Preparation and optimization of the environmental dust suppressant with agricultural waste straw

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Abstract

In order to reduce the dust pollution caused by the coal mining process, an environmental dust suppressant was synthesized by corn straw, sodium carboxymethyl cellulose (CMC) and additives. This study focused on the preparation conditions of this dust suppressant and the viscosity, surface tension, hardness, sedimentation time, contact angle, wind erosion resistance, and water retention capacity of the dust suppressant were investigated systematically. Response surface method was used to optimize the raw material formulation and preparation parameters. The optimum mass ratio of straw, CMC and alkali of the dust suppression was 65:20:15 (m/m), which was prepared under the conditions of the reaction time being 1.5 h, and the rotation speed being 300 r/min. The surface tension decreased from 72 mN/m to less than 50 mN/m with the addition of the additives. The prepared dust suppressant has a maximum viscosity of 363.6 mPa·s, the compressive strength could be up to 200 kPa. The wind erosion resistance of dust suppressant was significant, which could be up to 99 % at the wind speed of 14 m/s for 6 h. After spraying the dust suppressant, the gap between particles was filled with dust suppressant, and the adjacent particles were bound by strong mechanical action.

Introduction

As one of the major hazards produced in the coal mining process, dust is considered a severe threat to the safety production and health of miners. Coal dust is an important source of danger for coal worker's pneumoconiosis, which is common in major coal producing countries in the world (Zhou et al., 2018; Mo et al., 2017). According to statistics, occupational pneumoconiosis accounts for more than 90% of occupational diseases in China (Moreno et al., 2020). Pneumoconiosis has a high mortality rate, which seriously threatens the health and quality of life of workers (Liu et al., 2018). Therefore, dust control is of great significance to the coal industry.

At present, water spray technology is widely used to dust settling in China, which can reduce the dust concentration effectively. The dust suppression effect of sprinkling is remarkable, but the dust suppression time is short and the water consumption is large, so frequent sprinkling is needed to maintain the dust suppression effect (Dariusz, 2013; Wang et al., 2015). Hence, spraying fresh water is considered to be an unsustainable method. So, the dust suppressant has been widely used for its excellent performance (Liu et al., 2018). Nowadays, the development of dust suppressant technology is rapid, the commonly chemical dust suppressants include wetting dust suppressant (Chen et al., 2019; Gulia et al., 2018), adhesive dust suppressant (Ma et al., 2018), condensed dust suppressant (Fan et al., 2018; Xi et al., 2018) and compound dust suppressant (Wang et al., 2012; Zhou et al., 2018). For example, the graft copolymerization of guar gum and sodium alginate was used to produce a new kind of polymer dust inhibitor (Zhang et al., 2018; Zhou et al., 2018; Bao et al., 2020). Some progress has been made in the preparation of new materials for dust suppressant, but the preparation process is complicated, which requires the addition of polymer initiator and crosslinking agent to initiate the reaction. The wettability of water to material heap is poor, adding surfactant can improve its wettability effectively (Wei et al., 2020; Wang et al., 2018). However, due to secondary pollution and degradation problems, some usage

occasions are limited (Dixon-Hardy et al., 2008). Considering the reuse of wastes and environmental protection, some researches focus on the extraction and reuse of materials. Li (Li et al., 2020) extracted cellulose from waste paper to prepare an environmentally friendly dust inhibitor for surface mining. In addition, some studies have been carried out on the preparation of new dust suppressants from oil refining wastes and biodiesel by-products (Miguel et al., 2012). There are still some disadvantages, such as cumbersome preparation process, a variety of chemicals, secondary pollution to the environment and other problems, which are also the main problems faced by the compound dust suppressant. Environmental protection compound dust inhibitor has become the main trend of dust inhibitor (Yao et al., 2017). Therefore, there is an urgent need to develop an economic and environmentally friendly dust suppression method.

At present, straw as a sustainable green material has attracted more and more attention in recent years (Zeng et al., 2019; Jiang et al., 2016). Corn straw is considered to be one of the most abundant and renewable materials in the world that could be sustainably used in the biorefinery industry as raw materials (Yu et al., 2021; Ahring et al., 2016). The reuse of corn straw can contribute to the decrease of the waste and environmental pollution and the achievement of improving the added-value of renewable resources (Zhang et al., 2017; Cai et al., 2017; Zhou et al., 2018).

In this paper, an environmental dust suppressant was synthesized by corn straw, sodium carboxymethyl cellulose and additives. The formulation of raw materials and production process were optimized by response surface method (RSM). Furthermore, the performance of dust suppressant was evaluated and characterized comprehensively. An efficient dust suppressant compounding scheme was selected based on the parameters of viscosity, surface tension, hardness, sedimentation time, contact angle, wind erosion resistance, and water retention capacity. The mechanism of synergistic wetting of coal dust was explained from a microscopic perspective.

Experimental

2.1 Preparation of corn straw

The corn straw was obtained from the suburb of Shijiazhuang, Hebei Province, and was crushed into pieces about 2 mm using a grinder, then washed and dried for use.

2.2 Chemical Reagents

Sodium carboxymethyl cellulose (CMC) (>99%), whose structure is shown in Fig. 1, was directly used without any further purification. All the other chemicals, including sodium hydroxide (NaOH), sodium-alkene sulfonate (AOS), lauryl sodium sulfate (K-12), glycine betaine (CAB-35), anfotericolb (BS-12), polysorbate (Tween-80), alkylphenol ethoxylates (OP-10) were analytical reagents. Deionized water was used for the preparation of all solutions.

2.3 Dust Selection

Dust was taken from a coal field to simulate the real conditions. The collected samples were dried in a drying oven at 90°C for 3 h to remove excess water, then sieved through a mesh to filter the dust particles whose size was greater than 0.6 mm.

2.4 Dust Suppressant Preparation

The crushed corn straw (13g) was put into distilled water in a 500mL beaker. This system was placed inside a thermostat water bath, then stirred with a precision electric mixer constantly for 30 min at 300 rpm (Ronghua Instrument, Jiangsu, China). Then, sodium carboxymethyl cellulose (4g) was added into this system and stirred for 1 h at 400 rpm. After this step, 3g NaOH was injected into the system as the initiator, which will increase the accessibility of cellulose. The producing process of dust suppressant was shown in Fig.2.

The response surface method (RSM) is an important technique for predictive design of experiments, model development and for finding complex processes interactions for maximizing response (Ghafarzadeh et al., 2017). RSM was used to optimize the quality ratio of straw, CMC and alkali to determine the formulation of dust suppressant. By adopting the box-Behnken experimental design method, the qualities of the straw, CMC and alkali were taken as three influencing factors respectively, and three response surfaces were added, namely Y1 viscosity, Y2 surface tension and Y3 dispersion (Table1). For the optimization of the preparation process of dust suppressant, straw particle size, reaction time and stirring speed were chosen as three influencing factors, and added viscosity as the response surface (Table 2).

Table 1. Response surface optimization formula experimental factor level

factor	level		
-1	0	1	
A straw/g	5	6	7
B CMC/g	1	2	3
C alkali/g	0.5	1.0	1.5

Table 2. Response surface optimization technology experimental factor level

factor	level		
-1	0	1	
A straw particle size/mm	0.5	1.25	2.0
B time/h	1.0	1.5	2.0
C Stirring speed/(r/min)	300	500	700

2.5 Characterization of the Dust Suppressant

To investigate the influence of various factors on the dust suppressant performance, some performance indices were tested, including viscosity, surface tension, water retention rate at room temperature, hardness, and anti-wind erosion of consolidated soil.

The viscosity of the dust suppressant samples was measured using the Thermo Viscotester C viscosity tester made in Thermofisher technologies. Generally, viscosity is a physicochemical property that measures the degree of movement of layers of molecules moving over each other (Medeiros et al. 2012). High viscosity is a desired characteristic of a dust suppressant product because the wind cannot break through the layers of product on the particulate material with the higher the viscosity.

To measure the water evaporation properties of the dust suppressant, 20 g of dust suppressant was sprayed on the dish and was placed in the thermostat. The evaporation temperature was set as 40°C, 45°C and 50°C, respectively. The water evaporation of dust suppressant was recorded every 10 minutes and the mass of the dish was weighed and the water evaporation capacity was calculated according to Eq. (1).

Formula 1 in the supplementary files.

where m_1 = mass of the dust suppressant before evaporating; and m_2 =mass of the dust suppressant after evaporating.

To evaluate the wind erosion resistance of the dust suppressant, coal sample and gravimetric method was used to test the performance. The mass of the coal sample in the sampler was weighed and the wind erosion resistance was calculated according to Eq. (2).

Formula 2 in the supplementary files.

where w_1 = mass of the coal sample in the sampler without using dust suppressant; and w_2 = mass of the coal sample in the sampler with using dust suppressant.

Surface tension, which is a very important attribute for a dust suppressant solution, can determine the wetting effect of a solution toward other materials. In this paper, the surface tension of the solution was

measured using the platinum plate method on a JYW-200B surface tensiometer made by Kecheng Instrument, China.

In our experiment, the dispersion capability of dust suppressant was investigated. Higher dispersion capability would make it easy to spray the dust suppressant. The dispersion capability was measured with the method of flat plate measurement. A square of 5 cm × 5 cm was drawn on a 70 cm × 70 cm flat plate. 300 mL of dust suppressant solution was sprayed onto the flat plate evenly and the number of grids was counted.

In order to test the penetration capability between the dust suppressant and the dust. The penetration rate test was developed. 30 g dust suppressant was put into the tube and 0.2 g coal powder was thrown into the tube. The settling time of the coal powder in the tube was recorded.

The sand column model was used to test the compressive strength and to characterize the firmness of the dust inhibitor shell. The consolidated dust samples were mixed with the dust suppressant evenly in the mold according to the mass ratio, and the pressure on the surface of the sand column was investigated with the stress testing.

The hardness of the consolidated dust samples was determined by the shore hardness tester. The hardness value was recorded when the number was stable, and the measurement of quality difference was taken before and after the blowing test.

The surface morphology of the dust suppressant was observed and analyzed by a Hitachi S4300 field emission SEM (Hitachi Co., Japan).

Results And Discussion

3.1 Effect of the materials qualities on the viscosity of dust suppressant

The relevant factor those influence the viscosity of dust suppressant such as the materials qualities was considered and optimized using Design Expert software. In this investigation, the effect of the qualities of the straw, CMC and alkaline were discussed, just shown in Fig.3. From Fig.3 (a) and (b), we could see that the influence of CMC quality on the viscosity was the main factor. The viscosity of the dust suppressant increased with the increasing of CMC quality, because CMC could achieve hydrolysis at room temperature and formed a viscous colloidal form without heating. In Fig.3 (c) and (d), the effect of the straw and alkali mass on the viscosity was analyzed, it could be seen that these two factors had little influence on viscosity. The role of alkali in the system was contributed to the CMC hydrolysis, which was conducive to the formation of uniform and stable viscosity system, and alkali was also beneficial to the destruction of straw fibrous tissue (Jiang et al., 2016). From Fig.3 (e) and (f), the effect of the CMC and alkali quality on the viscosity was investigated and we could conclude that the CMC also had the higher effect on the viscosity. Based on the above analysis, CMC was the main factor affecting the viscosity of dust suppressant. With the increase of the quality of CMC, the viscosity increased, presenting a nearly linear

relationship. In practice, the reasonable viscosity of the dust suppressant was benefit for the spraying, so in our experiment, which was 250~350 mPa·s, the best mass ratio of the straw, CMC and alkali was 65:20:15 (m/m).

3.2 Effect of the preparation process on the viscosity of dust suppressant

In our experiment, the effect of preparation process on the viscosity of the dust suppressant was investigated, just shown in Table 3. Through the results of the experiment, we could conclude that when the particle size of straw was 0.5~2 mm, and the viscosity of the dust suppressant decreased firstly and then increased with the particle size increasing, which mainly because when the particle size was less than 1 mm, the powdered straw had good dispersion in the liquid. Within the test range, the viscosity firstly increased and then decreased with the extension of preparation time, the reason of which was little amount of CMC could quickly dissolve and gelatinized at room temperature, the long stirring time and the shear force of the stirring paddle reduced the CMC viscosity (Wang et al., 2019a; Wang et al., 2019b). The results of response surface analysis showed that in the beaker test, the stirring speed had no significant effect on the viscosity of the dust suppressant, and the mixing of powder could be guaranteed within the test range. The optimal parameters of straw particle size, reaction time and stirring speed could be obtained by optimization prediction of the process conditions, so in our experiment, when straw particle size was 2 mm, reaction time was 1.5 h, and rotation speed was 300 r/min, the viscosity of the dust suppressant was 350 mPa·s.

Table 3. Design scheme and results of the combined experiment with Box-Behnken

No.	straw particle size/mm	time/h	Stirring speed/（r/min）	viscosity/(mPa·s)
1	-1	0	-1	221.9
2	0	0	0	185.9
3	1	-1	0	323.6
4	0	1	1	181.3
5	0	0	0	182.7
6	-1	0	1	211.3
7	0	-1	1	182.4
8	1	0	1	335.6
9	-1	1	0	183.4
10	0	0	0	214.3
11	0	0	0	186.4
12	0	1	-1	177.8
13	1	1	0	311.3
14	-1	-1	0	210.2
15	0	0	0	187.1
16	0	-1	-1	196.3
17	1	0	-1	363.6

According to the influence of feeding sequence on viscosity (Table 4), when three kinds of raw materials were added separately and successively to prepare dust suppressant, the viscosity were almost all the same. But when two of them mixed firstly and then added with the third one, the viscosity was significantly reduced. The uneven hydrolysis inside the CMC surrounded by alkali led to the appearance of small CMC clumps. When the three were mixed, the viscosity was moderate. Based on the results, when CMC was mixed with other two, it was not conducive to the rapid hydrolysis of CMC, resulting in a low viscosity. So, these raw materials being added separately and successively was the chosen production process.

Table 4. Feeding sequence test of raw materials

No.	feeding sequence□	feeding sequence□	feeding sequence□	viscosity/□mPa·s□
1	straw	CMC	alkali	345
2	straw	alkali	CMC	325
3	CMC	straw	alkali	347
4	CMC	alkali	straw	336
5	alkali□CMC blending	straw	/	286
6	straw	alkali□CMC blending	/	276
7	straw□CMC blending	alkali	/	295
8	straw□alkali□CMC blending	/	/	313

3.3 Effect of additive on the dust suppressant

By comparing the contact angle and penetration time, the wetting characteristics of the compound solutions of additive were studied. AOS, K-12, CAB-35, BS-12, Tween-80 and OP-10 were chosen as typical additive to investigate the effect on the contact angle and penetration time of the dust suppressant, just as shown in Fig. 4. The additives exerted synergistic effects to enhance the performance of the dust suppressant.

Generally, the contact angle of liquid on the surface of solid is used to assess the liquid's capability of wetting solid under laboratory conditions (Orumwense, 1998; Kollipara et al., 2014). Smaller contact angle was, the higher performance between liquid and particles was. In this study, contact angles of different additives were measured. Each sample was measured three times and the average values were taken. Fig. 4 (a) presents the relationship between contact angles and mass fractions of additives. We could see from Figs. 4 (a), the contact angle between all kinds of dust suppressants and coal decreased firstly and then increased with the increasing of the mass fractions. Among the additives, the smallest contact angle of AOS was 40.76° when the mass fraction was of 0.2~0.3 %, which showed the best wetting ability. The addition of surfactant could significantly reduce the contact angle and enhance wettability. This was mainly due to the fact that anionic surfactants could dissociate negatively charged surfactant ions in aqueous solution and have good osmotic wetting and dispersion effects.

The shorter the penetration time of coal dust is, the faster the permeation and the stronger the wettability of surfactant solution on coal dust are. In our experiment, the penetration time of coal dust for the same quality in dust suppressant was measured by colorimetric tube settling method to characterize its wetting ability. Fig. 4 (b) present the penetration time of coal dust in six kinds of additive dust suppressants of different mass fractions. From Fig. 4 (b), we could see that the penetration time of coal dust in the dust suppressant of anionic additives were better than the other additives. In the anionic additives, AOS had the shortest penetration time, which showed that the dust suppressant had the best performance of wettability. The result of penetration time was similar to the contact angle.

The premise of coal wetting is that the surface tension of liquid is lower than the critical surface tension of coal (Kilau, 1990). The surface tension of pure water (about 72.8 mN/m) is much higher than the critical surface tension of coal wetting (about 45 mN/m), leading to its poor coal dust wetting effect (Shi et al., 2019). Fig. 5 showed the surface tensions and the contact angles of anionic surfactant (AOS) compound solutions under different mass fractions. With the higher mass fraction of AOS, the surface tensions and the contact angles follow the same trends, that is, decreases firstly and then increases. When the mass fraction of AOS was 0.27%, the surface tension was the smallest, which was 38.6 mN/m. And when the mass fraction of AOS was 0.3%, the contact angle was the smallest, which was 44.85°.

3.4 Effect of the materials of dust suppressant on the spraying dispersion

The performance and economics of a dust suppressant in practical applications are greatly affected by the performance of spraying. The spraying dispersion of the dust suppressant was investigated. Just shown in Fig. 6, the dispersion performance increased firstly and then decreased with the increasing of the straw qualities. Too little or too much straw is not conducive to spray the dust suppressant. In our experiment, 6 g of straw was the best quality. As mentioned above, with the increasing of the CMC content, the viscosity of dust suppressant increased, the cross-linking effect of straw was strengthened, and the dust suppressant was sprayed evenly. However, as the content of CMC continued to increased, the viscosity was too high, which led to the difficulty of spraying. When the mass of the straw, CMC and alkali was 6.0 g, 2.0 g and 1.1 g, respectively, the dust suppressant had the best performance of spraying, just shown in Fig. 7.

3.5 Performance of the water conservation and compressive strength

Nowadays, water scarcity is one of the most important challenges to the sustainable development in China. The dust suppressant must have the best performance of water conservation. In our experiment, the performance of water conservation had been investigated. In Fig. 8 (a), the evaporation rate of 50 ℃ was almost twice as fast as the evaporation rate of 40 ℃ after 120 minutes. The reason was that viscous CMC cross-links the hydrolyzed straw fragments to form a layer of colloidal straw fragments on the surface of the stack. This layer structure was conducive to retaining water and slowing down the rate of water evaporation, so that the stack surface could maintain a relatively wetted state for a long time, which was conducive to maintaining dust suppression effect for a long time, just shown as Fig. 8 (b).

When the dust suppressant was mixed with coal particles with a mass ratio of 1:1, the compressive strength could reach 222.7 kPa (Fig.9 (a)). The reason was that the dust suppressant acted as an adhesive after stirring with coal particles, which promoted the adhesion between coal particles. When the straw mass in the dust suppressor was reduced and the proportion of other raw materials remained unchanged, the compressive strength of the sand column significantly decreased. When the straw content was reduced to 2.55 g, the compressive strength was reduced to 176.1 kPa, just shown in Fig. 9 (b). For our dust suppressant, the straw acted as a skeleton inside the sand column, which strengthened the support of the sand column and increased the compressive strength.

3.6 Performance of the wind erosion resistance

The performance of the wind erosion resistance was carried out using a wind tunnel. The wind tunnel construction was composed of organic glass, which 2 m in length, 1 m in width and 1 m in height. The wind speed in tunnel reached 14 m/s. Inside the wind tunnel, there was a platform to fix the samples. The measurement time of wind erosion resistance was 360 minutes. Coal sample (250 g) was weighed and evenly placed on a circular dish, 600 mm in diameter and 300 mm in height. According to the equation (2), the performance of the wind erosion resistance was obtained, just listed in Table 5. When the spraying thickness of dust suppressor was higher than 2 mm, the wind erosion resistance rate could be up to 99 %. After spraying, the sample could dry in the natural environment, then to form a dense shell, which prevent the coal sample to be blown up.

Table 5. Performance of wind erosion resistance (%)

Spraying thickness(mm)	Sampling time (h)					
1	2	3	4	5	6	
2	99.6	99.6	99.6	99.5	99.5	99.5
3	99.8	99.8	99.7	99.7	99.7	99.6
4	99.8	99.8	99.8	99.7	99.6	99.6

3.7 Dust suppression mechanism analysis

The microstructures of the samples were observed and analyzed by SEM. As shown in Fig. 10 (a), the coal dust particles were loosely stacked together; the space between adjacent particles was larger and their surfaces were relatively smooth. After spraying the dust suppressant, the gap between particles was filled with dust suppressant, and the adjacent particles were bound by strong mechanical action (Fig.10 (b-d)). The sharp edges and corners of the particles were wrapped, and the particles had a certain degree of displacement under the action of flowing liquid dust suppressant. The result was that the entire dust surface was more uniform and stable. In the process of relative movement of particles after spraying, the particles first made contact with the surface of the product. Due to the certain viscosity of the product, the adhesive force was much greater than the van der Waals force caused by Brownian motion of particles, and the particle size increased due to the collision between particles and the product. At the same time, under the action of surfactant, the particles were effectively wetted by the product, the density of the bound particles increased, the gravity started to be greater than the buoyancy, and finally the dust particles settled, just shown in Fig. 10(e).

The straw fragments undergo partial hydrolysis by alkali, and partial hydrolysis of starch and macromolecule sugars results in a large number of exposed active groups such as hydroxyl group and carbonyl group. After CMC went through gelatinization, its polymer chain was easy to absorb water

molecule hydroxyl, hydrolyze, and at the same time polymerize with the active group exposed by straw. CMC connected each straw fragment like a net, just as shown in Fig.10 (f).

Conclusions

A novel environmental composite dust suppressant was made successfully with corn straw, CMC, and additives. Response surface method was used to optimize the raw material formulation and preparation parameters. The optimum mass ratio of straw, CMC and alkali of the dust suppression was 65:20:15 (m/m), which was prepared under the conditions of the reaction time being 1.5 h, and the rotation speed being 300 r/min. The researchers also explored the optimization and improvement on wettability. Additive contributed to the decreasing of the surface tension effectively, which could improve the wettability. The surface tension decreased from 72 mN/m to less than 50 mN/m. The prepared dust suppressant had a maximum viscosity of 363.6 mPa·s, the compressive strength could be up to 200 kPa. The wind erosion resistance of dust suppressant was significant, which could be up to 99% at the wind speed of 14 m/s for 6 h. After spraying the dust suppressant, the gap between particles was filled with dust suppressant, and the adjacent particles were bound by strong mechanical action.

Declarations

Authors' contributions

All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by Wenjun Liang, Hao Chi, Zhixue Zhang and Sida Ren. The first draft of the manuscript was written by Hao Chi, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Competing interest

The authors declare that they have no competing interest.

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Figures

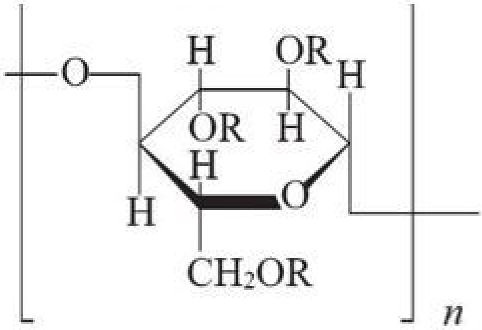


Figure 1

Structure of sodium carboxymethyl cellulose (CMC)

Figure 2

Producing process of dust suppressant

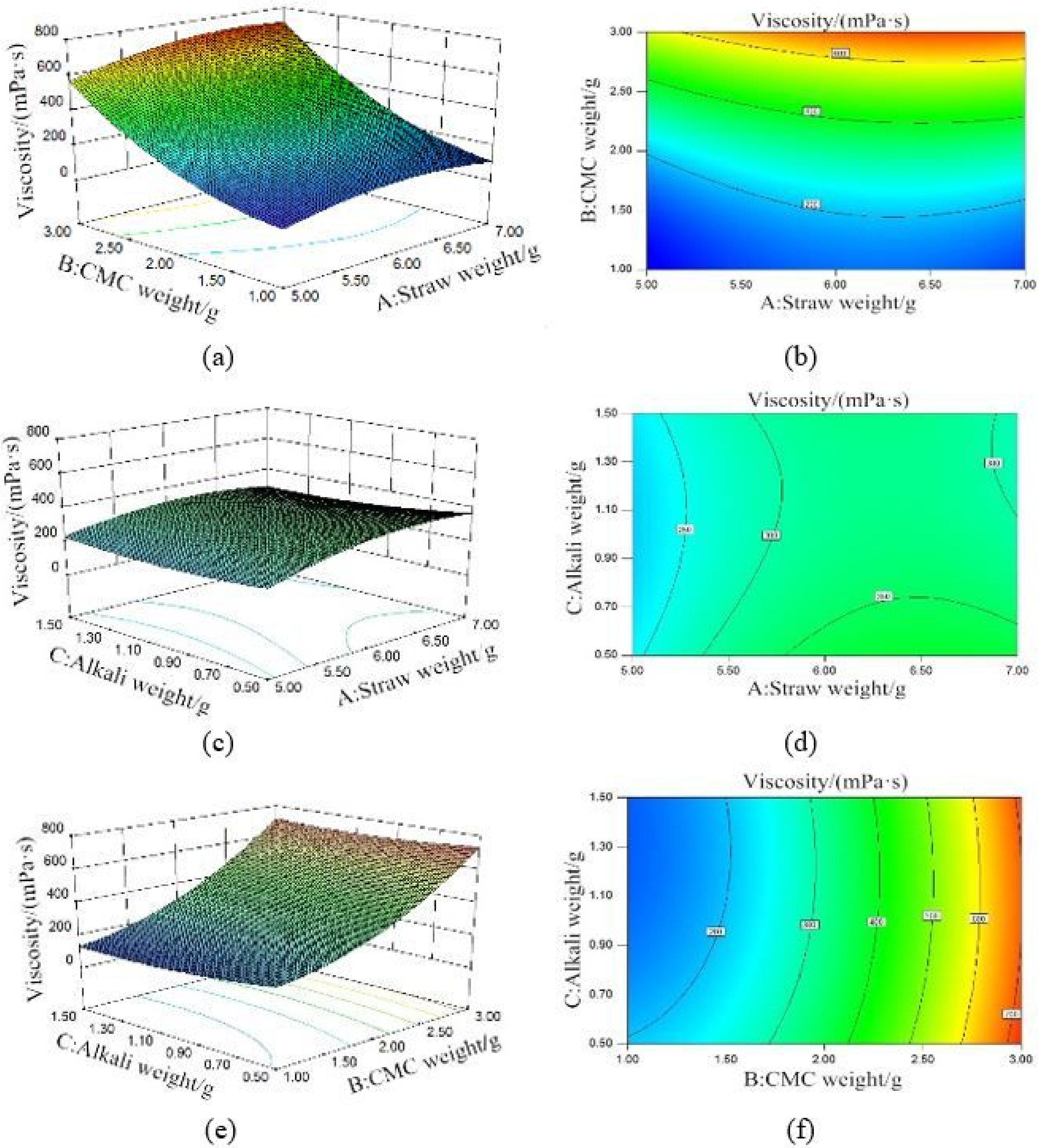
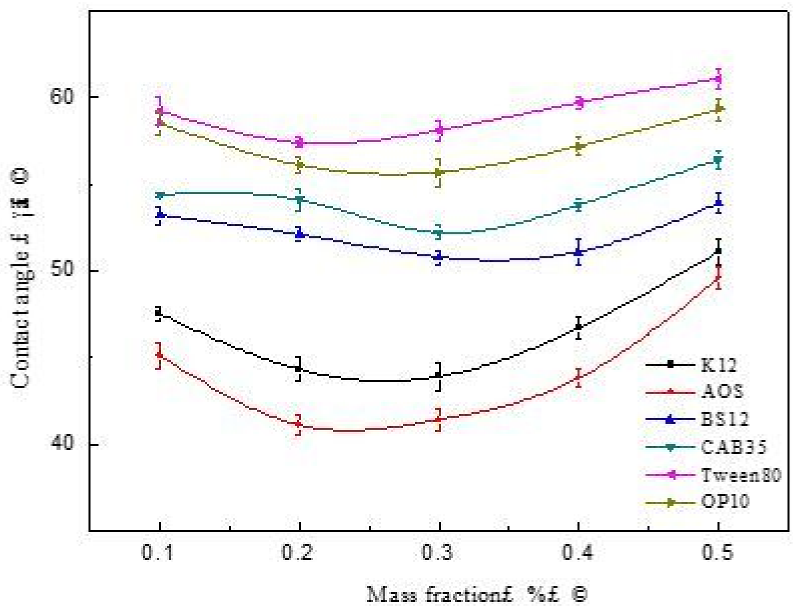
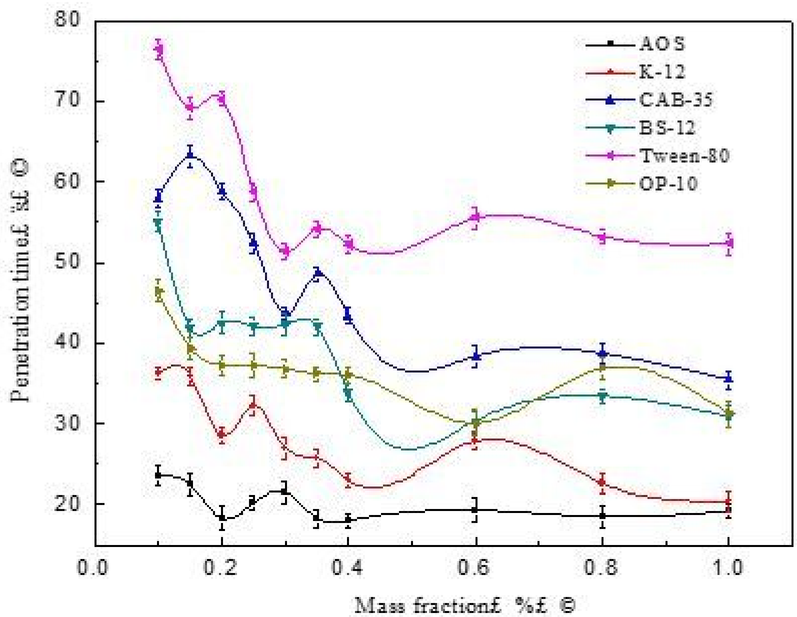


Figure 3

Response surface and contour map of the effect of materials qualities on viscosity



(a)



(b)

Figure 4

Effect of mass fractions of different additive on dust suppressant

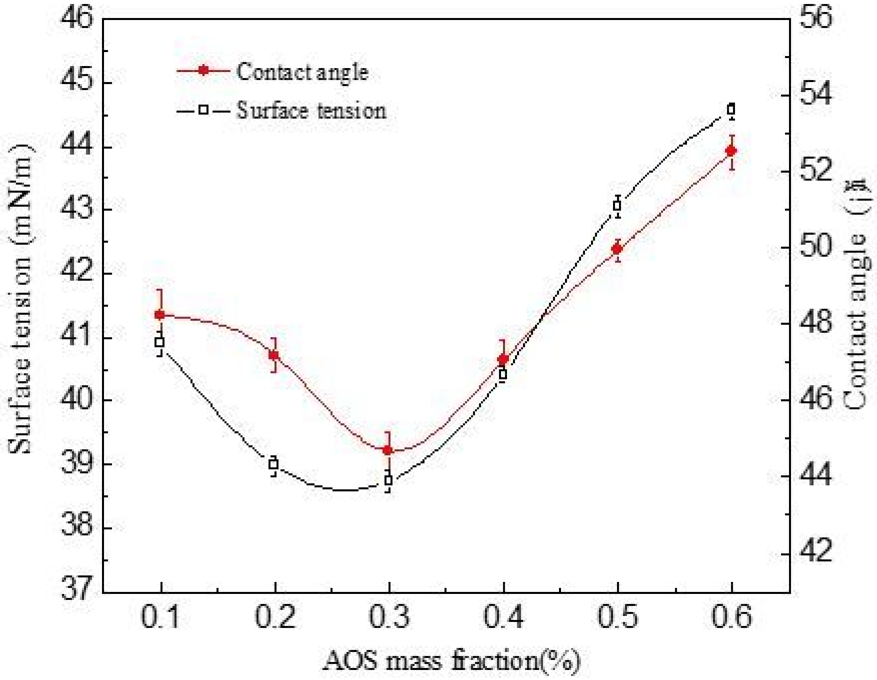


Figure 5

Effect of AOS on the performance of the dust suppressant

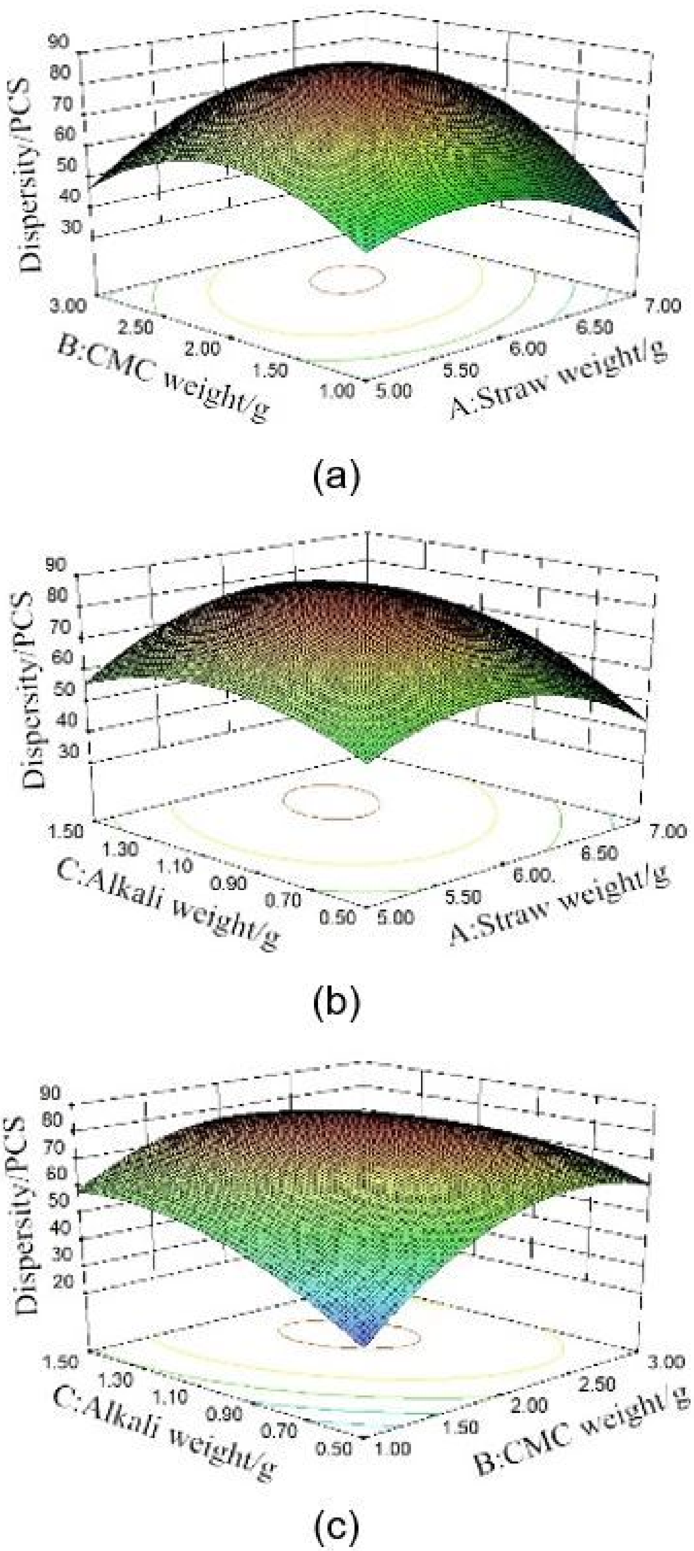


Figure 6

Effect of the materials of dust suppressant on the spraying dispersion

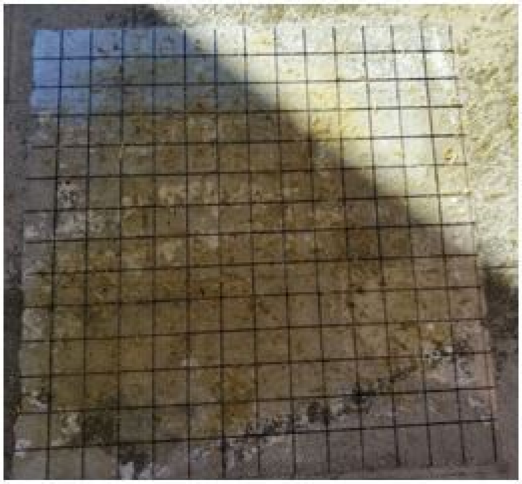
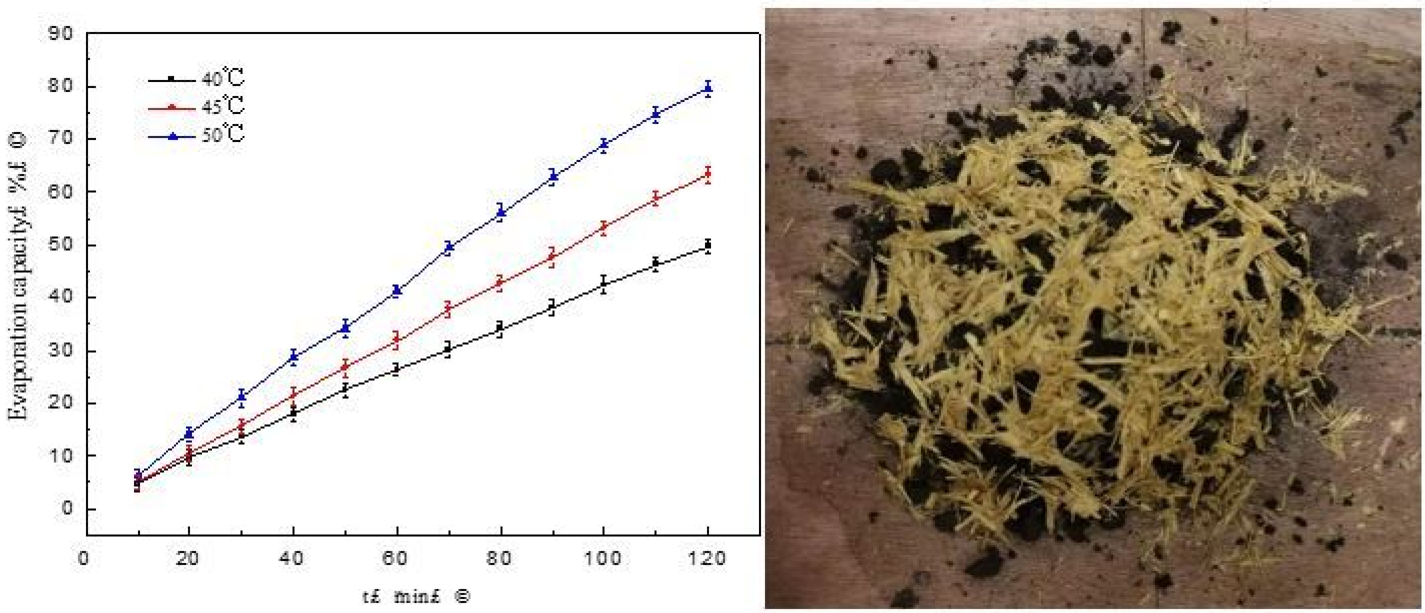


Figure 7

Spraying performance of dust suppressant



(a) (b)

Figure 8

Performance of the water conservation

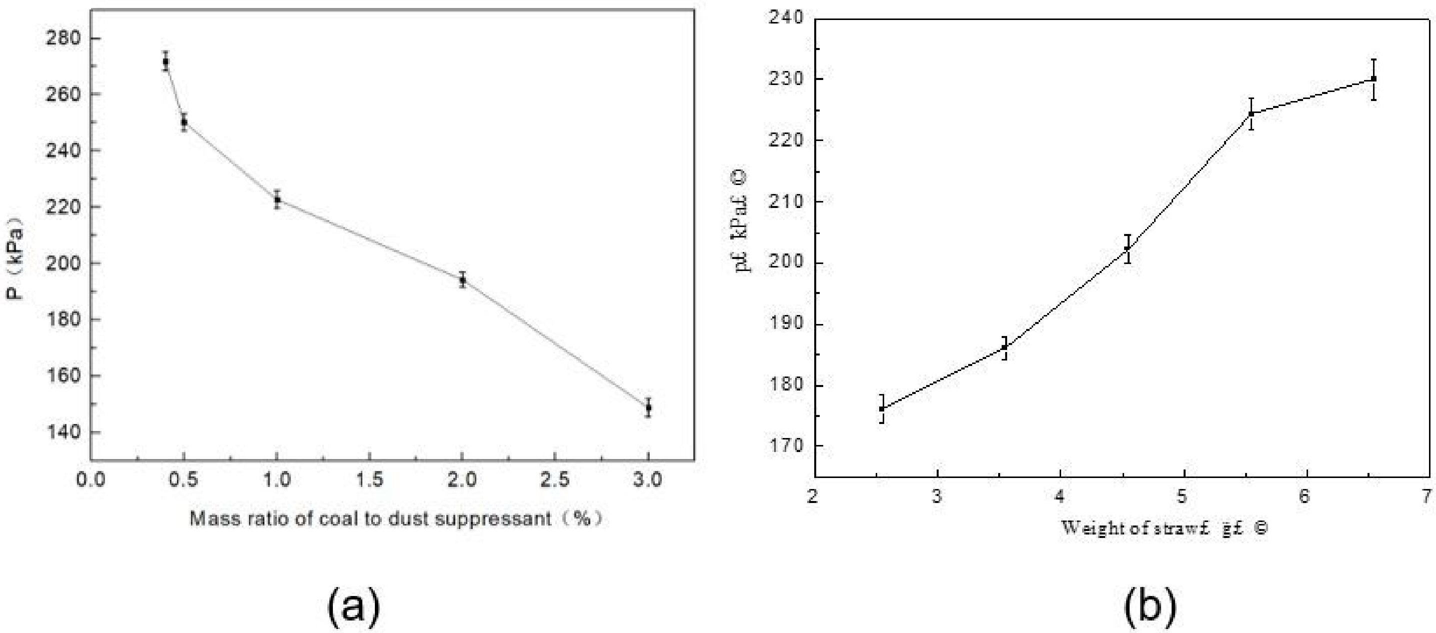


Figure 9

Effect of mass ratio of coal and straw on compressive strength

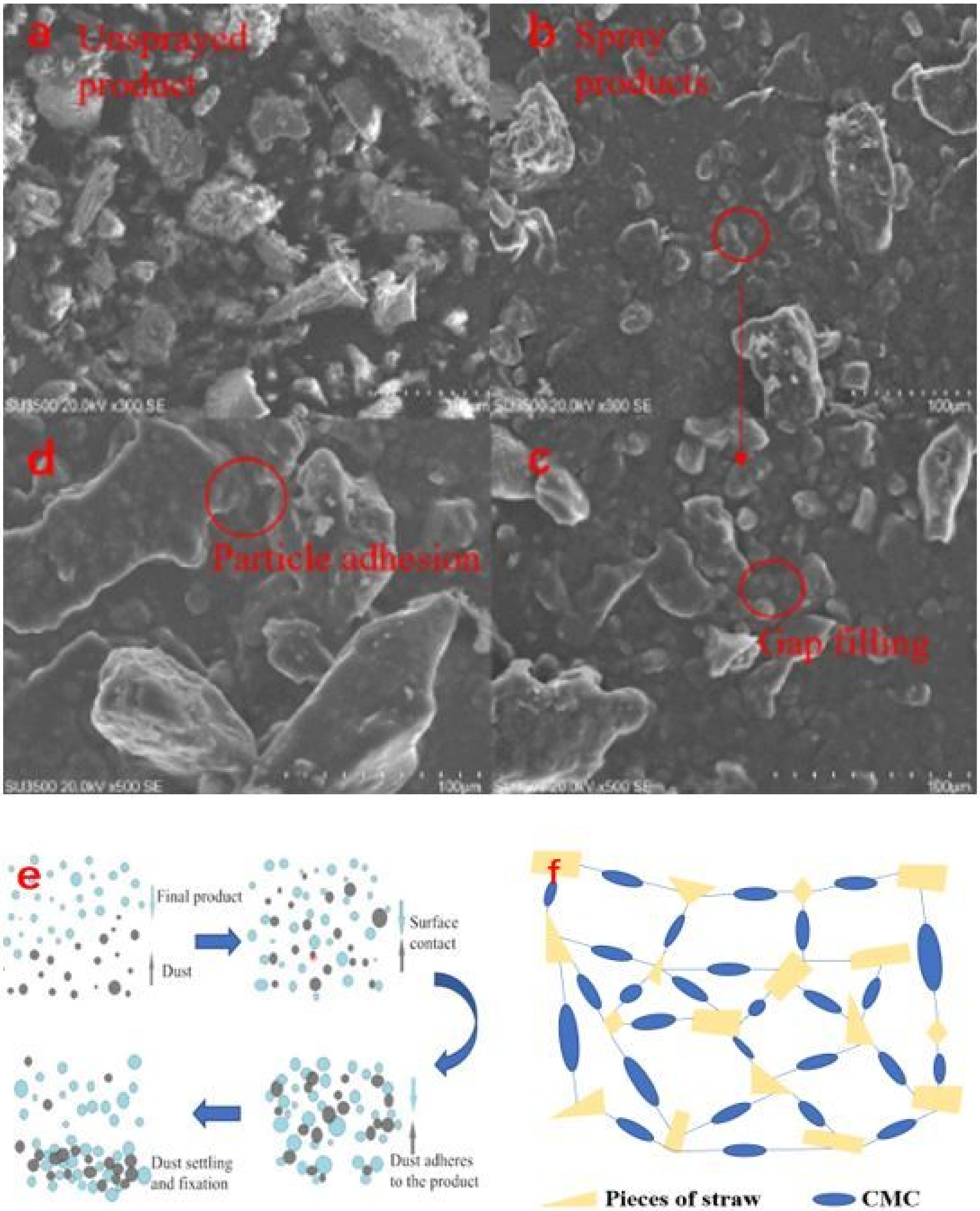


Figure 10

SEM micrographs of samples and schematic diagram of mechanism