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Experimental Study on the Efficacy of Water Infusion for Underground Mining of a Coal Seam

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Abstract: The main purpose of this study is to evaluate the efficacy of the water infusion method for various coalfaces of a coal seam by an experimental study. First, laboratory tests were performed on several coal samples taken from actual coalfaces to determine the general characteristics, especially the strength properties, with respect to the moisture content and time. The results obtained from the laboratory were employed to evaluate the appropriate parameters (e.g., water injection time and the optimum moisture content) for water infusion works in the field. A field test was then performed in order to assess the efficacy of water infusion for underground mining. The spalling depth (i.e., longwall face failure of coal wall, involving the stability of underground mining coalfaces) and mining velocity (i.e., involving the cost-effectiveness of mining constructions) were monitored at various coalfaces for both case studies (i.e., with and without water infusion). Expectedly, the field test results revealed that the spalling depth decreased significantly, whereas the mining velocity sped up considerably, at coalfaces using water infusion compared to at those without using the water infusion method. In conclusion, the promising findings obtained from the field test reinforced the efficacy of water infusion for underground mining coalfaces.

Keywords: experimental study; efficacy of water infusion; spalling depth; mining speed

1. Introduction

Underground mining is a risky industry due to potential failure or collapse near underground mining coalfaces, which can lead to common accidents in the mine, such as an interruption of mining or, more seriously, human loss [1]. To date, there have been many approaches used to prevent these accidents and the water infusion method is one of them. The water infusion method is the technique where water (i.e., with a certain pressure) is injected into the coal seam ahead of the working face, with or without surfactant. After being injected, water infuses into the seam through fractures, cracks, and cleats, and spreads out radially, far away from the holes [2]. The possibility of using the water infusion method as an effective means of longwall face failure reduction (i.e., reduction of lateral movement of coalfaces for underground coal seams) or dust control has been widely studied in the underground coal mining industry for more than 100 years. Underground mining is a risky industry, with many environmental issues involving dust around coalfaces. Studies on the water infusion method for dust control started early (around the 1970s). As the concept of this method, it requires a certain amount of water under pressure to be injected into coal seams through boreholes to increase the moisture inside the coal seams. In parallel, the dust generated from exploitation is significantly reduced. The conceptual mechanism of this method was reported in detail in the study by Wang [3]. The raw coal dust could be pre-wetted before the coal was crushed. Therefore, the dust source was considerably diminished due to the fact that a weakened dust floating ability is expected after the water is injected and transported along with the fracture systems of the coal seam. In addition, the injected water could be infiltrated into tiny pores of the coal seam. This process could help the whole body of coal become fully saturated and eventually reduce the huge amount of dust released during the crushing process by a longwall shear [2]. As early as the 1970s, Cervik, Sainato [4] reported deals with the water infusion of coalbeds. As found in their study, the respirable dust levels were reduced by about 50%–75% on a longwall section after using water infusion. Cervik, Sainato [5] kept studying the effects of water infusion, considering both aspects of cost effectiveness and dust control. An actual coal seam was selected for the field test of their investigation. They found that water infusion is an effective and economical method for reducing the generation of respirable dust on longwalls. The water infusion increased the moisture content of the coalbed and ventilation velocities in excess of 2.54 m/s then reduced dust levels further by dilution and prevented generated dust from boiling back. McClelland [6] continued the previous works by Cervik, Sainato [5] by conducting verification in three other case studies. Similar findings were observed in their study for both aspects of the environment and cost-effectiveness. More recently, water infusion techniques have been considered due to their advantages of a low cost and high efficacy. Recent studies have broadly focused on both experimental and numerical approaches [3,7–10]. The literature reviewed above clearly indicates the effectiveness of using water infusion techniques for dust control (i.e., environmental impacts). However, research on the utilization of these methods for effective longwall face failure reduction (i.e., reduction of the lateral movement of coalfaces, thus enhancing the stability and mining speed of a coal seam) has not yet been closely evaluated. It should be noted that after the water is injected into coal seams, stress ahead of working coalfaces is re-distributed with the slow relaxation of stress (pressure relief) [11]. In addition, the plasticity of the coal body can also be increased and the brittleness can be decreased with the presence of injected water [3]. With all the above effects, the lateral movement of coalfaces can be reduced and finally, the stability of the underground soft coal mining can be enhanced and the mining velocity can be sped up. In order to prove the abovementioned viewpoints, a comprehensive experimental study should be performed.

In this research, a series of tests (both in the laboratory and field) were carried out to explore the efficacy of the water infusion method for underground mining coalfaces, focusing on the new aspects of longwall face failure depth (i.e., spalling depth), which is the key factor for assessing the stability of coalfaces in underground mining construction, and the mining speed. Various aspects of moisture content, specific gravity, unit weight, permeability, and strength properties with respect to moisture content and time were first assessed in the laboratory to evaluate the appropriate parameters (e.g., water injection time and the optimum moisture content) for water infusion works in the field. Subsequently, for the field test, the spalling depth (i.e., longwall face failure depth) and mining velocity were monitored successively at various actual coalfaces for both case studies (with and without using the water infusion method). The efficacy of this method was evaluated based on a comparison of the aspects of spalling depth and mining speed for both case studies.

2. Stress Re-Distribution Ahead of Working Coalfaces of a Coal Seam with Water Infusion

Due to mining operations, a stress concentration occurs in-between the roof and the exposed coal seam wall. In particular, in a soft coal seam, the stress concentration on its wall increases significantly due to the boost of roof movement [12,13]. In the coalface of the seam, movement of overlying rock strata induces stress re-distribution in the coal ahead of the working face with abutment pressure. This pressure is generally larger than that of in situ rock [14]. For this reason, plastic deformation occurs along the coal seam. This causes original fractures and cracks in the coal seam. These fractures and cracks continue developing to form fracture or crack systems, weakening the strength of the coal seam [11]. After being injected, water infuses into the seam through these fracture and crack systems and spreads out radially, far away from the holes [2]. At first, water infusion enhances the moisture content in the whole body of the coal seam. In this condition, the plasticity of the coal body can also be increased and the brittleness can be decreased with the presence of injected water. Due to the modification of both mechanical properties of the coal seam, the stress concentration ahead of working coalfaces of a coal seam is re-distributed (i.e., with a considerable reduction of the acting pressure on the upper part of the coal seam) [2,11]. Figure 1 presents the stress distribution ahead of working coalfaces of a coal seam before and after water infusion [2,15].

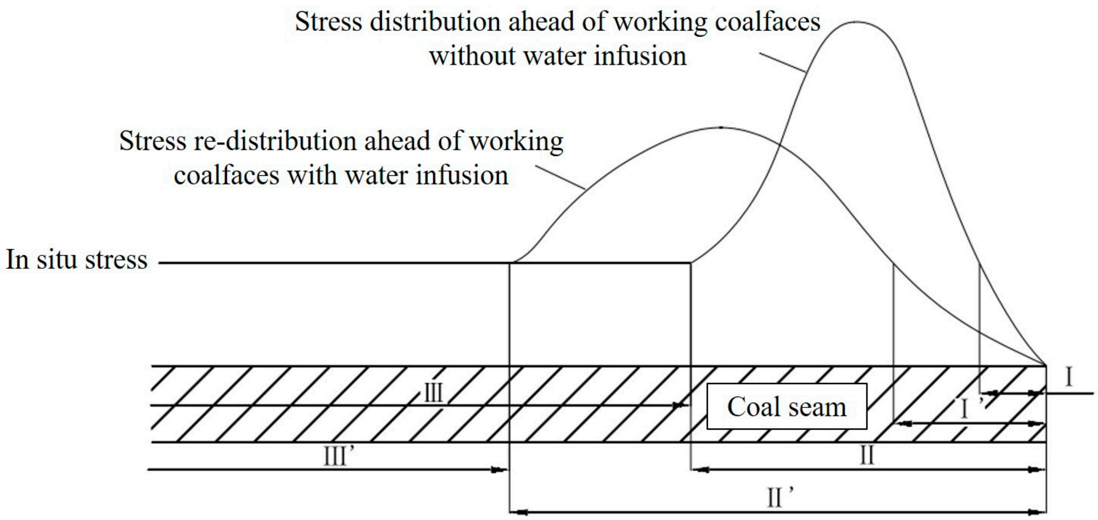


Figure 1. Stress distribution ahead of working coalfaces [2,15]. I—Stress relief zone before water infusion; II—stress concentration zone before water infusion; III—in situ stress zone before water infusion; I′—stress relief zone after water infusion; II′—stress concentration zone after water infusion; III′—in situ stress zone after water infusion.

The reduction of pressure acting on the upper part of the coal seam can be explained by theories of soil mechanics (i.e., only for a soft coal seam). Before water infusion, the coal seam is a three-phase material, consisting of a solid phase (i.e., coal particles), liquid phase (i.e., the injected water), and gas-phase, which is the same as a general soil. According to the principle of effective stress with saturated soil, stresses due to external forces (overburden stresses) can be distributed into two components: (1) effective stress (i.e., stress acting at the points of contact of soil particles) and (2) pore water pressure (i.e., the pressure of water in-between soil particles), as shown in Figure 2. In the case of no water infusion in the coal seam, the effective stress is much higher than the pore water pressure. As water is injected with a certain pressure, the coal seam might still be a three-phase material (i.e., partially saturated condition), or might become a two-phase material (i.e., fully saturated condition), consisting of only the solid phase and the liquid phase. This leads to a decrease in effective stress due to injected water, which might cause an increase in pore water pressure (i.e., with the same overburden stress). In this sense, the stress concentration ahead of working coalfaces of a coal seam is re-distributed (i.e., with a considerable reduction of the acting pressure on the upper part of the coal seam).

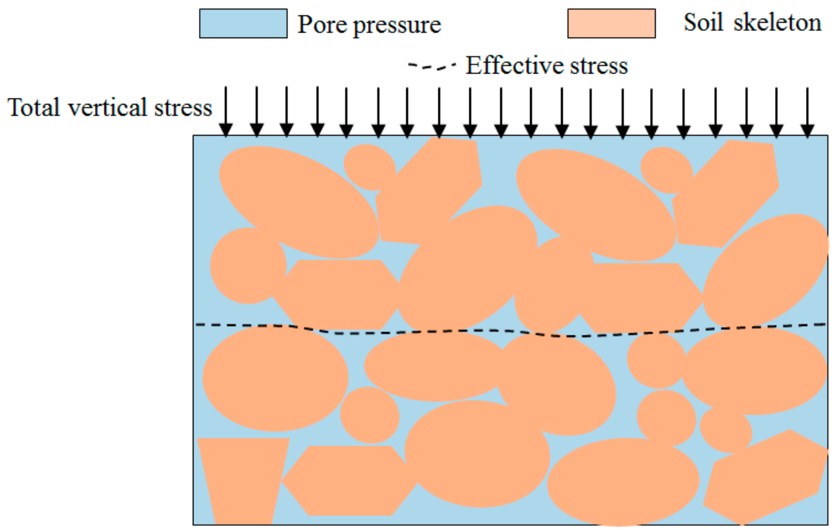


Figure 2. Principle of effective stress with saturated soil (reproduced with permission from Wesley, L. D, Principle of Effective Stress published by John Wiley & Sons [16]).

3. Experimental Program

3.1. Laboratory Test Program

The selected coal samples used for the laboratory test program in this study originated from Coal seam No 14-5 (Khe cham III coal mine, Quang Ninh, Vietnam) (See Figure 3). In total, 18 coal samples were taken from three different sections (i.e., six samples per section) along Coal seam No 14-5. The performance of all laboratory tests followed Vietnamese standards (TCVN 2012), such as those for the moisture content (TCVN 4196), bleeding (C 940), compressive strength (D 4832), flowability (D 6103), specific gravity (TCVN 4195), unit weight (TCVN 4202), permeability (TCVN 8723), and direct shear test (TCVN 4199). Table 1 summarizes all of the general characteristics of the coal samples from the laboratory test program.

Figure 3. Location coal seam No 14-5 (Khe cham III coal mine, Quangninh, Vietnam).

Table 1. General characteristics of the coal samples.

Properties	Section 1	Section 1	Section 1
Moisture content (%)	4.901	4.85	4.617
Unit weight (g/cm^3)	1.422	1.414	1.419
Specific gravity	1.521	1.51	1.518
Permeability (cm/s)	0.000380	0.000339	0.000362
Color	Black	Black	Black

In addition to the above general characteristics, the relationship between strength properties (i.e., from direct shear tests) and moisture content with time was also investigated in the laboratory to evaluate the appropriate parameters (e.g., water injection time and the optimum moisture content) for water infusion works in the field. The effect of moisture content (i.e., 12 different moisture contents) on the strength properties of coal was performed first to determine the optimum moisture content of the coal specimen. After that, the coal with the optimum moisture content was subjected to direct shear tests to determine the strength properties with respect to time. The tests were performed every 2, 18, 24, 36, 43, 43, 48, and 51 h.

3.2. Field Test Set Up

Coal seam No 14-5 (Khe cham III coal mine, Quang Ninh, Vietnam) is a coal seam with basic conditions, such as a thickness of 5 m, width of 105 m, length of 270 m, and inclined angle of 27°. Several water infusion boreholes were drilled at the coalfaces of the coal seam No 14-5 to assess the efficacy of the injection on the stability of underground mining coalfaces and the cost-effectiveness of mining constructions. The schematic layout sketch of water infusion boreholes is illustrated in Figure 4 [15].

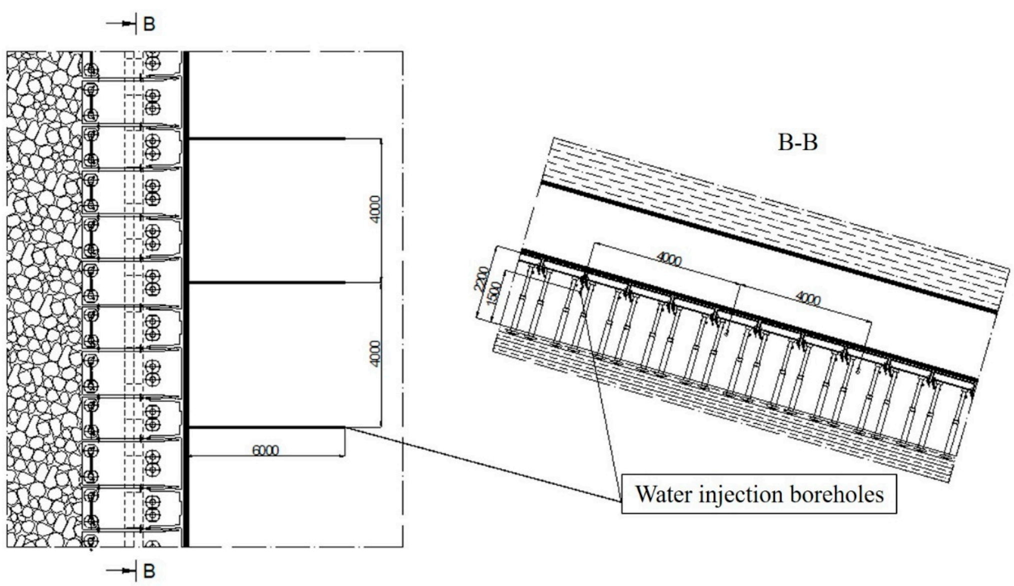


Figure 4. Schematic layout sketch of water infusion boreholes.

For the designed water injection, the diameter and length of the boreholes were 0.042 m and 6 m, respectively. The distance between each borehole was 4 m, which was determined based on the selected water injection pressure (3 MPa) and the permeability of coal. The required volume of water injection for one borehole was designed to be 12 m^3 as a function of unit weight, natural moisture content, optimum moisture content, and length of a water injection borehole [15]. As for the water injection method, the two methods of dynamic water injection and hydrostatic water injection are commonly considered in the field test. The first method is driven by pump pressure, whereas the second method is driven by the pressure in the anti-dust pipe network [11]. In this study, the dynamic water injection with a pump pressure was used in the field. A schematic diagram of the water injection system is shown in Figure 5.

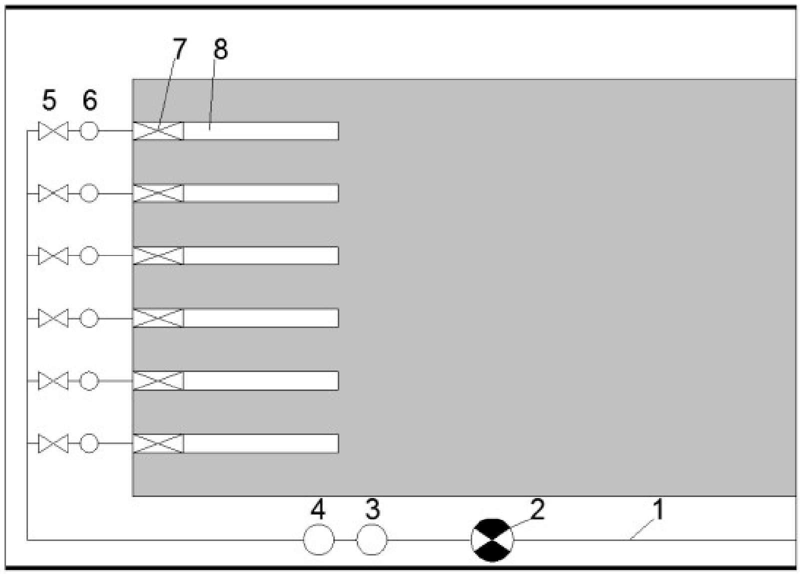
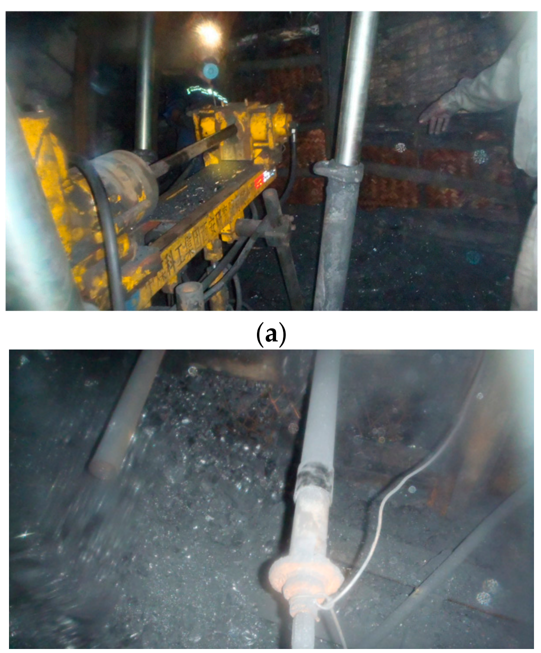


Figure 5. Schematic diagram of the water injection system: 1—water conduct pipe; 2—pressure pump; 3—flowmeter; 4—pressure gauge; 5—Valve; 6—pressure gauge; 7—plugs; 8—borehole.

Figure 6 shows pictures taken in the field of drilling (a), steel tube installing (b), and water injection (c). It should be noted that the pumping pressure was increased and regularly checked through the pressure gauge when operating the pressure pump. The pumping pressure was reduced gradually and then stopped after meeting the amount of water required for the borehole or when water leaked out from coalfaces.



(**a**)

(**b**)

(**c**)

Figure 6. Pictures taken in the field: (**a**) drilling; (**b**) steel tube installing; and (**c**) water injection.

4. Results and Discussion

4.1. Laboratory Test Results and Discussion

4.1.1. Effect of Moisture Content on the Strength Properties of Coal

The strength properties (e.g., cohesion and friction angle) are presented with respect to the moisture content in Figure 7. As shown in Figure 7a, when the moisture content of the coal increased from 7.07% to 22.58%, the value of cohesion also increased up to the maximum value of 15.4 kPa. This is due to a result of the cementation of water (i.e., water may act as "cement") [2] or the bonding coal particles [4], with an appropriate amount of moisture. This value decreased with a gradual increase in moisture content (22.58%–29.5%), due to a reduction of the bonding effect (i.e., a coal particle is easy to detach with a high moisture content). A similar effect of moisture content on the value of cohesion has been observed in other materials, such as , soil examined by Huang et al. (2012) [17], mudstone investigated by Liu and Zhu (2012) [18], and coal explored by Wang et al. (2016) [19], remodeled coal studied by Zhang et al. (2017) [20]. In the study by Huang et al. (2012) [17], the value of cohesion increased as the moisture content varied in the range of 3.0%–12.0% and then dropped rapidly after the peak due to an increase in moisture content (12.0%–27.5%). As the authors' explained in their paper, the enhancing cohesion effect might be a result of the cementation of water (i.e., water may act as "cement" with an appropriate amount of moisture content and it may shift to acting as a "lubricant" after a threshold value of moisture content). Liu and Zhu (2012) [18] found that the peak value of the cohesion of mudstone in terms of the moisture was 13.0% (i.e., increased as the moisture content varied in the range of 10.0%–13.0% and decreased as the moisture content ranged from 13.0% to 20.0%). A similar trend for coal was pointed out by Wang et al. (2016) [19], who demonstrated that the cohesion of coal was strengthened due to the bonding coal particles after adding water. However, the cohesion of coal being reduced after the threshold moisture content was explained by the reduction of friction between adjacent coal particles. In addition to the similar trend, the ranges of cohesive strength and moisture content in this study are very close to those in the study conducted by Zhang et al. (2017) [20], interestingly.

Meanwhile, the effect of moisture content on the friction angle of the coal specimen was also studied (Figure 7b). A very small change of the friction angle (i.e., a very slight decrease) can be observed for a considerable increase in the moisture content. The effect of moisture content on the friction angle was much less pronounced than that on cohesion, interestingly. This finding agreed well with that of Zhang et al. (2017) [20], as they concluded that the internal friction angle was almost independent of the moisture content. In conclusion, the moisture content of 22.58% was recommended as the optimum moisture content for further tasks (e.g., water injection time and field water injection).

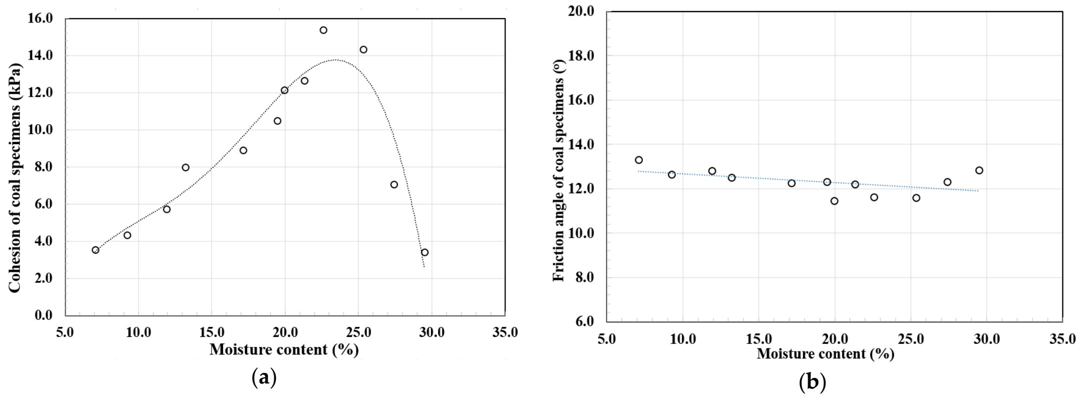


Figure 7. Effect of moisture content on the strength properties of coal samples: (**a**) Effect on cohesion; (**b**) effect on the friction angle.

4.1.2. Effect of Water Injection Time on the Strength Properties of Coal

In the field, water injection works are very important and always implemented before the mining process. Therefore, determination of the water injection time (i.e., based on the effect of the water injection time on the strength properties of coal) was also considered. Figure 8 shows the relationship between the strength properties (e.g., cohesion and friction angle) and water injection time. As expected, a similar trend was also observed; that is, the effect of the water injection time on cohesion was more pronounced than that on the friction angle. The value of cohesion gradually climbed from 14.56 kPa to16.15 kPa as the water injection time increased from 2 h to 18 h. After the peak value of 16.15 kPa, the value of cohesion started dropping with an increase in the water injection time (18–51 h). Therefore, the water injection works in the field were recommended to be conducted within 20 h before the next mining advance.

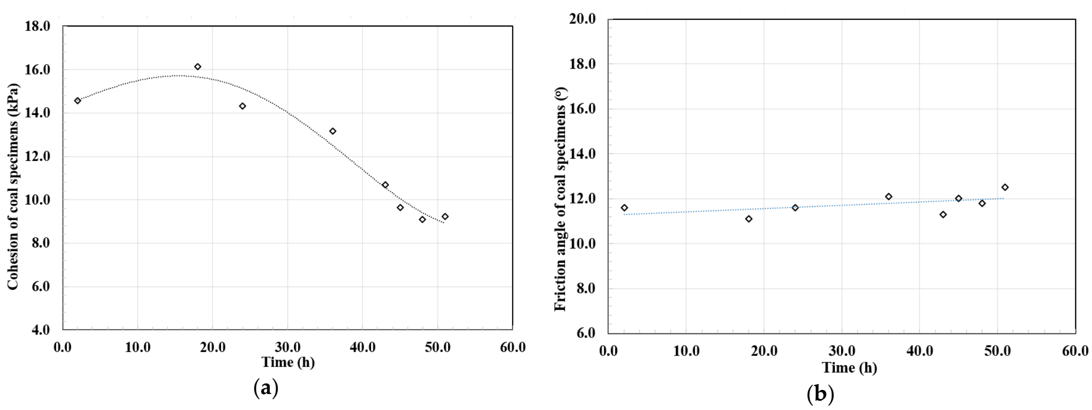


Figure 8. Effect of the water injection time on the strength properties of coal samples: (**a**) Effect on cohesion; (**b**) effect on the friction angle.

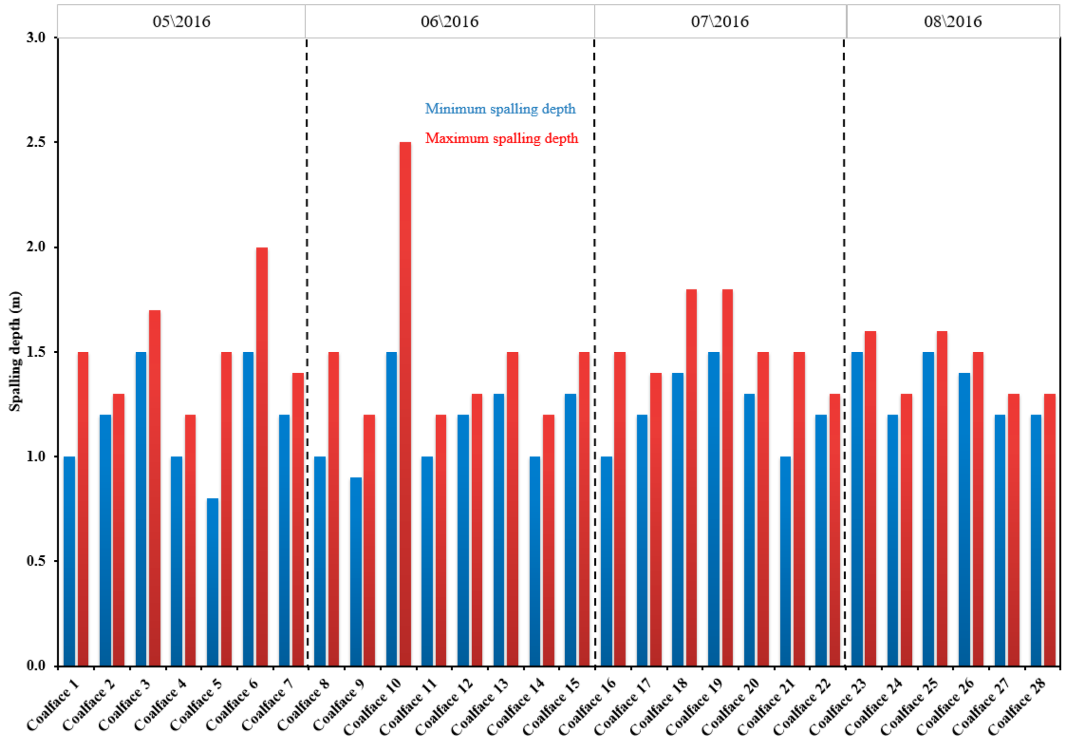
4.2. Field Test Results and Discussion

As mentioned earlier, in the case that the pressure, acting on the upper part of a coal seam, meets the maximum bearing capacity of the coal wall, the coal body starts failing and causes top spalling. Figure 9 shows two pictures, obtained from the field tests, of coalfaces before and after using water infusion techniques. The physical efficacy of the water infusion method for underground mining of the coal seam can be visibly observed first at the coalfaces. It can be explained by the fact that after water is injected into the seam, it leads to an increase in the moisture content of the coal seam. In this condition, the plasticity of the coal body can be increased and the brittleness can be decreased with the presence of injected water. Due to the modification of both mechanical properties of the coal seam, the stress concentration ahead of working coalfaces of a coal seam is re-distributed (i.e., with a considerable reduction of the acting pressure on the upper part of the coal seam) [11]. For this reason, less top spalling at the coalfaces could be expected due to the pressure acting on the top of the coal seam.

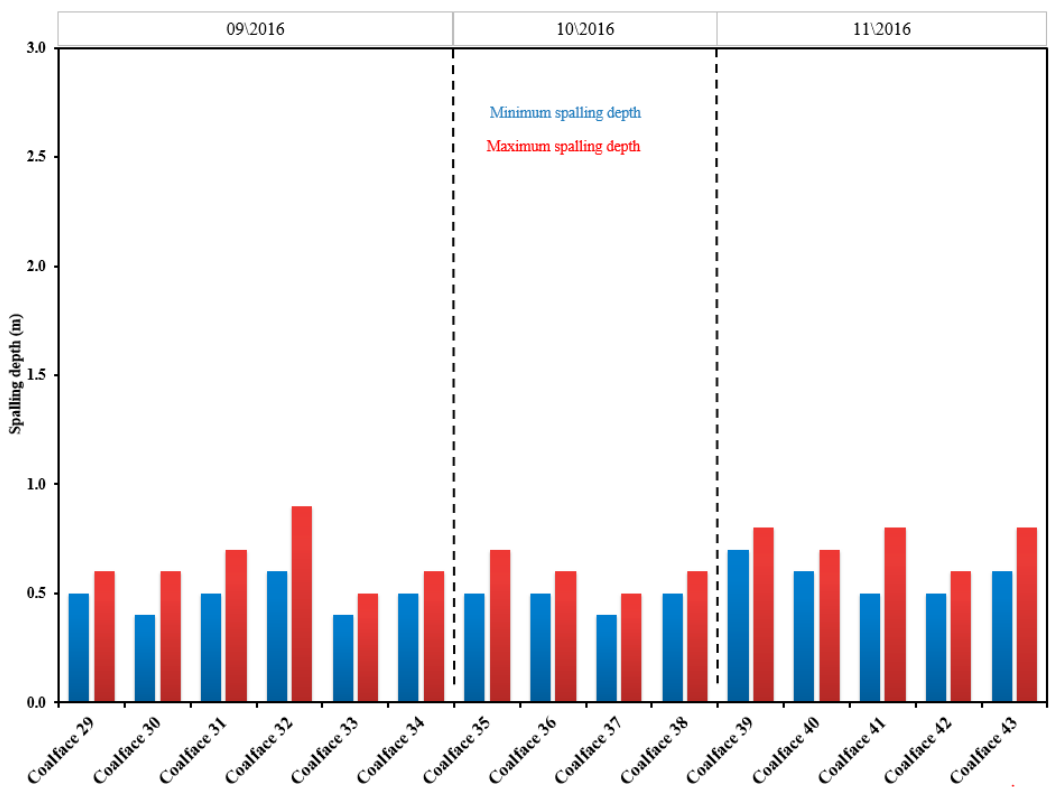
(**a**) (**b**)

Figure 9. Coalfaces before (**a**) and after (**b**) using water infusion.

In order to quantitatively evaluate the efficacy of water infusion for the stability of coalfaces in the field, the spalling depths were monitored successively at various coalfaces for both case studies (i.e., with and without water infusion). It should be noted that the depth of longwall face failure, the so-called spalling depth, is the key factor for assessing the stability of coalfaces in underground mining construction in Vietnam [15]. In total, 28 coalfaces (a case study of without water infusion) and 15 coalfaces (a case study of with water infusion) were measured in the field, from May 2016 to August 2016 and September 2016 to October 2016, respectively. Figure 10 illustrates the spalling depths of various coalfaces of the coal seam without (a) and with (b) using the water infusion method. As a result, the maximum and minimum spalling depths varied in ranges of 1.2–2.5 m and 0.8–1.8 m, respectively. As expected, these depths were reduced 2.8 times compared to those of coalfaces without using water infusion. All coalfaces had spalling depths of less than 0.9 m after using the water infusion method in the coal seam. In this sense, water infusion improved the stability of the coal seam in the aspect of spalling depth.



(**a**)



(**b**)

Figure 10. Monitored spalling depths of various coalfaces of the coal seam without (**a**) and with (**b**) the water infusion technique.

More importantly, coalfaces with and without the use of water infusion were also subjected to field measurements in terms of the mining speed (Figure 11). As shown, the mining speed of the coal seam using water infusion was larger than that of the coal seam without using the proposed technique (i.e., water infusion), regardless of coalfaces. In particular, the mining speed of the coal seam without using water infusion was only in the range of 6.6–8.1 m/month. As expected, this speed could reach a maximum of 14.4 m/month (i.e., increasing 1.8 times) compared to that of coalfaces without using water infusion. The higher stability of the coal seam (i.e., less spalling depths) might be the basepoint leading to the higher mining speeds of the seam sections using water infusion.

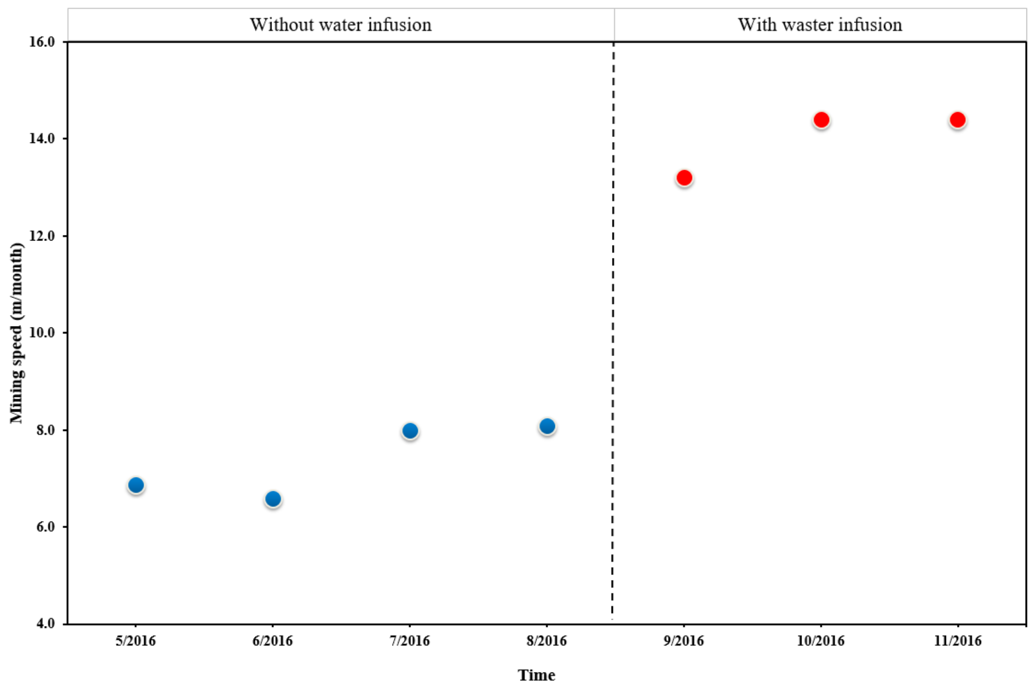


Figure 11. Mining speed of the coal seam with and without using water infusion.

Moreover, a relationship between mining speed and spalling depth is also depicted in Figure 12. The data were collected from all average values of mining speeds and spalling depths each month from May 2016 to October 2016. This relationship aims to determine if the spalling depth can be used to predict the mining speed at any coalface of the coal seam. As a general trend, a faster mining speed is achieved with a smaller spalling depth. This finding can be explained by the procedure of mining construction in the field. A coalface with a smaller spalling depth can move much faster to the next mining advance than a coalface with a larger spalling depth, mainly due to the shorter time of support structure installation. The underground mining industry in Vietnam states that if the monitored spalling depth (i.e., longwall face failure depth) is smaller than 1.5 m, a simple support structure like a timber support can be used. In the case of a considerable spalling depth (i.e., larger than 1.5 m), the use of a hydraulic support combined with timber is recommended to ensure the stability of humans and equipment working on coalfaces [15], as shown in Figure 13. In this sense, a longer time is required for support structure installation, which leads to a slower mining speed, in a coalface with a larger spalling depth than a coalface with smaller spalling depth. This observation is similar to that presented in a previous study by Zhang et al. (2016) [21]; that is, the smaller the spalling depth, the faster the mining speed. Based on this understanding, a simple mining speed prediction equation (i.e., linear function) was proposed for underground mining construction.

$$MS = -7.842 * SD + 19.2 \quad (1)$$

where

MS = mining speed (m/month);

SD = spalling depth (m).

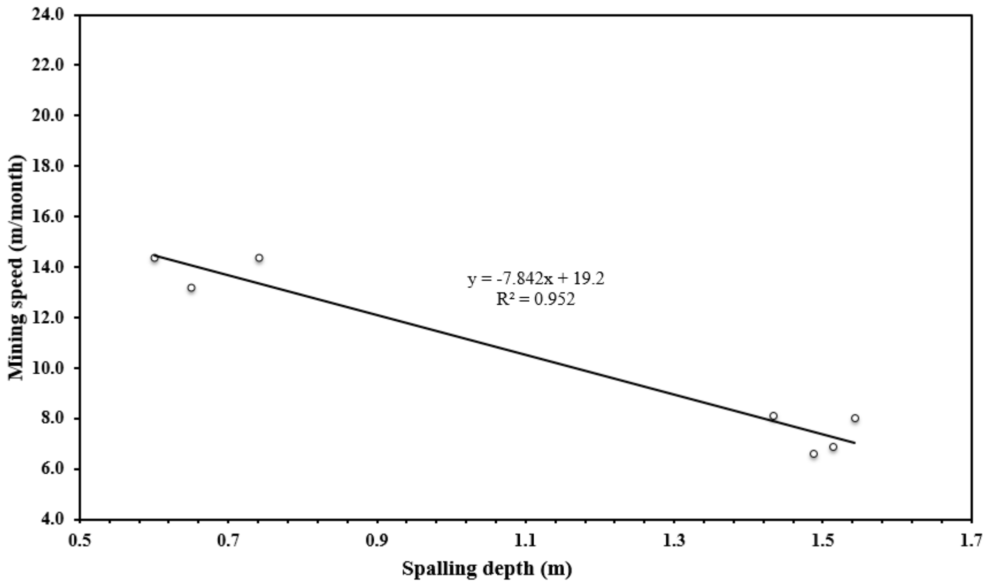


Figure 12. Relationship between the mining speed and spalling depth.

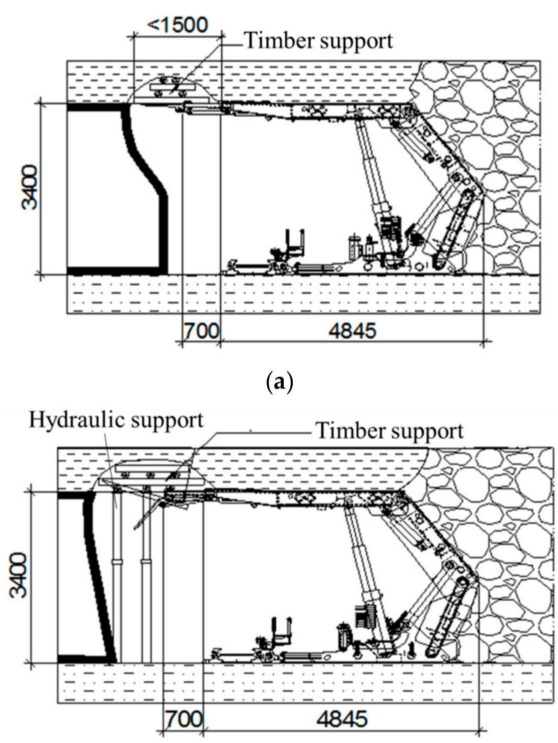


Figure 13. Support structure used during mining construction [15]. (**a**) Small spalling depth-coalface (<1.5 m). (**b**) Large spalling depth-coalface (>1.5 m).

The proposed prediction equation for mining speed was verified by a comparison of the predicted results and the measured results (Figure 14). A good agreement was observed between the predicted and measured ones in both training data and validating data (i.e., obtained from extra coalfaces). In this sense, the monitored spalling depth could be used to predict the mining speed of any coalface section. However, the spalling depth and mining speed could be changed, depending on the coal seam and surrounding rock conditions, such as the natural moisture of a coal seam. Therefore, the prediction model is only applicable for coalfaces in the coal seam used in this study. It should be noted that the water infusion method will be continued in the future for other coal seams. Hence, the prediction model could be verified with upcoming data.

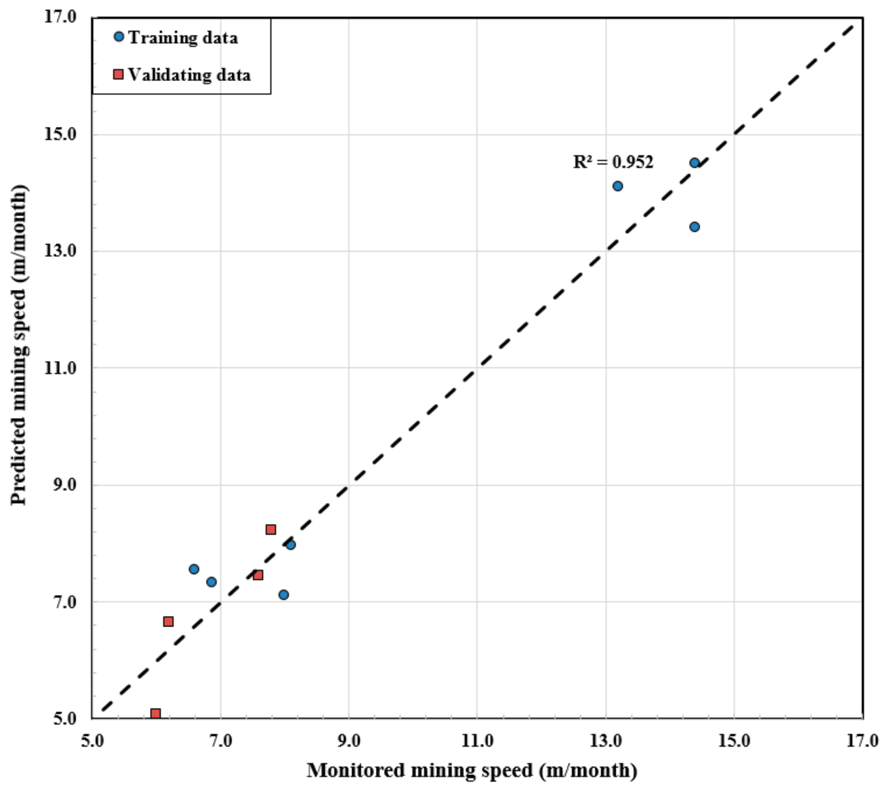


Figure 14. Comparison of the predicted mining speed and the measured mining speed using the proposed equation.

5. Conclusions

In this investigation, an experimental study on the efficacy of the water infusion method for the underground mining of a coal seam was performed. First, laboratory tests were performed on various coal samples taken from actual underground mining coalfaces to determine the coal properties. A field test was then carried out on the actual coalfaces (i.e., with and without using the water infusion method). Based on the results obtained from the experimental program, the following conclusions can be drawn:

1. The strength properties of the coal specimens were found to be functions of the moisture content and water injection time. The optimum moisture content (22.58%) and appropriate water injection time (within 20 h) were experimentally determined from the laboratory testing program. These obtained values were then employed to evaluate the efficacy of the water infusion method for the actual coal seam;
2. The physical efficacy (i.e., less longwall face failure) of water infusion for underground mining of the coal seam could be visibly observed first at the coalfaces. In addition, the quantitative

results obtained from the field indicated that smaller spalling depths and faster mining speeds were attained in the coalfaces using the water infusion technique than those without using the water infusion technique, expectedly. The mining speed of the coal seam rose to 14.4 m/month (i.e., increasing 1.8 times) compared to that of coalfaces without using water infusion, due to the smaller spalling depths (i.e., decreasing 2.8 times);

3. A linear relationship between spalling depth and mining speed was also discovered from the field test results; that is, the smaller the spalling depth, the faster the mining speed. In addition, the mining speed prediction equation was proposed for the field of underground mining construction. This proposed equation was verified and well-matched results (i.e., in both training data and validating data) of the predicted and measured data were clearly observed. However, the spalling depth and mining speed could be changed, depending on the coal seam and surrounding rock conditions, such as the natural moisture of a coal seam. Therefore, the prediction model is only applicable for coalfaces in the coal seam used in this study. It should be noted that the water infusion method will be continued in the future for other coal seams. Hence, the prediction model could be verified with upcoming data;
4. In conclusion, the greater stability and faster mining speed of the coalfaces using the water infusion technique than those without the water infusion technique, obtained from the field test, strongly reinforced the efficacy of water infusion techniques for the underground mining of a coal seam.

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Conflicts of Interest: Page: 14

The authors declare no conflict of interest.

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