Research Article

Mineralogical Characteristics of Phosphate Tailings for Comprehensive Utilization

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The mineralogical characteristics of a phosphate tailing were studied, and the occurrence state, mineral types, and embedded characteristics of phosphorus in the phosphate tailings were ascertained. The results show that the main minerals in the phosphate tailings are collophane. The main gangue minerals are quartz, dolomite, calcite, a small amount of potassium feldspar, plagioclase, chlorite, etc. Monazite was found in phosphate tailings. In addition, the coarse grain size of quartz and feldspar and fine embedded particle size of calcite and dolomite are also the main factors affecting the mineral processing of phosphate tailings. According to the analysis of mineralogical characteristics, the physical and chemical properties of phosphate tailings provided the basis for comprehensive utilization of phosphorus resources.

1. Introduction

A large number of phosphate tailings are produced in the process of phosphate ore dressing, and its output accounts for 20%–30% of the raw ore [1]. Part of the phosphate ore is mainly processed by ore washing, resulting in tailings containing phosphate and clay [2]. Traditionally, most of the phosphate tailings are mainly stored in tailings dams, which occupy a large amount of land with high disposal costs and resulting environmental hazards [3, 4]. With the development of “sustainable mining” [5], backfilling which is composed of mine tailings, cementitious material [6], and processed mine water [7], as a high-density slurry pumped into mined voids from underground mine operations, has increasingly been used. The reuse of tailings in backfilling operation to form an underground support system and a working platform [8] reduces the amount of waste required to be surface-disposed, thus mitigating the potential economic and environmental impacts associated with tailings disposal [9] and assists with waste management. Because P2O5 content in phosphate rock has an important impact on its application in industry and agriculture [10], reducing the phosphorus grade in phosphate tailings also helps to mitigate the amount of wastes for disposal. Therefore, more attention has been paid to the recovery of phosphorus from phosphate tailings [11]. The mineral characteristics of phosphate rock directly influence the mineral processing process [12]; on the other hand, the physical and chemical properties of phosphate tailings depend on the characteristics of phosphate rock and mineral processing process. Through the study of process mineralogy of the ore, we can find out the factors affecting mineral processing and formulate a suitable separation process to achieve the expected mineral processing index [13, 14]. Practice has proved that process mineralogy has guiding significance in mineral processing production, the transformation of technological process, the optimization of mineral processing process design, and the improvement of mineral processing process.
[15–17], while the application of automatic mineralogical tools provides more information about ore characteristics, process particle size, etc. [18–20]. The recovery of apatite from phosphate tailings can reduce the amount of tailings [21]. It plays a significant role in the recovery of phosphorus minerals in phosphate tailings. In this paper, the process mineralogy of phosphate tailings was studied by means of chemical multielement analysis, microscopic observation of ground smooth slices, energy spectrum analysis of scanning electron microscope (SEM), and X-ray diffraction (XRD). By finding out the structure, occurrence state, mineral types, and distribution characteristics of phosphate tailings, this study grasps the properties of phosphate tailings, providing a basis for the separation of phosphate tailings, and the physical and chemical properties of phosphate tailings, also providing a guide for further development of backfilling process.

2. Materials and Methods

The sample for this test is a phosphate tailing; the chemical composition and mineral composition of phosphate tailings were analyzed. The mineral structure, embedded properties, the mineral morphology, and element distribution of the main minerals in phosphate tailings were measured by polarizing microscope (Leica DM4500P), scanning electron microscope (Zeiss EVO18), and energy-dispersive spectrometer (Bruker XFLASH6100).

3. Results and Discussion

3.1. Multielement Analysis of Phosphate Tailings. The multielement analysis of phosphate tailings is carried out, and the results are shown in Table 1.

It can be seen from Table 1 that the P$_2$O$_5$ content of phosphate tailings is 15.76%, the SiO$_2$ content is 22.49%, the MgO content is 3.42%, the CaO content is 34.68%, and the content of sesquioxide (Al$_2$O$_3$ + Fe$_2$O$_3$) is 2.28%. In addition, the heavy metal elements such as Pb and Cd in phosphate tailings were analyzed, and their contents were all relatively low.

3.3. Mineral Composition. Through the study of X-ray diffraction spectrum, combined with light section microscope observation, chemical multielement analysis, and scanning electron microscope energy spectrum analysis, it is found that there are altogether 13 kinds of minerals in the ore, including phosphate, oxide, silicate, carbonate, and natural elements. Among them, phosphate accounts for 45%, oxide accounts for 18.3%, silicate accounts for 8%, carbonate accounts for 28.3%, and natural elements are few. The main useful minerals are collophane; the main gangue minerals are quartz, dolomite, calcite, and a small amount of potassium feldspar, plagioclase, chloride, etc. The X-ray diffraction spectrum of the sample is shown in Figure 2, and the mineral composition is shown in Table 2.

3.2. Phosphate Tailings Mineral Structure. Under a microscope, the main structures of minerals in phosphate tailings are as follows: Colloidal cryptocrystalline structure: one of the main structures, the colloidal phosphate monomer in the ore is cryptocrystalline; it is difficult to observe the mineral crystal particle size under the microscope, only its aggregate morphology can be observed, and some of them are contaminated with clay minerals to form a colloidal cryptocrystalline structure, as shown in Figure 1(a). Fine sand debris structure: one of the main structures, most of the collophane and quartz in the minerals are sand debris, with good abrasion, round-sub-round, and the particle size (0.06–0.3 mm) is mostly in the fine sand size. The cement is mainly dolomite, mainly porous cementation, as shown in Figure 1(b). Oolitic structure: part of the collophane sand debris has a zoning structure, which is formed by the relative enrichment of inclusions, forming an oolitic structure, as shown in Figure 1(c). Inclusion structure: one of the main structures in which some collophane in the ore contains pulverulent organic matter, which is difficult to identify under the microscope and constitute poikilitic texture, as shown in Figure 1(d).

Fine-grained structure: one of the secondary structures, some of the dolomite in the ore has a particle size between 0.06 and 0.3 mm and a degree of autotroph, and the particles are distributed in close contact with each other, or between collophane, forming this structure, as shown in Figure 1(e). Micropowder crystal structure: one of the secondary structures, some dolomite and quartz are in the form of micropowder crystals with a particle size of 0.01 mm–0.06 mm, the particles are semiautogenous-heteromorphic, and they are in close mosaic contact with each other, and the aggregate shape is irregular, forming the structure shown in Figure 1(f). Microscopic scalelike structure: one of the rare structures in which clay minerals such as chlorite, sericite, and kaolinite in ores are microscale, distributed between collagene aggregates or surrounded by collagenic aggregates, forming a microscopic scaly structure, as shown in Figure 1(g). Slab-column structure: one of the rare structures in which plagioclase is scattered in the form of plagioclase in the ore, as shown in Figure 1(h).

3.4. Dissemination Characteristics of Main Minerals

3.4.1. Phosphate. The collophane in the phosphate tailings is mostly in the form of sand debris with high roundness, which is mainly cemented by dolomite and calcite; a small part of collophane is poorly ground, showing subangular and irregular granular. Most of the collophane in the phosphate tailings are wrapped with fine-grained organic matter inclusions with particle size less than 0.01 mm, which has a great impact on the flotation of phosphate. The microscope of embedded characteristics is shown in Figure 5.

In terms of embedded particle size, the particle size of collophane aggregate is mainly concentrated in the range of 0.03–0.5 mm, and the fine particle size of <0.07 mm accounts for 35.8%. The particle size distribution of collophane aggregate is shown in Figure 4.

From the elements detected in the collophane, the dust spots in the collophane should be a mixture of clay minerals
In order to investigate the composition difference of different zones in oolites, the energy spectrum analysis of collophane oolites was carried out. The results show that the main difference of different zones in oolites lies in the different carbonaceous content of inclusions, forming oolitic structure. The electronic image is shown in Figure 6, and the energy spectrum analysis results are shown in Table 4.

Monazite: occasionally seen under electron microscope, connected with quartz, with particle size of 0.02–0.03 mm. The backscattered electron diagram and energy spectrum of monazite are shown in Figure 7.

3.4.2. Oxide. The oxide is mainly quartz, which is one of the main gangue minerals. It is distributed between calcite and dolomite particles in the form of xenomorphic granular and clastic. A few of them are wrapped in collophane. The pschepicity of clastic quartz is poor, which is generally mixed with dolomite and calcite, as shown in Figure 8. The grain size of quartz is between 0.03 and 0.2 mm, and 37.2% is less than 0.07 mm. The particle size distribution of quartz is shown in Figure 9.

No phosphorus element was detected in quartz by SEM energy spectrum analysis. The backscattered electron diagram and energy spectrum of quartz are shown in Figure 10. The results of energy spectrum analysis of quartz are shown in Table 5.

3.4.3. Carbonate. Carbonate minerals mainly exist in the form of dolomite and calcite, both of which are the main gangue minerals. They are semieuhedral to xenomorphic granular, closely connected with each other, and mainly distributed in collophane, quartz, and feldspar clasts, with different particle sizes. In the microcrystalline fine grain size scale, the micrographs are shown in Figure 11. The particle size ranges from 0.01 to 0.5 mm, and 60.9% of them are

### Table 1: Results of multielement analysis of phosphate tailings.

| Element | P₂O₅ | SiO₂   | MgO   | CaO   | TFe₂O₃ | CO₂   | Organic C | Total C |
|---------|------|--------|-------|-------|--------|-------|-----------|---------|
| Content (%) | 15.76 | 22.49  | 3.42  | 34.68 | 0.60   | 13.00 | 0.02      | 3.72    |
| Content (%) | 0.38  | 1.68   | 0.42  | 0.50  | 0.0002 | 0.0006| 0.002     |         |

Figure 1: Phosphate tailings’ mineral structure (TSPL represents transmitted single polarized light, and TCPL represents transmitted crossed polarized light). (a) Colloidal aphanitic collophane (Ap) detritus (TSPL). (b) Fine-grained sand clastic collophane (Ap), quartz (Qtz) (TSLP). (c) Oolitic collophane detritus (TSPL). (d) Dusty substance coated with collophane (Ap) (TSPL). (e) Fine-grained (0.1–0.3 mm) dolomite (Dol) (TSPL). (f) Microcrystalline quartz (Qtz) aggregates (TCPL). (g) Microscopic scalychlorite (Chl) (TCPL). (h) Allo-triomorphic granular plagioclase (Pl) (TSPL).
Table 2: Mineral composition.

| Type         | Mineral       | Molecular formula                     | Size (mm)       | Content (%) |
|--------------|---------------|---------------------------------------|-----------------|-------------|
| Phosphate    | Collophane    | Ca$_2$Ca$_3$(PO$_4$)$_3$(OH,F)        | <0.004, aggregate 0.03–0.5 | 45.0        |
|              | Monazite      | Ce[PO$_4$]                            | 0.02–0.03       | Very few    |
| Oxide        | Quartz        | SiO$_2$                               | 0.03–0.2        | 18.3        |
|              | Limonite      | FeOOH                                 | 0.04–0.1        | Very few    |
|              | Anatase/rutile| TiO$_2$                               | 0.02–0.05       | Very few    |
| Silicate     | Plagioclase   | Na[Al$_2$Si$_3$O$_8$]                 | 0.06–0.2        | 4           |
|              | Potassium feldspar | K[Al$_2$Si$_3$O$_8$]             | 0.06–0.2        | 3           |
|              | Chlorite      | (Mg, Fe, Al)$_3$(OH)$_6$[(Mg, Fe, Al)$_3$[(Si, Al)$_2$O$_10$](OH)$_2$] | <0.05          | <1          |
|              | Sericite      | K[Al$_2$[Al$_2$Si$_3$O$_10$](OH)$_2$] | 0.01–0.1        | Very few    |
|              | Sericite      | ZrSiO$_4$                             | 0.01–0.04       | Very few    |
| Carbonate    | Dolomite      | CaMg[CO$_3$]$_2$                      | 0.01–0.5        | 16.3        |
|              | Calcite       | CaCO$_3$                              | 0.01–0.5        | 12          |
| Natural elements | Carbonaceous | C                                     | <0.01           | Very few    |
| Sum          | —             | —                                     | —               | 99.6        |

Figure 2: X-ray diffraction spectrum of the sample.

Figure 3: Embedded characteristics of phosphate (TSPL represents transmitted single polarized light). (a) Clastic collophane (Ap), TSPL. (b) Clastic collophane (Ap), TSPL. (c) Collophane (Ap) and dolomite (Dol) connected, TSPL. (d) Oolitic collophane (Ap), TSPL.
Figure 4: Particle size distribution of collophane aggregate.

Figure 5: Backscattered electron diagram and energy spectrum of collophane.
Table 3: Results of energy spectrum analysis of collophane.

| Point | C   | O   | F   | Na  | Mg  | Al  | Si  | P   | Ca  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 6587  | 4.90| 36.18| 4.65| 0.44| —   | —   | —   | 14.22| 39.61|
| 6588  | 4.05| 34.46| 4.40| 0.42| 0.09| 0.06| 0.25| 14.36| 41.90|
| 6589  | 3.87| 35.91| 4.03| 0.34| 0.10| 0.20| 0.76| 13.08| 41.69|
| 6590  | 4.87| 37.35| 4.52| 0.55| 0.20| 0.15| 0.37| 13.67| 38.31|
| 6591  | 4.00| 30.43| 3.00| 0.17| 0.01| 0.16| 0.42| 15.90| 45.91|
| 6601  | 3.72| 36.72| 4.48| 0.72| 0.19| —   | 0.25| 13.60| 39.32|
| 6602  | 3.26| 36.42| 4.72| 0.62| 0.16| —   | —   | 13.59| 41.24|
| 6603  | 2.38| 35.89| 4.50| 0.64| 0.10| —   | —   | 13.85| 42.64|
| Average| 3.88| 35.42| 4.29| 0.49| 0.11| 0.07| 0.26| 14.03| 41.33|

Oxide content (%)

| Point | Na  | Mg  | Al  | Si  | P   | Ca  | Na  | Mg  | Al  | Si  | P   | Ca  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 6645  | 0.66| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6646  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6647  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6648  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6649  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6650  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6651  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6652  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6653  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6654  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|
| 6655  | 0.67| 0.18| 0.13| 0.56| 32.15| 57.83|

Figure 6: Backscattered electron diagram and energy spectrum of collophane oolite.

Table 4: The energy spectrum analysis results.

| Point | C   | O   | F   | Na  | Mg  | Al  | Si  | P   | Ca  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 6645  | 4.56| 34.01| 4.20| 0.51| 0.07| —   | —   | 13.92| 42.73|
| 6646  | 5.18| 36.66| 4.83| 0.55| 0.17| —   | —   | 13.40| 39.21|
| 6647  | 4.45| 35.71| 4.29| 0.41| 0.14| —   | —   | 13.68| 41.33|
| 6648  | 5.80| 38.27| 5.34| 0.37| 0.06| 0.00| —   | 12.47| 37.69|
| 6649  | 5.00| 36.96| 4.44| 0.43| 0.05| —   | —   | 13.06| 40.05|
| 6650  | 5.06| 36.48| 4.72| 0.68| 0.19| —   | —   | 13.49| 39.38|
| 6651  | 6.68| 48.15| —   | 0.83| 0.29| —   | —   | 11.54| 32.52|
| 6652  | 5.38| 36.69| 4.80| 0.65| 0.18| —   | —   | 13.13| 38.98|
| 6653  | 4.78| 36.93| 4.90| 0.69| 0.17| —   | —   | 13.17| 39.10|
| 6654  | 5.33| 38.46| 5.22| 0.76| 0.31| 0.12| 0.43| 12.74| 36.62|
| 6655  | 3.75| 31.80| 3.50| 0.63| 0.24| —   | —   | 14.52| 45.55|
| 6656  | 4.20| 34.16| 3.77| 0.42| —   | —   | —   | 14.92| 42.53|
| 6657  | 8.19| 36.47| 5.04| 0.37| 0.15| 0.07| 0.17| 13.25| 36.30|
| 6658  | 9.25| 32.57| 4.27| 0.25| —   | —   | —   | 14.16| 39.49|
smaller than 0.07 mm. The distribution size of dolomite and calcite is shown in Figure 12.

According to the energy spectrum analysis of scanning electron microscope, no phosphorus element is detected in dolomite and calcite, as shown in Table 6. The backscattered electron diagram and energy spectrum image are shown in Figure 13.

3.4.4. Silicate. Plagioclase and potassium feldspar are a small amount of gangue minerals, mainly in clastic form, distributed between dolomite and calcite in star shape, with poorly rounded, angular, and tabular shape, and the particle size is mainly 0.06–0.2 mm. The micrograph is shown in Figure 14. Chlorite: Microscale, occasionally seen between dolomite particles, particle size <0.05 mm, as shown in the micrograph of Figure 1(g).

3.4.5. Natural Elements. Carbonaceous: it is organic carbon. The monomer is mainly cryptocrystalline and wrapped in colophane. No independent carbonaceous is found. The

![Figure 7: Backscattered electron diagram and energy spectrum analysis of monazite.](image)

![Figure 8: Embedded characteristics of Quartz (TCPL represents transmitted crossed polarized light). (a) Quartz (Qtz) and dolomite connected, TCPL. (b) Clastic angular quartz (Qtz), TCPL.](image)
3.5. Distribution of Phosphorus. The phosphorus element (P$_2$O$_5$) is mainly distributed in collophane as an independent mineral. SiO$_2$ mainly exists in quartz in the form of independent minerals, a small amount in plagioclase, potassium feldspar, and chlorite, MgO mainly exists in dolomite in the form of independent minerals, and Al$_2$O$_3$ mainly exists in plagioclase and potash feldspar in the form of independent minerals. TFe$_2$O$_3$ mainly occurs in chlorite as isomorphism, and a small amount in limonite in the form of independent minerals.

Typical distribution of each element in the ore is shown in Figures 15 and 16. According to the element distribution in Figures 15(b) and 16(b), there are less inclusions in collophane, mainly pulverulent organic matter and clay, and a small amount of fine-grained quartz, which are very difficult to remove in mineral processing. Dolomite and calcite are mainly distributed in the form of cement between the collophane clasts, which are also the main ore associated with the collophane.
Figure 11: Embedded characteristics of carbonate minerals (dolomite and calcite) (TCPL represent transmitted crossed polarized light). (a) Euhedral rhombohedral dolomite (Dol), TCPL. (b) Calcite (Cal) and quartz (Qtz) connected, TCPL. (c) Calcite (Cal) and quartz (Qtz) connected, TCPL.

Table 6: Energy spectrum analysis results of dolomite and calcite.

| Number | C  | O    | Mg  | Ca  | Mineral  |
|--------|----|------|-----|-----|----------|
| 6581   | 12.01 | 49.90 | 10.71 | 27.39 | Dolomite |
| 6582   | 11.06 | 50.13 | 10.75 | 28.07 | Dolomite |
| 6684   | 13.04 | 50.28 | 0.14  | 36.54 | Calcite  |
Figure 13: Backscattered electron diagram and energy spectrum image of dolomite.

Figure 14: Embedded characteristics of silicate minerals (TCPL represents transmitted crossed polarized light). (a) Clastic potash feldspar (Kfs), TCPL. (b) Clastic plagioclase (Pl), TCPL.

Figure 15: Continued.
Figure 15: Backscattered electron diagram and element distribution diagram of collophane, quartz, dolomite, etc. (a) Backscattered electron image. (b) Backscattered element diagram. (c) Regional element distribution map.

Figure 16: Continued.
4. Conclusions

There are altogether 13 kinds of minerals in the ore, including phosphate, oxide, silicate, and natural elements, in which phosphate accounts for 45%, oxide accounts for 18.3%, silicate accounts for 8%, carbonate accounts for 28.3%, and natural elements are few; the main ore mineral is collophane, and the main gangue minerals are quartz, dolomite, calcite, a small amount of potassium feldspar, plagioclase, chlorite, etc. The main mineral structures have colloidal aphanitic texture, fine-grained sand chip structure, oolitic structure, and inclusion structure. The combination of mineral aggregates is relatively close, and the way of mutual cementation and association is relatively simple.

\[ \text{P}_2\text{O}_5 \text{ mainly exists in collophane as an independent mineral, MgO as an independent mineral in dolomite, SiO}_2 \text{ as an independent mineral in quartz, Al}_2\text{O}_3 \text{ in potassium feldspar and plagioclase as an independent mineral, and TiO}_2\text{O}_3 \text{ in chlorite in isomorphic form in the form of independent limonite.} \]

The particle size of collophane aggregate is mainly between 0.03 and 0.5 mm. The grain size of quartz is between 0.03 and 0.2 mm; the grain size of dolomite and calcite is between 0.01 and 0.5 mm; some of them are in the range of powder crystal (<0.06 mm), and some belong to fine-grained distribution; the grain size of potassium feldspar and plagioclase is between 0.06 and 0.2 mm. The granularity of quartz and feldspar is coarser, and the granularity of calcite and dolomite is finer.

![Figure 16: Backscattered electron diagram and element distribution diagram of collophane, calcite, and quartz. (a) Backscattered electron image. (b) Backscattered element diagram. (c) Regional element distribution map.](image-url)
The phosphate tailings contain relatively high content of Si and Ca and low content of heavy metals such as Cd and Pb, which has little impact on the environment. However, the tailings still have the value of comprehensive utilization because the content of P_2O_5 is 15.76%. Therefore, the phosphorus mineral in tailings can be further recovered by flotation, and then it can be used as filling material. Hence, the effect of phosphorus on the backfilling environment is also reduced. Furthermore, an appropriate filling material ratio can be designed to achieve the appropriate filling strength according to the mineral composition, chemical composition, and particle size distribution of phosphate tailings.

Data Availability
The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest
The authors declare that they have no conflicts of interest regarding the publication of this paper.

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References
[1] Q. Chen, Q. Zhang, A. Fourie, and C. Xin, “Utilization of phosphogypsum and phosphate tailings for cemented paste backfill,” Journal of Environmental Management, vol. 201, pp. 19–27, 2017.
[2] P. Zhang, “Comprehensive recovery and sustainable development of phosphate resources,” Procedia Engineering, vol. 83, pp. 37–51, 2014.
[3] Y. Chen, Z. Wei, M. Irfan, J. Xu, and Y. Yang, “Laboratory investigation of the relationship between electrical resistivity and geotechnical properties of phosphate tailings,” Measurement, vol. 126, pp. 289–298, 2018.
[4] K. Zheng, J. Zhou, and M. Gbozee, “Influences of phosphate tailings on hydration and properties of Portland cement,” Construction and Building Materials, vol. 98, pp. 593–601, 2015.
[5] Y. Zhao, A. Taheri, A. Soltani et al., “Strength development and strain localization behavior of cemented paste backfills using portland cement and fly ash,” Materials, vol. 12, no. 20, p. 3282, 2019.
[6] Q. Liu, D. Liu, X. Liu, F. Gao, and S. Li, “Research and application of surface paste disposal for clay-sized tailings in tropical rainy climate,” International Journal of Mining Processing, vol. 157, pp. 227–235, 2016.
[7] Y. Zhao, A. Taheri, M. Karakus, Z. Chen, and A. Deng, “Effects of water content, water type and temperature on the rheological behaviour of slag-cement and fly ash-cement paste backfill,” International Journal of Mining Science and Technology, vol. 30, no. 3, pp. 271–278, 2020.
[8] Y. Zhao, A. Soltani, A. Taheri, M. Karakus, and A. Deng, “Application of slag–cement and fly ash for strength development in cemented paste backfills,” Minerals, vol. 9, no. 1, p. 22, 2019.
[9] D. M. Franks, D. V. Boger, C. M. Côte, and D. R. Mulligan, “Sustainable development principles for the disposal of mining and mineral processing wastes,” Resources Policy, vol. 36, no. 2, pp. 114–122, 2011.
[10] M. A. Aitken, “Recovery of apatite from ore slimes using centrifugal heavy liquid separation,” JOM, vol. 71, no. 9, pp. 3202–3208, 2019.
[11] H. Boujel, G. Daldoul, H. Tilli et al., “The beneficiation processes of low-grade sedimentary phosphates of Tozeur-Nefta deposit (Gaﬂa-Melalexouu basin: south of Tunisia),” Minerals, vol. 9, no. 1, p. 2, 2019.
[12] A. Z. M. Abouzeid, A. T. Negm, and D. A. Elgillani, “Upgrading of calcareous phosphate ores by flotation: effect of ore characteristics,” International Journal of Mineral Processing, vol. 90, no. 1–4, pp. 81–89, 2009.
[13] F. Li et al., “Application of process mineralogy study in phosphate beneficiation in Yichang,” Industrial Minerals & Processing, vol. 43, no. 05, pp. 9–11, 2014.
[14] W. Ling, L. Kailua, and L. Zhengya, “Process mineralogy of a gold multi-metal ore in beiya, yunna,” Procedia Environmental Sciences, vol. 12, pp. 949–956, 2012.
[15] M. Abdollahi, A. Bahrami, M. S. Mirmohammadi, F. Kazemi, A. Danesh, and Y. Ghorbani, “A process mineralogy approach to optimize molybdenite flotation in copper - molybdenum processing plants,” Minerals Engineering, vol. 157, Article ID 106557, 2020.
[16] X. L. Ye and Y. W. Xiao, “Application of process mineralogy for process optimization in concentrator plant,” Nonferrous Metals (Mineral Processing Section), vol. 72, no. 4, pp. 13–33, 2020.
[17] J. Zhong et al., “Experimental study on process mineralogy of a collophanite in Yunnan,” Industrial Minerals & Processing, vol. 44, no. 03, pp. 4–5, 2015.
[18] Y. Jiao, K.-H. Qiu, P.-C. Zhang, J.-F. Li, W.-T. Zhang, and X.-F. Chen, “Process mineralogy of Dalucao rare earth ore and design of beneficiation process based on AMICS,” Rare Metals, vol. 39, no. 8, pp. 959–966, 2020.
[19] V. G. Greb, A. Guli, H. Weigand, B. Schulz, and M. Bertau, “Understanding phosphorus phases in sewage sludge ashes: a wet-process investigation coupled with automated mineralogy analysis,” Minerals Engineering, vol. 99, pp. 30–39, 2016.
[20] Y. Gu, R. P. Schouwstra, and C. Rule, “The value of automated mineralogy,” Minerals Engineering, vol. 58, pp. 100–103, 2014.
[21] M. S. Oliveira, R. C. Santana, C. H. Ataide, and M. A. S. Barrozo, “Recovery of apatite from flotation tailings,” Separation and Purification Technology, vol. 79, no. 1, pp. 79–84, 2011.