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Detection of Spontaneous Combustion Areas of Coal Gangue Dumps and Comprehensive Governance Technologies: A Case Study

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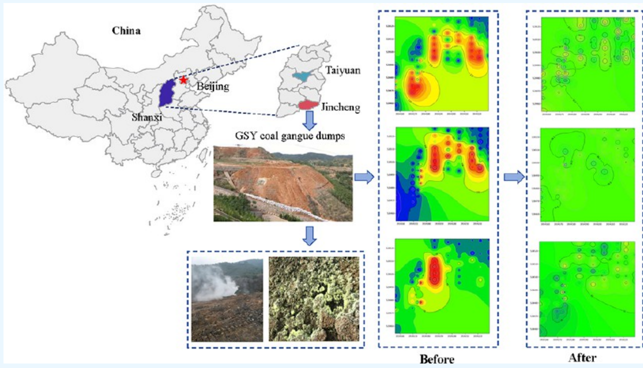
ABSTRACT: Spontaneous combustion of coal gangue dumps not only releases toxic and harmful gases, polluting the environment, but also leads to explosion accidents and casualties due to improper handling. This paper focuses on delineating the fire area, constructing a comprehensive fire prevention and extinguishing system, and restoring the ecological environment. Infrared thermal imaging was used to detect the shallow fire area, while intensive drilling was conducted to detect the deep fire area. The stability of the coal gangue dump was enhanced by perfusing three-phase foam for cooling and using a curing material to fill the cracks. Land reclamation was then performed to restore the ecological environment. The results indicate that spontaneous combustion of coal gangue dumps can trigger the spread of the fire area from the outside to the inside, gradually expanding due to the 'stack effect'. The sources of spontaneous combustion in gangue fire areas are mainly located 3−5 m below the flat surface, and the shallow and deep fire areas are interconnected, posing a significant danger. These research findings can serve as a reference for detecting fire areas in coal gangue dumps and controlling environmental pollution.



1. INTRODUCTION

Energy is a material foundation for the development of the human society. As China is a country that is poor in oil and gas and relatively rich in coal, its energy structure has been dominated by coal for a long time. According to statistics, China's raw coal production reached 4.56 billion tons in 2022, an increase of 10.5% over the previous year. The total coal consumption accounts for about 56.8% of the total national energy consumption. However, the production of 1 ton of coal is accompanied by the generation of 0.15−0.2 tons of coal gangue. With the growth of coal production in recent years, the discharge of coal gangue is also increasing.[1] Statistics show that the inventory of coal gangue in China has reached 450−500 million tons, with an annual increase of 37−55 million tons.[2] Due to the presence of combustible materials such as residual coal, carbonaceous mudstone, and broken wood, gangue is likely to combust spontaneously after being accumulated outdoor for a long time.

It is estimated that China has more than 5000 coal gangue dumps, of which approximately 1700 have combusted spontaneously, covering an area of about 1500 km^2.[3,4] Coal gangue dumps are prone to spontaneous combustion due to their high contents of sulfur and carbon. The resultant dust and toxic gases such as SO_2, H_2S, CO, and NO_x would lead to serious pollution to the atmospheric environment of mining areas.[5−8] Besides, acidic water and toxic elements such as Cu, Cr, As, and Pb formed by weathering and long-term eluviation would pollute the soil and water.[7,9−12] In addition, as a result of coal gangue spontaneous combustion, geological disasters such as collapse, landslide, debris flow, and explosion are likely to occur under high-temperature and high-pressure conditions inside the dumps, endangering the life of residents around mining areas and causing serious damage to the ecological environment.[13−15] In recent years, research on coal gangue worldwide mainly involves spontaneous combustion characteristics, detection of fire areas, and fire prevention and extinguishing materials.

Scholars have conducted plentiful research and experiments on spontaneous combustion of coal gangue. The research is mainly divided into two aspects, the micromechanism of coal gangue spontaneous combustion and the combustion characteristics of coal gangue. Proximate analyzer, thermogravimetry, and Fourier transform infrared spectroscopy are used to study the changes in free radicals and fixed carbon contents of coal gangue spontaneous combustion under different parameter condi-

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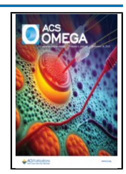

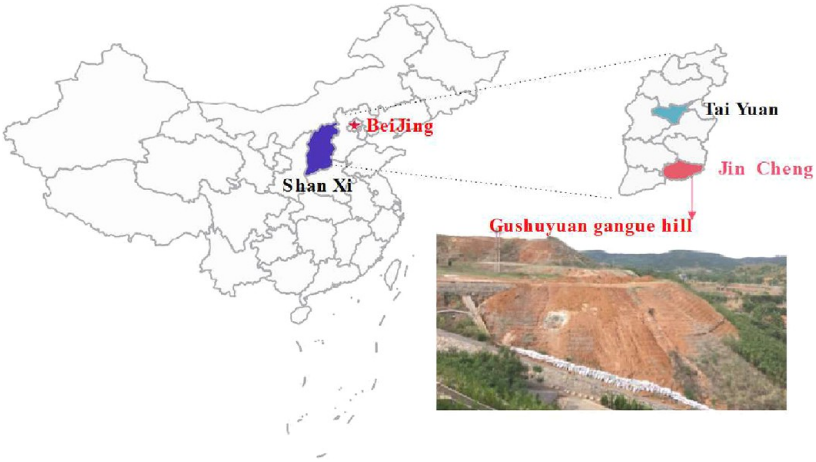

Figure 1. Location of the GSY coal gangue dump.

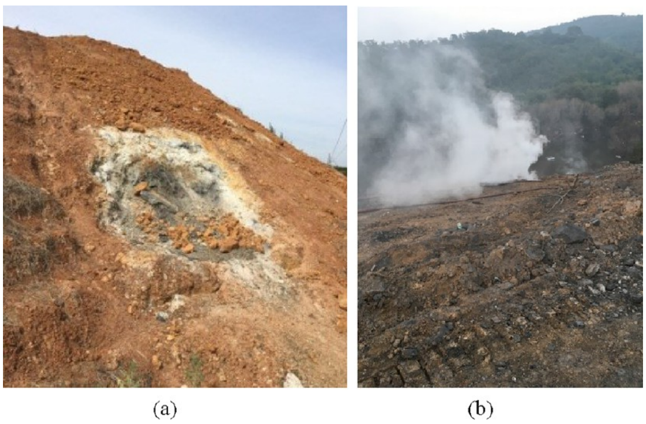

Figure 2. Local high temperature and noticeable smoke emitted from the slope: (a) Traces after combustion. (b) White smoke emitting from the slope.

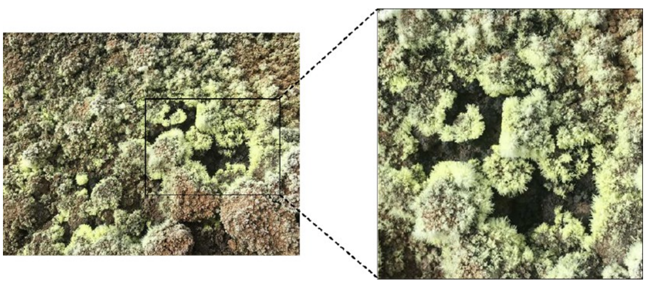

Figure 3. Sulfur crystals detected at the flat exhaust port of the dump.

tions.[16] Ren et al. believed that the combustion of coal gangue includes two stages, namely, volatile combustion and fixed carbon combustion, of which the latter is slower and more time-consuming.[17] Jiang et al. explored the effect of oxygen concentration on the variation of active groups during coal gangue oxidation, simulated the oxidation and heating processes of coal gangue at oxygen concentrations of 0, 5, 10, 15, and 21%, and measured the parameters of free radicals at different temperatures.[18] Wang et al. investigated the secondary oxidation characteristics of coal gangue under different ranks of pyrolysis. The results suggest that the rank of pyrolysis has a certain inhibitory effect on the emission of indicator gases in the combustion process of the coal gangue. The increase of pyrolysis rank raises the activation energy of oxidation reaction and delays the rapid oxidation of coal gangue, thus effectively reducing the risk of coal gangue spontaneous combustion.[19] Zhang et al. studied the thermal behavior and harm of coal gangue spontaneous combustion and tested the characteristics of heat release and heat transfer in the process.[20] The combustion behavior of 11 coal gangue was investigated by thermogravimetric analysis. The effects of feedstock properties (combustible matter and mineral matter) on the combustion characteristics of coal gangue were analyzed by Zhang et al., and the results show that the ignition temperature of coal gangue is affected by the volatile content and oxygen adsorption behavior jointly.[21]

Coal gangue piles are used as experimental models to study the characteristics of spontaneous combustion in coal gangue. This approach provides an empirical basis for investigating the distribution of temperature within coal gangue dumps and understanding the dynamic reaction mechanism of spontaneous combustion.[22] Jiang et al. studied the spontaneous combustion characteristics of coal gangue dumps and the variation law of their spontaneous combustion temperatures at different depths. It is concluded that the temperature of coal gangue dumps at a depth of 2.5 m is noticeably higher than the temperatures at other depths, and it rises the fastest; eventually, coal gangue at the depth of 2.5 m gradually develops into a source of spontaneous combustion.[23]

Fire area detection and treatment materials of coal gangue have also attracted extensive attention. The evolution of self-heating areas on five chosen coal-waste dumps in Upper Silesia (Poland) was quantitatively investigated with the aim of finding a cheap and fast method for detecting and localizing coal-waste fires on the dumps, and the appearance of hot spots and their migration and their disappearance were observed by Ádám.[24] Shao et al. employed a 3D thermal imaging methodology based on unmanned aerial vehicle (UAV) remote sensing data. The method was used to build the 3D temperature model and visualize the scope of coal gangue pile fires in the 1360 bench, the viewing bench, and the belt corridor of the Anjialing open-pit mine in China.[25] Ren et al. proposed a spatial analysis method to achieve early warning spontaneous combustion of coal waste dump after reclamation by integrating UAV and vegetation (Medicago sativa/alfalfa) growth status.[26] He et al. removed the interference information on the reflectance spectra from these images and established a relationship with the ground measured data to monitor changes in coal gangue.[27] Wu et al. carried out an oxidation heating experiment on coal gangue samples and

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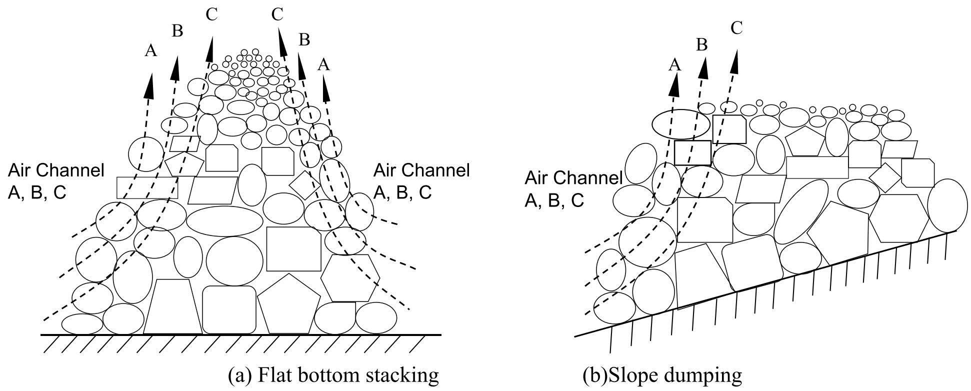

Figure 4. Air pass caused by "granular deflection."

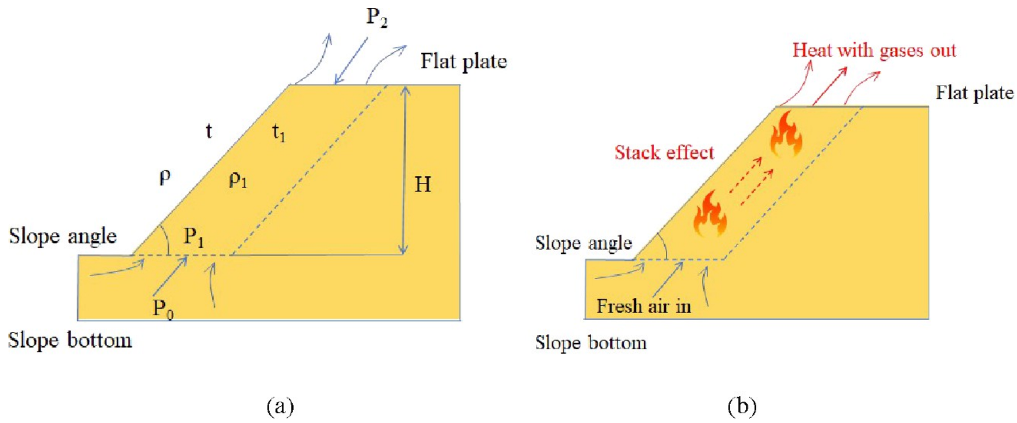

Figure 5. Schematic diagram of "stack effect" on the coal gangue dump: (a) Gangue dump is in equilibrium. (b) Equilibrium state of the gangue dump has been disrupted.

Table 1. Comparison of Fire Detection Technologies

fire detection methods	advantages	disadvantages
drilling	directly determine the location of the fire zone, high reliability	consuming a lot of manpower and resources
infrared remote sensing	no need for extensive on-site construction, high efficiency	unable to detect coal fire information in deep underground areas (below 30m)
magnetic	good anti-interference performance, stable performance, reliable operation, and economy	insufficient detection depth and resolution, insensitive to initial fire zones
spontaneous potential	easy, low-cost	insufficient detection depth and poor anti-interference performance
radon measurement method	deep detection depth, flexible equipment operation, low cost, and simple operation	the surface must have a certain thickness of cover

analyzed the law of radon release in the coal gangue at different temperatures. The on-site measurement results demonstrate that the isotopic radon measurement method can be adopted to detect coal gangue fire areas more accurately with less interference.[28] Wang et al. used the temperature and the radon concentration as the principal indicators, and the gas concentration was a secondary index for verifying the results to estimate the extent and depth of the fire in the coal gangue dumps.[13,29]

The main fire extinguishing methods for spontaneous combustion of coal gangue dumps include the excavation and cooling method, the grouting method, the overlay compaction method, the combustion control method, the low-temperature inert gas method, the water injection method, etc.[30,31] Zhang and Pan developed a coal gangue fire-extinguishing material of gel-foam to control spontaneous combustion of coal gangue.[32] To prevent spontaneous combustion of coal gangue dumps, Tang and Wang developed a type of bentonite-acrylamide superabsorbent hydrogel, which can be used for cooling, controlling combustion, and preventing coal gangue from reburning.[33] To overcome the short inhibition life of currently available inhibitors, a novel physicochemical composite inhibitor for the prevention of coal gangue spontaneous combustion was developed by Huang et al. The inhibition effect of the PAM/MMT 3%-$Ca(OH)_2$ 20% composite inhibitor was the best in the study, with an inhibition rate of 83.15%.[34]

In summary, the research on coal gangue worldwide in recent years mainly focuses on the mechanisms and characteristics of spontaneous combustion of coal gangue dumps, the detection of fire areas, and the development of treatment materials.[26,35−37] However, case studies on the spontaneous combustion of coal gangue dumps and its environmental remediation remain insufficient. In this study, the coal gangue dump at Gushuyuan Coal Mine in Jincheng City, Shanxi Province, China (referred to as the GSY coal gangue dump) was selected as the research

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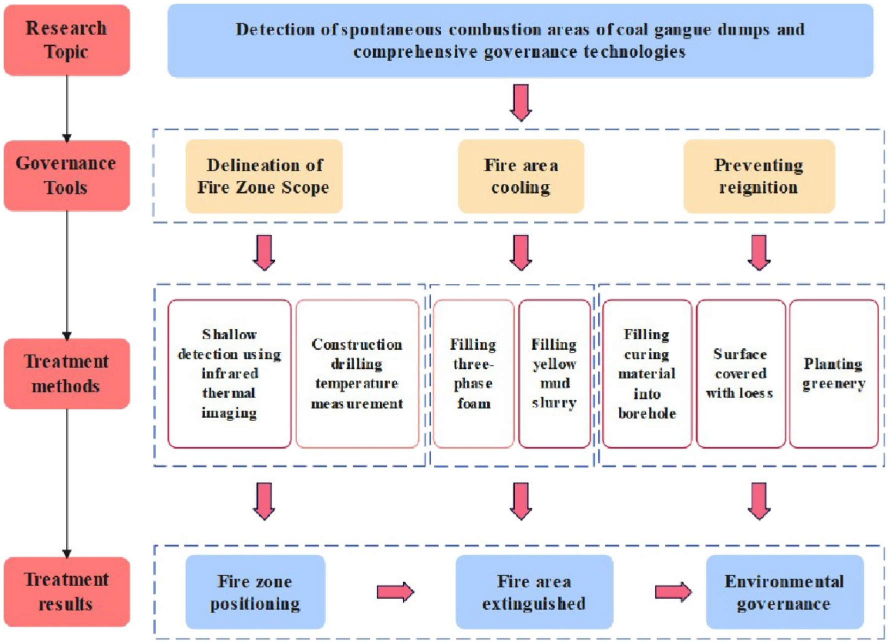

Figure 6. Technical strategy for the detection and environmental remediation of the fire area.

subject. The study included practical research on detecting and managing fire areas in gangue dumps and identified a set of economically efficient key technologies.

2. CHARACTERISTICS AND TREATMENT IDEAS OF COAL GANGUE DUMPS

2.1. Overview of the Coal Gangue Area. The GSY coal gangue dump is situated on the east side of the foot of the Baima Temple Mountain in the north of Jincheng City, Shanxi Province, China. The coal gangue dumping sites are located at the junction of Wanggutuo Village (eastern gangue dump) in Shangzhuang Township, Dazhang Village (central gangue dump), and Xiaozhang Village (western gangue dump) in Beishidian Township. Part of the eastern gangue dump was piled up by the gangue moved from the urban area to the Baima Temple in 1986, yet the other part, composed of the gangue from the 3# and 9# coal seams with a high sulfur content, is left over from the excavation and coal washing in 1991. The 9# coal gangue is of a relatively small quantity, with a total stacking capacity of 2 million tons per month. Most of the coal-washing-induced gangue, whose sulfur content is high (2.3% on average), is accumulated in the western gangue dump. Recently, a high-temperature spontaneous combustion area of 1500 m^2 (50 m in length and 30 m in width) was discovered at the northeast corner of the second platform in the eastern area (Figure 1), and the platform was 10 m high. A large high-temperature region appeared on the slope of the coal gangue dump, emitting noticeable smoke with a pungent odor (Figure 2). In addition, considerable sulfur crystals were precipitated at the exhaust port on the flat surface of the coal gangue dump (Figure 3).

2.2. Spontaneous Combustion Characteristic of Coal Gangue Dumps. The oxidation heating process of spontaneous combustion in coal gangue is similar to that of coal.[38] Therefore, this review does not delve into the details of this process. However, it is important to note that the accumulation mode of gangue differs from that of coal, which, in turn, affects the gas flow during the oxidation process of coal gangue. This distinction leads to differences in the spontaneous combustion characteristics of gangue and coal. During the natural stacking of waste dumps, whether they are piled up on the ground or stacked along a slope, a phenomenon known as "granular deflection" occurs. This leads to the formation of air channels within the gangue dumps, resulting in what is commonly referred to as the 'stack effect' of the coal gangue dumps, as depicted in Figure 4.

As shown in Figure 5a, before coal gangue in the accumulation tends toward oxidation heating, the temperature and density inside and outside the accumulation are equal, that is, $t = t_0$ and $\rho = \rho_0$. The fluid in the accumulation is in a state of equilibrium and does not flow. Equation 1 can be acquired according to the equation of fluid mechanics equilibrium:

$$P_0 = P_1 = P_2 + \rho gH = P_2 + \rho_0 gH \quad (1)$$

When the coal gangue in the accumulation starts to undergo oxidation heating, $t > t_0$ and $\rho_0 > \rho$.

$$P_0 = P_2 + \rho_0 gH; \; P_1 = P_2 + \rho gH$$

$$P_0 - P_1 = (P_2 + \rho_0 gH) - (P_2 + \rho gH) = gH(\rho_0 - \rho) \quad (2)$$

According to the equation of fluid mechanics, the greater the height difference between the top and bottom of the slope, the larger the pressure difference is between the two ends. Consequently, the fire area of the coal gangue dump will spread from one area to another, gradually expanding, which is called the "stack effect" (Figure 5b). Meanwhile, when the temperature difference inside and outside the spreading passage is larger, the density difference between hot air and cold air will be greater. As a result, the "stack effect" will become more obvious, and the fire area will expand accordingly. This explains why coal gangue dumps usually combust more intensely in the cold winter.

2.3. Technical Strategy for Treatment of Coal Gangue Fire Dumps. Spontaneous combustion of coal gangue dumps is normally concealed. Although it has certain appearances, such as the precipitation of sulfur crystals and the withering and death of plants, the scope of the fire area is not necessarily sporadic or

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superficial. Instead, according to the "stack effect," the external appearance usually indicates that vast stretches of a coal gangue fire area have been formed. Therefore, the first step in controlling the coal gangue fire area is to delineate the scope of the fire area. Then, further technical schemes can be established according to the actual situation. Table 1 presents a comparison of various methods for detecting coal gangue fire zones. Upon comparing these methods, it becomes evident that while the electrical method, the magnetic method, and the radon detection method offer economic advantages, the accuracy of fire area detection may be significantly reduced due to the impact of broken coal gangue. This reduction in accuracy can be confirmed through subsequent drilling. Considering the large size of the spontaneous combustion area in the gangue dump and the need for later treatment involving the construction of boreholes filled with fire-fighting materials, it is advisable to employ infrared temperature measurement for detecting shallow-fire areas and intensive drilling for detecting deep-fire areas.

In the selection of fire prevention and extinguishing technologies for coal gangue hill fire areas, traditional methods have several limitations. The excavation and cooling method is not suitable due to the uncertainty of the fire area's depth and scope. Additionally, this method requires significant time and effort but produces minimal results and may lead to secondary safety accidents during the cleaning process. Furthermore, conventional water injection and grouting methods are ineffective in completely eliminating the threats posed by the fire area, particularly when the fire area is located in the middle-upper part of the GSY coal gangue dump, where stacking is not possible. Inert gas injection, which is unable to effectively suffocate the fire source in the relatively fractured coal gangue dump, also has a poor fire extinguishing effect and the possibility of recombustion. To address these challenges, three-phase foam fire prevention technology is utilized to cool down the fire area, taking advantage of the good diffusivity and accumulation properties of the three-phase foam to eliminate high-temperature points. In order to prevent reburning of the coal gangue hill, solidified materials are injected to block air leakage channels. Finally, the coal gangue dump is covered with loess and reclaimed to restore the ecological environment. The technical route is illustrated in Figure 6.

3. DETECTION TECHNOLOGIES OF THE FIRE AREA

3.1. Detection of the Shallow Fire Area. The detection of the fire area consists of two parts: infrared temperature measurement for shallow-fire-area detection and intensive drilling for deep-fire-area detection. The shallow fire area was detected with the aid of a UNI-T hand-held infrared thermal imager, which boasts a low spatial resolution, a long observation distance, a large temperature measurement range, and high-temperature measurement accuracy. It can easily identify high-temperature locations through thermal imaging without the limitation of light, even in dark nights and other harsh environments. Shallow-fire-area detection was mainly conducted in smoke areas, dead-plant areas, and sulfur crystal precipitation areas.

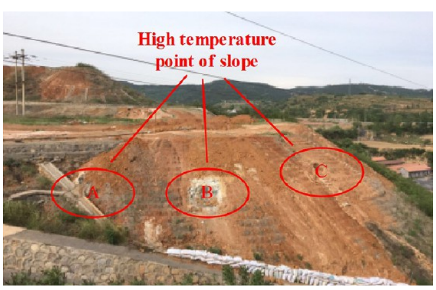

Figure 7. Slope fire area distribution.

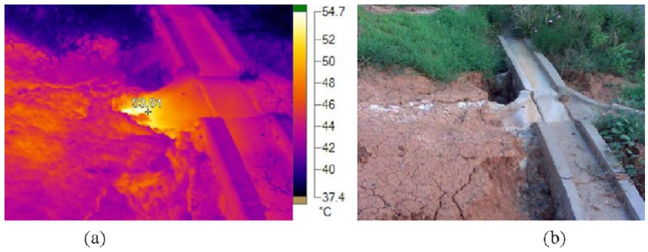

Figure 8. Fracture zone of the slope protection cement (high-temperature zone A): (a) Infrared thermal imaging temperature measurement image. (b) Condition of the fire area on site.

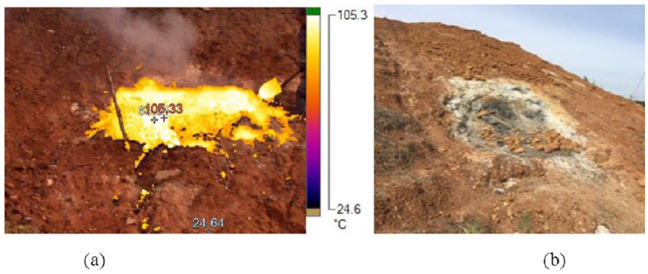

Figure 9. Sliding crack zone of the slope (high-temperature zone B): (a) Infrared thermal imaging temperature measurement image. (b) Condition of the fire area on site.

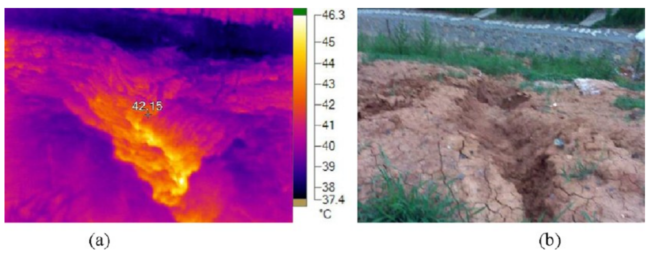

Figure 10. Crack zone scoured by rainwater (high-temperature zone C): (a) Infrared thermal imaging temperature measurement image. (b) Condition of the fire area on site.

After detection, three high-temperature zones A-C were identified on the gangue slope (Figure 7). A is the fracture zone of the slope protection cement (Figure 8); B is the sliding crack zone of the slope (Figure 9); and C is the crack zone scoured by rainwater (Figure 10).

3.2. Detection of the Deep Fire Area. Through theoretical calculation and numerical simulation verification, the effective diffusion radius of the three-phase foam is determined to be 3m.[39] During the field preparation process, the coverage of the three-phase foam can be enhanced by adjusting the proportion of water and soil in the solid phase, which reduces the viscosity of the slurry. However, to ensure complete detection and control of the fire area without any uncovered spots, the design is still based on a minimum diffusion radius of 3m. If the spacing between drilling holes in the same row is set to 6m, the maximum spacing between adjacent rows

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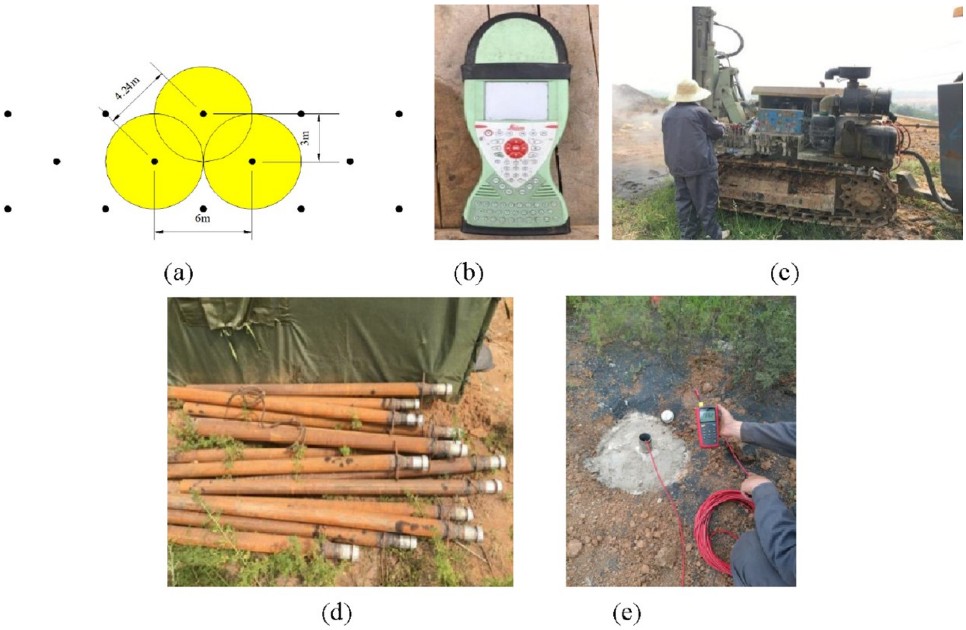

Figure 11. Temperature detection by intensive drilling in the deep fire area: (a) Layout of boreholes. (b) Borehole location by GPS. (c) Borehole construction. (d) Borehole casings. (e) Temperature detection.

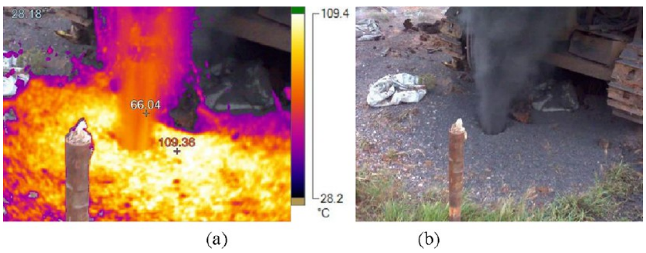

Figure 12. High temperature during drilling: (a) Infrared thermal imaging temperature measurement image. (b) Condition of the fire area on site.

Figure 13. Burning state of coal gangue.

can only be set to 3m. Setting it to less than 3m will not cover the entire coal gangue dumps. The boreholes were arranged in an equilateral triangle (Figure 11a). Their diameter was 125 mm. Besides, casings of 108 mm were installed for the convenience of perfusion in the follow-up fire area treatment (Figure 11d). GPS was adopted to locate the boreholes (Figure 11b), and a pneumatic drill was used to construct the boreholes (Figure 11c). The borehole temperature was acquired and statistically analyzed using a UT325 thermometer and a WRN series thermocouple (Figure 11e).

In this study, the location of the fire area was mainly identified by three indicators in the drilling process, that is, infrared thermal imaging for initial exploration, morphology of drill cuttings, and thermocouple temperature measurement for verification. First, the drill cuttings discharged from the boreholes were monitored by the infrared thermal imager. When the drill reached 3−5 m, the temperature of the drill cuttings reached 109 °C, suggesting that the drill had reached the fire area (Figure 12).

Second, the drill cuttings brought out with drill pipes were collected to estimate the burning state of the fire area (Figure 13). The drill cuttings were black coal gangue in the early stage of combustion. When the drill reached the combustion area, the drill cuttings were in the state of brick-red half coal gangue and half gangue ash, accompanied by high-temperature gas emission. When the drill arrived at the burned area, the drill cuttings appeared as gray dust, which were hot and flying. Therefore, the depth and distribution of the high-temperature region can be estimated by the drill cuttings.

3.3. Delineation of the Fire Area.

It was found through the above two steps that the deep fire area of the coal gangue dump was mainly concentrated 3−5 m underground. The temperature at deeper positions was just 30−50 °C. Thus, it was determined that the primary monitored area was at a depth of 3−5 m in the high-temperature boreholes. Furthermore, the borehole temperature was monitored to verify the fire area with the aid of a UT325 thermometer and a WRN series thermocouple. Due to the irregular surface of the slope in the investigated flat area, each borehole was located by GPS. Samples were collected from each borehole starting from a depth of 1 m, and the temperature was measured and recorded every 1 m. On this basis, the temperature contour map at different depths was constructed (Figure 14).

Further analysis indicates that a high-temperature region was formed between the flat surface and the slope, with the highest temperature being as high as 150 °C (at the depth of 4 m). The high temperature in the region of 3−5 m deep spread from the cracks on the slope to the inside of the coal gangue dump,

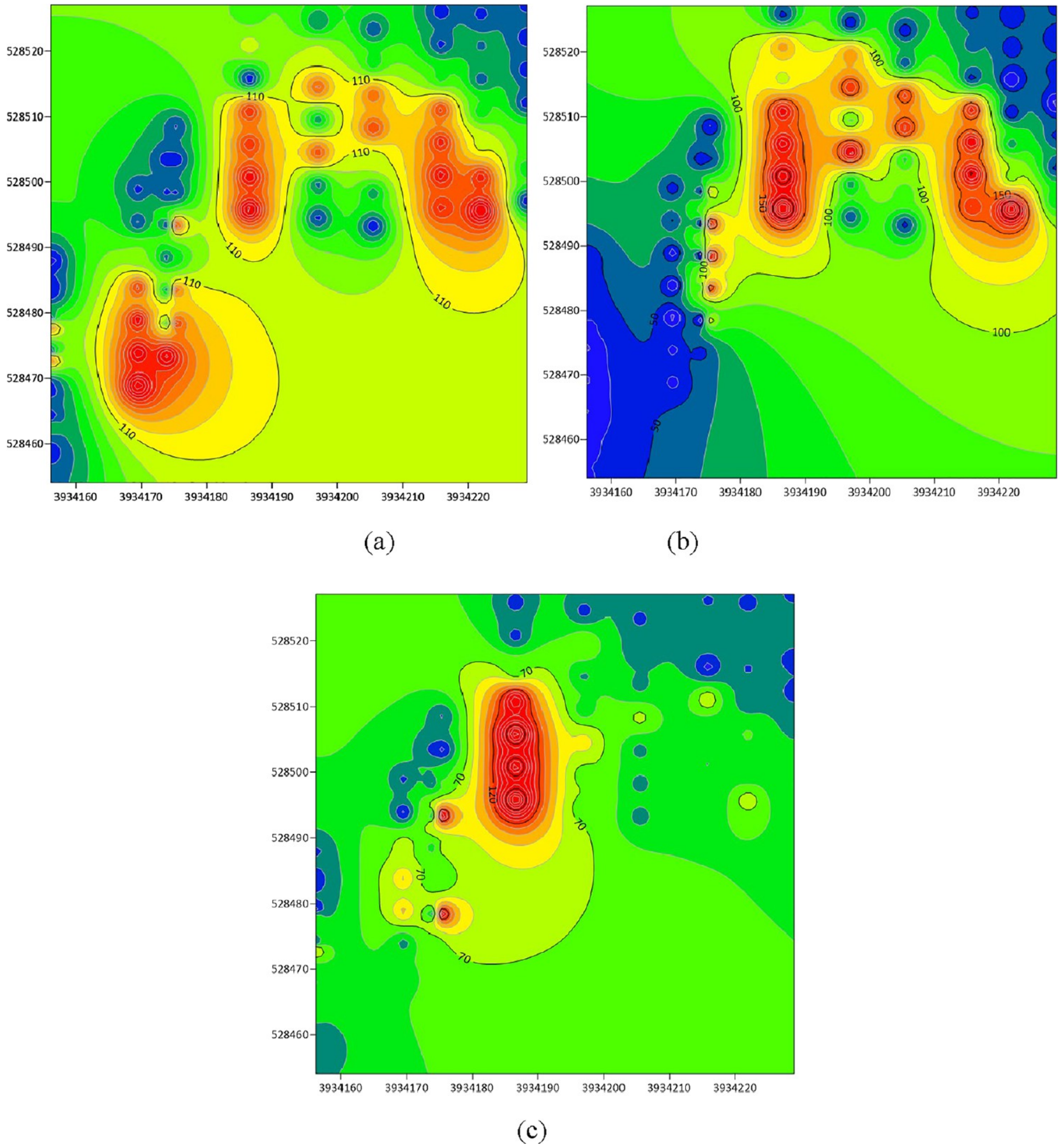

Figure 14. Temperatures of the gangue dump at different depths: (a) Depth of 3 m. (b) Depth of 4 m. (c) Depth of 5 m.

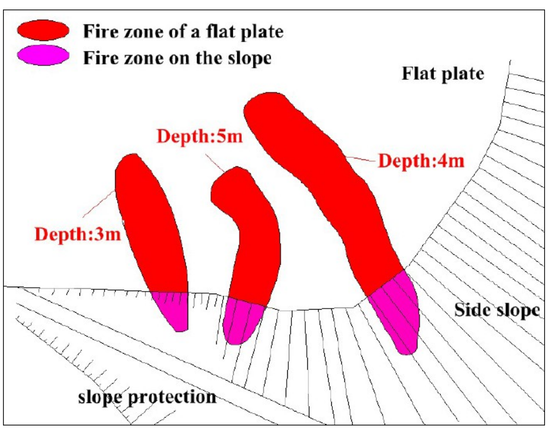

Figure 15. Final delineated scope of the coal gangue fire area.

forming three fire zones. The region within the range of 3−5 m depth was a high-temperature heat storage region, which was the source of the fire area. Due to the short distance from this region to the slope, oxygen was sufficient, and an open flame could be formed. This region ignited the surrounding coal gangue, thus developing into a larger fire area. The internal region was in a smoldering state as a result of insufficient oxygen supply. Therefore, the deep area of the coal gangue dump was in a high-temperature smoldering state, while the slope and gangue loose area were in combustion.

According to the temperature contour map at different depths located by GPS, the scope and depth of the fire area are delineated in the CAD engineering drawing (Figure 15). The detection results suggest that the shallow fire area and the deep fire area were interconnected due to the stack effect. In addition, as a result of air leakage on the slope, the high-temperature fire area developed and spread inward. The fire area was

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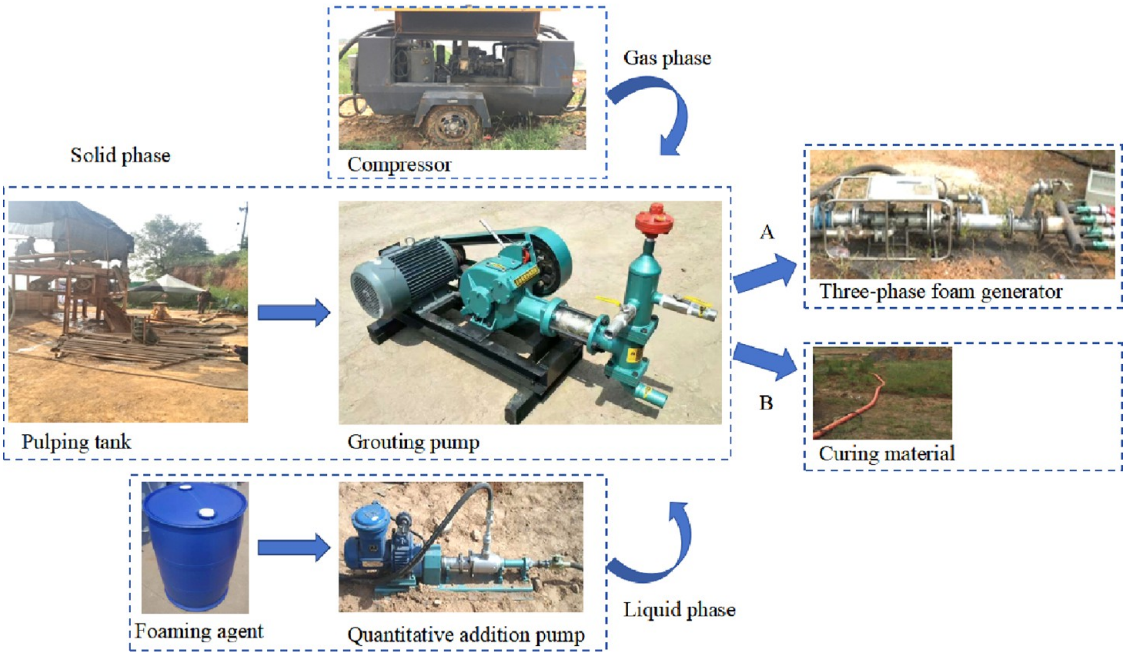

Figure 16. Diagram of installation of the comprehensive fire prevention and control system.

concentrated in the range of 3−5 m deep, the condition being the most serious at the depth of 4 m.

4. TREATMENT TECHNOLOGIES OF THE FIRE AREA

4.1. Construction of the Comprehensive Fire Prevention and Control System. A comprehensive fire prevention and control system, which was capable of perfusing water, yellow mud, three-phase foam, and curing material, was established according to the actual situation. This system consisted of a pulping tank, a grouting pump, a compressor, a foaming agent, a quantitative addition pump, and a three-phase foam generator (Figure 16). The pulping tank was responsible for producing yellow mud and the curing material. The grouting pump served to provide motive force for the water, yellow mud, and curing material, with a flow rate of up to 30 m^3/h and a pressure of over 10 MPa. The compressor could provide compressed air of 0.5 MPa at a rate of 2000 m^3/h. The quantitative addition pump was capable of accurately adding the foaming agent to the three-phase foam generator at a regulable flow rate of 0−1.5 m^3/H. The spiral foaming device inside the three-phase foam generator could fully mix compressed air, yellow mud, and foaming agent to form dense three-phase foam.

Figure 17. On-site perfusion of the three-phase foam.

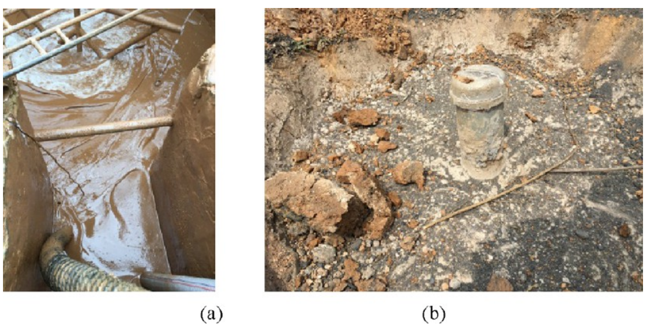

Figure 18. On-site preparation and perfusion of the curing material: (a) On-site preparation of the curing material. (b) Boreholes after the perfusion.

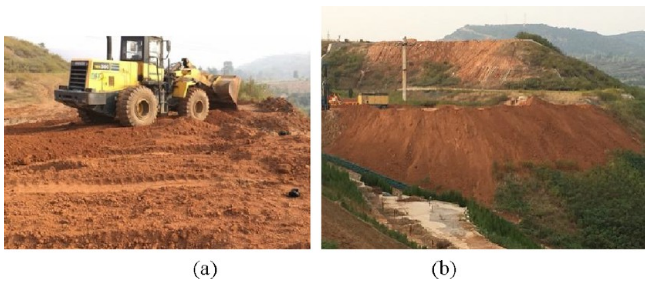

Figure 19. Loess backfilling on the coal gangue dump: (a) Loess backfilling with a forklift. (b) Slope and flat surface after backfilling.

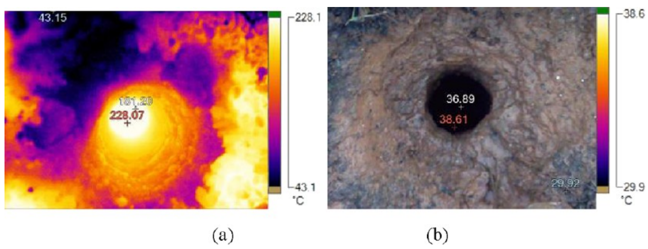

Figure 20. Chart of infrared temperature during drilling grouting: (a) Before governance. (b) After governance.

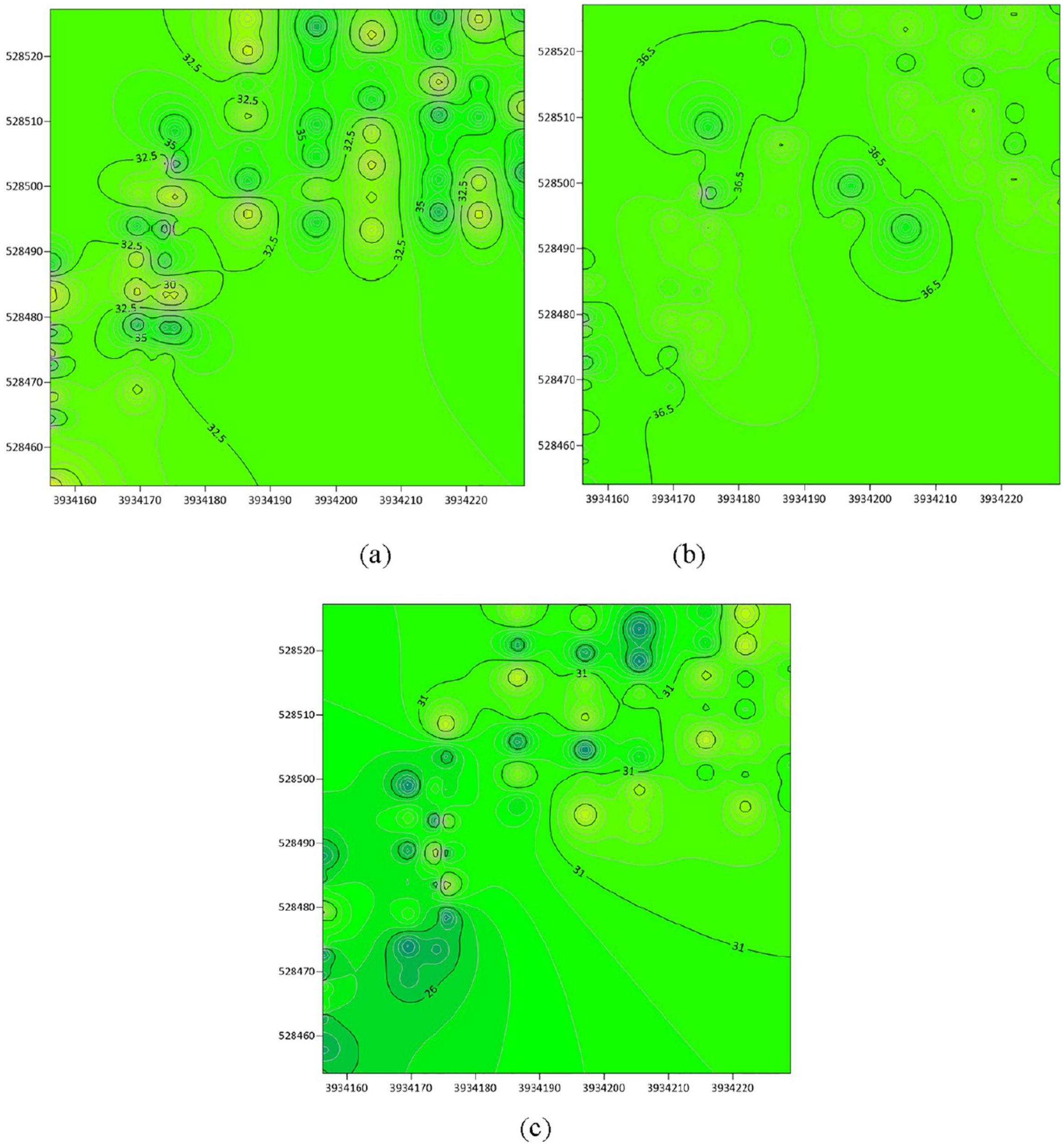

Figure 21. Temperatures at different depths after treatment: (a) Depth of 3 m. (b) Depth of 4 m. (c) Depth of 5 m.

Figure 22. Growing green plants on the slope.

4.2. Cooling with Three-Phase Foam. The three-phase foam is a dispersive mixture of gas phase (air), solid phase (yellow mud), and liquid phase (water) produced by foaming. The three-phase foam has a large volume and can accumulate upward, which is suitable for the concealed fire area of a coal gangue dump. It can practically act in the fire area of the accumulated coal gangue dump, absorb heat, cool down, and eliminate the fire source. Moreover, the yellow mud contained in the three-phase foam can effectively wrap the coal gangue and prevent the fire area from reburning. The procedure for preparing the three-phase foam is as follows. First, loess and water were mixed at a ratio of 1:3 to produce the yellow mud. Next, powered by a grouting pump, the yellow mud was transported to the three-phase foam generator and mixed with the foaming agent added by the quantitative addition pump. Finally, dense foam was produced under the action of compressed air, as shown in Figure 16A. The foaming ratio of this three-phase foam can reach more than 30 times; the foam stability time is 8−36 h; and the constructed system can produce the three-phase foam at 900 m^3/h. The prepared three-phase foam is displayed in Figure 17.

4.3. Filling Cracks with the Curing Material. To seal the air leakage passages and prevent the fire area from reburning, the coal gangue cracks need to be filled after the area cools down.

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Meanwhile, the curing material can effectively enhance the stability of the coal gangue dump, thus reducing the formation of new air leakage passages induced by the collapse of the coal gangue dump.

The adopted curing material is a kind of modified inorganic material of fly ash in the structure of fine powdered mesh. It is characterized with good water retention, long-term stability, and high seepage pressure. According to the on-site situation, the curing material, fly ash, and water were mixed into a slurry in a certain proportion, which could be completely solidified in a certain time. The slurry was prepared in a pulping tank. The ratio of water, fly ash, and curing material was set at 10:10:1, and the solidification time was 20−30 min, as shown in Figure 16B. During the perfusion, the diffusion radius of the slurry reached 2 m after 1 h and 3 m after 3 h. The perfusion ceased when the slurry started to seep out of the ground. On-site preparation and perfusion of the curing material are shown in Figure 18.

4.4. Land Reclamation. After the fire source was extinguished and the cracks were filled with the curing material, it was necessary to cover the slope and flat surface of the coal gangue dump with loess. Afterward, green plants could be planted to restore the ecology. The backfilling height of the loess was 0.5 m, and 255,000 m^3 of loess was used considering the looseness coefficient 1.2. The construction picture is presented in Figure 19.

5. RESULTS AND DISCUSSION

The whole process of coal gangue fire area treatment, including the delineation of the fire area, the construction of a comprehensive fire prevention and control system, and the perfusion of fire prevention and extinguishing materials, lasted 6 months. Eventually, the threat of the fire was eliminated. Borehole temperature fell from 228 °C to normal temperature (36 °C), as shown in Figure 20.

Moreover, temperatures at corresponding depths were measured with the aid of a UT325 thermometer and a WRN series thermocouple, and the temperature contour map at different depths was plotted (Figure 21). The comparison results of the temperature fields manifest that all high-temperature points dropped below 36.5 °C, indicating a notable treatment effect on the coal gangue fire area. Finally, green plants were planted on the slope, and the ecosystem around the dump was restored (Figure 22).

6. CONCLUSIONS

Spontaneous combustion of coal gangue dumps not only releases toxic and harmful gases but also pollutes water and soil. Even worse, it may cause explosion and collapse of gangue dumps. That is, it directly or indirectly endangers the safety of residents near mining areas and leads to serious environmental pollution. In this study, detection and environmental remediation were performed on the fire area of the GSY coal gangue dump, and the following conclusions were drawn.

(1) Just like spontaneous combustion of coal, spontaneous combustion of coal gangue is jointly induced by physical and chemical factors. However, the accumulation mode of gangue differs from that of coal. Spontaneous combustion of coal gangue dumps is likely to trigger the “stack effect,” which causes the coal gangue fire area to spread from the outside to the inside, gradually expanding.

(2) Through this infrared temperature measurement and drilling chip verification, it is shown that spontaneous combustion sources of gangue fire areas are mostly located in the region of 3−5 m below the flat surface and can provide evidence for similar experiments on coal gangue dumps.

(3) The fire area scope can be precisely delineated by applying infrared thermal imaging for shallow-fire-area detection and intensive drilling for deep-fire-area detection; the important thing is that the cost is low and can lay a solid foundation for subsequent governance. Fires can be effectively extinguished by perfusing a three-phase foam for cooling down and curing material for filling the cracks. Land reclamation and green plants can help to restore the ecology of mining areas and significantly improve the environment.

■ ASSOCIATED CONTENT

Data Availability Statement

The data presented in this study are available on request from the corresponding author.

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Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by X.Q., D.L., Y.Z., and J.Q. The first draft of the manuscript was written by Y.L., and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Notes

The authors declare no competing financial interest.

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■ REFERENCES

(1) Robertson, W. J.; Kinnunen, P. H. M.; Plumb, J. J.; Franzmann, P. D.; Puhakka, J. A.; Gibson, J. A. E.; Nichols, P. D. Moderately thermophilic iron oxidising bacteria isolated from a pyritic coal deposit showing spontaneous combustion. *Miner. Eng.* **2002**, *15*, 815−822.

(2) Liang, Y.; Liang, H.; Zhu, S. Mercury emission from spontaneously ignited coal gangue hill in Wuda coalfield, Inner Mongolia, China. *Fuel.* **2016**, *182*, 525−530.

(3) Liu, Y. G.; Yu, L. N.; Zhou, A. G. Analysis of Coal Gangue Pollution Control Technology. *Advanced Materials Research.* **2013**, *683*, 941−944.

(4) Xue, S.; Dickson, B.; Wu, J. Application of Rn-222 technique to locate subsurface coal heatings in Australian coal mines. *Int. J. Coal Geol.* **2008**, *74*, 139−144.

(5) de Silva, D.; Andreini, M.; Bilotta, A.; De Rosa, G.; La Mendola, S.; Nigro, E.; Rios, O. Structural safety assessment of concrete tunnel lining subjected to fire. *Fire Saf. J.* **2022**, *134*, No. 103697.

(6) Tan, B.; Zhang, F.; Zhang, Q.; Wei, H.; Shao, Z. Firefighting of subsurface coal fires with comprehensive techniques for detection and control: a case study of the Fukang coal fire in the Xinjiang region of China. *Environ. Sci. Pollut. Res.* **2019**, *26*, 29570−29584.

(7) Wang, S.; Luo, K.; Wang, X.; Sun, Y. Estimate of sulfur, arsenic, mercury, fluorine emissions due to spontaneous combustion of coal gangue: An important part of Chinese emission inventories. *Environ. Pollut.* **2016**, *209*, 107−113.

(8) Shao, Z. L.; Wang, D. M.; Cao, K.; Si, W. B.; Li, Y. Z.; Liu, J. L. Treatment of smouldering coal refuse piles: an application in China. *Environ. Technol.* **2020**, *41*, 3105−3118.

(9) Tang, Q.; Li, L.; Zhang, S.; Zheng, L.; Miao, C. Characterization of heavy metals in coal gangue-reclaimed soils from a coal mining area. *J. Geochem. Explor.* **2018**, *186*, 1−11.

(10) Song, S. J.; Peng, R. S.; Wang, Y.; Cheng, X.; Niu, R. L.; Ruan, H. Spatial distribution characteristics and risk assessment of soil heavy metal pollution around typical coal gangue hill located in Fengfeng Mining area. *Environ. Geochem. Health.* **2023**, *45*, 7215.

(11) Li, C. H.; Liang, H. D.; Chen, Y.; Bai, J. W.; Cui, Y. K. Distribution of surface soil mercury of Wuda old mining area, Inner Mongolia, China. *Hum. Ecol. Risk Assess.* **2018**, *24*, 1421−1439.

(12) Querol, X.; Izquierdo, M.; Monfort, E.; Alvarez, E.; Font, O.; Moreno, T.; Alastuey, A.; Zhuang, X.; Lu, W.; Wang, Y. Environmental characterization of burnt coal gangue banks at Yangquan, Shanxi Province, China. *Int. J. Coal Geol.* **2008**, *75*, 93−104.

(13) Wang, H. Y.; Tan, B.; Zhang, X. D. Research on the technology of detection and risk assessment of fire areas in gangue hills. *Environ. Sci. Pollut. Res.* **2020**, *27*, 38776−38787.

(14) Wang, Y. L.; Yin, D. X.; Lou, L. M.; Li, X. Y.; Cheng, P. L.; Huang, Y. Luotuo Mountain Waste Dump Cover Interpretation Combining Deep Learning and VDVI Based on Data from an Unmanned Aerial Vehicle (UAV). *Remote Sens.* **2022**, *14*, 4043.

(15) Abramowicz, A.; Rahmonov, O.; Chybiorz, R.; Ciesielczuk, J. Vegetation as an indicator of underground smoldering fire on coal-waste dumps. *Fire Saf. J.* **2021**, *121*, No. 103287.

(16) Deng, J.; Li, B.; Xiao, Y.; Ma, L.; Wang, C.; Lai-wang, B.; Shu, C. Combustion properties of coal gangue using thermogravimetry−Fourier transform infrared spectroscopy. *Appl. Therm. Eng.* **2017**, *116*, 244−252.

(17) Ren, J.; Xie, C.; Lin, J.; Li, Z. Co-utilization of two coal mine residues: Non-catalytic deoxygenation of coal mine methane over coal gangue. *Process Saf. Environ. Protect.* **2014**, *92*, 896−902.

(18) Jiang, X.; Yang, S.; Zhou, B.; Cai, J. Study on Spontaneous Combustion Characteristics of Waste Coal Gangue Hill. *Combust. Sci. Technol.* **2023**, *195*, 713−727.

(19) Wang, C.; Wang, D.; Xin, H.; Qi, Z.; Zhang, W.; Zhang, K. Study on secondary oxidation characteristics of coal gangue at different pyrolysis rank. *Fuel.* **2023**, *345*, No. 128231.

(20) Zhang, Y.; Zhang, Y.; Shi, X.; Liu, S.; Shu, P.; Xia, S. Investigation of thermal behavior and hazards quantification in spontaneous combustion fires of coal and coal gangue. *Sci. Total Environ.* **2022**, *843*, No. 157072.

(21) Yuanyuan, Z.; Yanxia, G.; Fangqin, C.; Kezhou, Y.; Yan, C. Investigation of combustion characteristics and kinetics of coal gangue with different feedstock properties by thermogravimetric analysis. *Thermochim. Acta* **2015**, *614*, 137−148.

(22) Li, A.; Chen, C.; Chen, J.; Lei, P.; Zhang, Y. Experimental investigation of temperature distribution and spontaneous combustion tendency of coal gangue stockpiles in storage. *Environ. Sci. Pollut. Res.* **2021**, *28*, 34489−34500.

(23) Jiang, X.; Yang, S.; Zhou, B.; Song, W.; Cai, J.; Xu, Q.; Zhou, Q.; Yang, K. The variations of free radical and index gas CO in spontaneous combustion of coal gangue under different oxygen concentrations. *Fire Mater.* **2022**, *46*, 549−559.

(24) Nádudvari, Á. Thermal mapping of self-heating zones on coal waste dumps in Upper Silesia (Poland) — A case study. *Int. J. Coal Geol.* **2014**, *128*−*129*, 47−54.

(25) Shao, Z.; Deng, R.; Zhang, G.; Li, Y.; Tang, X.; Zhang, W. 3D thermal mapping of smoldering coal gangue pile fires using airborne thermal infrared data. *Case Stud. Therm. Eng.* **2023**, *48*, No. 103146.

(26) Ren, H.; Zhao, Y. L.; Xiao, W.; Zhang, J. Y.; Chen, C. F.; Ding, B. L.; Yang, X. Vegetation growth status as an early warning indicator for the spontaneous combustion disaster of coal waste dump after reclamation: An unmanned aerial vehicle remote sensing approach. *J. Environ. Manage.* **2022**, *317*, No. 115502.

(27) He, D.; Le, B. T.; Xiao, D.; Mao, Y.; Shan, F.; Ha, T. T. L. Coal mine area monitoring method by machine learning and multispectral remote sensing images. *Infrared Phys. Technol.* **2019**, *103*, No. 103070.

(28) Wu, S.; Zhou, B.; Wang, J.; Yang, Q.; Dong, W.; Dong, Z. Isotope radon measurement method to identify spontaneous combustion regions in coal gangue hills: case study for a coal mine in China. *Int. J. Coal Prep. Util.* **2023**, 1−13.

(29) Wang, H. Y.; Fang, X. Y.; Du, F.; Tan, B.; Zhang, L.; Li, Y. C.; Xu, C. F. Three-dimensional distribution and oxidation degree analysis of coal gangue dump fire area: A case study. *Sci. Total Environ.* **2021**, *772*, No. 145606.

(30) Wu, Y.; Yu, X.; Hu, S.; Shao, H.; Liao, Q.; Fan, Y. Experimental study of the effects of stacking modes on the spontaneous combustion of coal gangue. *Process Saf. Environ. Protect.* **2019**, *123*, 39−47.

(31) Zhai, X.; Wu, S.; Wang, K.; Drebenstedt, C.; Zhao, J. Environment influences and extinguish technology of spontaneous combustion of coal gangue heap of Baijigou coal mine in China. *Energy Procedia.* **2017**, *136*, 66−72.

(32) Zhang, X.; Pan, Y. Preparation, Properties and Application of Gel Materials for Coal Gangue Control. *Energies.* **2022**, *15*, 557.

(33) Tang, Y.; Wang, H. Development of a novel bentonite−acrylamide superabsorbent hydrogel for extinguishing gangue fire hazard. *Powder Technol.* **2018**, *323*, 486−494.

(34) Huang, Z.; Le, T.; Zhang, Y.; Gao, Y.; Li, J.; Li, Z.; Ma, Z. Development and performance study of a novel physicochemical composite inhibitor for the prevention of coal gangue spontaneous combustion. *Fire Mater.* **2020**, *44*, 76−89.

(35) Wang, Q. Y.; Zhao, Y. L.; Xiao, W.; Lin, Z. H.; Ren, H. Assessing Potential Spontaneous Combustion of Coal Gangue Dumps after Reclamation by Simulating Alfalfa Heat Stress Based on the Spectral Features of Chlorophyll Fluorescence Parameters. *Remote Sens.* **2022**, *14* (23), 5974.

(36) Du, X. M.; Sun, D. Q.; Li, F.; Tong, J. A Study on the Propagation Trend of Underground Coal Fires Based on Night-Time Thermal Infrared Remote Sensing Technology. *Sustainability* **2022**, *14* (22), 14741.

(37) Wang, T.; Wang, H. Y.; Fang, X. Y.; Wang, G. D.; Chen, Y. Q.; Xu, Z. Y.; Qi, Q. J. Research progress and visualization of underground coal fire detection methods. *Environ. Sci. Pollut. Res.* **2023**, *30*, 74671−74690.

(38) Bai, G. X. Study on Thermodynamic Characteristics and Heat Transfer Method of Uncontrolled Fire in Coal Mine Gangue Mountain Spontaneous Combustion Based on System Dynamics. *Comput. Intell. Neurosci.* **2022**, *2022*, No. 5953322.

(39) Chen, J.; Jia, B.; Fu, S.; Wen, Y.; Liang, Y.; Tian, F. Novel PFA-Based Inorganic Three-Phase Foam for Inhibiting Coal Spontaneous Combustion. *Acs Omega.* **2023**, *8*, 24615−24623.

https://doi.org/10.1021/acsomega.3c05942
ACS Omega 2023, 8, 47690−47700