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Effects of Temperature on the Properties of the New Gel Foam

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Abstract. In order to prevent coal spontaneous combustion fire effectively, a new kind of fire-fighting material - gel foam was developed in this paper. The foaming volume and half-life of foaming agent at different concentrations were measured by ROSS-Miles. Four foaming agents with less dosage and higher foaming times were selected. Then different temperatures were set to test the temperature resistance of four foaming agents and record the foaming volume data. Through analyzing the experimental results, the three optimal foaming agents were selected for pairwise compounding. Through the compounding experiment, the compound foaming agent was prepared with mass fraction of 6‰ APG and AEC at a mass ratio of 4:3, and the foaming times reached 13 times. After the addition of foam stabilizer, the foaming times of the compound were up to 15 times at room temperature, and the glue forming time is 13min. The results show that the viscosity of gel foam decreases with the increase of temperature. The higher the temperature, the shorter the gelation time. The gel does not decompose at high temperatures.

Keywords. Gel foam, temperature, foam properties, gelatinizing property

1. Introduction

Coal is one of the important energy sources in China's economic and energy structure. Coal spontaneous combustion is one of the disasters in the coal mining process, which seriously threatens the safety of production. Therefore, it is of great economic and social significance to study the prevention measures of coal spontaneous combustion fire [1,2]. At present, common fire prevention technologies at home and abroad mainly include grouting, inhibitor, pressure equalization, inert gas, leak plugging, gel, foam and three-phase foam, etc. [3-5]. Among them, gel has been used as a medium to improve the stability of foam, forming a new fire-fighting material - gel foam. Gel foam is a polymer with a three-dimensional network structure [6-7]. After gelation, the bubbles are firmly trapped in the high viscosity gel film, which improves the elastic force and heat absorption ability of the foam, and can effectively reduce the flow of oxygen in goaf. After covering the coal body, a dense film can be formed on the

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surface of the foam body to permanently isolate oxygen, cover the high temperature fire source, and keep the surface of floating coal moist and prevent spontaneous combustion [8-10]. The theoretical and technical research on gel foam belongs to the research content of a new discipline, whose research results can effectively prevent coal spontaneous combustion and have very important theoretical and practical significance for ensuring safe mining in mines and constructing harmonious mining areas.

Domestic researcher Zhao prepared gel foam with low pollution, studied the influence of concentration and temperature on compound foaming agent, and analyzed the thermal stability of foam gel under different conditions [11-12]. Zhang used stirring method to measure the influence of each component of the hot foam gel system on the foam stability performance, evaluated the salt and temperature resistance performance, determined the formula of the foam gel system, and conducted experiments such as the evaluation of the blocking solvability [13]. Tian developed a new gel foam and used a self-made testing system to test the difference between the coal sample treated by gel foam and the original sample when the temperature rises [14]. The Fogler group of The University of Michigan made a detailed study on the direction and mechanical strength of its osmotic flow [15]. Savoly A et al. used two kinds of surfactants to compound prepare the foaming agent, which provided ideas for later experiments [16]. A.M. Tanafreshi et al. obtained different mechanisms between the sealing characteristics of gel and foam, and selected experimental materials according to air flow and other influencing factors [17].

Scholars at home and abroad have studied the foam properties of the gel foam at room temperature by compounding the surfactants, but for different ambient temperatures, the gel foam properties of different surfactants need to be further studied. In this paper, a new type of gel foam fire-fighting material for coal spontaneous combustion was put forward, and the influence of temperature on the temperature resistance and viscosity of gel foam for gel formation time was studied. In the process of mine fire extinguishing, there is a high demand for the plugging property of gel foam, so the plugging property of gel foam is further tested. According to the experimental results, the formula and proportion of gel foam are adjusted to determine the preparation of fire extinguishing materials with a relatively wide application range.

2. Preparation of Gel Foam

2.1. Experimental Steps

(1) Single foaming agent selection

In order to determine their best foam foaming agent concentration, 8 kinds of foaming agent were selected for the concentration gradient test, the concentration gradient was set to ten concentrations from 1‰ to10‰. Firstly, an electronic balance was used to weigh a certain amount of foaming agent and put it into a 250ml beaker, and measure 50ml tap water with a measuring cylinder. The foaming agent solution was prepared with a concentration of 1 to 10. Then, the temperature and humidity of indoor environment were measured by mechanical thermohygrometer, and the foaming volume of foaming agent solution was measured by Ross-miles. The volume and half-life of the foam produced were recorded. The foaming performance of the foam was measured by the foaming multiples of the foam produced. The foam stabilizing performance was measured by the foam volume attenuation as the initial 1/2 time. Four foaming agents were selected according to the foaming multiples as the measurement standard. Each blowing agent was tested three times and the average value was taken as the final result.

(2) The experiment of heat-resistant

The circulating water temperature of Ross-miles was set to 10℃, 20℃, 30℃, 40℃, and 50℃. The foaming volumes of 4 foaming agents with concentration of 6 at different temperatures were tested. The volume changes of foaming were recorded and three foaming agents were selected according to the foaming ratio.

(3) Foaming agent compound

The three foaming agents were mixed in pairs, and the mixing ratio was 1:0, 1:1, 1:2, 4:3, 2:3. The foaming volume of the foaming agent solution was measured by Ross-miles, and the foaming multiples were calculated.

According to [18], automatic surface tensiometer was used to measure liquid surface tension by ring-pull method in the experiment [19].

(4) Preparation of gel foam

4.5‰ polyacrylamide and 3‰ aluminum citrate were dissolved in clear water. After full stirring, 1‰ CMC-Na and 6‰ foaming agent were added for blending. 300mL of the mixed solution was placed in an agitator, the stirring time was set at 15min, and the revolution was set at 1000r/min. The gel foam was prepared by full stirring under a constant speed electric agitator, and the gelatinization time was recorded. Besides, rheological properties and blocking performance were tested.

2.2. Selection of Foaming Agent

2.2.1. Selection of a Single Foaming Agent

The selection of foaming agent type and the determination of mass concentration fraction should be based on the principle of foaming agent selection and several factors influencing the properties of gel foam [20]. Through literature review and a large number of previous experimental studies [21-24], 8 kinds of green foaming agents were selected, which are sodium dodecyl sulfate (SDS) , lauric acid sodium salt (LASS), sodium dodecyl benzene sulfonate (SDBS), sodium lauryl trimethyl ammonium bromide (CTAB), dodecyl (dimethyl) betaine (SB), lauryl propyl betaine (LAB), alkyl glucoside (APG)0814 and AEC. 50 mL foaming agent solution was measured with a measuring cylinder, and the concentration of foaming agent was set as 1‰~10‰ respectively. The indoor environment temperature and humidity were measured by mechanical hygrometer. The foaming volume of foaming agent solution was measured with a foam tester, and the volume and half-life of foaming agent solution were recorded. The foaming performance of the foam is measured by the foaming multiples of the foam produced. The foam stabilizing performance was measured by the foam volume attenuation time of 1/2 of the initial foam. Four foaming agents were selected according to the foaming ratio.

As can be seen from the figure 1 and figure 2, the foaming times of each foaming agent increase continuously with the increase of concentration, and the half-life shows a trend of first increasing and then decreasing. Among them, the foaming ratio of APG AEC sodium lauryl (dimethyl) betaine SB was better than that of other 4 foaming agents. At the mass concentration of 6‰, the foaming agent has the maximum foaming ratio and the longest half-life. Therefore, four foaming agents, which were APG, AEC, LASS and SB, were selected for the next experiment.

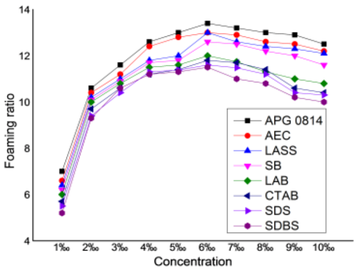

Figure 1. Foaming ratio of foaming agent.

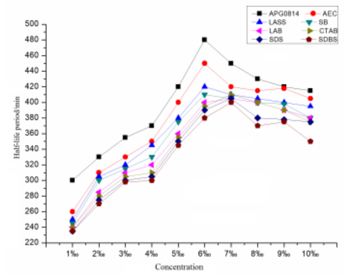

Figure 2. Half-life of foaming agent.

2.2.2. Analysis on the Temperature Resistance of Foaming Agent

In this experiment, a temperature gradient with an interval of 5°C was set, and the above four foaming agents were tested with other components unchanged. The experimental results are shown in figure 3.

From figure 3, room temperature four foam volume is the largest, with the increase of temperature, four kinds of foaming agent of foam volume decreases. This is because as the temperature increases, the space of gel foam mesh structure was destroyed by high temperature, and the water gel foam was gradually evaporates, foam liquid film become thin. When moisture evaporates to a certain degree, the bubble volume decreased dramatically, soon all bubble burst. In the process, the stability of APG and AEC is particularly outstanding.

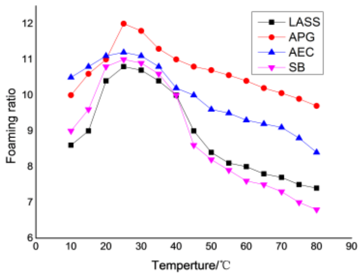

Figure 3. Relationship between temperature and foaming ratio.

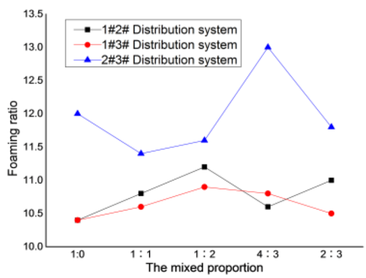

Figure 4. Foaming ratio of compounding foaming agent.

2.2.3. Compounding of Foaming Agent

According to the temperature resistance test of foaming agent, three foaming agents were selected for pairwise compounding, namely, 2#3# complex system, 1#2# complex system, 1#3# complex system, 1# LASS, 2# APG0814, and 3# fatty alcohol polyoxyethylene ether sodium carboxylate. The experimental temperature is 25 ℃. On the premise that the components of the foam and the components of other gel foams remain unchanged, the foaming agent concentration was 6‰, and the compound proportion determined is 1:0, 1:1, 1:2, 4:3, and 2:3.

From figure 4, when the mass concentration of 6 ‰, foaming agent of foam volume is more than a single, foaming agent after four kinds of foaming agent of two compound foam volume changes with the mixed proportion of 2 # 3 # of combined systems are the highest foaming ratio is about 13, 1 # 3 # supreme foaming ratio is about 11, 1 # 2 # supreme foaming ratio is about 11.2, including when the APG, with AEC to 4:3 for foaming effect is best.

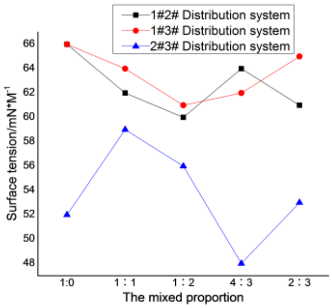

Figure 5. The surface tension of the complex system at various compounding ratios.

Comparison between figure 4 and figure 5 show that, synergy between the foaming agent, effectively enhance the foaming effect, because of the foaming agent molecules in the arrangement of a bubble in liquid membrane of a single molecule foaming agent in the ordering of the bubbles in the liquid film are closer, foaming agent force of attraction between the molecules is greatly enhanced, at the same time mutual repulsion between charged polar groups were weakened effectively [25] reduce the surface tension of gel foam is reached, make it easier to gel foam preparation [26], but when the mixed ratio is greater than or less than 4:3, not effectively reduce the surface tension, surface activity is restricted, the foaming effect is not optimistic. Compared with the three systems and their respective ratios, the optimal ratio of the 2#3# complex system is 4:3.

2.3. Selection and Concentration Determination of Gelling Agent, Crosslinking Agent and Foam Stabilizer

2.3.1. Selection of Foam Stabilizer and Determination of Concentration

When only the foaming agent is added, the foam is easy to be damaged, with short lasting time and strong fluidity. Therefore, it is necessary to add foam stabilizer to make the ordered arrangement of foam molecules in the liquid film, so as to make the three-dimensional structure more stable, enhance its stability, and increase the elasticity and self-repairing ability of the foam [27]. In this paper, cmc-na was selected as foam stabilizer. However, the intermolecular forces were significantly enhanced by cmc-na, a foam stabilizer, while the foaming agent mechanism was to reduce the surface tension, which was contradictory to each other. Therefore, it is particularly important to choose the appropriate concentration. Considering the economic performance, the mass fraction of foam stabilizer is 1‰ [28].

2.3.2. Selection of Gelling Agent and Crosslinking Agent and Determination of Concentration

The crosslinking agent and gelling agent are fully mixed, and the gelling agent is further fully dissolved in the solution. The gelling agent molecules can interact with the crosslinking agent molecules to form a stable three-dimensional network structure, so that the viscosity of the gel foam is effectively increased and the stability is enhanced. In the experiment, aluminum citrate with a concentration of 3‰ was selected as the crosslinker, and polyacrylamide with a concentration of 4.5‰ was selected as the gel.

3. Performance Analysis of Gel Foam

3.1. Analysis of Rheological Properties

The gel foam rheological properties is one of the important performance. In this experiment, a thermostatic water bath pot accurate to 0.1 was used to set a temperature gradient of 20~50, and gel foam was quickly prepared according to gel foam formula. MCR302 rheometer was used to measure the viscosity at the shear rate of $4.8s^{-1}$. The measurement results were shown in figures 6 and 7.

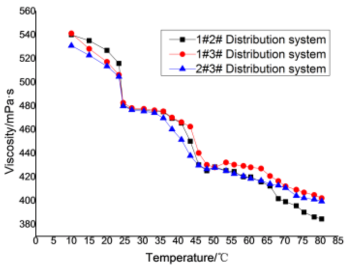

Figure 6. Diagram of viscosity with temperature.

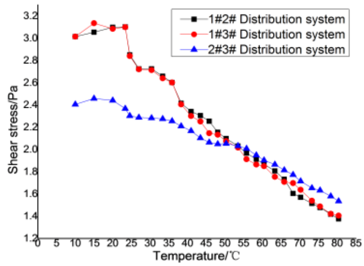

Figure 7. Diagram of shear stress with temperature.

At the shear rate of $4.8s^{-1}$, there is a negative correlation between the foam viscosity and temperature, that is, the viscosity of the gel foam of the complex system decreases with the increase of temperature. The increase in temperature intensifies the evaporation of liquid, foam wall water loss is accelerated, foam wall is thinner, toughness and resistance to frictional deformation decreased, strength and elasticity become poor. In addition, the spatial network structure of the gel foam is destroyed by high temperature, and the framework through which the tangles in the liquid film are broken down and the viscosity of the gel foam is reduced.

3.2. Analysis of Temperature Resistance of Gel Foam

In order to investigate the effect of temperature on the stability of gel foam, the solution was stirred into foam by agitator. Set the heating rate at intervals of 5°C and measure the volume of foam in the beaker. The test results are shown in figure 8.

As can be seen from figure 8, with the increase of temperature, the volume of ordinary water-based foam first remains unchanged, then increases and then decreases.

Before 55℃, the foam volume of the two beakers changes very little and tends to be consistent, indicating that there is no significant difference in their low-temperature performance. After the temperature exceeds 55℃, the amount of foam of ordinary foam increases gradually, and is slightly higher than that of gel foam between 55℃ an d 80℃. When the temperature exceeds 80℃, the amount of regular foam begins to decrease rapidly, while the amount of gel foam increases slightly. Final temperature 100 ℃, the average amount of foam to reduce to 2 # 3 # 4/5 of gel foam combined systems, and 2 # 3 # foaming ratio is about 13.2 times, combined systems are high temperature stage performance difference of the two obviously, gel foam is better than the ordinary foam. The temperature resistance of gel foam is significantly higher than that of ordinary water-based foam. Because of the interaction between gelling agent and crosslinking agent in the foam liquid membrane to form a three-dimensional network structure, water is firmly adsorbed in the colloidal structure. Gel foam has better thermal stability than water, its water loss at high temperatures is slow, so there won't be high temperature within a colloid, gel materials internal three-dimensional reticular structure stability is strong, colloid is not easy to produce explosive boiling phenomenon, therefore, temperature tolerance of gel foam system was obviously higher than that of ordinary bubble, high stability.

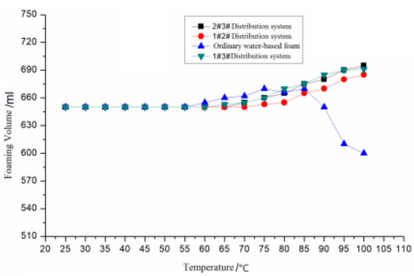

Figure 8. Relationship between temperature and foaming volume of gel foam.

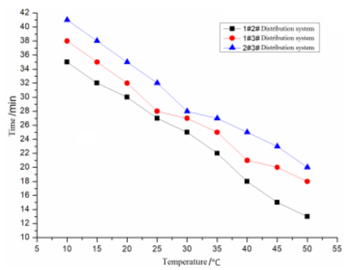

Figure 9. Variation of gel formation time with temperature.

3.3. Analysis of Gel-forming Performance

It is necessary to study the effect of temperature on the properties of gel foam, because the temperature is an important factor that affects the chemical reaction rate. After the temperature is constant, the foam is quickly beaten into shape, and the gelatinization time is recorded. The gelatinization time is measured by the tilt method. A 100mL gelatinization foam with complete foaming is taken into the measuring cylinder, and its tilt of 45° without movement time is taken as the gelatinization time.

Figure 9 shows that, at the same concentration, the gel time becomes shorter with the increase of base liquid temperature. When the concentration of 1#2# compounding system was 25℃, the gel formation time was 35min. With the increase of temperature, the gel time became shorter, and it was 20min at 50℃. When the foam concentration of 2#3# compound system was 25℃, the gel formation time was 30min, and the gel time became shorter with the increase of temperature, and it was 13min at 50℃. When the concentration of 1#3# compounding system is 25℃, the gel formation time is 32min. With the increase of temperature, the gel time becomes shorter and 18min at 50℃. This is because when the temperature increases, on the one hand, the molecules in the solution diffusion faster, the chain activity increases, and the speed of the intersection increased; On the other hand, as the number of molecules with activation energy increases, the rate of chemical reaction is accelerated and the time to gel is shortened. According to the basic requirements of underground fire extinguishing, the final setting time should be 10-20min. When the time for gel foam to gel is too short, the pipes are blocked, which may also lead to the solidification of fire extinguishing materials before they reach the ignition point, so that the coal can not be fully covered by the fluidity, which will not achieve the best fire extinguishing effect. When gel foam cannot form glue for a long time, it will flow down the seam to the low-lying place under the action of gravity. If the ignition area cannot be covered effectively in the height, the best fire-fighting effect will not be achieved.

4. Conclusion

In this paper, a compound foaming agent with good comprehensive performance was selected, the gel-forming material was screened, a gel-forming system was selected, and the optimal adding scheme was determined. The properties of the prepared gel foam were tested. The main conclusions are as follows:

(1) The foaming level of single foaming agent and three compound foaming agents was tested by roche foaming apparatus, and the temperature resistance of four foaming agents was investigated. The results showed that the foaming volume was the largest when the temperature was between 25 °C and 30°C, and the foaming volume gradually decreased as the temperature increased.

(2) The final preparation formula was determined as follows: foaming agent: APG: AEC=4:3, the concentration was 6‰, and the foam volume was up to about 650ml; Aluminum citrate with a concentration of 3‰, polyacrylamide with a concentration of 4.5‰, cmc-na with a concentration of 1‰.

(3) According to the experiments on the influence of temperature on the performance of the gel, under the same concentration, the higher the temperature of the solution, the faster the gel formation rate and the less time. The gel foam of the 2#3# compounding system took 13min to form the gel.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

[1] Xia TQ, Zhou FB, Wang XX, Zhang YF, Li YM, Kang JH, Liu JS. Controlling factors of symbiotic disaster between coal gas and spontaneous combustion in long wall mining gobs. Fuel. 2016 Oct 15; 182: 886-896.

[2] Deng J, Xiao Y, Li QW, Lu JH, Wen H. Experimental studies of spontaneous combustion and anaerobic cooling of coal. Fuel. 2015 Jun 15; 157: 261-269.

[3] Ren WX, Guo Q, Wang ZF. Application of foam-gel technology for suppressing coal spontaneous combustion in coal mines. Natural Hazards. 2016 Jul 29; 84(2): 1207-1218.

[4] Wu MY, Hu XM, Zhang Q, Xue D, Zhao YY. Growth environment optimization for inducing bacterial mineralization and its application in concrete healing. Construction and Building Material. 2019 Jun 10; 209: 631-643.
[5] Fan YJ, Zhao YY, Hu XM, Wu MY, Xue D. A novel fire prevention and control plastogel to inhibit spontaneous combustion of coal: Its characteristics and engineering applications. Fuel. 2020 Mar 1; 263: 116693-116693.
[6] Ren WX, Shi JT, Guo Q, Zhao QK, Bai L. The influence of dust particles on the stability of foam used as dust control in underground coal mines. Process Safety and Environmental Protection. 2017 Oct 13; 111: 740-746.
[7] Xue D, Hu XM, Cheng WM, Wei JF, Zhao YY, Shen L. Fire prevention and control using gel-stabilization foam to inhibit spontaneous combustion of coal: Characteristics and engineering applications. Fuel. 2020 Mar 15; 264(C): 116903-116903.
[8] Zhou XH, Li YF, Li CY, Song DP, Nie RS. Experimental study on solid foam characteristics of new fire extinguishing materials. Journal of Liaoning Technical University: Natural Science Edition. 2017 Jan 15; 36(1): 32-36.
[9] Zhang LL, Qin BT. Rheological characteristics of foamed gel for mine fire control. Fire and MaterIals. 2016 Mar; 40(2): 246-260.
[10] Zhu SL. Study on characteristics of foam gel for prevention and control of coal spontaneous combustion. Coal Science and Technology. 2019 Oct 15; 47(10): 223-228.
[11] Yu SJ, Jia BY, Zhang PF, Zhao H. Study on inhibition characteristics of new gel on coal by thermal analysis. Safety in Coal Mines. 2013 Apr 20, 44(4): 31-34.
[12] Yu SJ, Zhao H, Meng GD, Chen XL. Research on gelling and fire extinguishing characteristic of a new-style foamed gel. Fire Safety Science. 2013 Oct 15; 22(04): 219-225.
[13] Zhang XC, Zhang JH, Song ZX, Chen P, Wang CS. Performance evaluation and study of flooding control of foam gel in SZ36-1 oil field. Petrochemical Industry Application. 2012 Apr 25; 31(4): 9-12.
[14] Tian ZJ, Wang DM, Xu YL, Qin BT, Zhong XX. Research of inhibition characteristic of foam gel. Safety in Coal Mines. 2009 Jun 10; 40(6): 8-10.
[15] Matthew J M. Aging of foamed gel for subsurface permeability reduction. Journal of colloid And Interface Science. 1995 Mar 31; 175: 88-96.
[16] Savoly A, Elko D. Foaming agent composition and proeess. US: 2081299, 2003 Jul 29.
[17] Tafreshi AM, Marzo MD. Foams and gels as fire protection agents- viscosity and flow characteristics. Fire Safety Journal. 1999 Nov; 33(4): 295-305.
[18] The General Administration of Quality Supervision, Inspection and Quarantine and the Standardization Administration of the People's Republic of China. Foam extinguishing agent: GB 15308-2006[S], 2006 Dec 14. Beijing: China Standard Press. 2007 Jul 1.
[19] Chen FF, Gu WX, Zheng QR, Bao MW. Experimental discussion on "Determination of liquid surface tension by ring pull method". Guangdong Chemical Industry. 2011 Jun 25; 38 (06): 208-209.
[20] Li ZJ, Niu J, Zhou HB, Yang DJ. Study on foamed gel and its sulfide ores pontaneous combustion retardancy. China Safety Science Journal. 2015 Jun 15; 25(06): 57-61.
[21] Sheng YJ, Lu SX, Jiang N, Wu XJ, Li CH. Drainage of aqueous film-forming foam stabilized by different foam stabilizers. Journal of Dispersion Science and Technology. 2018 Sept 2; 39(9): 1266-1273.
[22] Zhao YL, Chen J, Sheng YJ, Chen X, Lu SX. Experimental study on flame spread along fuel cylinders in high pressures. Fire and Materials. 2019 Dec 21; 43(8): 1022-1030.
[23] Sheng YJ, Jiang N, Sun XX, Lu SX, Li CH. Experimental study on effect of foam stabilizers on aqueous film forming foam. Fire Technology. 2017 Oct 16; 54(1): 211-228.
[24] Zhang M, Cao Q, Zhang LC, Wu N. Study on the effect of several surfactants on the properties of fire extinguishing agent. ShanDong Chemical Industry. 2019 Nov 8, 48(21): 18-20.
[25] Guo Q, Ren WX, Zhu JT, Shi JT. Study on the composition and structure of foamed gel for fire prevention and extinguishing in coal mines. Process Safety and Environmental Protection. 2019 Aug 29; 128: 176-183.
[26] Engle MA, Olea RA, O'Keefe JMK, Hower JC, Geboy NJ. Direct estimation of diffuse gaseous emissions from coal fires: Current methods and future and future directions. International Journal of Coal Geology, 2013 Oct 23, 112(SI): 164-172.
[27] Xie ZH, Luan TT, Zhang Y. Development and application of gel foam materials for fire prevention and extinguishing. Journal of North China Institute of Science and Technology. 2014 Feb 15; 11(02): 42-47+58.
[28] Qin BT, Zhang LL. Experimental studies on preparation of multi-phase foamed gel for preventing spontaneous combustion of coal. Journal of Central South University (Science and Technology). 2013 Nov 26; 44(11): 4652-4657.