Mineralogical Characterization of Gasification Ash with Different Particle Sizes from Lurgi Gasifier in the Coal-to-Synthetic Natural Gas Plant

Maofei Niu, Yungang Fu, and Shuqin Liu*

ABSTRACT: The Lurgi gasifier in China is one of the most suitable technologies to produce synthetic natural gas (SNG) from coal; however, a large amount of byproduct ash is discharged during the Lurgi gasification process, causing many environmental problems. Based on ash samples collected from a commercial Lurgi gasifier in a Chinese coal-to-SNG plant, this paper studied the mineral composition and microscopic appearance of gasification ash with different particle sizes. The typical minerals were identified and investigated by comparing them with the ash from a laboratory fixed-bed reactor. The results showed that the main high-temperature minerals in the Lurgi gasification ash with different particle sizes under the gasification condition of 4 MPa and 1100 °C were anorthite (CaAl2Si2O8), augite (CaFeSi2O6), hematite (Fe2O3), and gehlenite (Ca2Al2SiO7). As the particle size of the Lurgi gasification ash increased, the quartz content increased but the residual carbon content decreased. Additionally, the high-temperature minerals were more likely to agglomerate with fine particles of the ash. The FactSage modeling showed that calcium-bearing minerals were formed earlier than iron-bearing minerals. The high Fe2O3 content in ash hindered the transformation of calcium-bearing minerals into the high-melting-point mullite, resulting in a low ash flow temperature. Additionally, the fine ash had a relatively high content of calcium-bearing minerals which was not conducive to its utilization as an additive in cement and concrete.

1. INTRODUCTION

The demand for natural gas as the main clean, low-carbon energy source has increased substantially in China, and external dependence will increase to as high as approximately 65% in 2030.1−3 Due to the characteristics of primary energy in China,4−7 many enterprises are investing in clean coal conversion processes, especially the development of commercial coal-to-synthetic natural gas (coal-to-SNG) projects. Therefore, the development of coal-to-SNG projects is conducive to ensuring China’s energy security. However, the reserves of low-rank coal account for 56.7% of the total reserves in China; currently, China’s planned coal-to-SNG projects are mainly distributed in Xinjiang and Inner Mongolia, where lignite and bituminous coal are the main types of coal.8−11 Lurgi gasification technology can handle low-rank coals with high ash, high moisture, and stable chemical bonds. As is well known, Lurgi gasification technology has low oxygen consumption and can produce a gaseous fuel with a relatively high CH4 concentration and high ratio of H2/CO; thus, it is the main gasification technology of coal-to-SNG at this stage.12 However, a large amount of byproduct ash is discharged during the Lurgi gasification process. So far, China’s coal chemical industry gasification ash emissions have exceeded 33 million tons/year. However, the utilization rate of gasification ash in China is less than 60%, which causes many environmental and social problems.13,14 Accordingly, the comprehensive study on Lurgi gasification ash is of great significance for improving the utilization efficiency of coal and identifying the impact of ash on the environment.15,16

The content of residual or unburned carbon in the gasification ash can directly reflect the carbon conversion of coal in the gasification process. Senneca et al.17 used loss on ignition (LOI) to analyze residual carbon content in ash. In the process of coal processing and utilization, the LOI value of residual carbon can be reduced as much as possible, which can provide an important reference for the effective utilization of coal.18 Wu et al.19 results show that the high unburned carbon content in coarse and fine slag hinders its application as cement and concrete admixtures. Acosta et al.20 found that there were cracks, smooth surfaces, and porous microstructures in the particles of different sizes by scanning electron
microscopy (SEM), and the edges of the particles had very narrow angles, which facilitated the melting or sintering of grains.

Wagner et al.21 studied the characteristics of unburned carbon in the Lurgi gasification coarse ash and divided unburned carbon particles into remnant "coal" particles, solid carbon, layered carbon, and porous carbon. Specifically, unburned carbon particles tend to concentrate in the gasification ash with a particle size of 4–13 mm. Van Dyk et al.22 used high-temperature X-ray diffraction (HT-XRD) and FactSage to study Lurgi gasification ash, and the results showed that anorthite and the gehlenite are formed by the reaction of anhydrite, alumina, and silica at 900–1100 °C, and the gehlenite can also be formed from the reaction of lime with alumina and silica. Zhao et al.23 studied the ash of a coal-fired power plant and indicated that the calcium oxide and calcium sulfate mainly came from the original calcium-bearing minerals in coal, while the Ca–Al–Si and Ca–S–X compounds were formed through the secondary reaction of CaO and CaSO4.

The Shengli coal ash belongs to low-fusibility ash. Ash fusion could be induced by low-melting-point minerals and low-temperature eutectics.28 Van Dyk et al.29 showed that due to the fluxing properties of the Ca and Fe minerals, Shengli coal rich in Ca and Fe has a low flow temperature (FT). At high temperatures, iron-bearing minerals reacted with quartz and anorthite to form low-temperature eutectics.

The mineral composition of feed coal is shown in Figure 2. It can be seen from the diffractogram that the minerals in feed coal are mainly quartz, and also contain calcium-bearing minerals such as gypsum and iron-bearing minerals such as pyrite.27 Additionally, combined with Section 2.1.2, CaO and Fe2O3 in coal ash components were mainly derived from gypsum and pyrite in feed coal.

### 2. RESULTS AND DISCUSSION

#### 2.1. Basic Properties of the Samples

##### 2.1.1. Coal Samples

Shengli coal from Xilingol League located in Inner Mongolia, northern China, was used in this paper. The particle size distribution of feed coal is shown in Figure 1. It can be seen that feed coal with particle size less than 5 mm accounts for only 1%. The particle size of feed coal fed into the Lurgi gasifier mostly is 5–50 mm, accounting for 77.79%. The results of the proximate analyses and ultimate analyses of feed coal have been analyzed in detail in previously published papers.26

The Shengli coal is low-ash, highly volatile, and medium-sulfur lignite.

![Figure 1. Particle size distribution of feed coal.](image)

**Figure 2.** XRD spectrum of feed coal: Q, quartz; G, gypsum; and P, pyrite.

**Table 2.** The percentage of major element oxides, as well as loss on ignition of feed coal, is listed in Table 1. The raw coal ash is mainly composed of SiO2, Al2O3, Fe2O3, CaO, and SO3, accounting for more than 86% of the total. The loss on ignition of ash is indicated at around 3.20%. In the Shengli lignite, the low contents of SiO2 and Al2O3 as well as high content of Fe2O3 and CaO result in lower ash melting points, according to results of Liu et al.15

The analysis results of the coal ash fusibility are given in Table 2. It can be seen that the coal ash shows medium melting behavior, beginning to soften at approximately 1192 °C and starting to flow at approximately 1220 °C. According to the classification of softening temperature (ST) of coal ash, Shengli coal ash belongs to low-fusibility ash. Ash fusion could be induced by low-melting-point minerals and low-temperature eutectics.28 Van Dyk et al.29 showed that due to the fluxing properties of the Ca and Fe minerals, Shengli coal rich in Ca and Fe has a low flow temperature (FT). At high temperatures, iron-bearing minerals reacted with quartz and anorthite to form low-temperature eutectics.

##### 2.2. Residual Carbon in Lurgi Gasification Ash

The particle size distribution of the Lurgi gasification ash and the residual carbon content are shown in Figure 3. The percentages of the Lurgi gasification ash with particle sizes <3, 3–6, 6–9, and >9 mm were 41.99, 25.11, 9.87, and 23.03%, respectively. It can be seen that most of the ash particles are smaller than 9 mm, accounting for 76.97%. Compared with the feed coal in Figure 1, it can be seen that...
Table 1. Ash Composition of Feed Coals (wt, %) and Loss on Ignition (LOI, %)

| oxide | SiO₂ | Al₂O₃ | Fe₂O₃ | CaO | MgO | TiO₂ | SO₃ | P₂O₅ | K₂O | Na₂O | LOI |
|-------|------|-------|-------|-----|-----|------|-----|------|-----|------|-----|
| content | 32.12 | 12.57 | 14.18 | 14.64 | 6.58 | 0.79 | 12.49 | 0.26 | 0.28 | 1.32 | 3.20 |

Table 2. Coal Ash Fusibility (Reducing Atmosphere)

| the ash fusibility of raw coal | deformation temperature (DT) | softening temperature (ST) | hemispherical temperature (HT) | flow temperature (FT) |
|-------------------------------|-----------------------------|-----------------------------|-----------------------------|---------------------|
| C high-fusibility ash         | 1158 °C                     | 1192 °C                     | 1210 °C                     | 1220 °C |
| C low-fusibility ash          | ST ≤ 1100 °C                | 1100–1250 °C                | 1250–1500 °C                | ST > 1500 °C |
| C fusible ash                 |                             |                             |                             |                    |
| C nonfusible ash              |                             |                             |                             |                    |

Figure 3. Particle size distribution of the Lurgi gasification ash and the residual carbon content.

after high-temperature and high-pressure treatment of feed coal in the Lurgi gasifier, the ash produced is mainly fine ash (<3 mm), and only a small part of coal can be sintered and agglomerated to form ash with larger particle size.

The residual carbon content in ash decreases with the increase in ash particle size, and the content of residual carbon in fine ash is significantly higher than that in coarse ash, which is consistent with the findings of Wagner et al. as shown in Figure 3. It can be seen that the residual carbon content of ash residue after gasification is generally low, with the maximum value of 3.52%, and the residual carbon content of ash with particle size >9 mm is only 1.49%, indicating that the Lurgi gasifier in Datang International Hexigen coal-to-SNG project has a high coal utilization rate. To improve the carbon conversion ratio in the gasifier, the particle size of the feed coal into the Lurgi gasifier should be increased appropriately because the coal with large particles stays in the gasifier for a long time and reacts more fully.

2.3. Mineral Composition Analysis of the Lurgi Gasification Ash. 2.3.1. Mineral Analysis of Gasiication Ash from Lurgi Gasifier. Figure 4 shows that the mineral composition of the Lurgi gasification ash is basically the same as that of the laboratory test ash, both containing a large amount of quartz and calcium-bearing high-temperature minerals. Additionally, more augite is present in the Lurgi gasification ash. The results show that the laboratory fixed-bed pressurized gasifier can simulate the on-site Lurgi gasifier well.

In the Lurgi gasification process gypsum (CaSO₄·2H₂O) contained in coal is first dehydrated to form CaSO₄. When the temperature reaches above 900 °C, CaSO₄ is reduced to CaS under the reducing atmosphere of the gasifier. When the temperature reaches 1000 °C, CaSO₄ is decomposed into CaO. Then, CaO continues a series of chemical reactions at high temperatures, forming anorthite and gehlenite with SiO₂ and Al₂O₃ in coal. The reaction is as follows (eqs 1–3)

\[
\begin{align*}
\text{CaSO}_4 & \rightarrow \text{CaO} + \text{SO}_3 \\
\text{CaO} + 2\text{SiO}_2 + \text{Al}_2\text{O}_3 & \rightarrow \text{CaAl}_2\text{Si}_2\text{O}_6 \\
2\text{CaO} + \text{SiO}_2 + \text{Al}_2\text{O}_3 & \rightarrow 2\text{CaO}\cdot\text{Al}_2\text{O}_3\cdot\text{Si}_2\text{O}_5
\end{align*}
\]

As shown in Figure 5, the SEM-EDS results show that the ash contains calcium aluminosilicate, which can be determined as gehlenite in combination with the XRD analysis.

As discussed in Section 2.1, the iron-bearing mineral contained in feed coal is pyrite. In an oxygen-rich atmosphere, the mineral decomposes at 400–500 °C to hematite (Fe₂O₃). When the temperature continues to rise, Fe₂O₃ and CaSiO₃ react to convert into calcium–iron silicate, which is stable at high temperature, at which CaSiO₃ is formed by the reaction of CaSO₄ in coal with SiO₂. Combined with XRD analysis, the phase may be pyroxene; the reaction is shown as (eq 4)

\[
\begin{align*}
\text{CaSi}_2\text{O}_5 + \text{Fe}_2\text{O}_3 & \rightarrow \text{CaFeSi}_2\text{O}_8
\end{align*}
\]

It can be clearly seen from Figure 6 that the average pore diameter of the porous structure is about 10 μm, and the sample is rich in iron. By XRD analysis, it can be found that iron exists in the form of hematite.

2.3.2. Mineral Composition Analysis of the Lurgi Gasification Ash with Different Particle Sizes. XRD diffractograms of four kinds of ash with different particle sizes of the Lurgi gasifier are shown in Figure 7. The main minerals of the Lurgi gasification ash with different particle sizes are the same,
which are quartz, augite, anorthite, hematite, and gehlenite. The Lurgi gasification ash with different particle sizes contains a large amount of an amorphous phase, which indicates that the minerals in coal have been completely melted and decomposed under high-temperature conditions and react with each other, resulting in the formation of ash with an amorphous phase as the main component. Meanwhile, quartz originating from coal reacts with other compounds to form silicate.

Minerals in XRD of the Lurgi gasification ash with different particle sizes were quantitatively analyzed, as shown in Figure 8a. With the increase in the ash particle size, the content of quartz in ash increased, while the content of gehlenite decreased, and the contents of anorthite and hematite increased first and then decreased. The content of quartz in the gasification ash is the highest, and quartz accounts for about 30−50% of the total mineral content in the gasification ash with different particle sizes. Due to the different particle sizes of coal in the Lurgi gasifier and the different residence times of coal particles in the gasifier, the reaction degree of coal particles is different, which leads to the difference in the mineral content in ash with different particle sizes. The results show that quartz in the ash tends to aggregate in coarse ash, while high-temperature minerals such as gehlenite tend to accumulate in fine ash.

Winnefeld et al.24 studied coal ash and showed that the higher the content of calcium in coal ash, the less the content of alkali aluminate silicate hydrates and the more obvious the pore structure. As shown in Figure 8b, calcium mineral content in ash decreases with the increase in particle size. Therefore, the fine ash has a relatively high content of calcium-bearing minerals, which may hinder its utilization as an additive in cement and concrete.

The correlation between the typical mineral content and the ash particle size is shown in Figure 9. The contents of high-temperature minerals (except quartz) in the ash were negatively correlated with the ash particle size (Figure 9a), and the contents of gehlenite and augite in the ash were also negatively correlated with the ash particle size (Figure 9c,d).
while the content of quartz was positively correlated with the ash particle size (Figure 9b). The results show that the quartz in the ash increased with the increase in the particle size, and the high-temperature minerals tended to nucleate on the ash with small particles, mainly including gehlenite and augite.

SEM images of the Lurgi gasification ash are shown in Figure 10. The Lurgi gasification ash mainly includes two types of particles: (1) irregular particles with a loose surface and many voids (Figure 10a) and (2) blocky or flaky large particles with a smooth surface. Under high magnification, there were a large number of fine particles and irregular massive particles in the ash, and a large number of small melt (fly ash) particles are attached to the surface of the ash (Figure 10b).

**2.4. Transformation Behavior of Calcium-Bearing Minerals during Lurgi Gasification.** As discussed in Section 2.1, the Lurgi gasification ash is dominated by calcium-bearing minerals. Exploring the transformation mechanism of calcium-bearing minerals is helpful in understanding the formation and transformation of high-temperature minerals in the Lurgi gasifier. This discussion is based on the experimental results of the Lurgi gasifier on a commercial scale, the thermodynamic simulation of mineral transformation, and the analysis of the influence of different ash compositions in feed coal on the formation and transformation of high-temperature minerals as shown in Figure 11. At 1000 °C, anorthite (CaAl2Si2O8) and gehlenite (Ca2Al2SiO7) become stable according to XRD results in the Sasol-Lurgi gasifier.22 The results of FactSage show that calcium aluminosilicate is formed above 1000 °C, and the anorthite and gehlenite were formed above 1150 °C in this work. The simulation results are
consistent with the previous experimental results. It can be seen from Figure 11 that the silica mineral form changes at high temperatures. After a slow solid-phase reaction, quartz is converted to tridymite and cristobalite, as shown in eq 5.

$$\text{SiO}_2 \rightarrow \text{tridymite} \rightarrow \text{cristobalite}$$

The main reactions of the three oxides in coal ash and their Gibbs free energy are shown in Table 3. It is well known that the value of the free energy can reflect the trend of the reaction. The $\Delta G$ of mullite was higher than that of gehlenite, anorthite, and calcium silicate. When CaO, Fe$_2$O$_3$, Al$_2$O$_3$, and SiO$_2$ coexist in a multicomponent system, the formation sequence was as follows: gehlenite (Ca$_2$Al$_2$Si$_2$O$_7$) → anorthite (CaAl$_2$Si$_2$O$_8$) → hercynite (Fe·Al$_2$O$_3$) and fayalite (2FeO·SiO$_2$) → mullite (Al$_6$Si$_2$O$_13$). The research shows that with the increase in the Fe$_2$O$_3$ content in coal ash, the formation of

![Figure 10. SEM of Lurgi gasification ash at (a) 430x and (b) 2000x.](image)

![Figure 11. Phase diagram of CaO$_2$·(SiO$_2$)$_2$·Al$_2$O$_3$·Fe$_2$O$_3$.](image)

| Table 3. Existing Mineral Reactions in Coal Ash and Their Gibbs Free Energy Changes$^{37,49}$ |
|----------------------------------------|---------|---------|---------|
| reaction                              | $\Delta G$ (kJ/mol) |
|                                       | 1000 °C  | 1100 °C  | 1200 °C  |
| R1 $2\text{SiO}_2 + 3\text{Al}_2\text{O}_3 \rightarrow \text{Al}_6\text{Si}_3\text{O}_{13}$ (R1) | $-15.40$ | $-18.06$ | $-20.70$ |
| R2 $\text{CaO} + 2\text{SiO}_2 + \text{Al}_2\text{O}_3 \rightarrow \text{CaAl}_2\text{Si}_2\text{O}_8$ (R2) | $-131.64$ | $-133.60$ | $-135.62$ |
| R3 $\text{CaO} + \text{SiO}_2 \rightarrow \text{CaSiO}_3$ (R3) | $-87.70$ | $-87.60$ | $-87.50$ |
| R4 $\text{CaO} + \text{SiO}_2 + \text{Al}_2\text{O}_3 \rightarrow \text{Ca}_2\text{Al}_2\text{Si}_2\text{O}_7$ (R4) | $-163.84$ | $-166.55$ | $-169.36$ |
| R5 $3\text{Al}_2\text{O}_3·2\text{Si}_2\text{O}_5 + \text{FeO} \rightarrow 2\text{FeO·Si}_2\text{O}_3 + \text{FeO·Al}_2\text{O}_3$ (R5) | $-75.78$ | $-69.60$ | $-63.38$ |

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mullite and wollastonite can be effectively inhibited, thus reducing the melting temperature of coal ash. In conclusion, the high Fe₂O₃ content in raw coal ash in an oxygen-rich atmosphere hinders the transformation of calcium-bearing minerals into high-melting-point mullite, resulting in a low ash flow temperature combined with the results of Section 2.1.2.

The surface of coal particles shrinks with the reaction of coal particles with gasification agents H₂O and O₂. Meanwhile, the included minerals soften and melt at high temperatures, forming high-temperature minerals. According to the results of XRD, the main high-temperature mineral was CaSO₄, which was formed by the rapid sulfation of CaO and the dehydration of gypsum. The fusion and consolidation of included minerals, as well as the sintering of excluded calcium-bearing minerals and excluded aluminosilicate minerals formed calcium-bearing silicoaluminate as the main high-temperature minerals, and the formation process is shown in Figure 12.

Figure 12. Formation and evolution mechanism of calcium-based minerals in the Lurgi gasification ash.

3. CONCLUSIONS

This study mainly determined and quantified the mineral transformation behavior, especially the transformation of calcium-bearing minerals in the Lurgi gasification ash with different particle sizes. The results showed that the ash produced by the Lurgi gasifier was mainly fine ash (<3 mm), and only a small part of coal could be sintered and agglomerated to form ash with larger particle size. The content of carbon residue in the Lurgi gasification ash decreased with the increase of particle size. Therefore, the fine ash has a relatively high content of calcium-bearing minerals, which may hinder its utilization as an additive in cement and concrete. The transformation mechanism of calcium-bearing minerals showed that the main high-temperature minerals were aluminosilicate, which was formed by the fusion and coalescence of included minerals and the sintering of excluded calcium-bearing minerals. Furthermore, FactSage modeling showed that when CaO, Fe₂O₃, Al₂O₃, and SiO₂ coexisted in a multicomponent system, calcium-bearing minerals were formed earlier than iron-bearing minerals. The high Fe₂O₃ content in Shengli lignite hinders the transformation of calcium-bearing minerals into high-melting-point mullite, resulting in a low ash flow temperature.

4. EXPERIMENTAL SECTION

4.1. Field Tests. The planned scale of Datang International Hexigten coal-to-SNG Co., Ltd. project is 12 million cubic meters per day. Operation parameters and gas compositions in the Datang Hexigten coal-to-SNG Project are shown in Table 4. The gasification agent for the Lurgi gasifier is a mixture of steam and oxygen, and the temperature and pressure selected for commercial gasification tests are 1100 °C and 4 MPa, respectively. According to the table, the methane content of crude gas produced by the on-site Lurgi gasifier reaches 13%. The ratio of H₂ to CO is close to 3 to 1, which is favorable for the methanation of syngas. It can be seen that the annual output of the on-site Lurgi gasification ash can reach 2.37 million tons.

The gasification ash was taken from the on-site of Datang International Hexigten coal-to-SNG Co., Ltd. The different particle size ash samples of the Lurgi gasifier are shown in Figure 13. The sampling method of ash samples is detailed in the previously published journal articles.

4.2. Laboratory Tests. The pressurized fixed-bed gasifier was used for laboratory gasification tests, as shown in Figure 14. It consisted of a reaction tube, electric heaters, pressure controllers, and a condenser. The reaction tube was made of an 800H nickel–iron–chromium alloy 50 mm in diameter and 600 mm in length.

The feed coal (40 g) with a particle size of 5–13 mm (the particle size range of coal used in the gasification site is 5–50 mm) was put into the pressurized fixed-bed gasifier and heated to 1100 °C with a rate of 10 °C/min at 4 MPa, and Al₂O₃ porcelain balls were placed underneath and on the coal samples. The gasification agent mixture of oxygen and steam was injected and reacted with the coal sample for 30 min at 1100 °C. The gasification ash was collected when the furnace cooled to ambient temperature.

4.3. Thermodynamic Modeling. Thermodynamic modeling can assist in understanding, as well as predicting, what may happen to coal and mineral sources during gasification at high temperatures. In this paper, the phase diagram and equilibrium modeling in FactSage 7.2 were used to calculate the transformation behaviors of minerals at different temperatures in a specified atmosphere. The ash components of the

Table 4. Operation Parameters and Gas Compositions in the Datang Hexigten Coal-to-SNG Project

| Feed coal (million t/a) | Ash (million t/a) | SNG (million N m³/day) | H₂ | CO | CO₂ | CH₄ | Ca²⁺ | H₂S |
|------------------------|------------------|------------------------|----|----|-----|-----|------|-----|
| 18.25                  | 2.37             | 12                     | 39.04 | 14.45 | 31.89 | 12.82 | 0.50 | 0.70 |
feed coal were mainly SiO₂, Al₂O₃, Fe₂O₃, and CaO, and the ratio of silicon to calcium was 2.3. Therefore, the phase diagram in FactSage was used to calculate the quasi-ternary phase diagram of (SiO₂)₂.₃CaO−Al₂O₃−Fe₂O₃ for analyzing the effect of different ash compositions on mineral transformation. Also, the calculated temperature range was 800−1350 °C with a pressure of 4 MPa, and the step size was 50 °C.

4.4. Product Analysis.

(1) Proximate analyses were determined in accordance with the Chinese Standard GB/T 212-2008. Ultimate analyses, including carbon, hydrogen, nitrogen, and total sulfur, were measured following the Chinese Standards GB/T 476-2008, GB/T 19227-2008, and GB/T 214-2007.

(2) The ash composition was determined using a Japanese Seiko Co., Ltd. model, SEA-1000A X-ray fluorescence spectrometer, according to GB/T 1574-2007.

(3) The feed coal and the Lurgi gasification ash were crushed, ground, and sieved. Minus 200 mesh samples were selected for XRD analysis, which was performed on a powder diffractometer (D/max-2500/pc XRD, Rigaku, Japan) with a Ni-filtered Cu Kα radiation and a scintillation detector. The XRD pattern was recorded over a 2θ range of 2−90° at a scan rate of 9°/min and a step size of 0.02°. Jade6.5 (MDI, Livermore, CA) software was used to analyze the XRD curve for qualitative and quantitative analysis. To evaluate more fully the petrological characteristics of the coal gasification residue, a scanning electron microscope (SEM, S-4300, Japan) and an energy-dispersive X-ray spectrometer were used to study the morphology of the minerals at an accelerating voltage of 15 kV.

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Notes
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