Physicochem. Probl. Miner. Process., 60(1), 2024, 183765 | Physicochemical Problems of Mineral Processing

http://www.journalssystem.com/ppmp | ISSN 1643-1049

Role of maceral groups in coal beneficiation: A short review

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Abstract: Macerals are the basic constituents of coal that can be distinguished and identified under the microscope. Depending on the difference in optical properties, the macerals are divided into four maceral groups, including liptinite, vitrinite, huminite and inertinite. These maceral groups not only affect coal mining and utilization but also play different roles in coal beneficiation. According to the different properties of maceral groups, they can be separated (or enriched) to provide high-quality raw materials for the coal industry. This review briefly introduces the international maceral classification system and reviews in detail the role of maceral groups in coal beneficiation combined with their properties.

Keywords: coal, macerals, beneficiation, mineral processing

1. Introduction

Coal is a biogenic rock formed by plants in a specific geological environment through coalification over a long period of time (Hatcher et al., 1997; Ward, 2016). Different coal-forming plants and long-term coalification have led to the fact that coal is destined to be a complex mixture. To better study and utilize coal, a new subdiscipline of coal science, coal petrology, has been developed. Coal petrology is the discipline used to study the coal composition, properties and utilization from the petrological view and methods. Coal petrology also used to determine the cause and rational application of coal (Bai, 2017). The purpose of coal petrology is to study the formation process of coal and to guide the rational utilization of coal. Furthermore, coal petrology is divided into basic coal petrology and applied coal petrology. The former research mainly focuses on the identification, classification and characterization of properties of coal components, while the latter focuses on the relationship between coal petrology and industrial coal production. Coal petrography not only confirmed that coal was converted from plants but also reclassified coal in terms of petrographic composition, which gave coal scientists an effective method to characterize coal composition other than its chemical composition (Zhang et al., 2017). Coal petrology in coal mining and utilization is widely studied, and the conclusion showed that the coal petrographic composition significantly affects coal coking production, coal gasification and coal liquefaction (Shu et al., 2014; Roberts et al., 2015; Keboletse et al., 2021; Wang et al., 2021). The importance of macerals in coal beneficiation is also gradually gaining attention from researchers. This paper reviewed the recent beneficiation study related to coal macerals, and provided some opinions on future research.

2. Macerals and their classification

The second industrial revolution gave a great impetus to the development of social productivity, which rapidly increased the demand for energy in human society. Energy engineers have found in production that there are significant differences in product yield and quality when using coal from different regions for production. Researchers are eager to learn more about coal. The concept of coal petrology was developed in the 1930s. Stopes first introduced the concept of maceral in 1935, corresponding to the mineral in petrology. Maceral can be used to distinguish the coal composition under a microscope (Chandra et al., 1976). With the development of science and technology, advanced scientific instruments

DOI: 10.37190/ppmp/183765

have been developed, which provide the basis for researchers to better study maceral. Diverse characterization methods have allowed researchers to gain a deeper understanding of the maceral, which has made the birth of applied coal petrology possible. Around the 1950s, some scholars have already conducted research on the application of coal petrology in relation to coke production (Ammosov et al., 1959).

More macerals were discovered and studied, and each maceral was classified according to morphological characteristics and chemical properties. A coal classification system based on coal petrology was gradually formed. The 1963 edition of the International Handbook of Coal Petrology included Stopes Heerlen definitions of bituminous coal macerals, which is probably the earliest international standard coal petrology classification system. To standardize the terminology for international coal research, the International Commission on Coal and Organic Petrology (ICCP) gave definitions and classification systems for vitrinite, inertinite, liptinite and huminite during 1994-2017 (ICCP, 1998; Committee et al., 2001; Sýkorová et al., 2005; Pickel et al., 2017). The classification was named ICCP system 1994. In this system, subgroups called the maceral group, maceral subgroup and maceral were defined by the reflectance level, destruction and morphology or/and degree of gelatinization, respectively (ICCP, 1998). The subdivision of the maceral groups is given in Table 1.

In coal beneficiation, the maceral group was given more attention, and subgroups and macerals were usually not considered because they have similar properties in beneficiation. Huminite was also often ignored because lignite is typically used as a fuel, and engineers were more concerned with the moisture and calorific value of the product.

3. Maceral group structure in coal beneficiation

3.1. Structural difference

Coal is porous. Using scanning electron microscope (SEM) or other microscopic observation equipment to observe macerals, it can be found that inertinite has more pores than vitrinite and liptinite (Yao et al., 2009; Golab et al., 2013; Mishra et al., 2017; Cardott et al., 2018). The differences in pore structure are generally related to the formation of maceral groups. For example, inertinite is usually trans by fine detrital fragments (Committee et al., 2001), but vitrinite is derived from parenchymatous and woody tissues of roots. The latter is denser than the former.

In addition to the physical structure, the chemical structures of the maceral groups are also different. ^{13}C nuclear magnetic resonance (NMR) is widely used in the characterization of the carbon skeleton structure of fossil fuels (Moroeng et al., 2019; Ping et al., 2020), which can give the chemical structure of coal. Ping et al. (2021) analyzed the chemical structure of subbituminous coal by ^{13}C NMR and concluded that vitrinite has more side chains of aliphatic hydrocarbons than inertinite, while inertinite has more aromatic rings and more oxygen-aliphatic structures than vitrinite. They also indicated that inertinite has a large aromatic carbon structure and a higher aromatic degree than vitrinite by calculating the structure parameter (Fig. 1, Table 2).

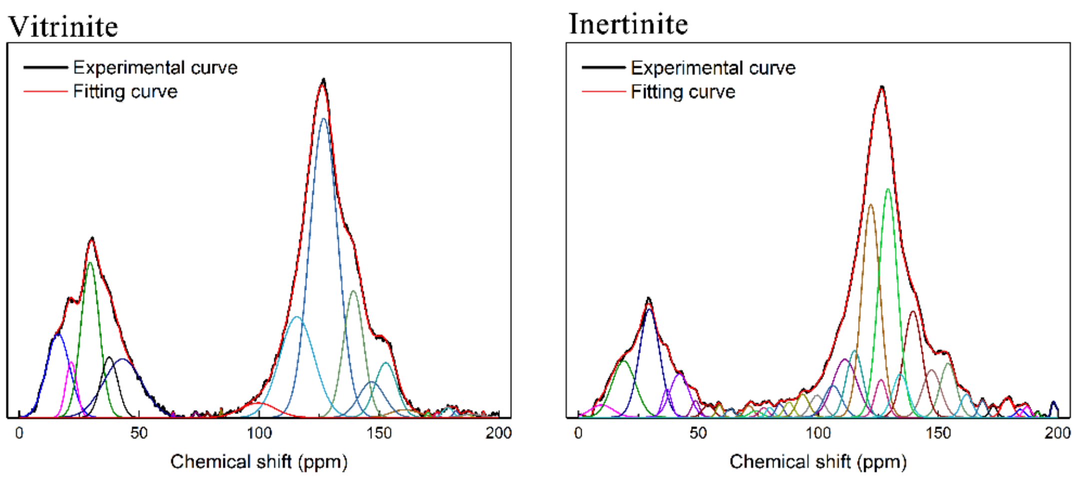

Fig. 1. The ^{13}C NMR peak fitting results (Ping et al., 2020)

Table 1. Subdivision of the maceral groups (Anon, 1998; Committee et al., 2001; Sýkorová et al., 2005; Pickel et al., 2017)

Maceral Group	Subgroup	Maceral	Maceral type	Maceral variety
Vitrinite	Telovitrinite	Telinite		
		Collotelinite		
	Detrovitrinite	Vitrodetrinite		
		Collodetrinite		
	Gelovitrinite	Corpogelinite		
		Gelinited		
Inertinite	Macerals with plant cell structures:	Fusinite		
		Semifusinite		
		Funginite		
	Macerals lacking plant cell structures:	Secretinite		
		Macrinite		
	Fragmented inertinite:	Micrinite		
		Inertodetrinite		
Huminite	Telohuminite	Textinite		A(dark)
				B(light)
		Ulminite		A(dark)
				B(light)
	Detrohuminite	Attrinite		
		Densinite		
	Gelohuminite	Corpohuminite	Phlobaphinite	
			Pscudophlobaphinite	
		Gelinite	Levigelinite	
			Porigelinite	
Liptinite	Cutinite			
	Suberinite			
	Sporinite			
	Exsudatinite			
	Chlorophyllinite			
	Alginite			
	Liptodetrinite			
	Bituminite			

Table 2. Structural parameters of vitrinite and inertinite (Ping et al., 2020)

Macerals	f_a	f_a^C	f_a'	f_a^H	f_a^N	f_a^P	f_a^S	f_a^B	f_{al}	f_{al}^H	f_{al}^*	f_{al}^O	X_b
Vitrinite	64.81	1.06	63.75	45.26	18.49	5.35	3.47	9.68	35.19	23.23	9.77	2.20	0.152
Inertinite	72.35	2.90	69.45	49.67	19.78	4.80	3.67	11.31	27.65	14.47	6.79	6.39	0.163

Note: f_a: total aromatic carbon; f_{al}: total aliphatic carbon; f_a^C: carbonyl; f_a': in an aromatic ring; f_a^H: protonated and aromatic; f_a^N: nonprotonated and aromatic; f_a^P: phenolic or phenolic ether; f_a^S: alkylated aromatic; f_a^B: aromatic bridgehead; f_{al}^*: -CH_3; f_{al}^H: CH or CH_2; f_{al}^O: bonded to oxygen; X_b: aromatic cluster size parameter

It is known that with increasing coal rank, the pore structure in the coal gradually decreases, while the graphitization degree increases. XRD is a common instrument for studying the crystal structure of high rank coals. The 002 and 10 peaks in the XRD spectrum can represent the crystal structure of the coal (Fig. 2), and sharp, narrow, and high-intensity peaks indicate an organized carbon structure (Zhang et al., 2008). The γ-edge is related to the content of aliphatic chains (Ergun et al., 1959). By fitting the above peaks, the crystal structure parameters of the coal can be calculated (Wang et al., 2010; Hattingh et al., 2013).

Zhang et al. (2019) studied a kind of inertinite-rich lignite and showed that the inertinite had smaller $d_{(002)}$ values, larger aromatic diameter L_a and height of aromatic layers L_c, which indicated that the aromatic rings in the inertinite were more tightly arranged than those in vitrinite. Zhou (2021) studied bituminous coal and reached a similar conclusion. Their studies also found that with the increase in the vitrinite maximum reflectance, the crystal structure of vitrinite begins to approach that of inertinite.

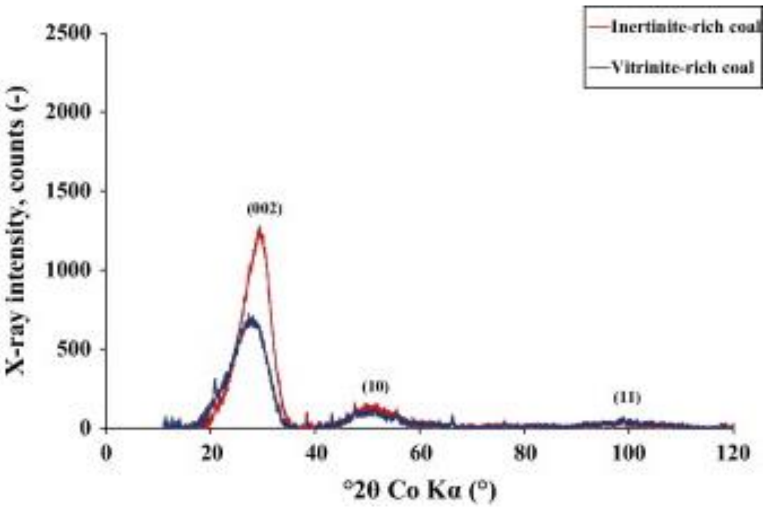

Fig. 2. Baseline corrected and smoothened XRD diffractograms (Roberts et al., 2015)

3.2. Structure differences utilization in coal beneficiation

Structural differences make the maceral groups have different densities. It is generally considered that the density of inertinite is the greatest, that of liptinite is the lowest, and the density of vitrinite is moderate. The density differences are related to the elemental content and chemical structure of each maceral group. In addition, inertinite is more likely to be combined with minerals; for example, fusinite cells are often filled with clay, which affects the density of maceral groups (Ward, 2016).

Depending on the difference in density, the enrichment of maceral groups can be achieved. Coal processing according to density difference is the simplest method, which has a large processing capacity and low cost.

Dyrkacz et al. (1982) developed the density gradient centrifugation techniques (DGC). This method can separate fully liberated maceral groups based on their density difference. However, the high demand for density media limits this technique in industrial applications. Zhu et al. (2019) and Xian et al. (2021a,b) used a dense medium cyclone and Falcon concentrator to achieve maceral group enrichment by using gravity beneficiation. Chang et al. (2021) attempted to apply dry beneficiation to maceral group enrichment and developed a multistage pulverization liberation technique by using an air-jet pulverization-grading system (Fig. 3).

Gravity beneficiation is a simple method for enriching maceral groups, but similar to the other beneficiation, all coal beneficiation needs to be based on adequate liberation between the target and useless minerals. Coal liberation is mainly achieved by grinding. Coal grinding is necessary. Not only do minerals need to be separated from organic matter, but maceral groups also need to be separated from each other. This is because inertinite is generally formed by fragments (Committee et al., 2001), which are easily oxidized and lose activity during coal formation; thus, inertinite is generally negative for coal utilization and conversion. In addition, inertinite is more likely to form complex intergrowths with minerals, which will increase the ash content of the product.

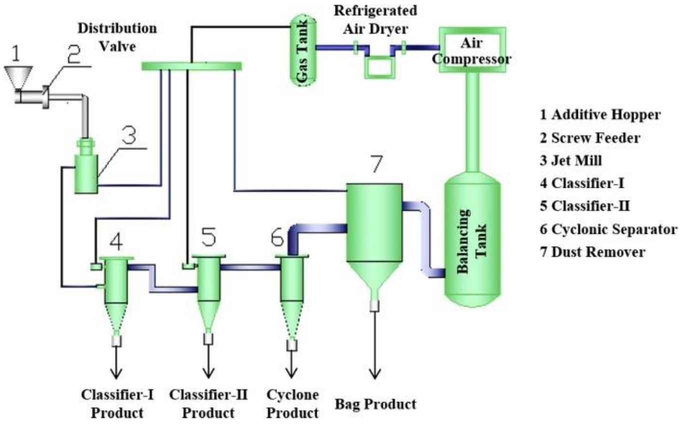

Fig. 3. Schematic of the jet milling crushing-classification system (Chang et al., 2021)

Different structures also give maceral groups different mechanical properties. Mechanical properties are one of the main properties of maceral groups. There are many parameters related to the mechanical properties of materials, such as Poisson's ratio and Young's modulus. These parameters are closely related to the physical properties and chemical properties of the material. Li et al. (2013) investigated the Young's modulus of anthracite coal, and the results showed that the Young's modulus of anthracite coal was negatively correlated with the vitrinite content and positively correlated with the inertinite, i.e., the less vitrinite there was, the greater the Young's modulus. Wang (2020) and Hou (2020) obtained similar results in the hardness and elastic modulus measurements of maceral groups.

Zhang et al. (2020) studied the compressibility of medium and high coal rank coals and concluded that the vitrinite content is positively correlated with the elastic modulus, while the inertinite content is negatively correlated with it, i.e., the vitrinite can convert stress force into elastic forces to avoid being broken. Hou et al. (2020) measured the hardness and elastic modulus of vitrinite, inertinite and liptinite by depth-sensing nanoindentation, and the hardness values of the three maceral groups were 0.52GPa~0.78 GPa, 0.78 GPa ~1.37 GPa and 0.18 GPa ~0.52 GPa, respectively; the elastic modulus of the three maceral groups was 5.46 GPa ~6.97 GPa, 7.19 GPa ~8.91 GPa and 2.60 GPa ~4.42 GPa. Zhang (2021b) found that the maceral group content also affects the Young's modulus and Poisson's ratio of coal. They calculated the brittleness index of coal by equations 1-3. The results show that the vitrinite content is positively correlated with the brittleness index, and the inertinite content is negatively correlated with the brittleness index.

$$E = \frac{\rho(3\Delta ts^2 - 4\Delta tc^2}{\Delta ts^2(\Delta ts^2 - \Delta tc^2)} \tag{1}$$

$$\mu = \frac{0.5\Delta ts^2 - \Delta tc^2}{\Delta ts^2(\Delta ts^2 - \Delta tc^2)} \tag{2}$$

$$BI = 0.5 \cdot \left(\frac{E - E_{min}}{E_{max} - E_{min}} + 0.5 \cdot \frac{\mu - \mu_{max}}{\mu_{min} - \mu_{max}}\right) \cdot 100 \tag{3}$$

where E is Young’s modulus, GPa; μ is Poisson’s ratio, dimensionless; ρ is the density, g/cm3; Δts is the transverse wave time difference, μm/s; Δtc is the longitudinal wave time difference, μm/s; BI is the coal brittleness index, dimensionless; Emax and Emin are the maximum and minimum values of Young’s modulus in a certain coal seam section in a certain lock, GPa; and μmax and μmin are the maximum and minimum values of Poisson’s ratio in a certain coal seam section in a certain block, dimensionless.

Li et al. (2017) showed that Young's modulus is negatively correlated with the pore volume of coal, i.e., the smaller the pore is, the higher the Young's modulus. Wang et al. (2020) suggested that for vitrinite, the decrease in aliphatic carbons and the increase in the ratio of total aromatic carbon to total aliphatic carbon could promote the elastic modulus.

In general, the different chemical and physical structures endow the maceral groups with different mechanical properties, which will have an impact on coal beneficiation.

In addition to grinding aiming at liberation, grinding can also be carried out when the coal utilization equipment has a size requirement for the coal. Studying the relationship between coal rock composition and grindability helps engineers predict mill working status, which can improve equipment efficiency and reduce equipment failure.

The grindability of the maceral group is a complex parameter about its brittleness, hardness and inner cracks, which is related to the coal rank, maceral group content and distribution. The grinding properties of coal are usually quantified by the Hardgrove grindability index (HGI); a low HGI means that the coal is difficult to finely ground.

Different scholars also have different opinions about the grindability of maceral groups. Hower et al. (2000) found that for Kentucky coal, vitrinite has a positive effect on increasing HGI, while a high inertinite content decreases HGI. Man et al. (1998) indicated that inertinite has better grindability because its particles are always small after grinding.

Hower et al. (2000) established a relationship between HGI and maceral group content for Kentucky high volatile bituminous coal. Trimble et al. (2003) classified Kentucky coals according to the vitrinite maximum reflectance and gave the equations of HGI and maceral group content for each reflectance level. Jorjani et al. (2013) studied the relationship between HGI and maceral group content of Kentucky coal using a multiple linear regression method. By comparing the coefficient of determination of the equation, they concluded that the maceral group content, mineral content and moisture as a function of the HGI can better reflect the relationship between HGI and petrography.

Fu et al. (2017) studied maceral group grinding behavior by using mineral liberation analysis. They found that after grinding, the inertinite formed short but numerous cracks, which were mostly distributed in a fragmented pattern (Fig. 4), while the vitrinite after the same grinding produced long and wide cracks, which were distributed in a dendritic or linear pattern. They also found that the grinding medium has an impact on grinding. The ball mill mainly relies on the instantaneous impact force to crush the coal, and the particles with small hardness will be crushed first, while the force on the particles is more even when using the rod mill, which makes the rod mill more helpful for the inner cracks of particles growing along the maceral group interface (Fig. 5).

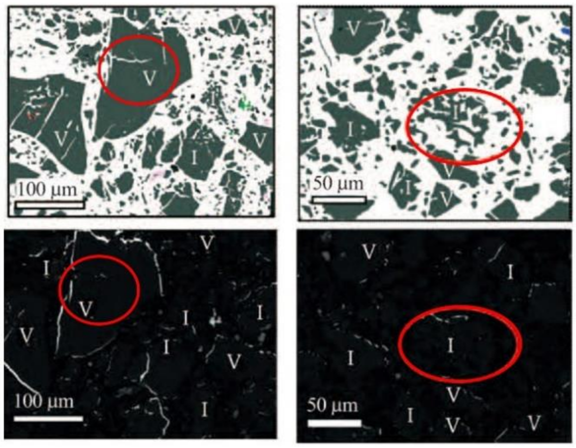

Fig. 4. Mineral liberation analysis of grinding products (left: vitrinite; right: inertinite; top: MLA colorful image; bottom: back scattering image) (Fu et al., 2017)

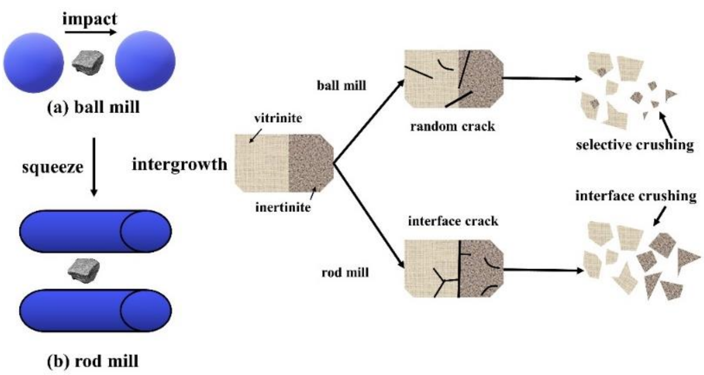

Fig. 5. Liberation models of coal macerals with different grinding methods (Fu et al. 2017)

Zhu et al. (2020) studied the grinding properties of a low rank Chinese coal. They found that the vitrinite content decreased with decreasing particle size, while the inertinite content and liptinite increased with decreasing particle size in the coal products. This conclusion was also confirmed by the studies of Men et al. (2015) and Tao et al. (2020). However, Jorjani et al. (2013) and Du et al. (2019) studied maceral group liberation and found that inertinite and liptinite are not easily ground and are enriched in coarse particles, while vitrinite is friable and easily ground into small particles.

By studying maceral group grinding, scholars believe that grinding can be performed by certain methods that increase the release of maceral groups or enrich them in a limited size range. A study by Sriramoju et al. (2021) on Indian coals found that using a reasonable grinding procedure can help the crack generate at the maceral groups interface, which will improve liberation and improve product quality. They found that the maceral group liberation proportion in the autogenous grinding product was 8% higher than that in conventional grinding. They indicated that the autogenous grinding grinds particles by frictional collision, comparing the iron ball as a medium. This grinding method can reduce the impact force, which will promote maceral group liberation and separation during grinding (Sriramoju et al., 2019). Zhang et al. (2020) concluded that maceral group particles were easy to overgrind when using ball mills in grinding, which creates a problem for separation, whereas when rod mills are used for grinding, the maceral groups are better enriched in products of different size ranges.

Nag et al. (2022) used a horizontal plate crusher to replace the hammer crusher in coal pre-grinding. The new crusher can crush coal by shear force. Coal petrographic analysis showed that shear power can better liberate maceral groups. In addition, the product size range of this kind of crusher is much narrower than that of traditional crushers.

Zhao et al. (2011b) investigated the maceral group liberation effect by microwave-assisted coal grinding. Vitrinite will remain stable in microwaves, while inertinite more easily cracks in the microwave field, which makes microwave-assisted grinding more selective, and inertinite is easily broken into small particles. Zhao concluded that selective breaking is related not only to the mechanical properties of the maceral group but also to the moisture and mineral content of the inertinite. The high moisture and mineral content makes the inertinite more susceptible to microwave effects during grinding and crushing. Most studies show that the maceral group liberation particle size is below 0.5 mm, but a study by Zhang et al. (2017) on four different rank coals shows that a coarser upper particle size can also have a better liberation effect.

The diverse coal-forming conditions provide different physical and chemical compositions for macerals. Maceral group structure differences play an important role in coal beneficiation. Different structures determine different densities, which enables engineers to achieve the enrichment of macerals by gravity beneficiation.

The inertinite usually plays a negative role in coal beneficiation, not only because the inertinite is inactive but also because it has a poor grindability (for most coals) and does not separate easily from other groups. The study of mechanical properties can fully grind or release maceral groups and improve the efficiency of subsequent processes.

4. Maceral group surface properties in coal beneficiation

4.1. Surface properties

The difference in chemical structure means that the surface groups are necessarily different in each maceral group. X-ray photoelectron spectroscopy (XPS) and Fourier transform infrared spectroscopy (FTIR) are commonly used to study the surface structure of coal (Xia et al., 2018; Li et al., 2021; Zheng et al., 2021). Chen et al. (2012) indicated that liptinite has the lowest aromaticity and the longest aliphatic chains with the least amount of branching, while inertinite shows the highest aromaticity and degree of condensation of aromatics by using FTIR (Fig. 6). Li (Ding, 2009) concluded that inertinite contains more oxygenated groups, especially carboxylic acid groups, while liptinite contains few oxygenated groups because it is converted from stable substances in plants (Fig. 7). The vitrinite surface generally shows intermediate characteristics between those of inertinite and liptinite.

Different surface structures make the maceral groups have a difference in hydrophobicity. Arnold et al. (1989) evaluated the wettability of maceral groups using the captive bubble and sessile drop contact angle techniques. They indicated that wettability was closely related to vitrinite maximum reflectance and coal rank. They found that liptinite has the highest hydrophobicity, while fusinite has the lowest hydrophobicity. Most studies have proven this conclusion (Shu et al., 2002; Ofori et al., 2010). However, Bujnowska (1985) considered that inertinite has the highest hydrophobicity by studying Polish subbituminous coal from the Janina mine. They attributed the hydrophobic difference to the fact that the inertinite is more aromatic and contains fewer side chains, especially oxygenated side chains.

In summary, it is certain that coal hydrophobicity is a function of coal rank, and for a certain rank and the same degree of oxidation, the hydrophobicity is closely related to the petrographic. The maceral groups have different hydrophobicity, which will have an impact on flotation or dewatering because these processes are closely related to surface properties.

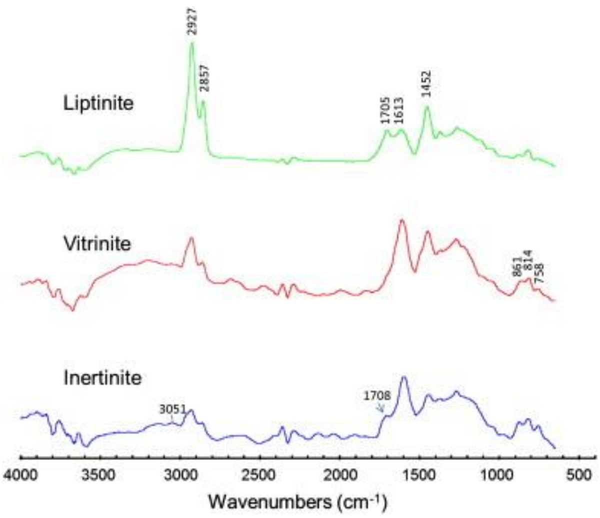

Fig. 6. Micro-FTIR spectra of liptinite, vitrinite and inertinite from coal (Chen et al., 2012)

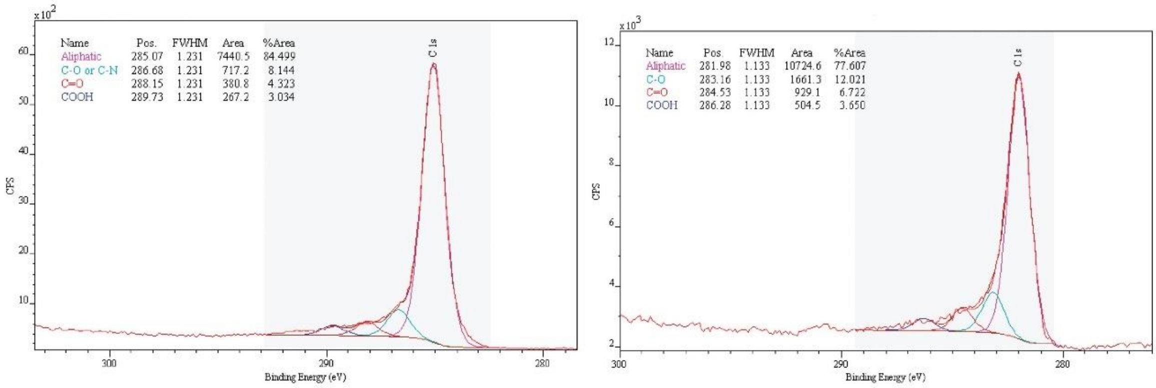

Fig. 7. The C1 s spectrum and its compositions of bright coal (left) and dull coal (right) (Ding, 2009); bright coal: rich in vitrinite; dull coal: rich in inertinite.

4.2. Surface property differences utilization in coal beneficiation

Flotation machines and flotation columns are common equipment for flotation, and they can all be used in maceral group separation (Shu et al., 2002; Barraza et al., 2011; Sahoo et al., 2020). Both the flotation machine and flotation column have better enrichment performance. However, scholars seem to prefer using flotation columns for separating maceral groups. Since the flotation column separates the fine particles better, the fully liberated fine particles are more suitable for separation using the flotation column.

Barraza J et al. carried out a pilot-scale flotation column experiment for the Yolanda coal (Table 2) and obtained a 99.8% vitrinite-rich concentrate at pH 7.5 and a frother concentration of 0.0125% (Barraza et al., 2005). Hower et al. (2000) used flotation columns from the Powell Mountain Coal Mayflower Preparation Plant to enrich vitrinite from 32.7% to 61.2% and inertinite from 4.9% to 20.2%.

Table 2. The proximate analysis and maceral content of Yolanda coal (Barraza et al., 2005)

	Proximate analysis, wt% db			Maceral content, vol%, mmf		
	Ash	VM	FC	Vitrinite	Inertinite	Liptinite
Yolanda coal	15.8	23.2	61.2	96.8	0	3.2

mmf: mineral matter free; db: dry basis

Similar to gravity beneficiation, maceral group flotation is also aimed at separating vitrinite and liptinite from inertinite and minerals. Although inertinite generally has better wettability and less floatability, it is still derived from the same coal as the other maceral groups. Therefore, a better flotation performance requires some methods to enhance the difference in surface properties between inertinite and the other maceral groups.

Nonpolar oils and alcohols are the most commonly used flotation agents for coal, and they are also often used for maceral group flotation (Kopparthi et al., 2018). Barnwal et al. (2000) performed maceral group flotation using diesel and pine alcohol oil and noted that vitrinite had the highest flotation rate, followed by liptinite, and the slowest flotation rate was observed for inertinite. The recovery of liptinite reached 59.12% under optimal conditions. Holuszko et al. (2015) reviews the effect of chemical reagents on maceral group flotation. Their review shows that flotation will have selectivity when using different collectors or adding certain chemical reagents into slurries, and certain maceral groups will float as concentrates.

The different surface properties affect the isoelectric point of the maceral groups. By adjusting the pH of the solution, the flotation separation of the maceral groups can be improved (Hussain et al., 1996; Vilasó-Cadre et al., 2021). Zhang (2015) pointed out that there was a correlation between the zeta potential and the flotation effect by studying eight different ranks of Chinese coal. A suitable zeta potential can enhance particle agglomeration, which will improve the vitrinite enrichment performance in flotation, but it was an exception for high-rank coal. However, Honaker's study (Honaker et al., 1996) showed that solution pH had little effect on the flotation rate of vitrinite and liptinite of Illinois No. 6 coal but had a large effect on that of inertinite. In addition to the zeta potential, the particle size composition of the raw coal also affects the separation of maceral groups. Jorjani et al. (2013) studies have shown that vitrinite is enriched in fine-ground coal and liptinite is enriched in coarse-ground coal, which results in coarse flotation products containing more liptinite. Reclassification of flotation products according to particle size may help to improve enrichment efficiency.

Pretreatment of the raw coal also contributes to enhancing the difference in surface properties. Zhao et al. (2017, 2018) indicated that flotation assisted with an electric field can promote the aggregation of homogeneous maceral groups. Inertinite is more likely to be impacted and form flocs enriched in the tailings. They also studied (Zhao et al., 2011a) the influence of microwave treatment under a hydrogen or methane atmosphere on the floatability of macerals. The results showed that microwave treatment can enhance the surface difference between vitrinite and inertinite, which will increase the enrichment rate of maceral groups. The highest enrichment rates of 92.71% and 54.35% were obtained in vitrinite and inertinite under a hydrogen atmosphere, respectively.

After the flotation process, the concentrate contains a large amount of moisture that needs to be removed. The fully liberated maceral groups have a very small particle size, which can adversely affect the dewatering behavior.

Ping et al. (2021) found that different maceral groups also have different dewatering behaviors. Dewatering tests showed that the filter cake moisture of inertinite was higher than that of vitrinite; moreover, the filtration rate of inertinite was also significantly slower than that of vitrinite (Fig. 8). The difference in filtration was attributed to the high hydrophilicity of inertinite increasing the pressure needed, which resulted in moisture retention in the cake capillaries. The structural properties also influence the dewatering behavior. Inertinite is usually easily ground into fine particles, which will lead to the formation of denser filter cakes, and these particles will form a dense filter cake, which will hinder cake desaturation.

Furthermore, Ping et al. (Ping et al., 2022) used surfactants to promote dewatering in vitrinite and inertinite. They found that the nonionic surfactant (lauryl polyoxyethylene ether, Brij35) had the best dewatering performance on vitrinite. The cationic surfactant (dodecyl-trimethylammonium bromide, DTAB) had the best dewatering performance on inertinite. Mechanistic studies showed that although surfactants reduced the sample hydrophobicity, they could promote dewatering by reducing the filtrate surface tension. The difference in zeta potential is closely related to the type of filtering aid. Selecting filtering aids based on maceral group content has potential research value.

Inertinite still plays a negative role in the processing related to surface properties. Beneficiation engineers are committed to increasing the difference between maceral groups to remove inertinites as much as possible or reducing the difference between maceral groups to eliminate the impact of inertinites on coal beneficiation.

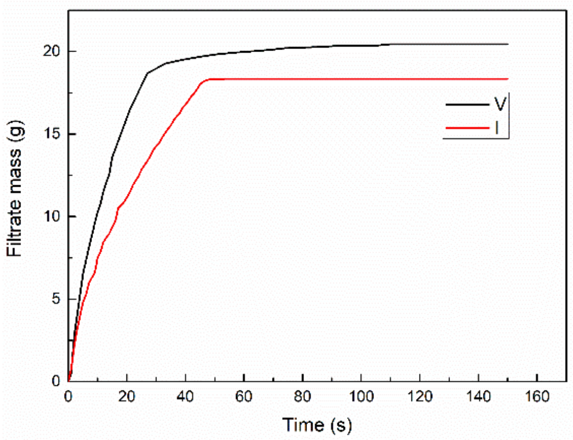

Fig. 8. Cumulative mass-time curve of filtrate (Ping et al., 2021)

5. Electrical properties and electrostatic enrichment

Northwest China is a major coal producing area, where coal t has a high inertinite content. Scholars and engineers hope to obtain high-quality industrial materials by enriching vitrinite. However, water resources are scarce in northwestern China, which makes studying dry beneficiation necessary.

A conducting particle will change its motion path when it is affected by an additional electric field, while maceral groups have differences in electrical properties because there are differences in their physical and chemical properties. Based on the above properties, maceral group separation can be achieved by the triboelectrostatic method (Fig. 9). This method is a kind of dry beneficiation that is more suitable for beneficiation in water-lacking areas.

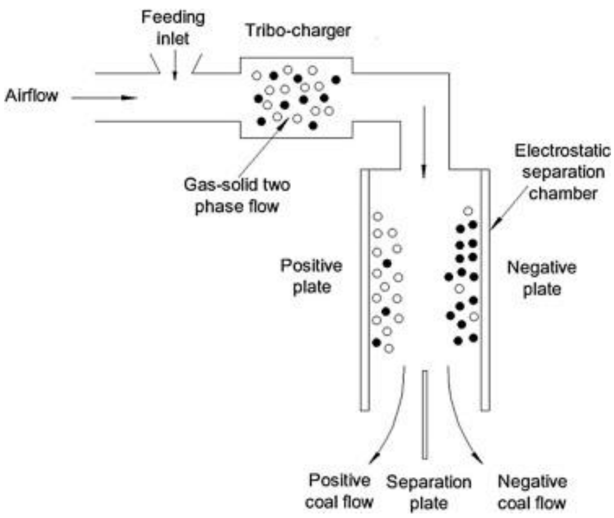

Fig. 9. Schematic diagram of the triboelectrostatic beneficiation system (He et al., 2017).

He et al. (2018a) conducted extensive studies on the charging mechanism of maceral groups. They pointed out that inertinite has a dense crystal structure and less amorphous carbon, making it more difficult to lose electrons during the tribo-charge process. The relative dielectric constant of inertinite is always higher than that of vitrinite, which makes inertinite develop a negative charge and enrich with positive charges, while vitrinite develops the opposite. The dense crystal structure makes it more difficult for the inert group to lose electrons during the friction process. Furthermore, inertinite has a more porous structure and more oxygenated groups, which increases its specific surface area and wettability. The strong hydrophilicity and large specific surface area make inertinite more susceptible to humidity during separation (He et al., 2017, 2018a, b, 2021). He et al. (2018a) indicated that high-temperature and low-humidity environments were more favorable for obtaining higher vitrinite contents and yields.

Inertinite is more susceptible to the influence of operating parameters and the environment during electrostatic enrichment. According to this property, engineers achieved maceral group separation. Zhang et al. (2021a) thought that extreme operating parameters would have a negative impact on separation and gave optimal parameters were a friction wheel speed of 3220.14 rpm, a separation voltage of 30.18 kV, and a feed rate of 1.44 g/s. By pretreatment, the triboelectric separation performance can be further enhanced. Kerosene is more suitable as a modifier than diesel oil. When the kerosene dosage is 3.0 kg/t, the triboelectric charge of vitrinite and inertinite is the largest, which is beneficial to the separation. The vitrinite content increased from 54.38% to 69.78%, and the recovery was 73.52%. Xian et al. (2021) concluded that the optimum humidity and temperature for electrostatic enrichment were 20% and 40°C, respectively. In this environment, the relative dielectric constants and specific charge of vitrinite and inertinite are most favorable for obtaining good separation performance. Under optimal conditions, the vitrinite content increased from 52.45% to 72.03%, and the vitrinite recovery was 67.86%.

Increasing the difference in electrical properties between maceral groups can also improve the triboelectrostatic enrichment performance. He et al. (2018b) found that polyamide is the best material for tribo-charging. Polyamide was the only material with which vitrinite and inertinite showed opposite charge polarity in triboelectrification.

Triboelectrostatic enrichment is a promising beneficiation method for separating maceral groups. However, similar to other beneficiation methods, it requires the use of fully liberated material to obtain a high-quality product. He et al. (2021) pointed out that vitrinite will be enriched in the 105 μm -150 μm concentrate, while inertinite will be enriched in tailings less than 74 μm, which means that for higher quality products, triboelectrostatic enrichment needs to be combined with advanced powder separation technology.

6. Summary and future work

The different structures and surface properties allow maceral groups to be separated in many different methods.

The engineers and scholars, who studied the properties of maceral groups and their behavior in beneficiation, have found that inertinite often plays a negative role in coal beneficiation. Inertinite has low grindability and poor liberation characteristics. Since it contains large amount of ash, it is easily influenced by the environment and retains more moisture in filter cakes. However, because of these differences, they can be separated to improve the concentrate quality by increasing the property differences between maceral groups in some ways (even though these methods reduce yields and increase costs). There are some shortcomings in the current study, and more attention should be given to future work.

1. The study of maceral mechanical properties is mainly focused on coal mine safety, geological structure, etc. There are few studies on coal beneficiation that combine mechanical properties with grinding properties. We believe that these studies will be conducted in the future. Furthermore, to achieve good separation results, advanced powder technology is required to liberate intergrowth particles.
2. Gravity separation is a simple method for enriching maceral groups. This is more favorable for enriching vitrinite from low-rank, inertinite-rich coal. More gravity separation equipment should be considered for maceral group enrichment, which would facilitate the industrial application of maceral group enrichment studies.

3. Maceral group enrichment flotation is a branch of conventional coal flotation, while ash content and yield are the most important indexes in conventional flotation. Few studies have mentioned the ash and yield in maceral group enrichment flotation, and it is almost absent that papers discuss how to balance the product indexes of conventional flotation with those of maceral group enrichment flotation. We believe that this work should be fully discussed to correspond to the industrial demands of maceral group enrichment. Theoretically, it is most reasonable to separate the maceral groups by flotation. However, the properties of the maceral groups are very close to each other, which limits the selective flotation used in separation maceral groups. Better enrichment performance may be achieved by more complicated flotation control, such as a combined solution environment, agent and equipment operating parameters, but this requires more effort. The different coals always have different beneficiation behaviors, while the differences between maceral groups are small. It may be possible to better produce coal by studying the effect of coal maceral groups on the separation process.

Acknowledgments

Thank you to the support of the National Natural Science Foundation for this project. Thank you to the support of the key science and technology project of China Coal Group and the Youth Innovation Fund of China Coal (Tianjin) Underground Engineering Intelligent Research Institute Co., LTD. for this project.

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