen pipes with different sieve opening spacings. The borehole protection effect and gas drainage efficiency of a bare borehole, a borehole protected by a traditional PVC screen pipe, and a borehole protected by a new ABS screen pipe were compared on site, and the gas drainage efficiency and borehole protection performance of the borehole protected by the ABS screen pipe were verified. The research results are of great significance for solving gas drainage borehole instability and for improving gas drainage efficiency in soft coal seams.

2. Experimental System and Methods

2.1. Experimental System

The experimental device consists of a loading system (TYS-500 pressure-testing machine), a cylindrical sandbox (with an outer diameter, height, wall thickness, cover thickness, and cover diameter of 400 mm, 400 mm, 6 mm, 20 mm, and 390 mm, respectively), a foil resistance strain gauge, a static resistance strain tester (DH3818), and a strain-type miniature earth pressure box, as shown in Figure 1. The sandbox cover can move up and down and bear pressure. A small hole with a diameter of 10 mm was opened in the middle of the sandbox wall to lead out the strain gauge and the earth pressure cell test wires connecting to the static strain tester. The deformation of the screen pipe was measured by the strain gauge. The pressure on the screen pipe was measured by the earth pressure box embedded in the sandbox at the corresponding position.

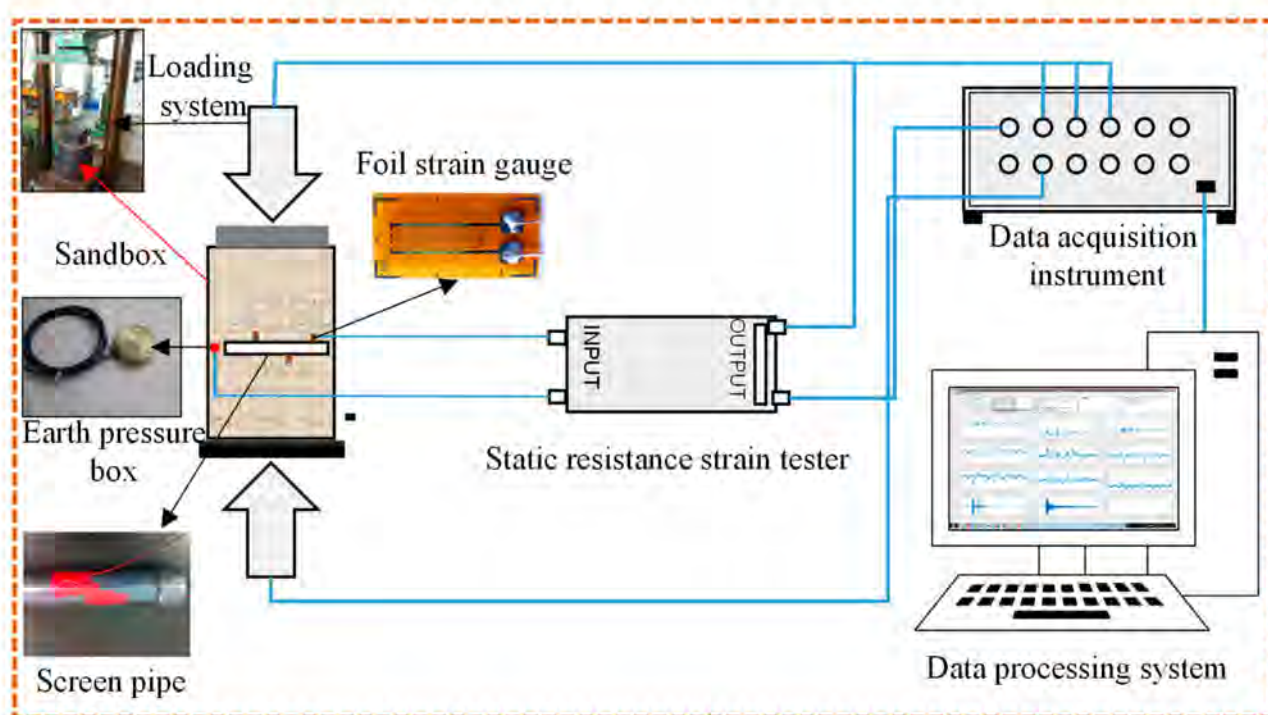


Figure 1. Schematic of the experimental system.

2.2. Screen Pipe Sample Preparation

The loading experiment mainly studied the effect of the screen pipe material and sieve opening spacing on the pipe compressive strength, which relates to borehole protection ability. The cost, compressive strength, flame retardancy, antistatic property, and fabrication technology of various types of screen pipes were considered comprehensively, and ABS,

PP, and PVC screen pipes were eventually prepared for the loading test. According to the standard specifications of plastic screen pipes and underground gas drainage drilling equipment, the inner and outer diameters of the pipes were determined to be 32 mm and 40 mm, respectively, and the length was 300 mm. To prevent sands from flowing into the screen pipes and affecting the reliability of the test results, sieve openings were sealed by tape, and pipe ends were covered by plugs during the experiment, as shown in Figure 2.

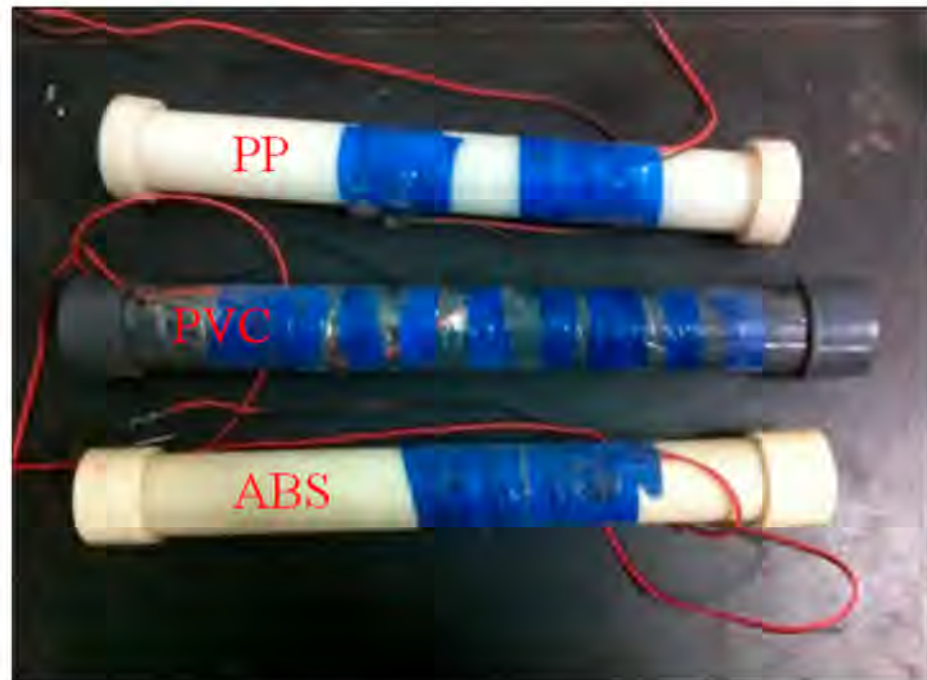


Figure 2. ABS, PP, and PVC screen pipe samples.

When carrying out the experiment on the effect of the sieve opening spacing on the compressive strength of the screen pipes, samples of ABS, PP, and PVC pipes with sieve opening spacings of 30 mm, 50 mm, and 70 mm, respectively, were prepared. The sieve opening diameter was 10 mm. Moreover, similar to the sieve opening pattern of the screen pipes that are currently used at mines, two sets of perforations were applied along the pipe perpendicularly, forming sieve opening patterns, as shown in Figure 3.



Figure 3. Screen pipes with different sieve opening spacings.

2.3. Experimental Methods

In the experiment, strain gauges were pasted using quick-drying adhesive, and strain gauges and signal wires were fixed using tape to prevent them from falling off during compression. The experimental process is shown in Figure 4. The compressive testing includes three steps: (1) The cylindrical sandbox is filled with sand, and the earth pressure box and the screen pipe connected to the strain gauge are buried at the same level to

simulate a protected gas drainage borehole in a soft coal seam. (2) The loading is vertically applied on the sandbox cover to load the buried screen pipe. Every time the applied pressures increase by 5 tons, all sensors record a set of data. (3) The pressure of each group of tests is maintained for 10 min before pressure release.

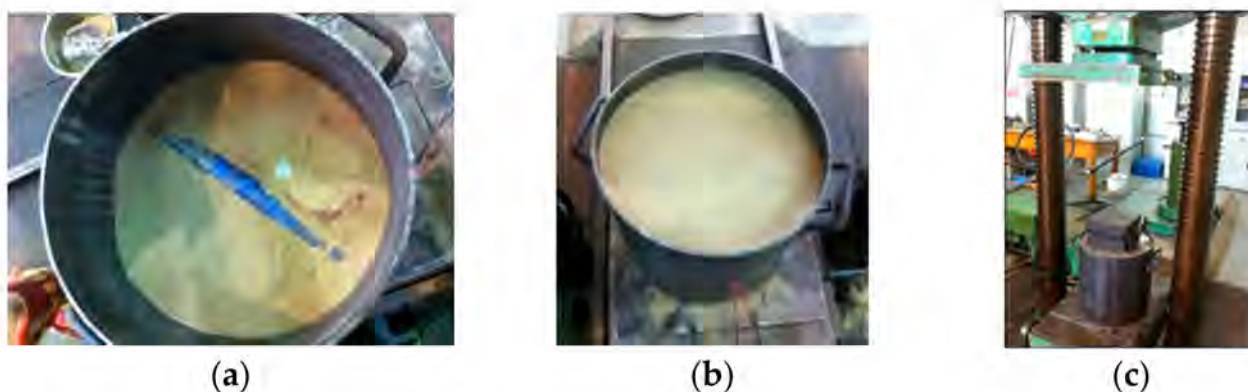


Figure 4. Schematic of experimental preparation and loading process. (a) Screen pipe embedding process; (b) sand box after burying the screen pipe; (c) loading process.

This paper makes a comparative study by changing one factor to control the other unchanged factors. The factors include the loading stress, material, and sieve opening spacing. The response is the radial strain. A lower radial strain means a better borehole protection effect, as shown in Table 1.

Table 1. Factors and response of experimental research.

Factor	Response	Effect on Borehole Protection
Material (PVC, ABS, and PP)	Radial strain	A lower radial strain means a better borehole protection effect
Sieve opening spacing		
Loading stress		

3. Experimental Results

3.1. Compressive Performance of Screen Pipes Made of Different Materials

The radial strain vs. loading stress curves for the PVC, ABS, and PP pipes are shown in Figure 5. The radial strains of the PVC, ABS, and PP screen pipes show linear increasing trends when the loading stress is increased. Under the same load, the radial strain of the ABS screen pipe is much smaller than that of the PVC and PP screen pipes. When the loading stress is less than 3 MPa, there is little difference in the radial strains of the PVC and PP screen pipes, but the radial strain of the PVC screen pipe is larger than that of the PP screen pipe when the pressure is higher than 3 MPa.

PVC screen pipes are now the most commonly used screen pipe in coal mines in China. The ratio of the radial strain of the ABS and PP screen pipes to that of the PVC screen pipe during the experiment was calculated to further compare the compressive performance among the screen pipes. The calculation results are shown in Figure 6. It can be seen from the figure that, when the loading stress varies, the radial strain of the PP screen pipe is about 93% of the radial strain of the PVC screen pipe, not showing much difference. In contrast, the radial strain of the ABS screen pipe is only about 4%–17% of that of the PVC screen pipe. In conclusion, the ABS screen pipe has the highest compressive resistance, followed by the PP pipe. The compressive performance of the ABS pipe is more superior to that of the PP and PVC pipes under larger loads.

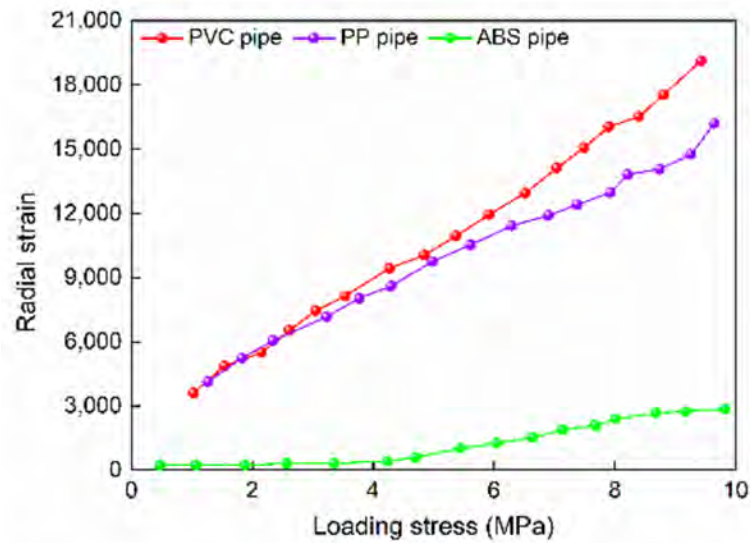


Figure 5. Variation curves of radial strains and loading stress of PVC, ABS, and PP screen pipes.

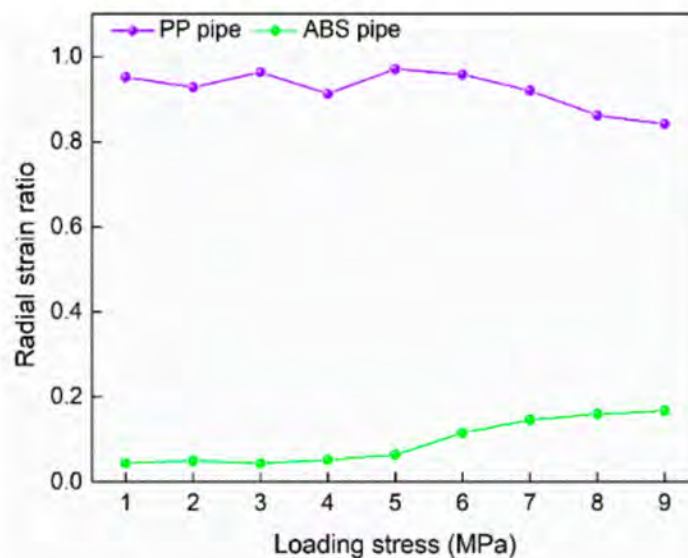


Figure 6. Radial strain ratios of PP screen pipe and ABS screen pipe to PVC screen pipe.

3.2. Influence of the Sieve Opening Spacing on Pipe Compressive Strength

The relationship between the strain and the loading stress during the loading process of various screen pipes with different sieve opening spacings is shown in Figure 7. There is a linear functional relationship between the loading stress and strains of the screen pipes with different sieve opening spacings. Under the same load, the strains of the screen pipes increase with a decrease in the sieve opening spacing. When the sieve opening spacing is 30 mm and the loading pressures of the PVC and PP screen pipes are 3.6 MPa and 7.5 MPa, respectively, the corresponding radial strains reach the maximum range of the strain gauge. However, when the loading stress of the ABS screen pipe is 9 MPa, its radial strain is only about 11,000, as shown in Figure 7a. The relationship between the loading stress and the radial strain of each type of screen pipe is almost the same when the sieve opening spacing is changed to 50 mm or 70 mm. Figure 7b,c show that the radial strains of the PVC and PP screen pipes reach the limits of the strain gauge when the pressure is increased to 10 MPa, while the radial strain of the ABS screen pipe almost stays below 4000 when the pressure is increased to 10 MPa.

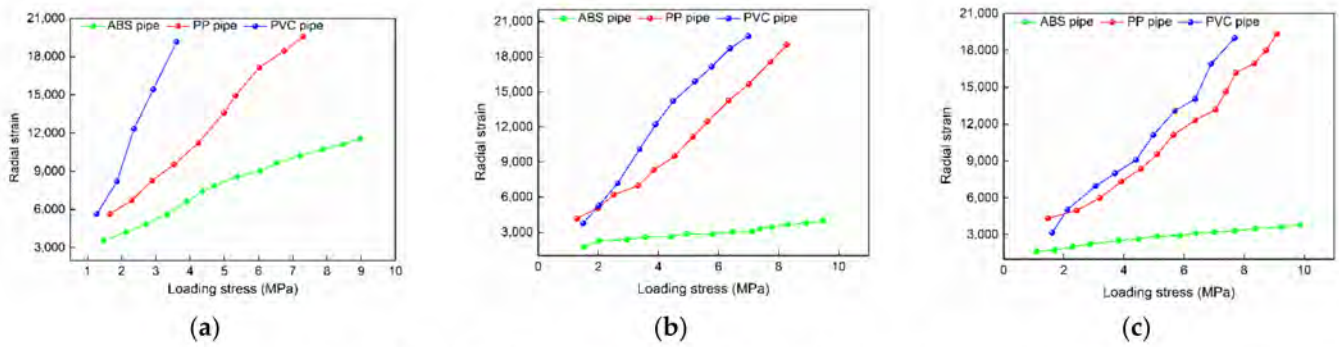


Figure 7. Loading stress–strain curves of various types of screen pipes with different sieve opening spacings: (a) 30 mm; (b) 50 mm; (c) 70 mm.

Figure 8 shows the stress–strain curves of the different types of screen pipes with diverse sieve opening spacings during the loading process. The curves indicate that the compressive strength of the ABS screen pipe is higher than that of the PVC and PP screen pipes regardless of whether they have sieve openings. For the ABS screen pipe, the radial strain increases with a decrease in the sieve opening spacing under the same stress. When the sieve opening spacing of the ABS screen pipe is 30 mm, the compressive strength of the screen pipe is much lower than that with the other two sieve opening spacings. When the sieve opening spacings are 50 mm and 70 mm, the stress–strain curves of the screen pipes almost overlap, indicating that their compressive performances are nearly the same.

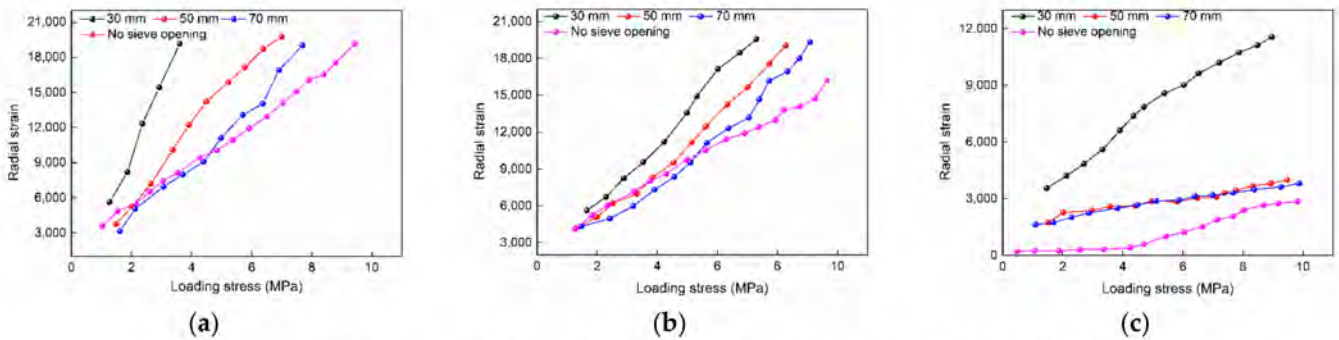


Figure 8. Loading stress–strain curve of three kinds of pipes with different sieve opening spacings: (a) PVC; (b) PP; (c) ABS.

Figure 9 shows the change rate of the strain for the three different screen pipes with loading stress under different screen opening spacings. The change rate of the strain of the loaded screen pipe increases with an increase in the screen opening spacing. The sieve opening spacing has the greatest influence on the change rate of the PVC and ABS screen pipes, and it has a small influence on the change rate of the PP screen pipe. The strain change rates of the PVC and ABS screen pipes with 30 mm sieve openings are significantly higher than those without sieve openings. When the screen opening spacing is the same, the increasing rate of the strain of the ABS screen pipe is the lowest. Its maximum value is only about 18% of the PVC screen pipe and 40% of the PP screen pipe. When the sieve opening spacings are 50 mm and 70 mm, the strain change rates of these three types of screen pipes with an increasing loading stress are nearly the same. Based on the above analysis, both the borehole protection effect and gas drainage efficiency could be improved when the gas drainage borehole was protected by the ABS screen pipe with a sieve opening spacing of 50 mm in the soft coal seams.

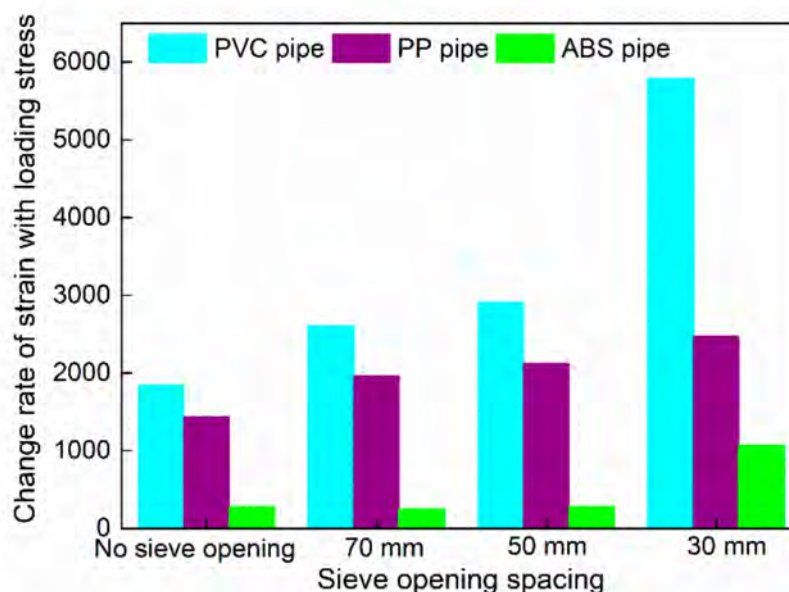


Figure 9. Change rate of strain with loading stress under different screen opening spacings.

4. Field Testing on Gas Drainage Efficiency with Screen Pipes

4.1. Gas Drainage Concentration Variation under Different Borehole Protection Conditions

Due to the lack of in-hole monitoring equipment to monitor the borehole protection effect after the screen pipe was installed, this study selected the gas drainage efficiency to reflect the borehole protection effect of the ABS screen pipe with a sieve opening spacing of 50 mm. Field tests on gas drainage efficiency were carried out in the coal seam II-1029 in Haizi coal mine, China. The coal seams are soft, with a Protodyakonov coefficient of 0.7. Previous experimental results show that the borehole protection capabilities of PP and PVC pipes are comparable. Therefore, a bare borehole, a borehole with a traditional PVC pipe, and a borehole protected by an ABS pipe were set up on site to compare gas extraction efficiencies. The borehole spacing, diameter, depth, and inclination were 3 m, 113 mm, 70 m, and 17° , respectively. The test arrangement is shown in Figure 10. The PVC and ABS screen pipes with lengths of 50 m were installed in boreholes #1 and #2, respectively. After installation, the three boreholes were sealed concurrently with a sealing length of 18 m. Gas drainage concentration and negative pressure monitoring devices were installed to monitor the gas drainage efficiency of each borehole.

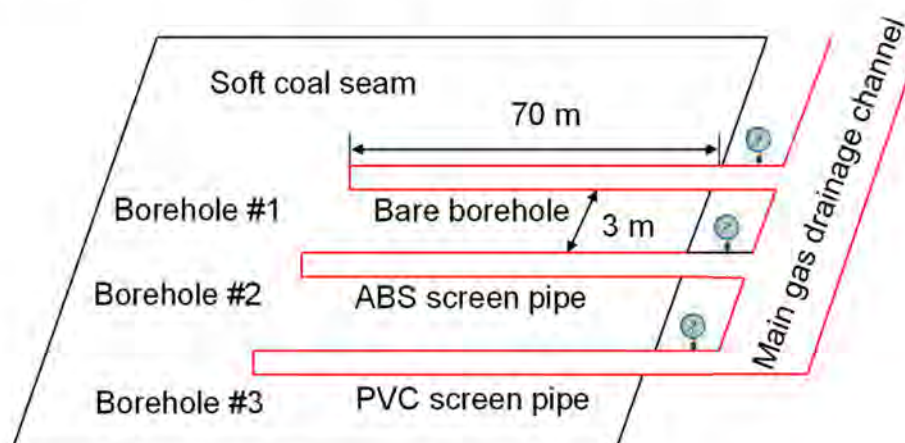


Figure 10. Schematic diagram of borehole layout.

The variation in gas drainage concentration in each drainage stage is shown in Figure 11. The gas drainage concentration in the early stage is lower than that in the later stage, mainly because the studied mine is in soft coal seams with low permeability and the borehole wall is relatively intact. The average gas drainage concentration of the bare borehole is 113% higher than the borehole with the ABS screen pipe and 255% higher than the borehole with the PVC screen pipe. This is due to the installed screen pipe hindering the gas flow. Moreover, the gas drainage concentration of the borehole with the traditional PVC pipe is much lower than that of the other two boreholes, because the sieve opening spacing of the PVC pipe currently used in the mine is 100 mm with less openings, allowing the smallest gas flow.

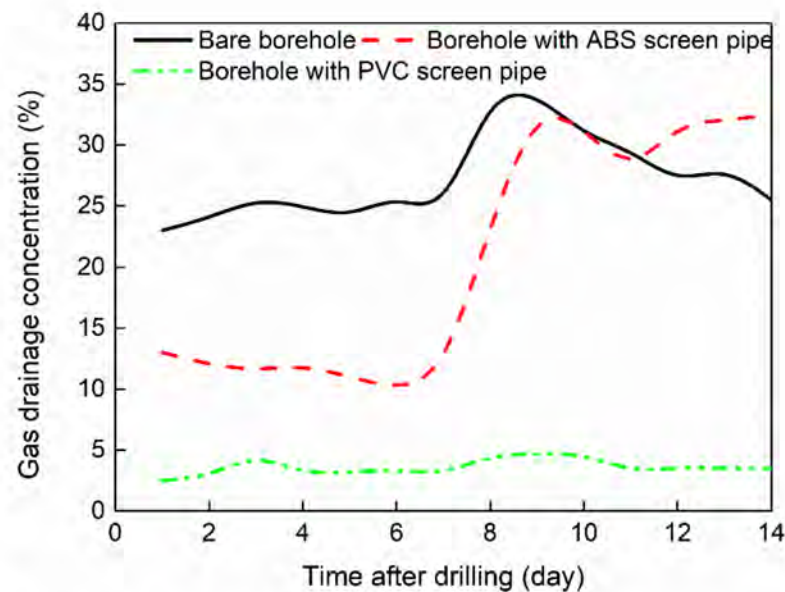


Figure 11. Variation in gas drainage concentration under different borehole protection methods.

On day 7, the coal mass near the borehole started cracking under induced stresses, and the gas drainage concentration increased rapidly until it reached the maximum on day 9. Compared with the initial stage, the borehole wall in this stage had more coalesced fractures for gas flowing. The gas drainage concentration of the borehole protected with the ABS pipe rose from 46% on day 7 to 98% on day 9 compared to the bare borehole. A slight borehole collapse could have occurred in the bare borehole on day 9, affecting the gas drainage of the bare borehole. The borehole protected with the ABS screen pipe was less affected by the borehole collapse due to the protection provided. After day 9, the gas flow resistance increased, and the gas drainage concentration decreased rapidly due to borehole deformation. The ABS screen pipe provided protection to the borehole wall, and the concentration of the gas drainage was relatively higher than that of the gas drainage through the bare borehole.

4.2. Influence of the Pipe Diameter on Gas Drainage Efficiency

To explore the effect of screen pipe diameter on gas drainage efficiency, the borehole protection effects of ABS screen pipes with different diameters were compared in experiments. The arrangement of the boreholes was the same as that described in Section 4.1. Borehole #1 was a bare borehole, borehole #2 was protected by a 40 mm-diameter ABS screen pipe, and borehole #3 was protected by a 32 mm-diameter ABS screen pipe. Continuous gas drainage monitoring lasted for 30 days since the beginning of the test. The variation in gas drainage concentration in each borehole is shown in Figure 12. In the creep deceleration stage of the borehole, the gas drainage efficiency of the bare borehole was much higher than that of the boreholes protected by ABS screen pipes with different diameters. On the

5th day, the gas drainage concentration of the bare borehole was 2.2 times the one with the 40 mm ABS screen pipe and 2.7 times the one with the 32 mm ABS screen pipe. On day 9, the gas drainage concentration of the borehole protected by the 40 mm ABS screen pipe was close to that of the bare borehole and 18% higher than that of the borehole protected by the 32 mm ABS screen pipe. From day 9, the gas drainage efficiency of the borehole using the 40 mm ABS screen pipe began to increase in comparison to that of the bare borehole. The gas flow channels declined, and resistance grew due to the drainage borehole collapse. The gas drainage efficiency of the bare borehole began to decrease sharply.

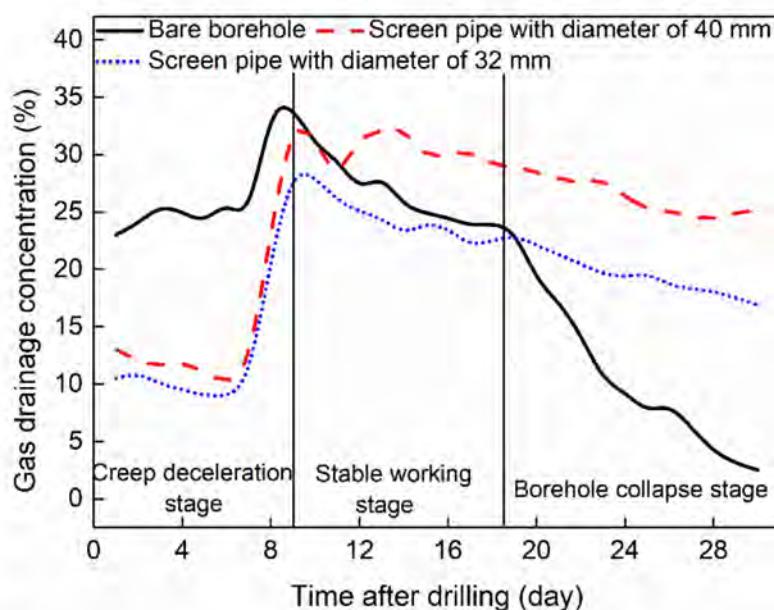


Figure 12. Influence of screen pipe diameter on gas drainage efficiency.

From day 19, the gas drainage efficiency of the borehole with the 32 mm ABS screen pipe began to increase in comparison to that of the bare borehole. On day 30, the gas drainage concentration of the boreholes protected by the ABS screen pipes with 40 mm and 32 mm diameters were 9 times and 5.7 times higher than the concentration of the bare borehole, respectively. The borehole protected by the 40 mm ABS screen pipe had better borehole protection and gas drainage performance compared with the 32 mm one. This may be due to the larger diameter screen pipe supporting the borehole from collapse in an earlier stage. However, the installation of the screen pipe might be difficult if the diameter is too large since the drill hole is generally not straight.

5. Conclusions

This paper focused on improving gas drainage borehole protection technology using screen pipes, aiming to address the problems of gas drainage borehole collapse and low gas drainage efficiency in soft coal seams. The compressive resistance and borehole protection effects of PVC, PP, and ABS screen pipes with different sieve opening spacings were studied through experiments. The borehole protection effect and gas drainage efficiency of the optimized screen pipe were examined in field tests. The experiments show that the radial strains of PVC, PP, and ABS screen pipes have a linear positive correlation with loading stress. The radial strain of the new ABS screen pipe was approximately 4–17% of the traditional PVC screen pipe when the loading pressure ranged from 1 to 9 MPa. The compressive strength of the ABS screen pipe was significantly higher than that of the PVC and PP screen pipes. The pipe radial strain increased with a decrease in the screen opening spacing under the same load. The compressive performances of the ABS screen pipes were almost the same with the screen opening spacings of 50 mm and 70 mm. The ABS screen

pipe with a 50 mm sieve opening spacing was selected for better gas drainage efficiency. The field tests showed that the gas drainage concentration of the bare borehole in the creep deceleration stage was 113% higher than that of the borehole with the ABS screen pipe and 255% higher than that of the borehole with the PVC screen pipe. The screen pipe protection began to play an important role at the stable working stage, as the borehole wall began to deform and collapse. On the 30th day of gas drainage, the gas drainage concentration of the borehole with the ABS screen pipe protection was about 9 times that of the bare borehole. Properly increasing the screen pipe diameter can improve borehole service life and gas drainage efficiency. The 40 mm diameter ABS screen pipe with a 50 mm sieve opening spacing provided the best borehole protection and gas drainage efficiency among all field test conditions.

Author Contributions: S.H.: writing—original draft, investigation, methodology, conceptualization, and funding acquisition. S.O.: validation, conceptualization, and methodology. F.H.: methodology and conceptualization. L.J.: investigation, formal analysis, funding acquisition, and supervision. Y.M.: writing—review and editing, and formal analysis. T.C.: methodology and formal analysis. All authors have read and agreed to the published version of the manuscript.

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