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Physicochemical factors affecting the wettability of copper mine blasting dust

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Abstract To investigate the factors affecting the wettability of copper mine blasting dust, the primary blasting dust was collected from an open-pit copper mine and separated into hydrophilic blasting dust (HLBD) and hydrophobic blasting dust (HBBD) using water flotation method. The physicochemical properties of HLBD and HBBD were measured and compared with each other. The properties included particle size distributions (PSDs), micromorphologies, pore structures, mineral components and surface organic carbon functional groups. The results show that particle size and pore structure of the blasting dust are the main factors affecting its wettability. Specifically, particle size of HBBD is smaller than that of HLBD, and their respiratory dust (less than 10 μm) accounts for 61.74 vol% and 53.00 vol%, respectively. The pore structure of HBBD is more developed, and the total pore volume of HBBD is 1.66 times larger than that of HLBD. The identical mineral compositions were detected in HLBD and HBBD by X-rays diffraction (XRD); however, the surface organic hydrophobic component of HBBD is slightly larger than that of HLBD, this may be the reason for the poor wettability of HBBD. This study is significant to understand the effects of physicochemical properties of copper mine blasting dust on its wettability.

Keywords Blasting dust · Copper mine · Wettability · Physicochemical properties

1 Introduction

Blasting remains one of the most widely used methods in open-pit mines worldwide (Singh et al. 2015; Pérez et al. 2018), although it produces massive emissions of fine particles and toxic gases (Akbari et al. 2015; Abdollahisharif et al. 2016; Liu et al. 2019a; Taylor et al. 2014). Those fine particulates not only can increase the prevalence of pneumoconiosis in mineworkers (Petavratzi et al. 2005; Xu et al. 2018), but also pollute atmospheric environment (Csavina et al. 2012).

Many studies have been performed to control mine blasting dust in recent years. Yu et al. (2018), Huang et al. (2019a, b) studied the diffusion process of blasting dust from mines using numerical simulation. Abdollahisharif et al. (2016) proposed a green biocompatible approach (i.e., ionized water stemming) to reduce the toxic gases and dust caused by the blasting in surface mining. Jin et al. (2007) experimented with the same approach in an underground

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driving rock tunnel. In addition, water filled ampoules and water filled balls were used to reduce the blasting dust in India (Bhandari et al. 2004). As described above, although many new techniques are proposed to suppress mine dust, water spray and chemical dust suppressant are still the most widely utilized methods for dust control in the field (Konorev and Nesterenko 2012; Du and Li 2013; Huang et al. 2019a, b; Gonzalez et al. 2019).

For water spray and chemical dust suppressant, dust wettability is a vital parameter and can largely determine the suppressant efficiency (Xu et al. 2018; Liu et al. 2019b). Therefore, considerable studies were conducted on the wettability of mine dust recent years. Study performed by Wang et al. (2019a, b) shows particle diameter is one of the most significant factors affecting the wettability of coal dust among many physical and chemical factors. Xu et al. (2017) investigated the effects of chemical properties of coal dust on its wettability, showing the proximate components and surface carbon functional groups of coal dust are highly correlated with its wettability, and increased moisture content and large carbonyl group content can improve coal dust wettability. In addition, Li et al. (2013) studied the effects of surface physical properties of respirable coal dust on its wettability, and their results demonstrate the pore structure of coal dust, besides of particle size, has a significant effect on its wettability, and larger pore volume and larger surface area lead to poor wettability. As mentioned above, lots of studies were performed on the wettability of coal dust, however, there are few studies performed on the wettability of ore dust, such as blasting dust in metal mines. Our previous studies (Liu et al. 2019a) investigated the wettability of iron mine blasting dust, but to our knowledge, there is still no study on the wettability of copper mine blasting dust.

The objective of this study is to investigate the effects of physicochemical properties of copper mine blasting dust on its wettability. First, the primary blasting dust was collected from the Dexing open-pit copper mine located in Jiangxi province, China; then, the hydrophilic blasting dust (HLBD) and hydrophobic blasting dust (HBBD) were separated using water flotation method; after that, the physicochemical properties of HLBD and HBBD were comprehensively characterized. These properties included wettability, particle size distribution (PSD), micromorphology, pore structure, mineralogy, and surface organic carbon functional groups. Finally, these properties of HLBD and HBBD were compared with each other to identify the main factors affecting the wettability. This study is significant to understand the physicochemical properties of copper mine blasting dust and their effects on the wettability.

2 Materials and experiments

2.1 Collection and pretreatment of the blasting dust sample

As shown in Fig. 1, the primary blasting dust was collected from the Dexing open-pit copper mine in Jiangxi Province, China.

Frist, the mixture of deposited dust and small stones (Fig. 2a) was collected together in a plastic bag at the blasting site and immediately transported to the laboratory. Then, the blasting dust (Fig. 2b) was separated from the mixture using a 200 mesh (74 μm) sieve. After that, the blasting dust was slowly poured into deionized water (prepared by a reverse osmosis instrument and with a surface tension of 73.02 mN/m), as shown in Fig. 2c and d, the blasting dust was divided into two parts. The particles floated on the surface of deionized water were unwetted dust, called hydrophobic blasting dust (HBBD); in contrast, the particles deposited at the bottom of deionized water were wetted dust, called hydrophilic blasting dust (HLBD). Finally, HBBD and HLBD were extracted with a slide glass and dried at 100 °C for 2 h. The same experimental method was carried out in our previous study (Liu et al. 2019b).

2.2 Wettability test

Contact angle (CA), the angle between base line and tangent line of water drop and as indicated in Fig. 3a, is a parameter that can directly reflect the wettability of dust (Chen et al. 2019). In this study, the dynamic CAs between the blasting dust and deionized water were measured on a

Fig. 1 Top view of Dexing open-pit copper mine **a** and its blasting scene **b**

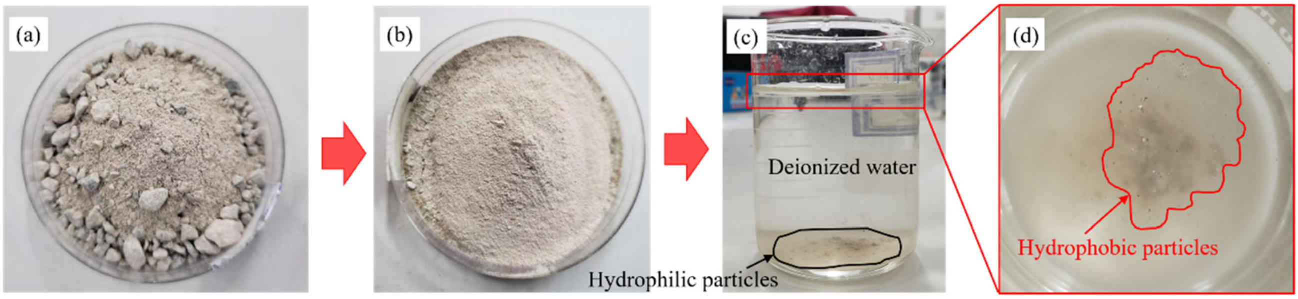

Fig. 2 The mixture of blasting dust and small stones **a** blasting dust **b** hydrophilic blasting dust **c** and hydrophobic blasting dust **d** in deionized water

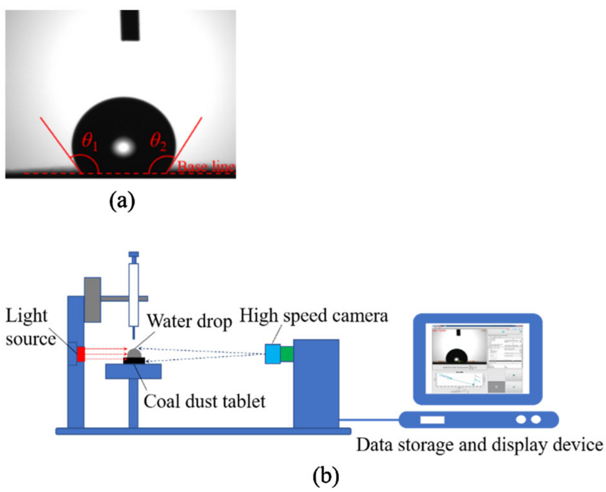

Fig. 3 Schematic diagram of contact angle **a** and Theta Lite TL101 apparatus **b**

Theta Lite TL101 apparatus at 7.5 Hz for 6 s. As shown in Fig. 3a, the average value of θ_1 (left CA) and θ_2 (right CA) were recorded by a OneAttension software. The schematic diagram of the CA testing apparatus is shown in Fig. 3b.

2.3 Physical properties test

2.3.1 Particle size distribution (PSD) and micromorphology test

The deposition property of dust in human respiratory system is almost dependent on the PSD of the particulates (Oberdörster et al. 2005). In this study, the PSDs of HLBD and HBBD were measured in a laser particle size analyzer (LPSA) (Winner 2000) with a 20 vol% alcoholic solution used as dispersion liquid. In addition, to verify the PSD results and investigate the micromorphology of the blasting dust, scanning electron microscope (SEM) tests of HLBD and HBBD were performed on a SU8000 apparatus. The test results were analyzed using an ImageJ software.

2.3.2 Pore structure test

The pore structure of a particle can affect its wettability by adsorbing air to form an air film (Yang et al. 2010). Low-pressure N_2 gas adsorption (LP-N_2GA) experiments were conducted for HLBD and HBBD on a 3H-2000PS2 apparatus for relative pressures (P/P_0, gas pressure/saturated vapor pressure) ranging from 0.010 to 0.995. As shown in Table 1, multiple adsorption theories were used to calculate the pore parameters of the blasting dust (Clarkson and Bustin 1999; Nie et al. 2015). The measurement was carried out only once considering the high accuracy of the apparatus.

2.4 Chemical properties test

The mineral compositions and carbon functional groups of HLBD and HBBD were characterized by X-ray diffraction (XRD) and X-ray photoelectron spectroscopy (XPS) tests, respectively. The XRD patterns were obtained from diffraction angles of 5°–100° with an angular speed of 2°/min on an Ultima IV (Rigaku) at 40 kV and 40 mA with a Ni-filtered Cu Kα radiation source. The data were then

Table 1 Utilized multiple adsorption theories and corresponding pore parameters

No.	Multiple adsorption theory	Pore parameter
1	Brunauer–Emmett–Teller (BET)	Specific surface area (SSA)
2	Langmuir	SSA
3	Barrett–Joyner–Halenda (BJH)	Mesopore volume and mesopore size
4	Dubinin–Radushkevich (D–R)	Micropore volume
5	Density functional theory (DFT)	Pore size distributions and cumulative pore volumes

analyzed using MDI Jade 6.1 software. The XPS tests were carried out on an AXIS ULTRA spectrometer (Kratos) with an Al Kα radiation source and a detection area of 700 μm × 300 μm. The binding energies were calibrated using the C 1s peak with a reference of 248.8 eV. Four carbon functional groups were fitted using XPSPEAK 4.1 software, and their relative contents (n) were calculated with Eq. (1):

$$n_j = \frac{S_j}{\sum_{i=1}^{N} S_i} \tag{1}$$

where, n_j is the relative content of the functional group j, S_j is the peak area of the functional group j, and N is the number of fitting peaks.

3 Results and discussion

3.1 Wettability analysis

Figure 4 illustrates the shapes of water droplets formed on the surface of the blasting dust platelets at different times. The shapes of the water drop on the both HBBD and HLBD surfaces flatten continuously with time because of thermodynamic and kinetic adsorption into the blasting dust platelets (Susana et al. 2012). Figure 4 clearly shows that the wettability of HLBD is higher than that of HBBD as the water drop shapes on HLBD are consistently thinner than on HBBD. This result verified the effectiveness of water floatation method (Fig. 2) for separating hydrophilic and hydrophobic particles from copper mine blasting dust.

Figure 5 shows the curves of CAs of HBBD and HLBD over time. The CAs of HBBD and HLBD at 0 s (initial contact angle) are 74° and 31°, respectively; after that, they decrease sharply over time in a parallel manner. After 1.07 s, the CA of HLBD is too small to identified, while the HBBD contact angle is 38° with a slow decreasing rate. This result indicates that the wettability of HBBD is essentially different from that of HLBD and provides the basis for studying the factors affecting the wettability of copper mine blasting dust by comparing its physical and chemical properties.

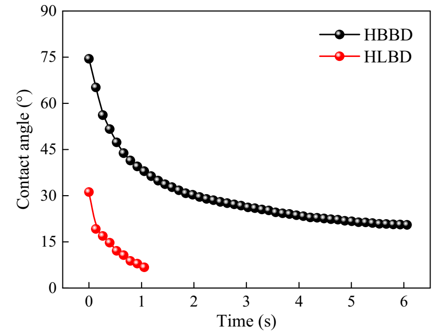

Fig. 5 Contact angles of HBBD and HLBD over time

3.2 Particle size distribution (PSD) analysis

The particle size of the blasting dust was measured using a laser particle size analyzer (LPSA). Figure 6 shows the differential and accumulative PSDs of HBBD and HLBD, and Table 2 summarizes the particle size value of D_{10}, D_{50}, D_{90} (where 10 vol%, 50 vol%, and 90 vol% of dust is less than the particle size values, respectively), and P_{10} (the percentage of dust with particles less than 10 μm in size). Figure 6c illustrates the meaning of the symbols in Table 1.

Figure 6 and Table 2 indicate that the size distributions of HBBD and HLBD present a single peak structure, and the D_{50} value of HBBD (7.71 μm) is less than that of HLBD (9.94 μm). The D_{50} values of HBBD and HLBD are all smaller than that of coal dust reported by Kollipara et al. (2014). This result suggests that the blasting dust is more likely to be inhaled than coal dust due to its finer size. In addition, the volume percentage of respirable dust (smaller than 10 μm, i.e., P_{10}) in HBBD is higher 8.74 vol% than that in HLBD. Therefore, HBBD is more difficult to suppress than HLBD because of its stronger hydrophobicity

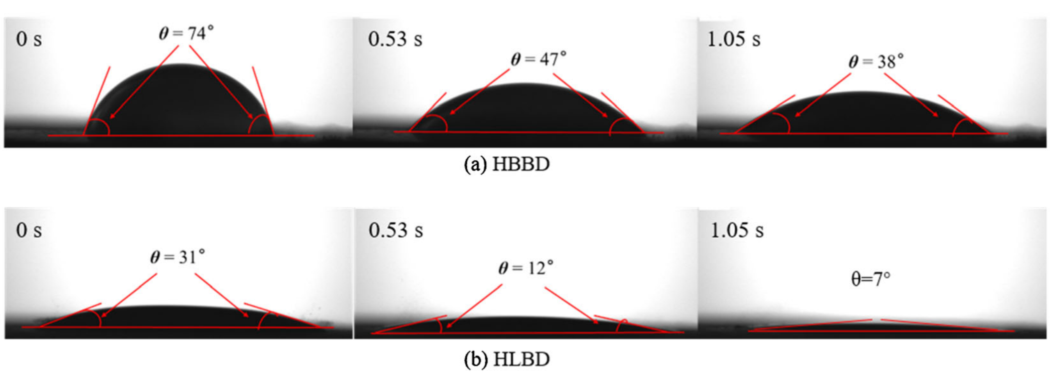

Fig. 4 Images of water droplets on a compressed HBBD platelet **a** and HLBD platelet **b** at various times

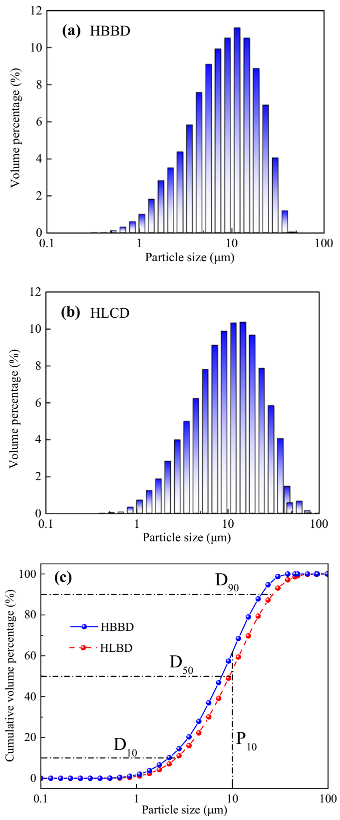

Fig. 6 Differential PSD of HBBD **a** and HLBD **b** and their accumulative PSD **c**

Table 2 Particle size distribution of HBBD and HLBD

Dust sample	D_{10} (μm)	D_{50} (μm)	D_{90} (μm)	P_{10} (vol%)
HBBD	2.16	7.71	20.06	61.74
HLBD	2.62	9.94	26.37	53.00

and smaller particle size. Consequently, HBBD is more harmful to humans in open-pit copper mines.

According to the studies conducted by Yang et al. (2010) and Li et al. (2013), smaller dust particles have a more unsaturated surface, which causes the adsorption of air and formation of an air film on the dust surface. The air film prevents water drops from direct contacting the particles; thus, the air film lowers the wettability of the dust. For this reason, more considerations are needed on suppression technology for small hydrophobic blasting dust in copper mines.

3.3 Micromorphology analysis

Figure 7 shows the SEM pictures of HBBD and HLBD. It can be seen that HBBD particle size is smaller than that of HLBD, which is consistent with the LPSA result. In addition, the micromorphology of the blasting dust consists mainly of irregular flakes and needles, which is completely different from the irregular spherical or bulky morphology of coal dust (Li et al. 2013; Kollipara et al. 2014; Hong et al. 2017). This phenomenon is caused mostly by the difference in production mechanisms between the blasting dust and coal dust. Coal dust is caused by friction between a cutting machine and the coal body, whereas the blasting dust is produced from rock under strong explosive wave action (Liu et al. 2019b). Furthermore, hardness of rock from that of coal may also contribute to distinct dust micromorphology. A comparison of Fig. 7a and b shows that HBBD contains a number of needle shape particles, and they adhere together and form rough surface; however, HLBD contains most of flake or block shape particles, and their surface is smoother than HBBD surface. That is, HBBD surface roughness is larger than that of HLBD. This is consistent with the results reported by Yang et al. (2010), Li et al. (2013) and Wang et al. (2019a, b), i.e., smaller dust particles have rougher surfaces. Surface roughness can enhance both hydrophilicity and hydrophobicity, which depends on the wettability of the substance (Tian and Jiang 2013). Specifically, hydrophilic surface can be enhanced more hydrophilic by increasing its surface roughness, but hydrophobic surface will get more hydrophobic when its surface become more roughness.

3.4 Pore structure properties analysis

Figure 8 illustrates the adsorption-desorption isotherms of HBBD and HLBD. The adsorption volume of HBBD at the highest pressure is 14.2 cm^3/g, which is higher than that of HLBD (8.2 cm^3/g), indicating that the porosity of HBBD is more developed than that of HLBD. Table 3 shows the quantitative comparison of HBBD and HLBD pore parameters, including specific surface area (SSA), pore volume, and pore size, which were calculated based on the theories of BET and Langmuir, BJH and D-R, and BJH, respectively.

The result shows that the Langmuir SSA and the BJH pore sizes are all larger for HBBD than for HLBD. The mesopore volume (BJH volume) and total volume of HBBD are also much greater than that of HLBD, demonstrating that HBBD pore structure is more complex than that of HLBD.

Moreover, as shown in Fig. 9, pore size distributions and cumulative pore volumes of the blasting dust were obtained based on DFT theory. The results indicate that under the action of an explosive wave, the HBBD and HLBD micropores are more developed than the coal dust reported by Yang et al. (2010), and their maximum pore volume is reached at pore sizes of 1.14 nm and 0.84 nm,

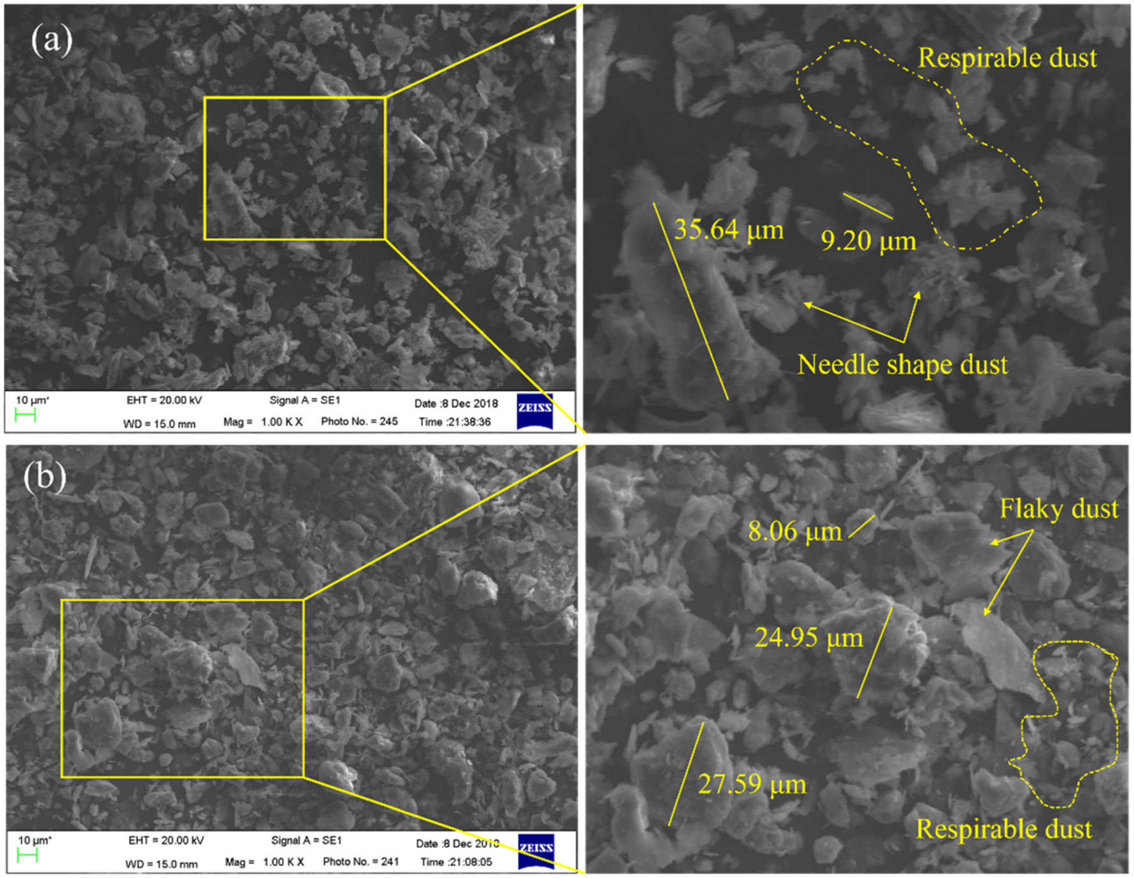

Fig. 7 SEM images of HBBD **a** and HLBD **b**

respectively. After that point, pore volume decreases with increasing pore size. HLBD micropore volume is also larger than that of HBBD for pore sizes less than 1.09 nm (Fig. 9a). As a result, the D-R volume of HLBD is larger than that of HBBD (Table 3). However, when the pore size is larger than 1.09 nm, HBBD pore volume is always larger than that of HLBD, and the maximum cumulative pore volume of HBBD is 1.68 times that of HLBD.

3.5 XRD and XPS analyses

The mineral component is a key chemical factor affecting the wettability of dust because it determines the surface energy (Tian and Jiang 2013). The three identical mineral compositions in HBBD and HLBD were observed from XRD patterns, i.e., quartz, calcite, and muscovite, as shown in Fig. 10. This result indicates that mineral composition is not the reason for the different wettability of HBBD and HLBD.

The surface organic component is another chemical factor affecting wettability of dust (Xu et al. 2017). In this section, XPS tests were performed for HBBD and HLBD. As shown in Fig. 11, the C 1s spectrogram was divided into four peaks using the peak-split method, and relative peak areas (RPEs) were calculated following Eq. (1). Table 4 presents the results.

Generally, oxygen-containing functional groups are hydrophilic, and aliphatic hydrocarbons (C–C/C–H) are hydrophobic (Zhou et al. 2015; Wang et al. 2017; Xu et al. 2017). Table 4 shows that the hydrophobic groups on the surface of the blasting dust are more numerous in organic carbon groups. The relative peak area (RPA) of hydrophobic groups in HBBD is slightly higher than that in HLBD, whereas all hydrophilic HLBD groups have a higher RPA. This phenomenon indicates that the hydrophobic carbon functional groups may affect the wettability of the blasting dust, but more experiments are needed to support this conclusion.

4 Conclusion

To investigate the factors affecting the wettability of copper mine blasting dust, the hydrophilic blasting dust (HLBD) and hydrophobic blasting dust (HBBD) were separated from the blasting dust at the Dexing copper mine;

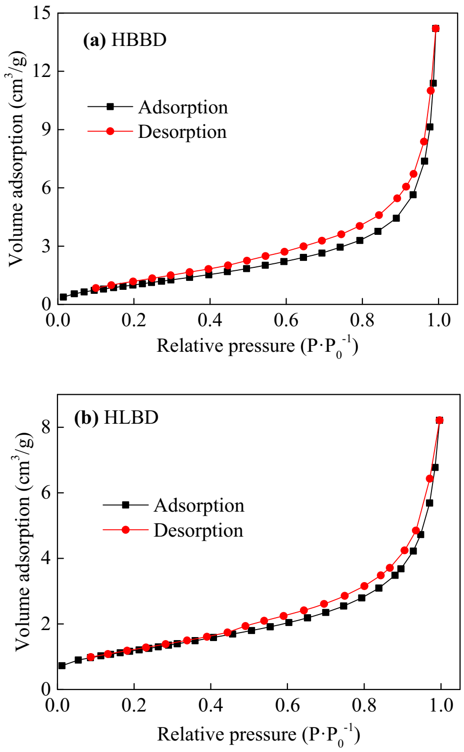

Fig. 8 Adsorption-desorption isotherms of HBBD **a** and HLBD **b**

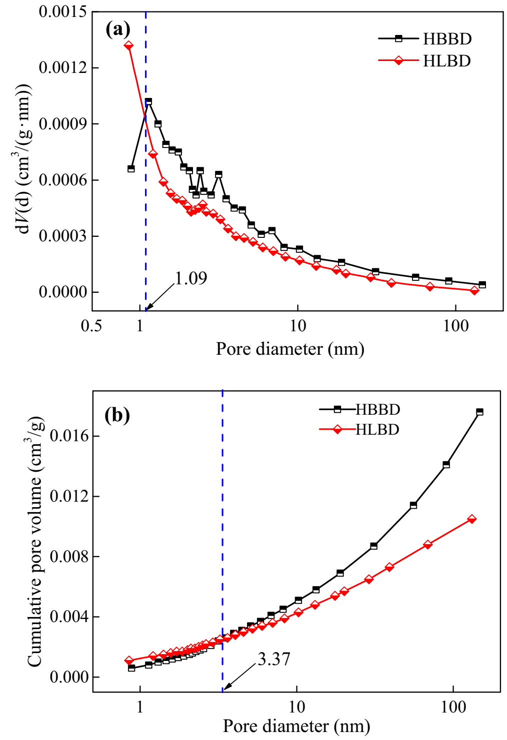

Fig. 9 Pore size distributions **a** and cumulative pore volumes **b** of HBBD and HLBD

Table 3 Pore structure parameters of HBBD and HLBD

Dust Sample	SSA (m^2/g)		Pore volume (cm^3/g)			BJH[d] pore size (nm)
	BET SSA	Langmuir SSA	BJH[a] volume	D-R[b] volume	Total volume[c]	
HBBD	4.24	7.26	0.0241	0.0015	0.0256	12.625
HLBD	4.29	6.99	0.0133	0.0021	0.0154	10.505

[a]Mesopore volume

[b]Microvolume

[c]Total volume = mesopore volume + microvolume

[d]Mesopore size

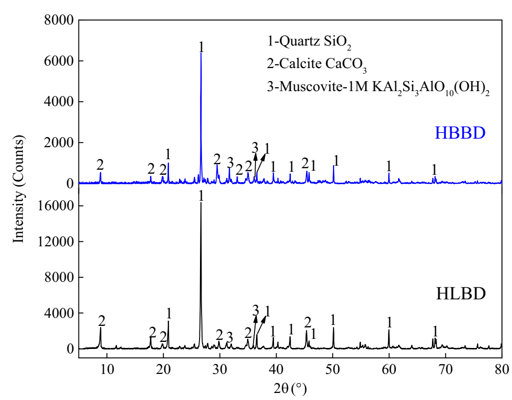

Fig. 10 XRD patterns of HBBD and HLBD

and then, their physicochemical properties were comprehensively measured. The following conclusions were drawn from this study:

(1) The particle size of the blasting dust is small; P_{10} (the percentage of dust with particles less than 10 μm in size) of HBBD and HLBD is 61.74% and 53.00% by volume, respectively. HBBD is difficult to suppress due to its stronger hydrophobicity and a larger number of respiratory particles.

(2) HBBD has a more developed pore structure than HLBD based on the LP-N_2GA test and SEM images. The total pore volume of HBBD is 1.66 times that of HLBD. The developed pore structure promotes the formation of an air film on the dust surface that lowers its wettability.

(3) Particle size and pore structure are two key factors affecting the wetting properties of the blasting dust. Smaller blasting dust have more complex pore structure and lower wettability.

(4) The mineral composition of the blasting dust is not a factor affecting its wettability as the same mineral compositions were found in HBBD and HLBD. However, the surface organic hydrophobic component in HBBD is slightly larger than that in HLBD,

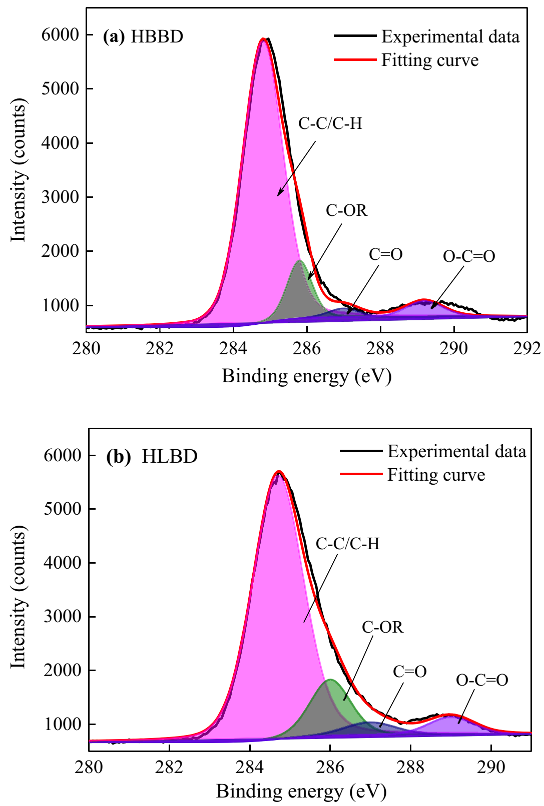

Fig. 11 C 1s XPS patterns of HBBD **a** and HLBD **b**

Table 4 Relative peak areas (RPA) of carbon functional groups

Dust sample	C–C/C–H		C–O		C=O		O–C=O	
	BE (eV)	RPA (%)	BE (eV)	RPA (%)	BE (eV)	RPA (%)	BE (eV)	RPA (%)
HBBD	284.8	83.11	285.8	10.51	287.0	2.04	289.2	4.33
HLBD	284.7	78.17	286.0	13.33	287.0	3.81	289.0	4.69

Notes: *BE* binding energy, *RPA* relative peak area

which may be another factor causing the wetting ability of HBBD to be lower than that of HLBD.

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Authors' contributions Jianguo Liu conceived and designed the investigation, collected data, performed the analysis, and wrote the paper. Longzhe Jin was the academic supervisor who conceived the study and provided financial support. Jingzhong Guo, Jiaying Wang and Tianyang Wang helped for the experiments.

Availability of data and materials Not applicable.

Code availability Not applicable.

Compliance with ethical standards

Conflict of interest The authors declare no conflicts of interest.

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