The Fluidity and Sprayability Characteristics of -200 Mesh Sulfur Powder

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Highlight:

- Moisture content and static electricity are important factors for sulfur performance.
- -200 mesh sulfur powder fluidity was in not good and sprayability in prone tendency.
- Considered special production equipment for its fluidity and sprayability.
- Charge-to-mass ratio more has a significant effect on the compression.
- Wet base moisture content has a more significant effect on the degree of dispersion.

Abstract

To study the fluidity and sprayability characteristics of sulfur powder, powder comprehensive characteristic tester was utilized. The results show that the fluidity was in not good level and prone to be sprayable. With the moisture content less than 1.2%, the fluidity property was also in not good level, and continuous increase in the moisture content or the charge-to-mass ratio tended to trigger off bad or even worse fluidity. When the moisture content of the wet basis was less than 0.7%, the sulfur powder was prone to spray. Raising the moisture content from 0.7% to 1.5%, or increasing the charge-to-mass ratio from -6.9 to -11.4 $nC \cdot g^{-1}$ also led to may be sprayable tendency, while a further increase in one of the two parameters no sprayable tendency. It can be concluded that in the chemical industry, special treatment is needed for sulfur production equipment to improve its fluidity and sprayability.
Keywords: Powder; Charging characteristic; Fluidity; Sprayability; Chemical engineering.

1 Introduction

Sulfur, featured with high resistivity, is one of flammable explosive powders [1]. In the application of sulfur, however, the sulfur powder is required to be processed into ultra-fine material before feeding and transmission and other production process for better performance and energy of sulfur [2,3]. These ultra-fine powders, due to their poor fluidity [4,5], impede the feeding process, and the remaining of some materials in silos will accumulate, or even deteriorate, causing pollution or danger to the raw materials [6,7]. Meanwhile, in the process of industrial dry pulverization, transportation and collection, a strong electrostatic field will be produced in the space with accumulated static electricity, and its electrostatic potential can be as high as tens of thousands of volts. If the electrostatic voltage is discharged to a grounding body, it is easy to generate static sparks and cause a blasting accident [8,9,10]. In recent years, the research on the igniting characteristics of sulfur powder is relatively mature, but in the field of chemical materials, the research on the electrostatic characteristics and flow characteristics of sulfur powder is relatively conservative [11,12,13,14]. The fluidity and static electricity of sulfur powder are of great significance to the production, storage, pulverization, transportation, packaging and other unit operations of the powder.

There are two main methods for testing fluidity of powders at present, namely measurement of the angle of repose and the Carr index [15,16,17]. The difference in powder fluidity from the appearance can be explained by measuring the angle of repose, but the operator is required to be experienced in measuring the size of the angle of repose, and the angle of repose measured by different methods or operators will be different [18]. The Carr index [19,20], named after Professor Carr, aims to index each eigenvalue and accumulate the index based on the comprehensive study of several single powder physical property values that affect the powder fluidity and sprayability through a large number of experiments. This method is designed to comprehensively measure the fluidity of powders by calculating various fluidity parameters of powders for full understanding of characteristics of powders, and has been widely used in the comprehensive evaluation of powder characteristics and the design and development of powder systems for it is rapid and easy to operate with accurate results and wide range of application.

The operation of various units such as storage, pulverization, transportation and packaging of sulfur powder is closely related to its flow characteristics and jet flow characteristics [13,17]. In the process of industrial production of sulfur powder, high static electricity is inevitably generated, and humidification method to reduce the amount of static electricity is also the most effective method at present [18,22].

Previous studies [23,24] have shown that the moisture content of sulfur and the interaction force between particles (mainly electrostatic effect in the production of sulfur) can affect the fluidity of the powder. Based on the Carr index, this paper explores the fluidity and sprayability characteristics of sulfur powder by changing the moisture content of the sulfur powder and the charge-to-mass ratio with the utilization of the powder comprehensive characteristic tester, hoping to guide the design of chemical equipment to avoid the occurrence of arches or unstable flow rates in the production process and to meet the needs of continuous and automated production of sulfur.

2 Experimental

2.1 Evaluation index

The Carr index is a comprehensive index that measures powder fluidity and sprayability, and is further divided into Carr fluidity index F_w and Carr sprayability index F_D. The Carr index includes main components, containing angle of repose (θ_r), degree of compression (C_p), plate angle (θ_s) and degree of agglomeration (C_h), apparent density (ρ_a), tap density (ρ_p), collapse angle (θ_f), difference angle (θ_d), and dispersion (D_s), etc. Among them, the F_w refers to the weighting of multiple indexes such as θ_r, C_p, θ_s, and C_h. Formula as shown below:

$$F_W = C_\rho + \theta_r + \theta_s + C_\mathrm{h} \tag{1}$$

The formula for calculating sprayability index (F_D) can be calculated below:

$$F_D = F_W + \theta_f + \theta_d + C_\mathrm{s} \tag{2}$$

Table 1 and Table 2 represents the evaluation of fluidity index and sprayability index respectively.

2.2 Experimental materials and equipment

A local chemical company provided the powder sulfur used in this study, particle size about 200 mesh screening 97% (the particle size is most commonly used in the industry), moisture content of wet base ≤0.051%, initial charge-to-mass ratio less than -0.019 $nC\cdot g^{-1}$. Main component of sulfur are listed in Table 3. Additionally, all separation tests were conducted at a relative humidity of 68-70% and a temperature of 22-25 °C.

As shown in Figure 1, the BT-1000 powder comprehensive characteristic tester used in this study, instrument test items include parameters such as θ_r, θ_f, θ_s, D_s, ρ_p, ρ_a, θ_d, C_p, C_h, etc. Other testing instruments consisted of Laser particle size analyzer LS-13320, Anemometer Swema Air 50, Digital charge meter JCI-178 (range: 0 to 200 nC, equipped with JCI-150 faraday tube), WDKSD-FT-EX Temperature and Humidity measuring instrument (temperature range: -20 to 80 °C and range of relative humidity: 0 to 100 percent), electronic balances, etc.

2.3 Measuring principle and method

θ_r is the angle between the powder accumulation layer and the horizontal plane in the state of static equilibrium. The powder passes through the funnel after being sieved and dispersed for the first time, and falls naturally on a special platform in a specific vibration mode (sine wave). In general, the larger θ_r is, the worse the fluidity of the powder gets.

θ_f is the angle between the formed collapse surface and the horizontal plane of the platform after the accumulation layer collapses, when a certain impact force is given to the powder accumulation layer in the static state, followed by destruction of the static state and falling dust. The smaller θ_f is, the easier the natural flow of the powder will be. The measurement of θ_f with an instrument is conducted by applying the same impact operation three times to θ_r.

θ_d refers to the difference between θ_r and θ_f. The larger θ_d is, the easier the powder is to spray.

θ_s is the average value of the angle between the free surface (inclined surface) of the powder on the flat plate and the angle after vibration after lifting the flat plate buried in the powder vertically upwards. In the actual measurement process, θ_s is expressed as the average of the angle after the flat plate is lifted and the angle at which the unstable powder is removed after the flat plate is impacted. The smaller θ_s, the stronger the fluidity of the powder.

ρ_a refers to the density after the powder is naturally filled in a specific container.

ρ_p refers to the density after the powder is filled in a specific container, and the container is vibrated, thereby destroying the voids in the powder and making the powder in a tightly packed state. By measuring the tap density, the fluidity and porosity of the powder can be calculated.

$C_p = \dfrac{\rho_p - \rho_a}{\rho_p}$, the compression degree is also called the compression ratio. The smaller the compression, the better the fluidity of the powder.

D_s is the degree of difficulty of powder dispersion in the air. It is required to measure the percentage of the sample outside the receiving pan to the total amount of the sample after dropping 10 g sample from a certain height. The degree of dispersion is related to the dispersibility, floatability and splashing of the sample.

C_h is an indicator of the dispersion of reactive powders based on the characteristics of the powders during sieving. The test method is as follows:

(1) Use apparent density to select three suitable sieves according to the conditions in Table 4, install the sieve.

(2) Weigh 2 g of powder with a balance and pour all into the upper sieve. At the same time, set a timer and start the sieving vibrator for sieving (when apparent density ≤1.6 $g \cdot cm^{-3}$, the vibration time= (120-62.5) ×apparent density, besides is 20 s).

(3) Weigh the residual amount on each layer of sieve after the screening, and then calculate the agglutination C_h according to the equation below:

$$C_h = (\text{upper layer\%} + \text{middle layer\%} \times \frac{3}{5} + \text{lower layer\%} \times \frac{1}{5}) \qquad (3)$$

3 Results and discussion

3.1 Effect of static electricity and moisture content of wet basis on angle of repose, the collapse angle, the difference angle and the plate angle of sulfur powder

As shown in Figure 2, angle of repose, collapse angle, and plate angle of the -200 mesh sulfur powder were 49°, 41° and 59°. At the same time, the angle of repose, the collapse angle and the plate angle were increased with the sulfur powder of mass ratio. When the sulfur powder charge-to-mass ratio was -7.9 $nC \cdot g^{-1}$, the angle of repose was 70°. Continuous increase in the sulfur powder charge-to-mass ratio resulted in gradually stable value of the angle of repose. The collapse angle and the plate angle tended to be unchanged when the charge-to-mass ratio were -14.1 and -3.259 $nC \cdot g^{-1}$ respectively.

It can be seen from Figure 3 that the angle of repose, the collapse angle and the plate angle were increased with the increase of the moisture content of wet basis of the sulfur powder. (1) When the moisture content of wet basis of the sulfur powder was 2.2%, the angle of repose was 75°. Increasingly more moisture content in the wet basis led to gradually stable value of the angle of repose. (2) The moisture content of the wet basis was 1.8% as the collapse angle and the plate angle were stable.

In addition, as shown in Figure 2 and 3, the difference angle decreased with increasing charge-to-mass ratio of the sulfur powder and increased with more moisture content of the wet basis. This phenomenon indicates that the static electricity and water content are the important reasons for the poor fluidity of the sulfur powder. In the industrial processes of dry pulverization and collection, the agglomeration and blockage caused by static electricity are more difficult to be affected by the force.

3.2 Effect of electrostatic quantity and moisture content on compressibility, dispersity and degree of aggregation of sulfur powder

Tap density and apparent density refer to the mass of the powder measured in a container of unit volume under specified conditions. As shown in Figure 4, the dry and static-free sulfur powder has an apparent density of 0.5 $g \cdot cm^{-3}$. (1) As the charge-to-mass ratio increased, the apparent density of the sulfur powder increased gradually, and the rate of increase decreased gradually; (2) when the charge-to-mass ratio was higher than -16.3 $nC \cdot g^{-1}$, the apparent density was 0.67 $g \cdot cm^{-3}$, and remained basically unchanged; (3) with increased moisture content of the wet basis, the density of sulfur powder loosely increased, and when the moisture content of the wet basis increased to 3.0%, the apparent density increased to 0.545 $g \cdot cm^{-3}$; (4) the effect of the charge-to-mass ratio and the moisture content of the sulfur powder on the tap density is basically the same as that on the apparent density, and the effect of the charge-to-mass ratio on the tap density is still significant. When the ratio increased from -0.237 to -16.337 $nC \cdot g^{-1}$, the tap density of sulfur powder almost doubled. And when the moisture content of wet basis increased from 0 to 0.8%, the tap density increased to 43%. With further increased moisture content of the wet basis, the apparent density of the sulfur powder had no obvious changes.

The degree of compression indicates the extent how the material is compressed. When the degree of compression is less than 20%, the fluidity of the material is good. When it is greater than 40%, the fluidity is lowered to be difficult to automatically flow out of the container. The ratio of the difference between the tap density and the apparent density to the tap density is usually used to characterize the compression of the powder. As presented in Figure 5, (1) when the charge-to-mass ratio increased from -0.237 to -5.745 $nC \cdot g^{-1}$, the degree of compression rapidly increased from 23.8% to 29.3%, and when the charge-to-mass ratio continued to increase, the degree of compression decreased; (2) the influence of the moisture content of the wet basis on the degree of compression is more intuitive. When the moisture content of the wet basis was between 0 and 0.6%, the compression degree increased from 22.2% to 27.9%, and when the moisture content of the wet basis continued to increase, the compression degree was basically kept at about 28.3%.

The dispersibility, floatability and splashing of the sulfur powder can be visually observed by the degree of dispersion. As shown in Figure 6, sulfur powder with a degree of dispersion at about 10% was featured with poor dispersibility, and the degree of dispersion further decreased with increase in the charge-to-mass ratio or in the moisture content of the wet basis. The moisture content of wet basis has a significant effect on the dispersibility of sulfur powder. When the water content of wet basis increased to 3%, the dispersion was only 1.9%. The effect of charge-to-mass ratio on dispersion is small, and when the ratio of charge to sulfur increased to -18 $nC \cdot g^{-1}$, the dispersion decreased to 7.2%.

The degree of agglutination is an indicator of the dispersion performance of the reaction powder according to its characteristics during sieving. As can be seen from Figure 7, the influence of moisture content on the degree of agglomeration is very significant. The moisture content of wet basis increased from 0 to 3.0%, and the agglutination increased from 2.1% to 55.6%. The effect of the charge-to-mass ratio on the degree of agglutination increased linearly and slowly. When the mass ratio increased from 0 to -18.531 $nC \cdot g^{-1}$, the agglutination increased from 1.8% to 12.5%.

3.3 Effect of static electricity of sulfur powder and moisture content of wet basis on Carr index

According to Formula 1 and 2, by measuring each fluidity index and sprayability index of samples and accumulating the results, a comprehensive evaluation of flowability and sprayability can be concluded, as detailed in Table 5-6.

Figure 8 shows the effect of charge-to-mass ratio of the sulfur powder and the moisture content of the wet basis on the Carr's fluidity index. As presented Figure 8, (1) fluidity of the -200 mesh sulfur powder was in not good level; (2) when the moisture content of the wet basis increased from 0 to 1.2% (or the charge-to-mass ratio was less than -7.2 $nC \cdot g^{-1}$), the fluidity property of the sulfur powder was also not good; (3) Continuous increases in moisture content or the charge-to-mass ratio led to an even worse state of the fluidity of the sulfur powder. In our previous research [24], it was found that the actual water content in processing sulfur powder should not be higher than 1%. Therefore, in the production process, this poor fluidity may cause great difficulties in processing, and even will bring difficulties to the design of the length and size of the pipeline. Especially during crushing and classifying, it is necessary to consider more focus on dispersion and vibration to improve its fluidity.

As shown in Figure 9, -200 mesh sulfur powder was prone to be sprayable. When the moisture content of the wet basis was less 0.7% or the charge-to-mass ratio less -6.9 $nC\cdot g^{-1}$, the -200 mesh sulfur powderwas also in prone level. With increased moisture content from 0.7% to 1.5%, or charge-to-mass ratio from -6.9 to -11.4 $nC\cdot g^{-1}$, the -200 mesh sulfur powder was in may be tendency to spray. Continuous increase in moisture content or charge-to-mass ratio resulted in no sprayable conditions. Since the moisture content of sulfur in actual production is not to exceed 1% [24], that is to say, sprayability maybe exists or is prone to take place in the production of sulfur powder. To avoid sprayable cases, it is necessary to increase the charge-to-mass ratio to more than -11.4 $nC\cdot g^{-1}$, but increasing static electricity is unfavorable in sulfur production. Therefore, a comprehensive evaluation is needed, and specifically, it is best to consider dust removal equipment during processing and sealing measures during delivery to reduce environmental pollution.

4 Conclusions

1. The angle of repose (θ_r), degree of compression (C_p), plate angle (θ_s) and degree of agglomeration (C_h), collapse angle (θ_f) all increase with higher charge-to-mass ratio and more moisture content of the wet basis, while the difference angle (θ_d), and dispersion (D_s) decrease with the increase in the charge-to-mass ratio and the moisture content of the wet basis. The charge-to-mass ratio has a more significant effect on the compression of the sulfur powder, and the moisture content of the wet basis influences the degree of dispersion more obviously.

2. The fluidity of -200 mesh sulfur powder was not good. When the water content is less 1.2% (or the charge-to-mass ratio less -7.2 $nC\cdot g^{-1}$), its fluidity remained the same state. Continuous increases resulted in bad or even worse fluidity of the sulfur powder. Therefore, in the production process, this poor fluidity may cause great difficulties in

processing, and may even fail to achieve the intended design goals. In the chemical production, special treatment for equipment in sulfur production is required for the sulfur production equipment to improve its fluidity.

3. The moisture content and electrostatic content are more important for the sprayability of sulfur powder. -200 mesh sulfur powder was prone to be sprayable. When the moisture content of the wet basis was less 0.7% or the charge-to-mass ratio less -6.9 $nC\cdot g^{-1}$, the -200 mesh sulfur powder was prone tended to spray. With increased moisture content from 0.7% to 1.5%, or charge-to-mass ratio from -6.9 to -11.4 $nC\cdot g^{-1}$, the -200 mesh sulfur powder was may be sprayable. Continuous increase in moisture content or charge-to-mass ratio would no this tendency. Based on comprehensive evaluation of static electricity and sprayability of sulfur, it is best to consider dust removal equipment during processing and sealing measures during delivery to reduce environmental pollution.

Conflict of interest

The authors declare no competing financial interest.

Acknowledgements

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Figures:

Figure 1. BT-1000 powder comprehensive characteristics tester.

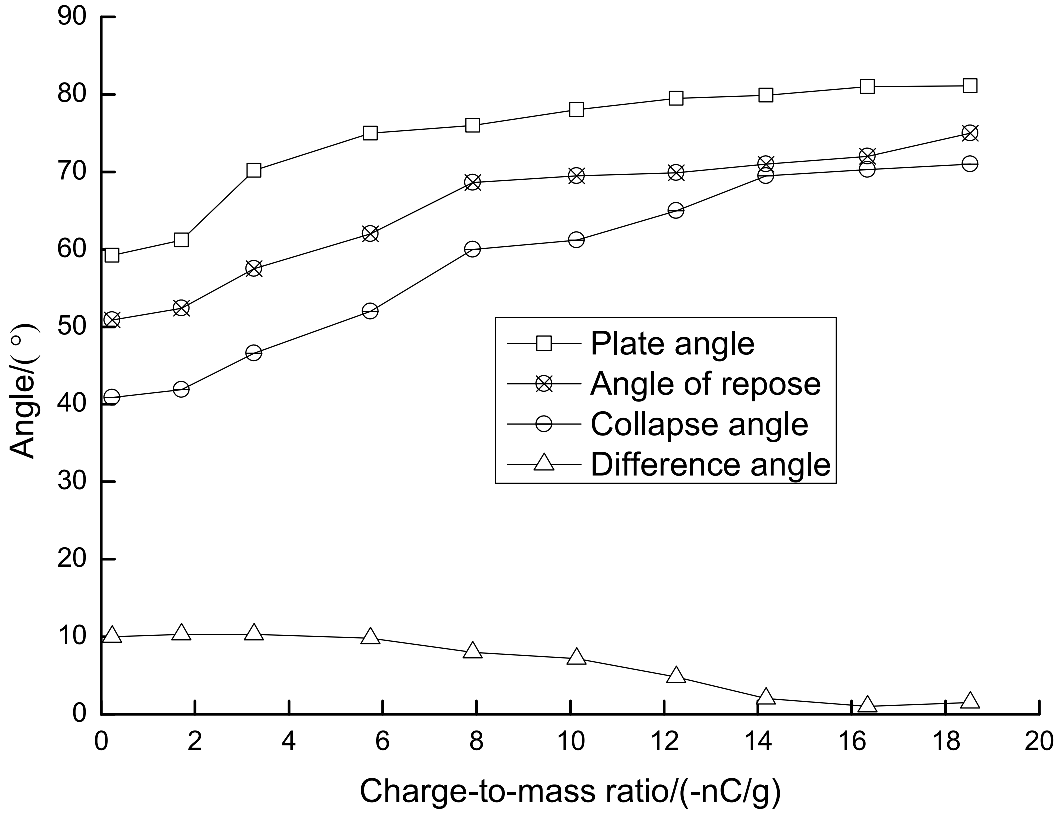

Figure 2. Effect of charge-to-mass ratio on sulfur angle of repose, collapse angle, difference angle and plate angle.

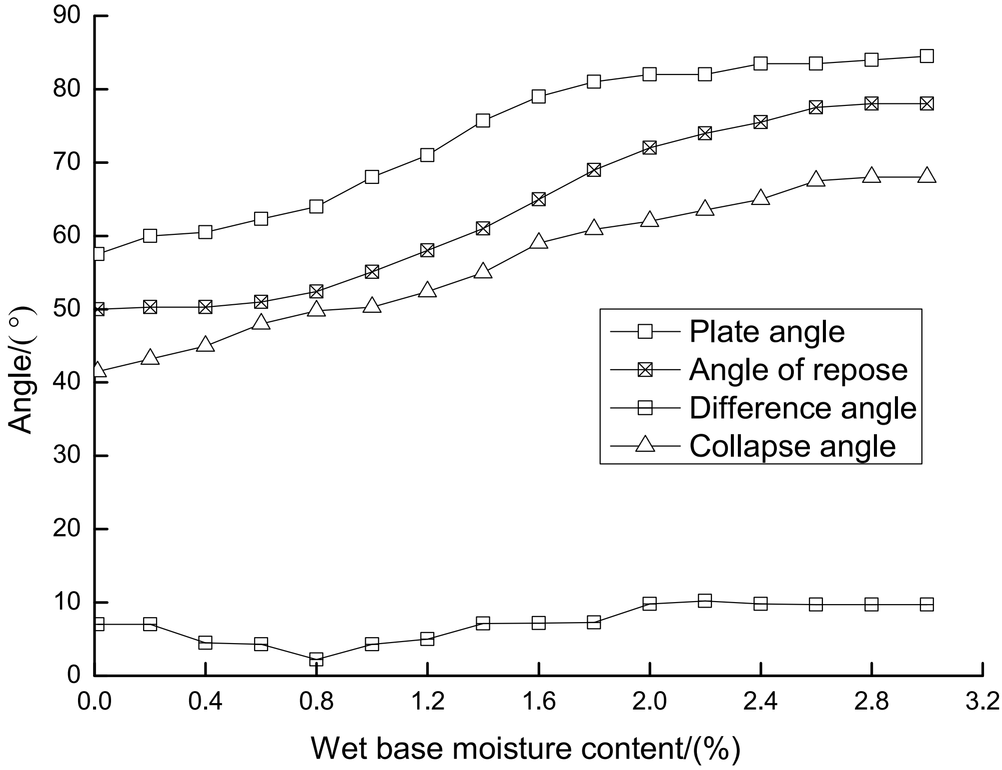

Figure 3. Effect of wet base moisture content on angle of repose, collapse angle, difference angle and flat angle of sulfur powder.

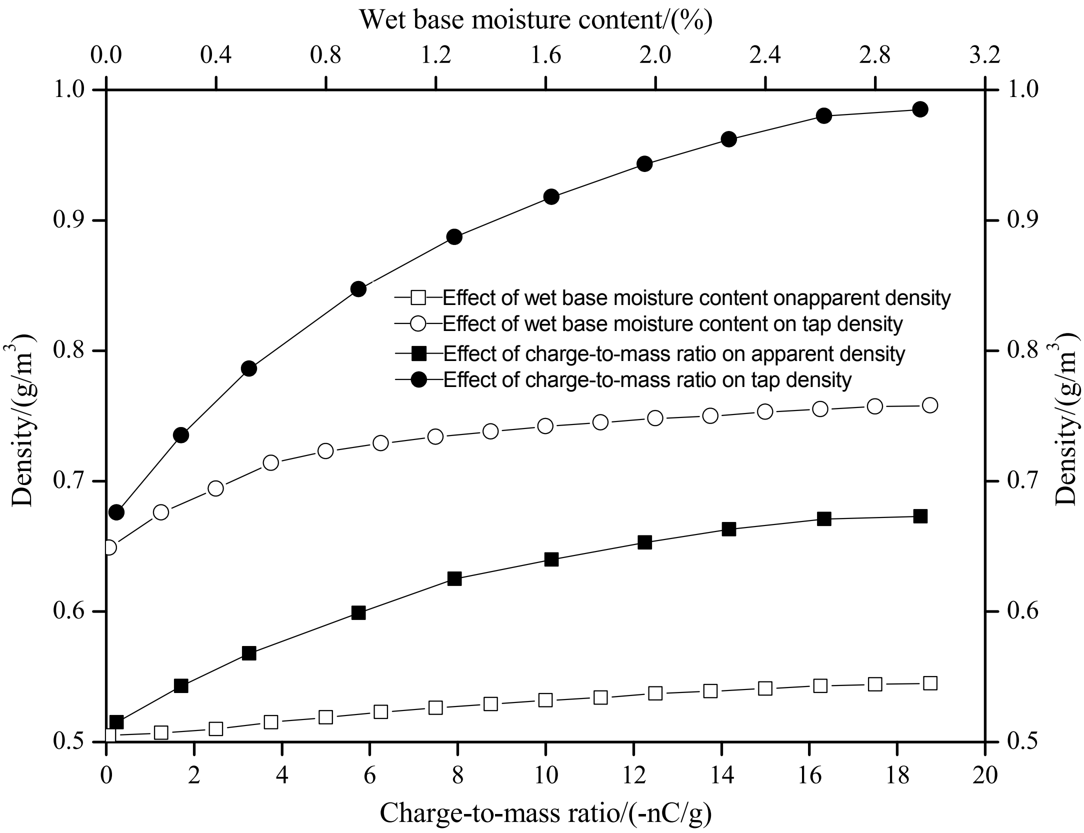

Figure 4. Sulfur powder charge-to-mass ratio, wet base moisture content on the apparent density and tap density.

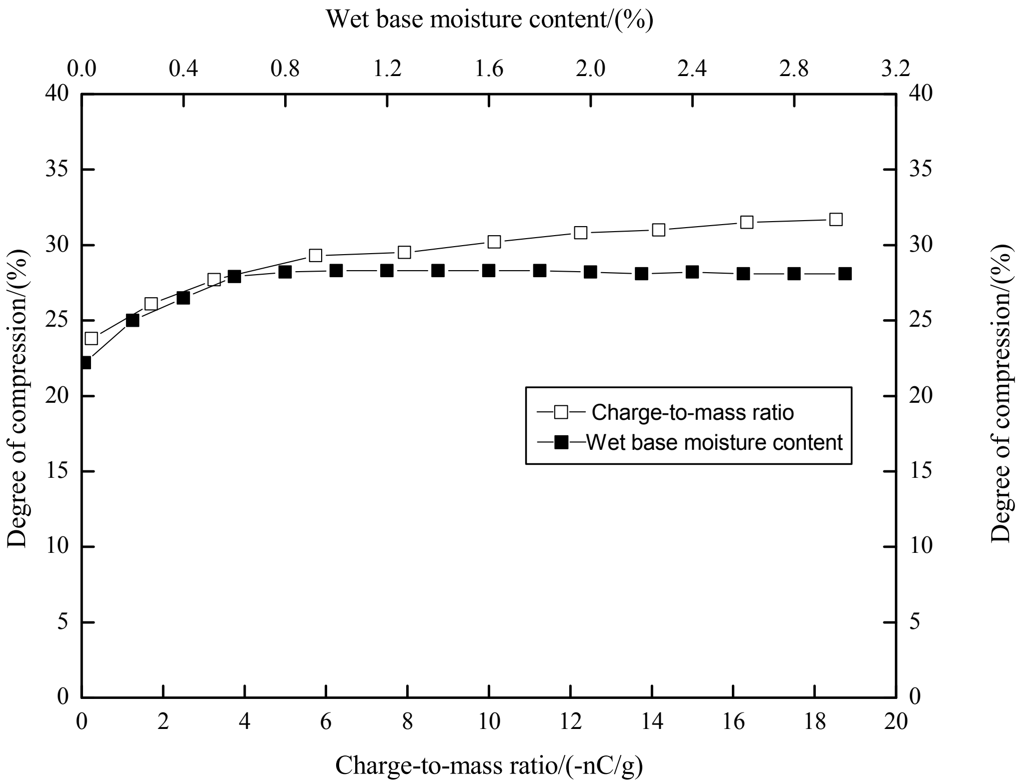

Figure 5. Sulfur powder charge-to-mass ratio, wet water moisture content on the degree of compression.

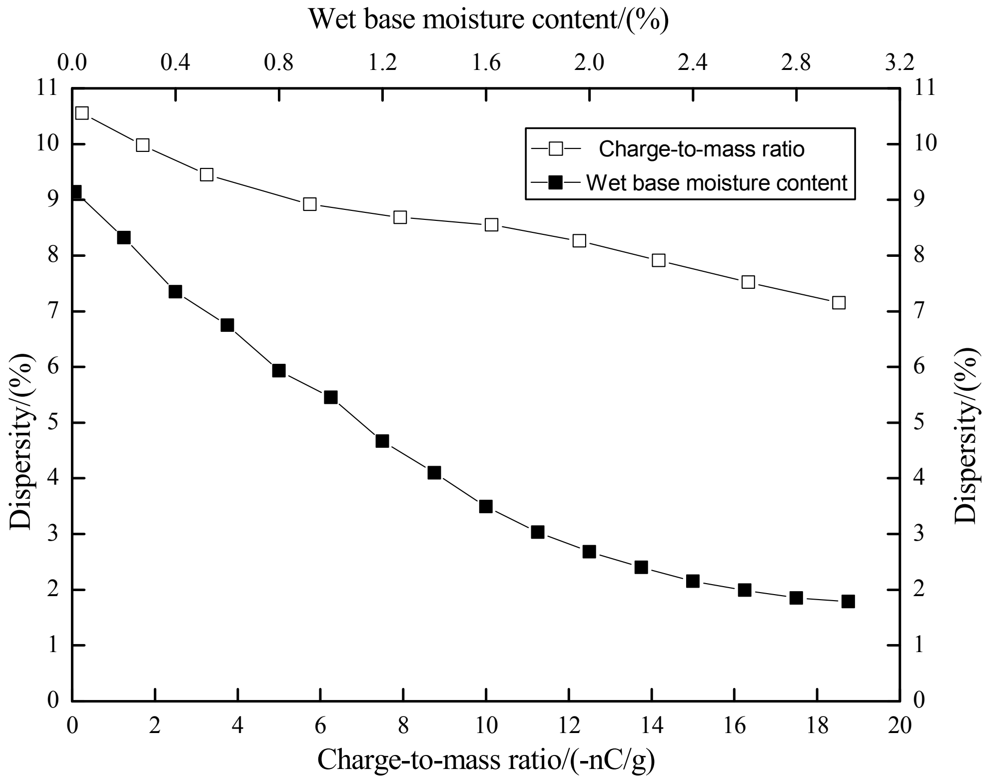

Figure 6. Sulfur powder charge-to-mass ratio, wet base moisture content on the degree of dispersion.

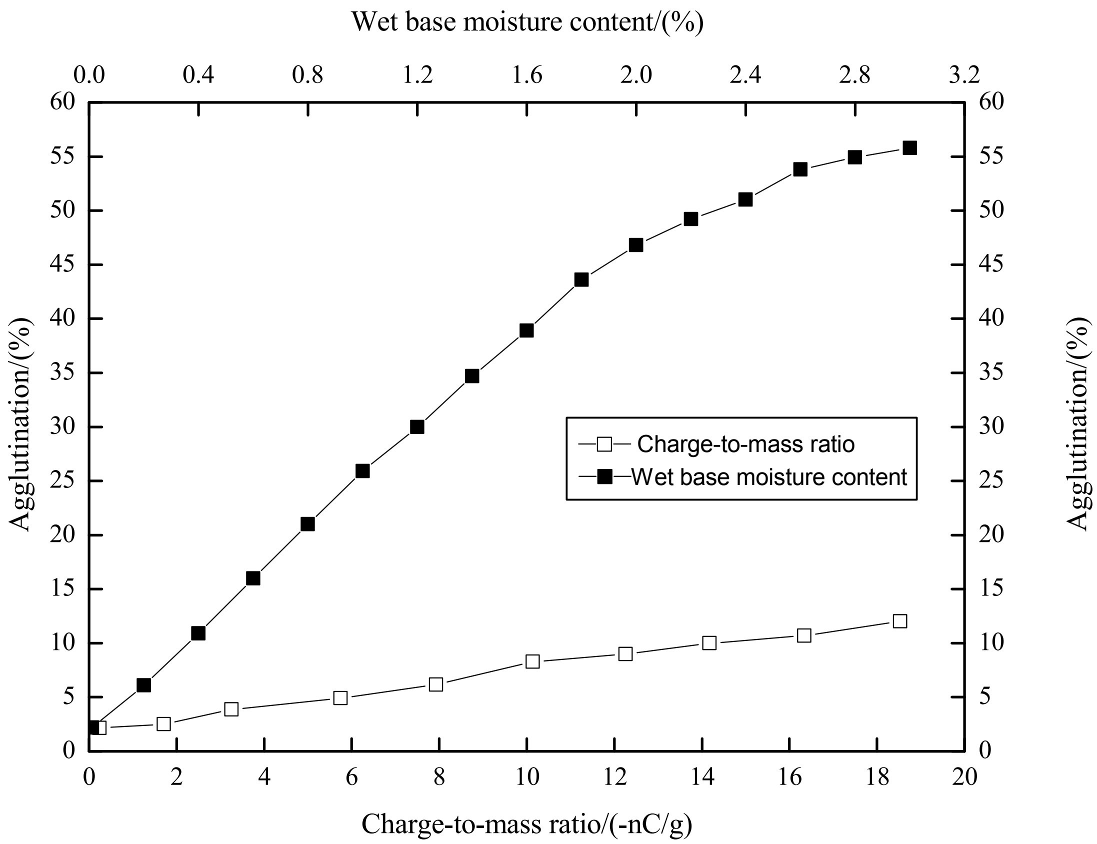

Figure 7. Sulfur powder charge-to-mass ratio, wet water moisture content on the degree of agglutination.

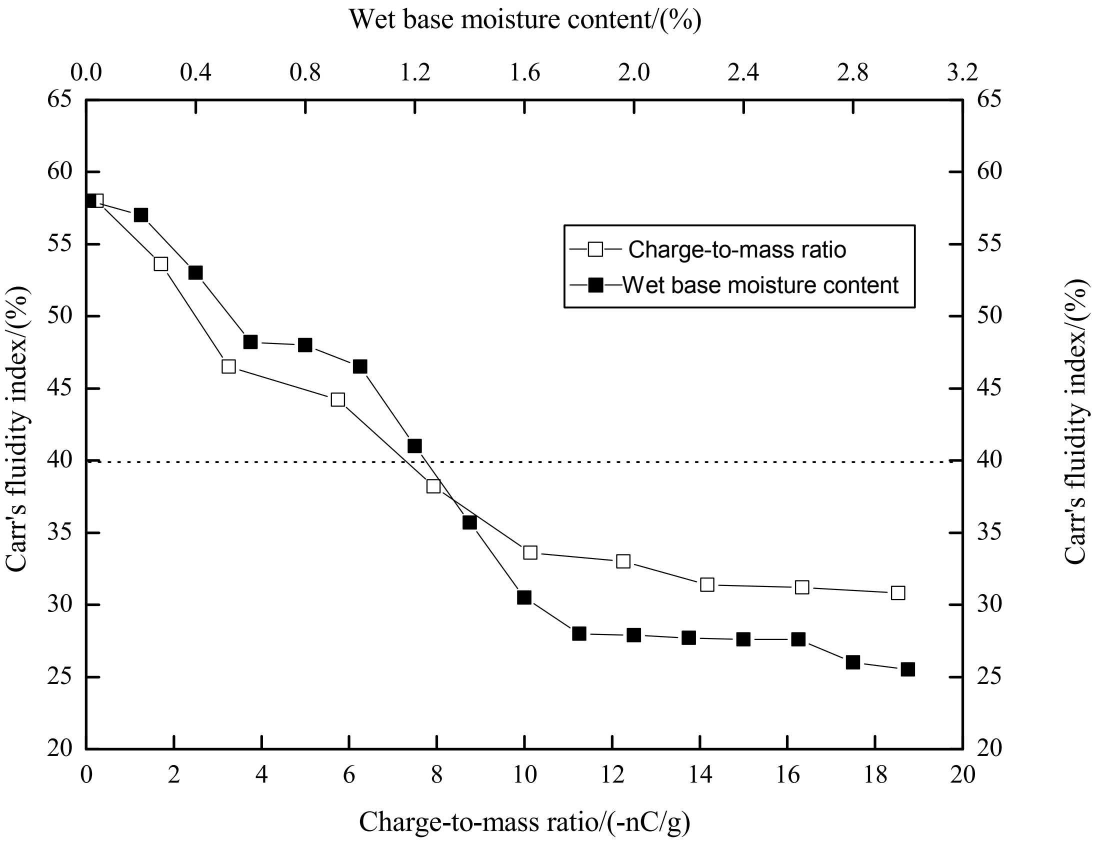

Figure 8. Effect of sulfur powder charge-to-mass ratio and wet basis water moisture content on Carr fluidity index.

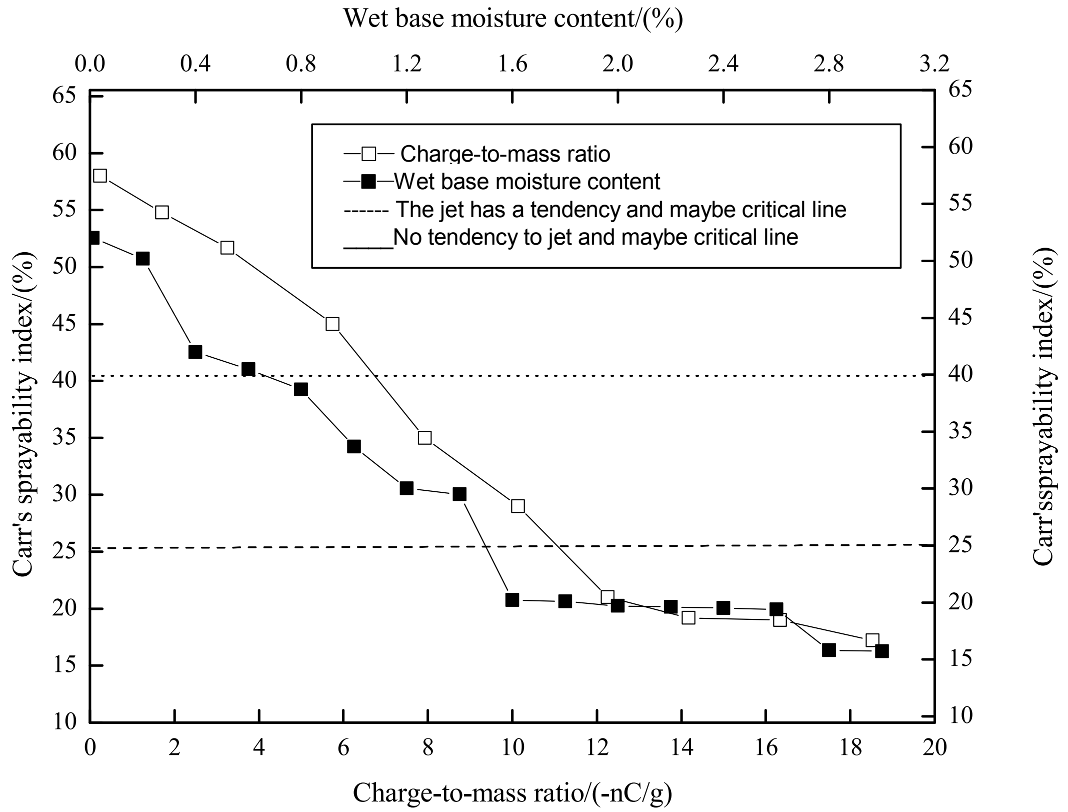

Figure 9. Effect of sulfur powder charge-to-mass ratio and wet base water moisture content on Carr sprayability index.

Tables:

Table 1. Fluidity evaluation.

Fluidity evaluation	Fluidity index
Best	90-100
Good	80-89
Quite good	70-79
General	60-69
Not good	40-59
Bad	20-39
Very bad	0-19

Table 2. Sprayability evaluation.

Degree of sprayability	Sprayability index
Very strong	80-100
Quite strong	60-79
Prone	40-59
Maybe	25-39
No	0-24

Table 3. Main component of sulfur.

Raw material	Main component/ (%)						
	S	H_2O	Ash	H_2SO_4	organic substance	As	Fe
Sulfur	99.99	0.018	0.015	0.002	0.03	0.00008	0.00004

Table 4. Screen and apparent density.

Apparent density（g/cm^3）		0.16～0.4	0.4～0.9	0.9～1.5
Screen/μm	upper layer	425	250	150
	middle layer	250	150	75
	lower layer	150	75	45

Table 5. Carr powder fluidity index evaluation table.

Fluidity evaluation	Fluidity index	Arch prevention measures	angle of repose		Compression		plate angle		Uniformity *		Agglutination *	
			Angle	Index	%	Index	Angle	Index	Unit	Index	%	Index
			<25	25	<5	25	<25	25	1	25		
Best	90-100	No	26-29	24	6-9	23	26-30	24	2-4	23		
			30	22.5	10	22.5	31	22.5	5	22.5		
			31	22	11	22	32	22	6	22		
Good	80-89	No	32-34	21	12-14	21	33-37	21	7	21		
			35	20	15	20	38	20	8	20		
			36	19.5	16	19.5	39	19.5	9	19		
Quite good	70-79	Yes	37-39	18	17-19	18	40-44	18	10-11	18		
			40	17.5	20	17.5	45	17.5	12	17.5		
General	60-69	Critical	41	17	21	17	46	17	13	17		

		point of	42-44	16	22-24	16	47-56	16	14-16	16		
		arching	45	15	25	15	60	15	17	15	<6	15
			46	14.5	26	14.5	61	14.5	18	14.5	7-9	14.5
Not good	40-59	necessary	47-54	12	27-30	12	62-74	12	19-21	12	10-29	12
			55	10	31	10	75	10	22	10	30	10
		Need	56	9	32	9.5	76	9.5	23	9.5	30	9.5
Bad	20-39	strong	57-64	7	33-36	7	77-89	7	24-26	7	32-54	7
		measures	65	5	37	5	90	5	27	5	55	5
		Need	66	4.5	38	4.5	91	4.5	28	4.5	56	4.5
		special	67-89	2	39-45	2	92-99	2	29-35	2	57-79	2
very bad	0-19	equipment										
		and	90	0	>45	0	>99	0	>35	0	>79	0
		technology										

Remarks*：Sulfur powder is a high degree of agglutination, and the value of the degree of agglutination is selected to determine the fluidity index.

Table 6. Carr powder jet index evaluation table.

Degree of sprayability	Sprayability index	Preventive measures	Fluidity index		Collapse angle		Difference angle		Dispersion	
			Angle	Index	Angle	Index	Angle	Index	%	Angle
			>60	25	10	25	>30	25	>50	25
			59-56	24	11-19	24	29-28	24	49-44	24
			55	22.5	20	22.5	27	22.5	43	22.5
Very strong	80-100	RS *	54	22	21	22	26	22	42	22
			53-50	21	22-24	21	25	21	41-36	21
			49	20	25	20	24	20	35	20
Quite strong	60-79	RS	48	19.5	26	19.5	23	19.5	34	19.5
			47-45	18	27-29	18	22-20	18	32-29	18
			44	17.5	30	17.5	19	17.5	28	17.5
			43	17	31	17	18	17	27	17
			42-40	16	32-39	16	17-16	16	26-21	16

			39	15	40	15	15	15	20	15
			38	14.5	41	14.5	14	14.5	19	14.5
Prone	40-59	SRS	37-34	12	42-49	12	13-11	12	18-11	12
			33	10	50	10	10	10	10	10
			32	9.5	51	9.5	9	9.5	9	9.5
Maybe	25-39	RS is required at flow rate or input state	31-29	8	52-56	8	8	8	8	8
			28	6.25	57	6.25	7	6.25	7	6.25
			27	6	58	6	6	6	6	6
No	0-24	No	26-23	3	59-64	3	5-1	3	5-1	3
			>23	0	>64	0	0	0	0	0

Remark: RS meaning need cross seal