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Non-explosive mining and waste utilization for achieving green mining in underground hard rock mine in China

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Abstract: Innovations of mining technologies were proposed by beneficial utilizations of unfavorable factors such as high geostress, high geotemperature and high mining depth to achieve green mining as mining depth increases inevitably. Cuttability of deep hard rock was investigated by experimental and regressed analyses to find the reasonable stress adjustment method to improve non-explosive mechanized fragmentation for hard ore-rock. A non-explosive mechanized and intellectualized mining method was proposed to continuously and precisely exploit phosphate underground, which promoted the high-recovery, low-waste and high-efficiency exploitation of phosphate with recovery rate over 90%, dilution rate near 5% and cutting efficiency about 107.7 t/h. A circular economy model and the backfill system were proposed to conduct resource utilizations of solid waste, by which the utilization amount of waste increased year after year. In 2018, the utilization amounts of phosphogypsum, yellow phosphorus slag and waste rock increased to 1853.6×10^3 t/a, 291.1×10^3 t/a and 1493.8×10^3 t/a, respectively.

Key words: hard rock mine; non-explosive mining; waste backfilling; circular economy; waste utilization; green mining

1 Introduction

Mining technology has been profoundly developed as the rapid innovation of mining machine, manufacturing industry and information technology, and has to be innovated from the heavy pressures of environmental protection and occupational safety. The fully non-explosive mechanized mining and heading machines and the gangue backfill technology have provided a significant support for massive, high-efficient, safe, intelligentized and green excavation of underground coal resource [1−3]. However, the hard ore-rock in non-coal mine is still mainly excavated by drilling and blasting so far, which hinders the green mining of deep hard ore-rock with goals of high-recovery, high-efficiency, low-waste and low strata damage [4−8]. Therefore, the non-explosive mechanized excavation method based on tunnel boring machine (TBM) and roadheader has been a preliminary development in mining and tunnelling engineering as an alternative technology to drilling and blasting method in hard rock, owing to some advantages like continuous operation, personnel safety, high construction quality and low excavation disturbance [9−12]. For non-explosive excavation machine, the mining parameters, such as cutting height, cutting speed, cutting power, feed rate, and cutting sequence can be flexibly adjusted to accommodate with ore-rock properties. The adaptability of mining machine is based on the precise ore-rock model including structural, geological, geomechanical and grade properties of ore-rock using deterministic and geostatistical modeling methods [13−17]. Then, the conception and practice of intellectualized mining has been conducted to achieve fine exploitation of underground minerals based on the multidimensional information perception and intellectualized excavation machine [18,19]. Adopting non-explosive mechanized and intellectualized mining, the qualified ores can be precisely excavated with low waste rock mined, which can significantly reduce the costs of mineral processing and the production of mine waste and increase the recovery of resources. In addition, the non-explosive mining has no blasting disturbance for strata and can continuously cut ore-rock, which can improve overburden stability and mining efficiency. Relative to

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non-explosive mechanized and intellectualized mining, the waste backfilling is the other strategy to promote green mining of underground minerals, by conducting resource utilization of solid waste and filling mined-out areas for low-waste exploitation of ore and movement control of strata, respectively. Therefore, the non-explosive mining and waste backfilling are the significant strategies to achieve the green mining of underground minerals.

In this work, a non-explosive mechanized mining method using a roadheader with many conical picks mounted was proposed and conducted to continuously cut phosphate ore in the Kaiyang Phosphate Mine, Guizhou, China. An intelligent mine was preliminarily established to achieve fine exploitation of underground phosphate with high recovery, high efficiency and low waste. Furthermore, a circular economy model and backfill system were proposed and constructed to promote resource utilizations of solid waste produced from phosphate mining and phosphorus chemical industry, such as phosphogypsum, yellow phosphorus slag and waste rock. Finally, the recovery rate and dilution rate of phosphate ore and the utilization amounts of phosphogypsum, yellow phosphorus slag and waste rock were counted to evaluate the effectiveness of the efforts mentioned above.

2 Innovations of mining technologies

The statistical data plotted in Fig. 1 and Fig. 2 show that the maximum mining depth has exceeded 4000 m, and the mining industries have entered deep mining or ultra deep mining according to the associated definitions in different countries. The mines whose mining depths are greater than 1000 m in the world are mainly non-ferrous metal mines, and all of them are hard rock mines. The deep mining in hard ore-rock will be an inevitable trend for exploitations of metal mineral resources.

High geostress, high geotemperature and high mining depth are the three major unfavorable factors that impede deep mining and cause disasters. High geostress may lead to rockburst, high temperature causes poor working environment, and high mining depth leads to difficulties in lifting and drainage. Many previous studies focus on controlling and removing these unfavorable factors. Actually, these unfavorable factors can be changed into beneficial effects: (1) high geostress is beneficial to rock fracturing and rock fragmentation; (2) high geotemperature can accelerate the interaction between minerals and leaching solution during in-situ leaching mining; (3) high mining depth can produce high hydraulic pressure, which can power the mining equipment and hydraulic lifting. Therefore, the beneficial utilizations of unfavorable factors can be achieved in deep mining. Meanwhile, the increasing difficulties in ore hoisting will force mining methods to be innovated with the minimizing hoisting. Underground mining conditions will be affected by high stress, high temperature and high depth. So, underground mining methods should be innovated to achieve green mining of mineral resources as mining depth increases, as shown in Fig. 3.

Schematic infrastructures required for underground mining with different mining depths are illustrated in Fig. 3(a). For solid mineral resources in the surface and shallow underground, the drilling and blasting method was widely used to fragment and excavate orebody.

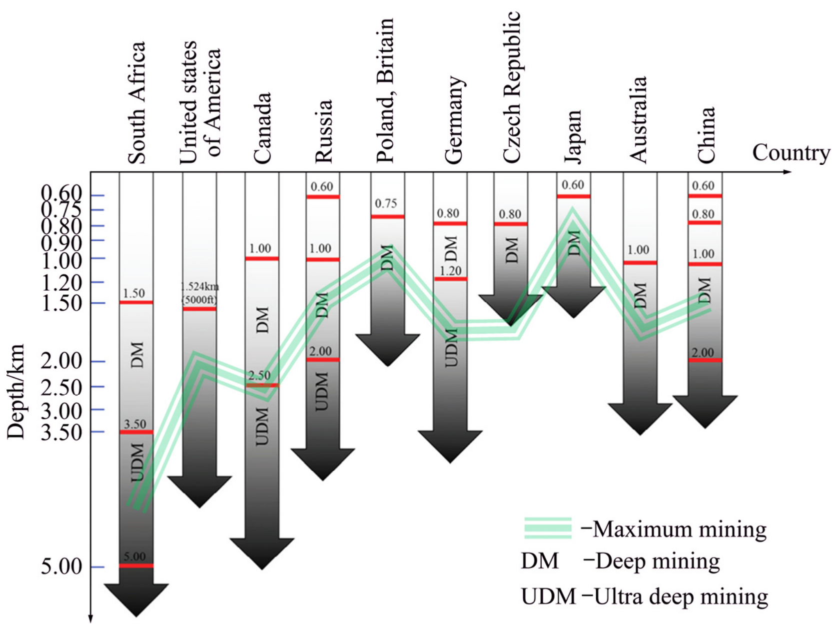

Fig. 1 Maximum mining depths and definitions of deep mining and ultra deep mining in different countries

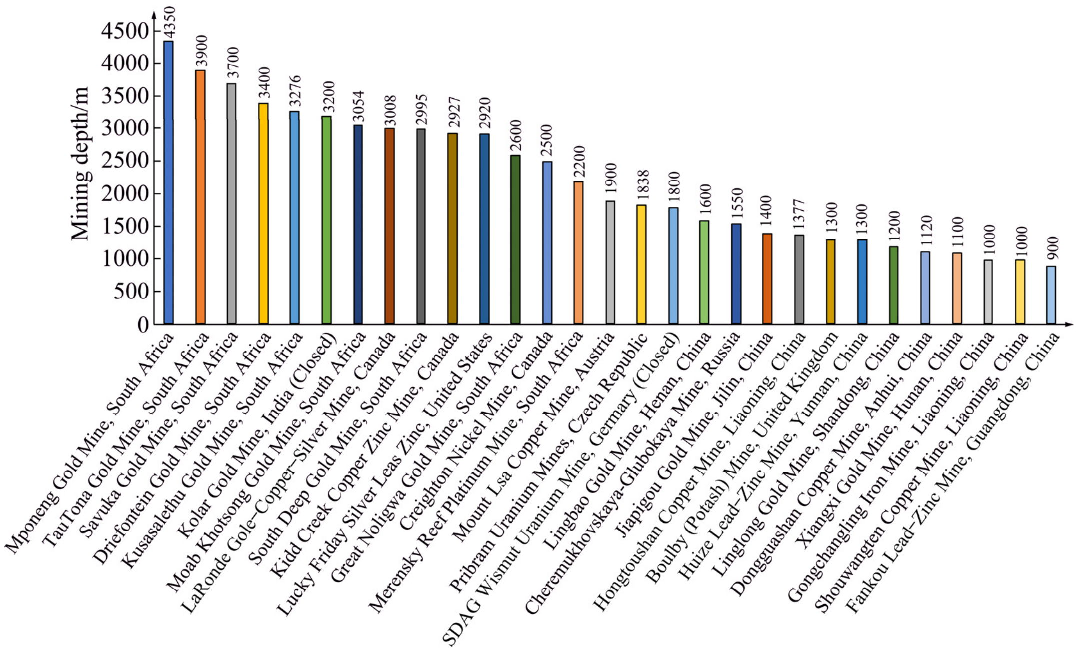

Fig. 2 Mining depths of typical metal mines around world

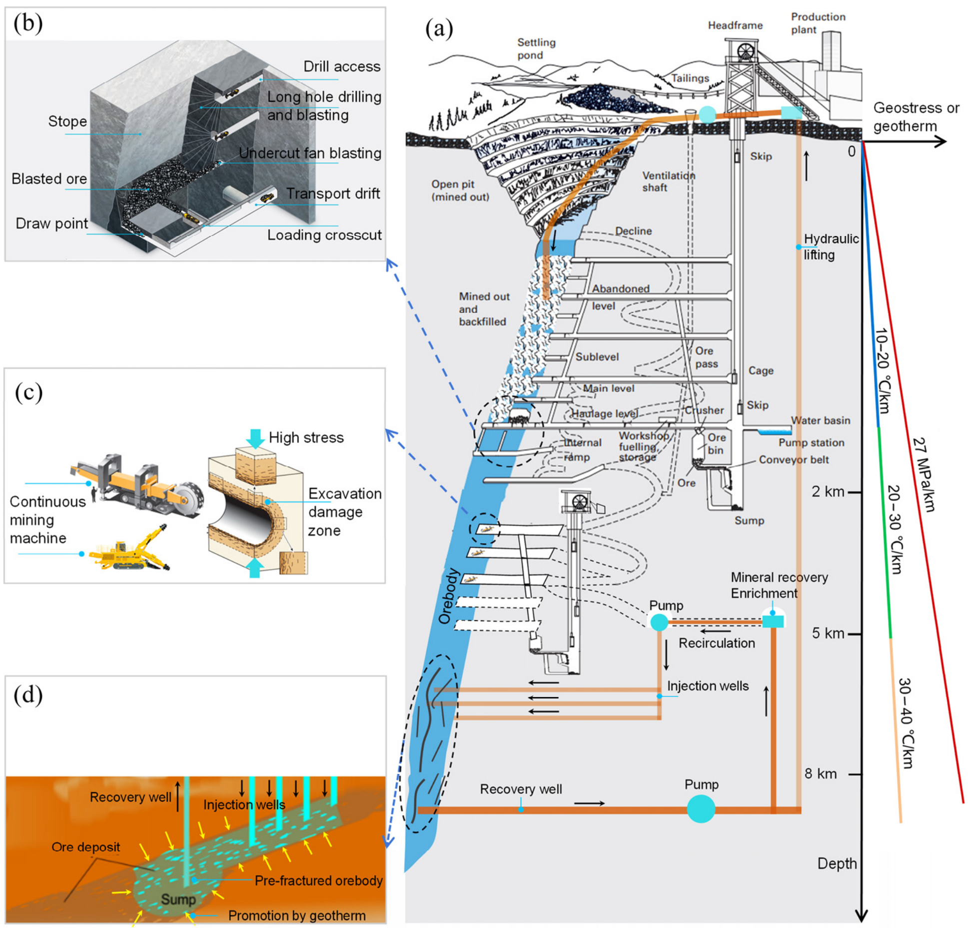

Fig. 3 Progressive innovations of mining technologies with increase in mining depth: (a) Schematic diagram of mining methods corresponding to different mining depths; (b) Drilling and blasting method during surface and underground shallow mining; (c) Non-explosive mechanized and intellectualized mining method during deep mining; (d) In-situ leaching method during ultra-deep mining

During drilling and blasting processes in surface and underground shallow mining, the stress and load conditions which the ore-rock around openings is subjected to are in a single load mode with dynamic load of blasting for rock fragmentation or excavation-induced stress concentration controlled for rock stability. Safe and efficient drilling and blasting, rock support and backfilling methods and the associated equipment are the fundamental technologies, and the rock statics and rock dynamics are the basic theories for directing surface and shallow mining. For deep hard rock, the high stress is a prominent factor for influencing underground mining. High stress can induce pre-fracturing in hard ore-rock to improve its cuttability, and makes it necessary to control excavation boundary and eliminate blasting disturbance then to ensure rock stability. Therefore, non-explosive mechanized and intellectualized mining method should be used and developed to finely cut orebody. In deep mining, the important technologies include monitoring and positioning of accumulation zone with high stress, in-situ perception of rock properties, excavation-induced stress adjustment and pre-fracturing methods, non-explosive mechanized and intellectualized mining machines, etc. The high stress and high geotherm are the prominent factors for influencing ultra-deep mining. High stress can enhance the pre-cracking blasting to produce fractures for seepage, and high geotherm can improve the reaction between leaching solution and cracked ore-rock. Meanwhile, large lifting height urges that only direct lifting of minerals is saving, hydraulic lifting can be used, and geothermal energy can be also exploited synchronously. Thus, in-situ leaching method can be used and developed to exploit minerals in ultra-deep underground, which includes the important technologies of pre-cracking blasting coupled with high geostress, intellectualized raising for a well and new efficient pre-cracking methods. During deep and ultra-deep mining, the ore-rock around openings is subjected to the coupled static-dynamic loads referring to high geostress and multiple dynamic disturbances (excavation, blasting, fault slip, strata movement, roof caving, etc). Therefore, the coupled static-dynamic loading theory and the mechanism and control theory of unconventional rock failures (rockburst, slabbing, zonal disintegration, etc) should be developed to establish the deep rock mechanics to guiding and safeguarding the deep and ultra-deep mining.

Deep mining is the present situation and inevitable development trend of the world mining industry for exploiting minerals from 1500 to 5000 m underground. Therefore, the non-explosive mechanized and intellectualized mining is urgent to be developed, in which the cuttability of deep hard rock under different stress conditions is a key factor to determine the feasibility of non-explosive mechanized and intellectualized mining.

3 High-recovery, low-waste and high-efficiency exploitation

3.1 Cuttability of deep hard rock

A true triaxial testing apparatus was used to perform rock indentation tests by a conical pick to investigate the influence of confining stress condition on rock fragmentation performances. The experiment apparatus and loading frame adopted in the rock indentation tests are shown in Fig. 4(a). A high-speed camera was used to photo the moment of rock fracturing and rock failure. The confining stresses with different levels provided by the *Y*-direction loading were applied to a pair of sides of the cubic rock specimens. Then, a static concentrated force exported from the *Z*-direction loading was applied to the top faces of the cubic rock specimens by an actual conical pick to fragment hard rock specimens including granite, marble, sandstone and phosphate ore-rock. The peak pick forces at rock failures under different uniaxial confining stresses were recorded in rock indentation tests and regressed by a fitting model, the results of which are plotted in Fig. 4(b). The peak pick forces required for rock fragmentations increase first and then decrease with increases in uniaxial confining stresses applied to rock specimens. The change trends of peak pick forces for the four types of rock specimens are similar as the uniaxial confining stresses increase, but the values of peak pick forces are closely related to the rock strength. The failure patterns of rock specimens are shown in Fig. 4(c). The rock specimens are completely split into two pieces with the same sizes at the low uniaxial confining stresses from zero to near 30% of uniaxial compressive strengths (UCSs) of rock materials. At the medium uniaxial confining stresses from near 30% to 80% of UCSs of rock materials, the partial splitting failures occur, in which the rock specimens are partially split into two pieces with the different sizes. The rockburst occurs at rock failure with the rapid ejection of rock fragments at the high uniaxial confining stress more than 80% of UCS of rock material. These results have confirmed that confining stress plays a significant role in influencing rock cuttability. As illustrated in Fig. 4(d), hard rock is easy to be split efficiently and safely with complete splitting occurring and low pick force required under low uniaxial confining stress, in which the rock has the best cuttability. As the uniaxial confining stress increases, the rock cuttability is impeded first and then promoted by stress concentration, the rock fragmentation is inefficient because the rock is only partially split with requirement of high pick force, and the unsafe rock failure with rockburst is prone to be induced by rock fragmentation at

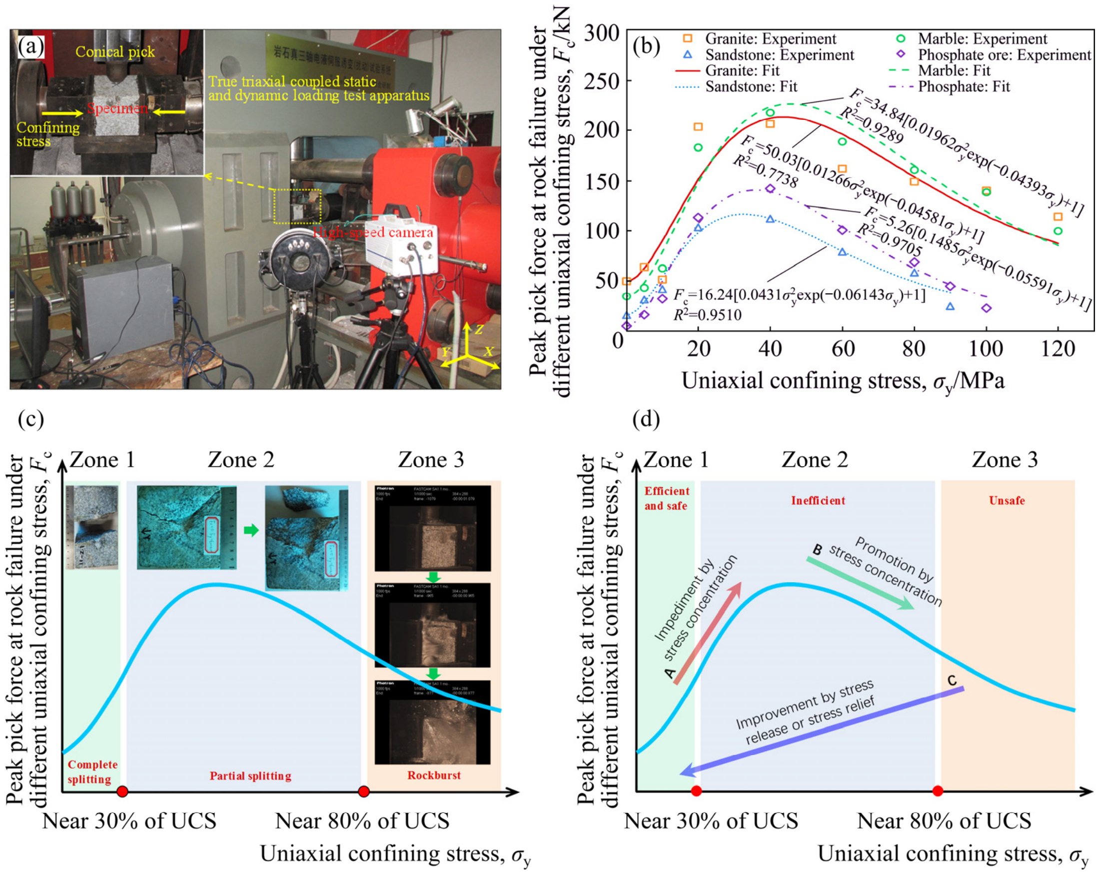

Fig. 4 Experimental and regressed results of cuttabilities of hard rocks: (a) Experiment apparatus and loading frame for rock fragmentation by conical pick; (b) Peak pick forces at rock failures; (c) Failure patterns of rock specimens under different uniaxial confining stresses; (d) Stress adjustment methods for improving cuttability of hard ore-rock

high uniaxial confining stress. The excavation-induced high stress around opening is a prominent condition in deep hard rock. Therefore, some measures of stress release or stress relief should be conducted to change stress condition to improve the rock cuttability, which generally include (1) reasonable excavations of some intersectant entryways to add new free faces of pillar to induce stress concentration on pillar, (2) timely backfilling and flexible supports in mining stope to induce stable release of high stress to produce pre-fracturing in ore-rock and prevent rockburst, and (3) pre-excavations of slits and boreholes in orebody to artificially relieve the high stress in over-compressed pillar. The measures mentioned above are beneficial to application of non-explosive mechanized mining based on rotary cutting of conical picks in deep hard ore-rock.

3.2 Non-explosive mechanized and intellectualized mining

Non-explosive mechanized mining is an alternative method to traditional drilling and blasting, which benefits from some unfavorable factors: continuous mining, high construction quality, low excavation disturbance, and high operation safety. Non-explosive mechanized mining is also a significant foundation for intellectualized mining. In the Kaiyang Phosphate Mine, the mining stope was prepared for non-explosive mechanized mining, the structure diagram of which is depicted in Fig. 5. First, as shown in Fig. 5(a), a preparation laneway was excavated along the strike of orebody, and the field image of exposed rock mass is shown in Fig. 5(b). Then, several cutting entryways were excavated along the dip of orebody, as shown in Fig. 5(c). After that, several peninsula-type pillars were formed, as shown in Fig. 5(d).

The excavation damage zone (EDZ) will occur in the surrounding rock mass around pillar with the stress redistribution in pillar after excavation unloading. After excavations of preparation and cutting entryways, the observation boreholes were drilled in rock mass around entryways. Then, a high-definition digital borehole televiewer was used to measure the fracture distribution on the wall of borehole to determine the scope of the EDZ. The borehole appearance, high-definition digital camera, monitoring operation, display panel of televiewer and the shot images of borehole walls are shown in Fig. 6(a). The observation results show that the thickness of the EDZs in the rock mass around the pillar

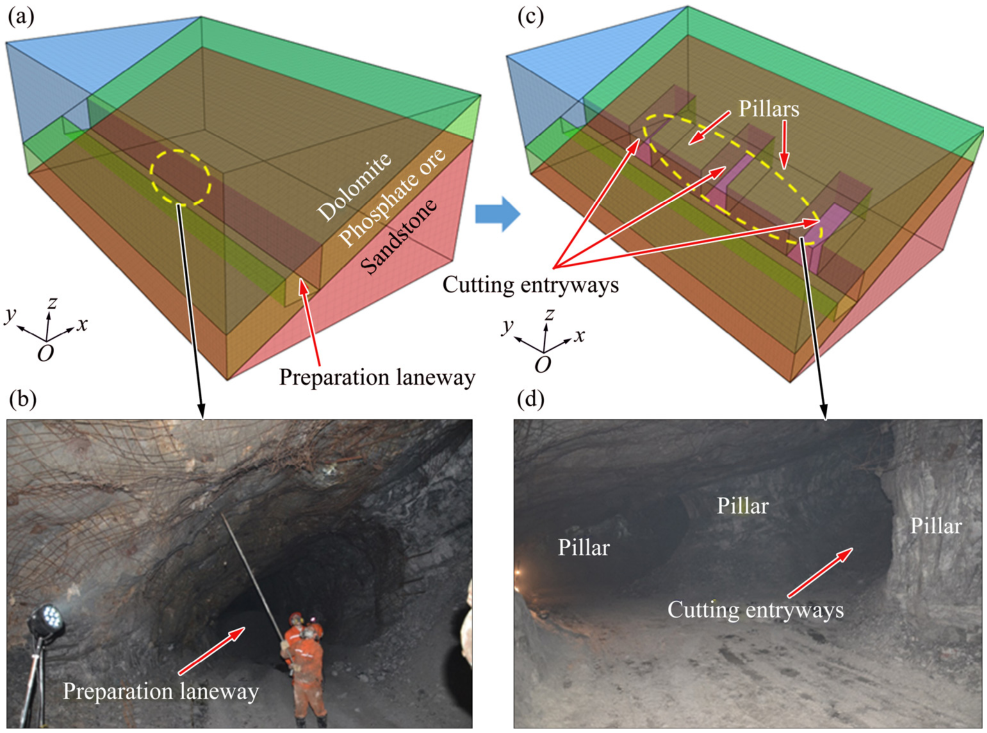

Fig. 5 Stope preparation for non-explosive mechanized mining: (a) Excavation of preparation laneway; (b) Field scene of preparation laneway; (c) Excavations of cutting entryways; (d) Field scenes of cutting entryways

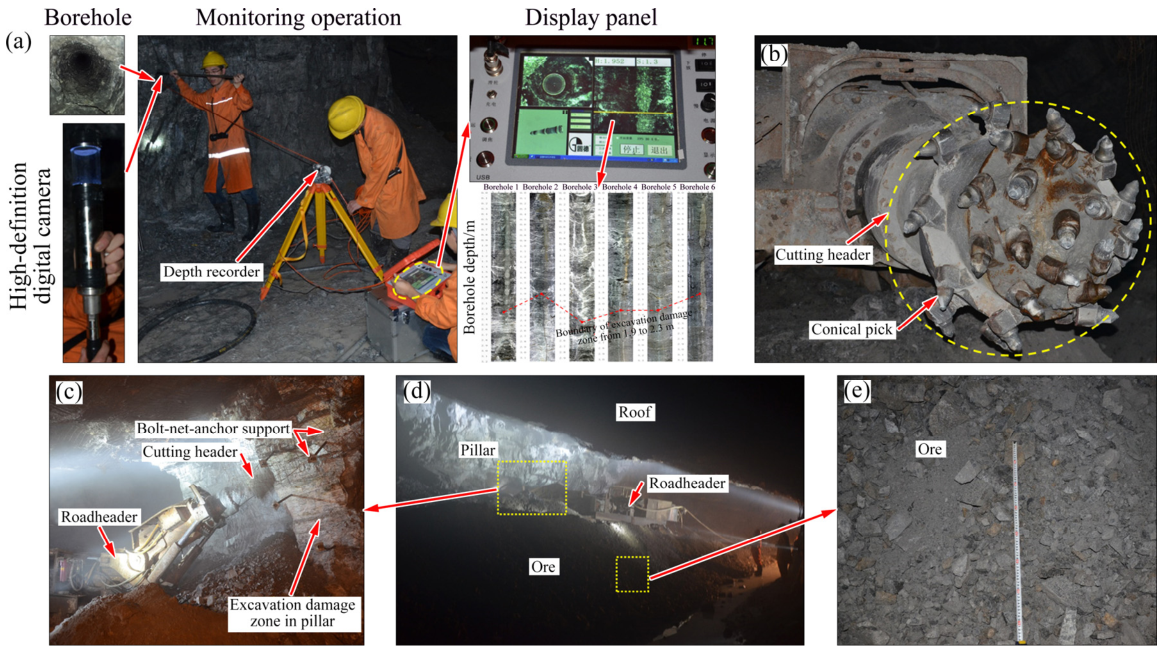

Fig. 6 Non-explosive mechanized mining processes: (a) Monitoring excavation damage zone around pillar using high-definition digital borehole televiewer; (b) Conical picks mounted on cutting header used for ore-rock fragmentation; (c) Cutting operation of roadheader for mining ore-rock in excavation damage zone in pillar; (d) Scene of mining stope; (e) Scene of ore pile

are 1.84−2.54 m, which meets the requirement of non-explosive mechanized mining. A longitudinal-axis cantilever roadheader was used to break ore-rock in EDZ around pillar, and the mining thickness in a cutting step should be equal to the thickness of the EDZ. The roadheader had a cutting header with many conical picks mounted spirally, as shown in Fig. 6(b), which could be rotated to continuously cut ore-rock. The field scene of cutting operation using roadheader for mining ore-rock in EDZ around pillar and the layout of mining stope are shown in Fig. 6(c) and Fig. 6(d), respectively. The mean of utilization rate of working time is 64%, which means that 64% of running time of roadheader has been used for cutting ore-rock. The cutting power of roadheader can be adjusted timely according to ore-rock strength to match the cuttability of ore-rock. The mean of cutting efficiency is 107.7 t/h, and the pick consumption rate is 0.013 pick with per ton of ore-rock mined-out. The ore pile mined by roadheader is shown in Fig. 6(e). The particle size of ore is obviously smaller than that of ore mined by drilling and blasting method, which could reduce the cost of ore crushing for mineral processing.

In order to adapt to the Industry 4.0 of intelligent era, the intelligent mine was constructed in the Kaiyang Phosphate Mine by the implementation steps shown in Fig. 7(a). There are three paths to establish the intelligent mine from traditional mine. Control methods of production processes in mine go through three steps, such as manual operation, remote control and perception using internet of things, to establish the intelligent mine-information and control platform. For mine modeling, three progressive steps have been developed, such as two-dimensional (2D) mine map, three-dimensional (3D) geological and geomechanical model and digital mine, to achieve the diversified digital modeling. Corresponding to and depending on the three steps of production processes and mine modeling, respectively, the intellectualized mining equipment has been created by the following three steps: mechanized mining, remote mining and intellectualized mining. The structure diagram for establishing an intelligent mine in the Kaiyang Phosphate Mine is shown in Fig. 7(b). The intelligent mine includes the following three items: visualized mineral resource and mining environment, intellectualized operation process and mining equipment, and scientific production information and decision management. The above three items are integrated in a 3D visualized integration platform to achieve intelligent design, visualized monitoring, automatized equipment, unmanned production system and integrated management and control platform. The running of the 3D visualized integration platform is driven by means of digital modelling software, information collection system, optical fiber network, man-machine interaction system and data transmission system.

In the Kaiyang Phosphate Mine, various function modules of intelligent mine are shown in Fig. 8. Mining design and support design are performed in orebed

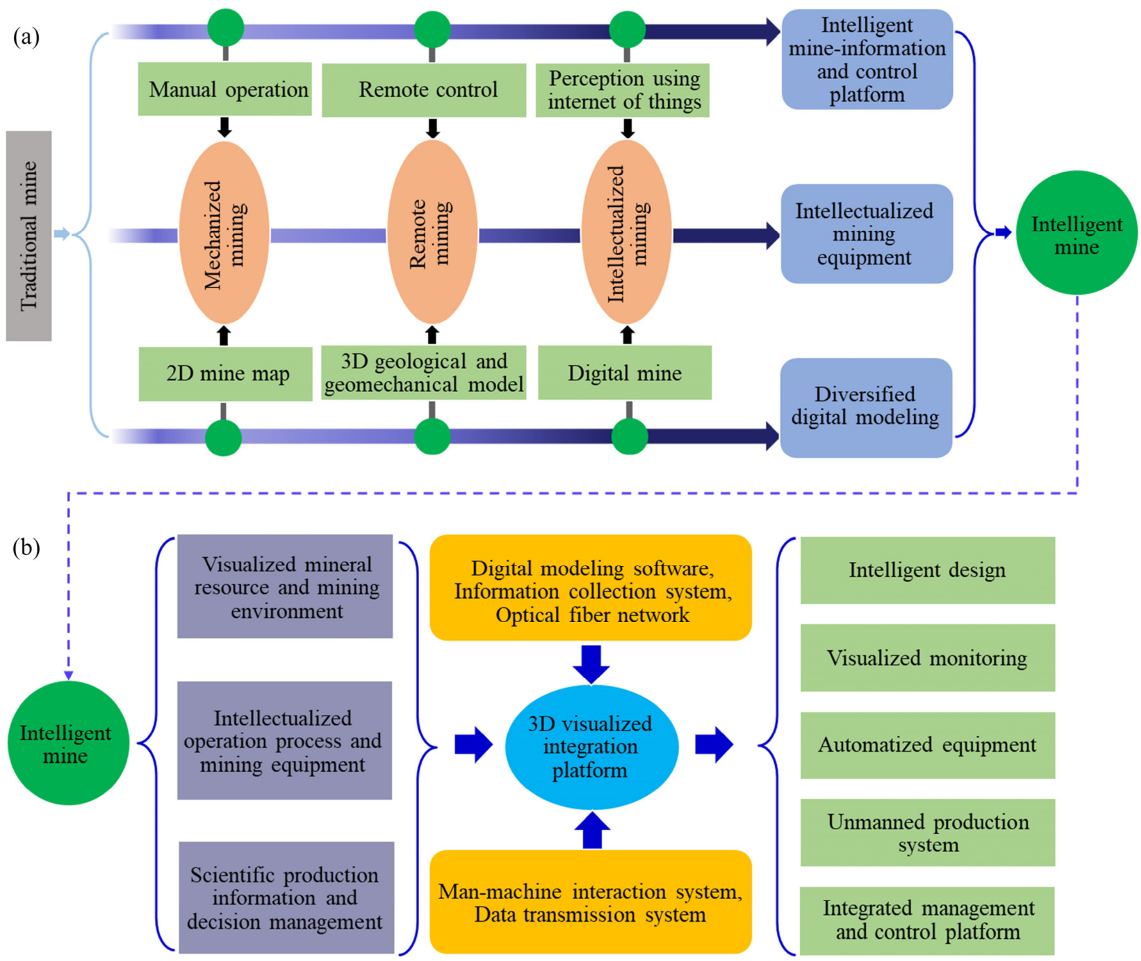

Fig. 7 Intellectualized mine construction procedure: (a) Implementation steps of intelligent mine from traditional mine; (b) Structure diagram for establishing intelligent mine

Fig. 8 Intellectualized mine construction in Kaiyang Phosphate Mine: (a) Intelligent design; (b) Visualized monitoring; (c) Automatized equipment; (d) Unmanned production system; (e) Integrated management and control platform

model including geometric, geological and geo-mechanical properties of orebed and ore-rock to achieve intelligent design. Underground sensors, transmission network and surface monitoring room are used to visualizedly monitor the microseismic events around mining stope. Automatized equipment used in mine includes drilling jumbo, roadheader, rock breaker, scraper and backfill system. The running of production systems including ventilation, metering, belt transport and control are unmanned. An integrated management and control platform is established to carry out surface supervision, production management, material management, equipment management, etc.

Mechanized mining uses a flexible cutting header to fragment ore-rock, which can precisely control mining boundaries. Intellectualized mining process has a capability of intelligent perception of boundaries between orebed and waste rock based on the precise orebed model. Benefiting from these advantages, the underground phosphate mining can produce few waste rock and fully exploit phosphate ore to achieve low-waste and high-recovery exploitation of underground phosphate. After the implementations of mechanized and intellectualized mining, the recovery rate reaches more than 90%, and the dilution rate drops to less than 5%.

4 Circular economy in underground mine

4.1 Utilization of mine solid waste

Green mining is still a worldwide challenge for exploitation of underground minerals to get sustainable development of mining and its associated industries [20]. Industrial solid waste puts tremendous pressure on environmental protection. The production and utilization properties of industrial solid waste are shown in Fig. 9, according to the statistical data from the Ministry of Ecology and Environment of the People’s Republic of China in 2015. Mine solid waste is a major kind of industrial solid waste produced in the ore mining, mineral processing and associated industrial processes, which mainly includes waste rock (or gangue), tailings and industrial waste gypsum. Resource utilization of mine solid waste based on circular economy is the significant task for solving resource and environment problems, which is also the essential process for achieving

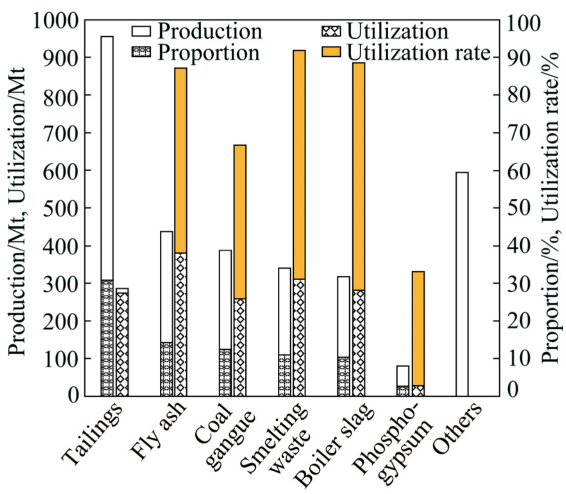

Fig. 9 Production and utilization properties of industrial solid waste [21]

green mining of underground minerals with low-waste, high-recovery and low environmental impact. Resource utilization strategies of mine solid waste in China are drawn in Fig. 10. In summary, there are five strategies for resource utilizations of solid waste that is correlated with mine and mineral processing: (1) combustion for thermal energy utilization and gasification (only for coal gangue); (2) recycling of beneficial minerals and elements and inorganic chemicals; (3) manufacturing building materials or other industrial materials; (4) use for subgrade and foundation materials, reclamation and backfilling; (5) use in agriculture.

A large amount of waste rock will be produced with underground mining of phosphate. Meanwhile, a large amount of phosphogypsum and phosphorus slag will be exported from phosphorus chemical industry during phosphate processing to produce phosphate fertilizer and yellow phosphorus, respectively. The stacking of these solid wastes will occupy a great deal of land and pollute the environment. Therefore, a circular economy model was conducted in the Kaiyang Phosphate Mine, as shown in Fig. 11. Phosphate mined underground and the treated wastewater were transported to phosphorus chemical industry to produce phosphate fertilizer and yellow phosphorus with outputs of phosphogypsum and yellow phosphorus slag which were used to make subgrade material and gypsum brick and fill the underground mined-out areas. Waste rock was excavated from underground mining of phosphate in which the dolomite was crushed into sand to make subgrade material and fill mined-out areas with backfilling slurry, and the red shale was ground to make shale brick. Meanwhile, the waste rock was also used to directly backfill the mined-out areas in mining stope, which was cemented with backfilling slurry. In addition, the gypsum brick and shale brick could be laid to make walls for retaining backfill in underground openings. Through the above processes, the recycling of the waste rock and wastewater from underground mining and the solid waste from phosphorus chemical industry was achieved to conduct circular economy. The content of P_2O_5 in phosphate ore in the Kaiyang Phosphate Mine is over 33.67%, which is no need to mineral separation and processing and can be directly used as raw material to phosphorus chemical industry. Therefore, there is no tailing in the Kaiyang Phosphate Mine. For other phosphate mine having tailings, the tailings can be also used as backfill material with phosphogypsum and phosphorus slag.

4.2 Solid waste and resource utilization in phosphate mine

The phosphate production of the 11 top countries in the world from 2010 to 2018 is shown in Fig. 12. It can be seen that China is the world's largest producer of phosphate ore, and the production amount has been increasing year after year, because China is the world's most populous country having the biggest demand for agriculture [23−25]. The phosphate reserves of the 11 top phosphate-producing countries and the ratios of production to reserves in 2018 are shown in Fig. 13. The phosphate resource is very valuable in China, by consideration from the largest phosphate production, relatively few phosphate reserves and relatively high ratio of production to reserves. Therefore, the development of fine exploitation of underground phosphate resource is significant in China.

A large amount of solid waste will be produced in phosphate mining and processing, including phosphogypsum, waste rock, tailings and yellow phosphorus slag. Among these, phosphogypsum is the largest solid waste and the most harmful to the environment [26−28]. The phosphogypsum output correlated with phosphate production from 2010 to 2017

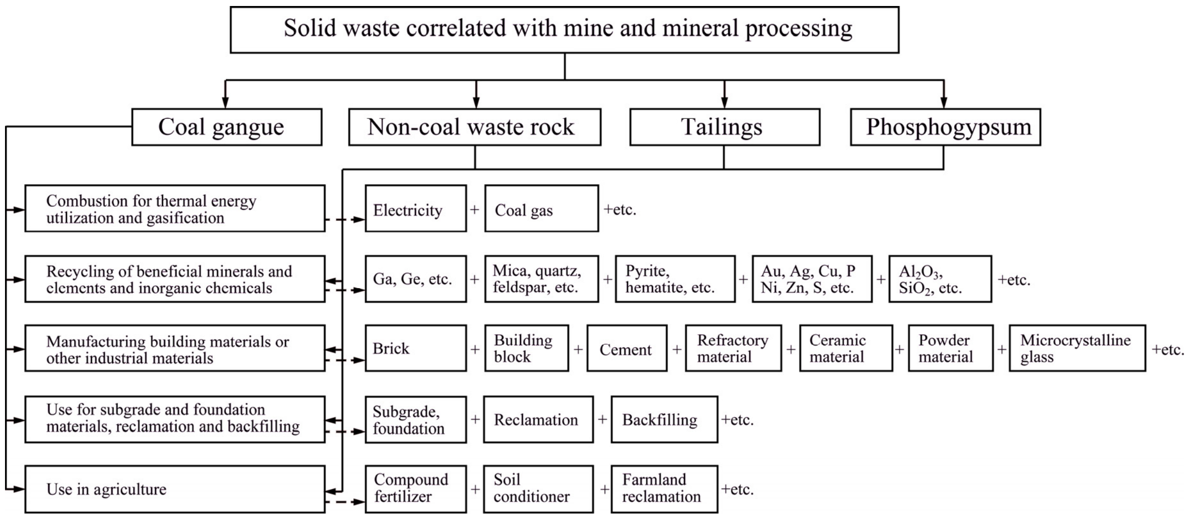

Fig. 10 Resource utilization strategies of mine solid waste

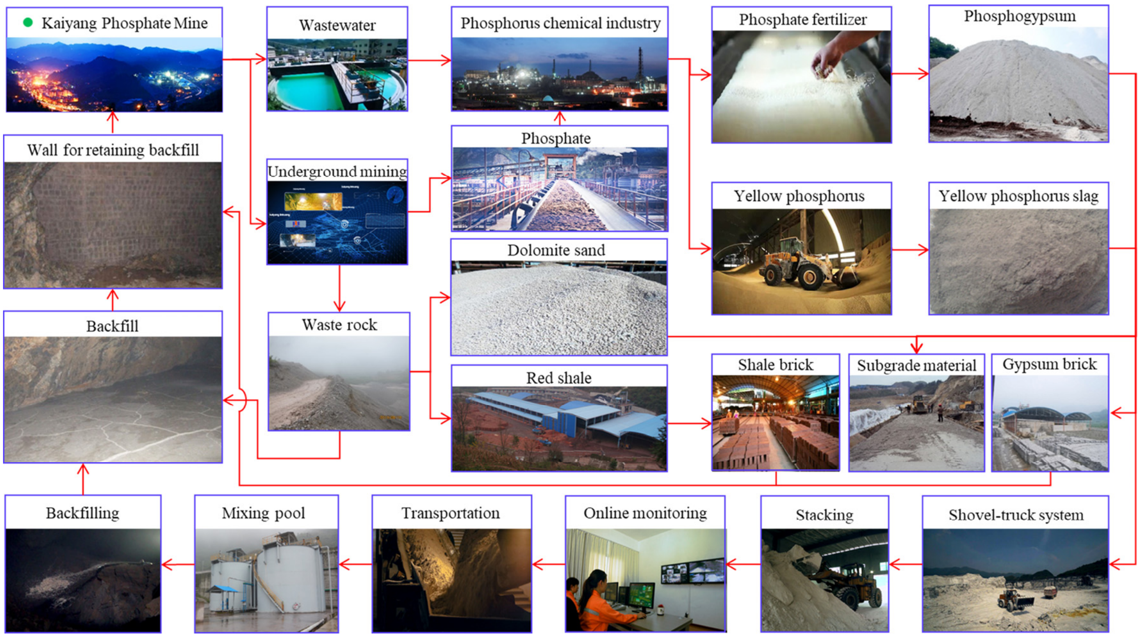

Fig. 11 Development model of circular economy in Kaiyang Phosphate Mine

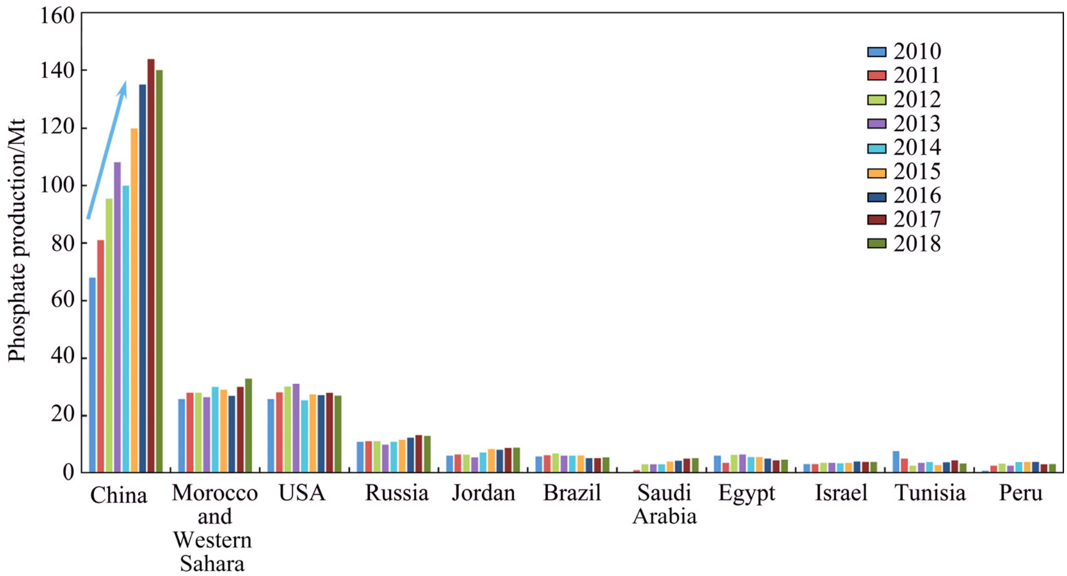

Fig. 12 Phosphate production of 11 top countries in world from 2010 to 2018 [22]

in China is shown in Fig. 14. The statistical results of the outputs of phosphate fertilizer and phosphogypsum, the utilization of phosphogypsum, the utilization rate of phosphogypsum and the output of phosphogypsum per ton of production of phosphate fertilizer from 2010 to 2017 in China are shown in Fig. 15. The data indicate that there is about 0.52−0.91 t of phosphogypsum output per ton of phosphate production and about 4.79−6.01 t of phosphogypsum output per ton of production of phosphate fertilizer. Resulting from heavy requirements of phosphate and phosphate fertilizer, the phosphorgypsum output is bound to be high. Fortunately, the phosphogypsum output has no obvious increase due to the developments of phosphate mining and processing, and the phosphogypsum utilization presents a gradual increase as a result of diverse resource utilization aspects of phosphogypsum shown in Fig. 16, although the phosphate production has been increasing year after year. These efforts cause that the ratio of phosphogypsum output to phosphate production drops generally, and the utilization rate of phosphogypsum rises overall. Therefore, it is significant for mineral exploitation and environmental protection to continue to develop the phosphate mining and processing technologies and the resource utilization methods of the associated solid waste.

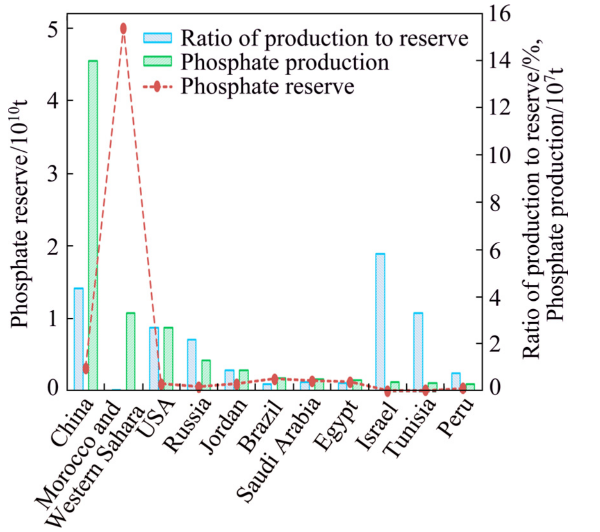

Fig. 13 Phosphate reserves of 11 top phosphate-producing countries and ratios of production to reserves in 2018 [25]

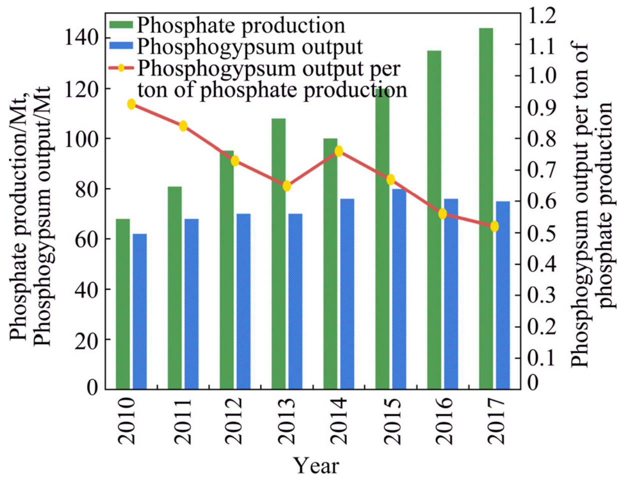

Fig. 14 Phosphogypsum output correlated with phosphate production from 2010 to 2017 in China [27−29]

4.3 Paste-like backfill for utilization of mine waste

The backfilling processes include conveyance of backfill material using shovel−truck system, stacking and belt transportation of backfill material, stirring of backfill material using mixing pool, backfilling into underground mined-out area, and online monitoring of backfilling processes. The backfill system and its properties are shown in Fig. 17. As shown in Fig. 17(a), phosphogypsum, phosphorus slag, grated waste rock, cement and water were mixed in mixing pool using mixers to prepare backfill slurry with mass concentration of 57%−64.5% to make paste-like backfill for good liquidity and cementation, low bleeding rate and high compressive strength, according to the experimental curves of yield stress of slurry with its mass concentration changing, as plotted in Fig. 17(b). The prepared paste-like slurry passed through backfilling

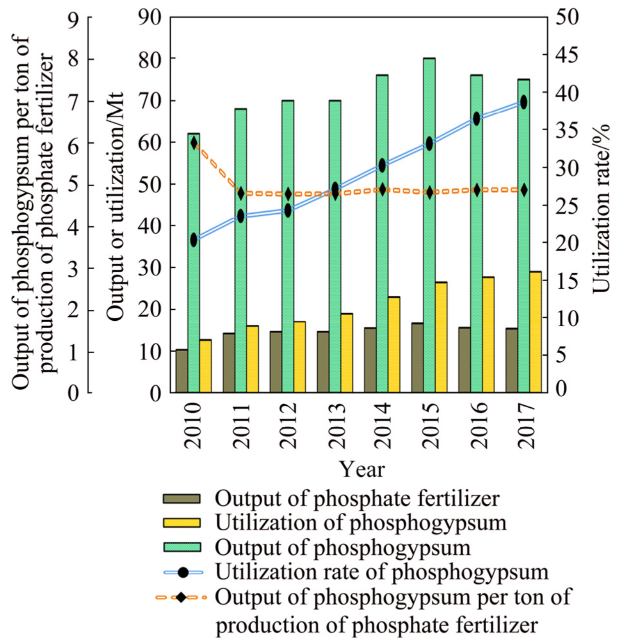

Fig. 15 Outputs of phosphate fertilizer and phosphogypsum, utilization of phosphogypsum, utilization rate of phosphogypsum and output of phosphogypsum per ton of production of phosphate fertilizer from 2010 to 2017 in China [29−31]

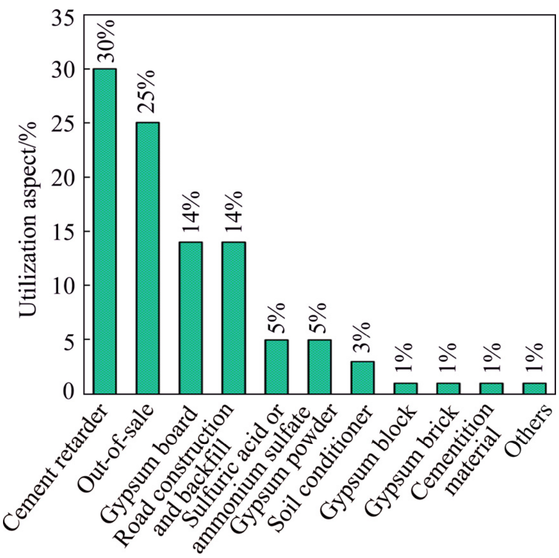

Fig. 16 Utilization aspects of phosphogypsum in China in 2017 [31]

pipeline and was pumped into mining stope to form backfill body with underground waste rock, according to the backfilling system shown in Fig. 17(c). The mixing time of backfill materials should be around 60 min in order to achieve the maximum unconfined compressive strength of backfill body, according to the experimental results of unconfined compressive strength changing with mixing time of backfill materials and curing age of backfill body, as depicted in Fig. 17(d).

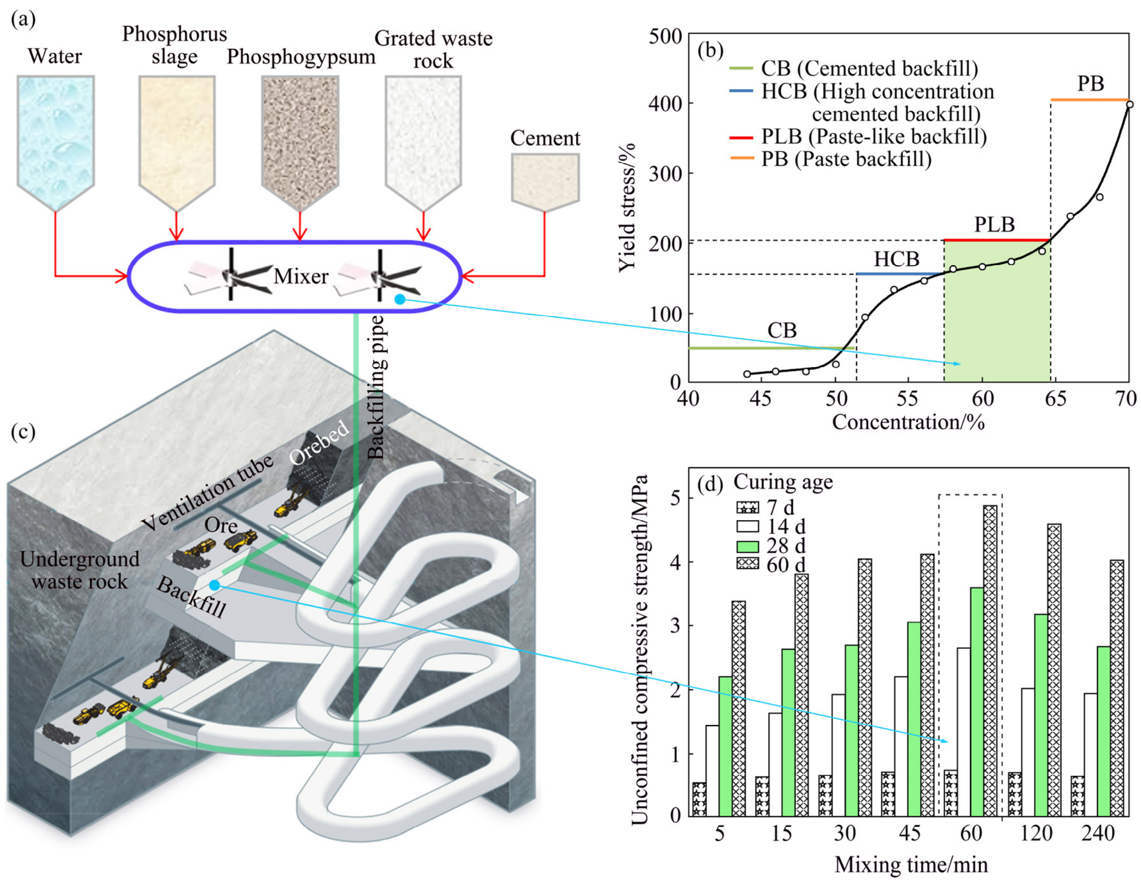

Fig. 17 Backfill system and its properties in Kaiyang Phosphate Mine: (a) Preparation of backfill slurry; (b) Slurry concentration of paste-like backfill for good liquidity and cementation, low bleeding rate and high compressive strength [23]; (c) Pipeline transportation of backfill slurry and backfilling with underground waste rock; (d) Unconfined compressive strength of hardened backfill samples at different mixing times and curing ages [32]

Through the applications of circular economy and paste-like backfill, resource utilizations of mine waste have been improved significantly. The utilization of phosphogypsum has reached over 1800×10^3 t/a, the utilization of yellow phosphorus slag has reached near 300×10^3 t/a, and the utilization of waste rock has reached near 1500×10^3 t/a.

5 Results and discussion

The recovery and dilution of phosphate and the resource utilizations of solid waste have been improved significantly after implementations of mechanized and intellectualized mining, circular economy and paste-like backfill in the Kaiyang Phosphate Mine. The statistical data from 2011 to 2018 are listed in Table 1.

The recovery and dilution rates of phosphate changing from 2011 to 2018 are drawn in Fig. 18. The recovery rate of phosphate increased and stabilized over 90%, and the dilution rate of phosphate ore decreased and finally stabilized near 5%, benefitting from the continuous applications of non-explosive mechanized and intellectualized mining technologies. These results about recovery and dilution properties meet the requirements of high-recovery and low-waste exploitation of underground phosphate.

The resource utilizations of solid waste, such as phosphogypsum, yellow phosphorus slag and waste rock, were conducted by circular economy model and paste-like backfill in the Kaiyang Phosphate Mine, the results of which are depicted in Fig. 19. The resource utilizations of solid waste were improved gradually with circular economy and waste backfilling conducted continuously. From 2011 to 2018, the utilizations of phosphogypsum, yellow phosphorus slag and waste rock increased from 486.7×10^3 to 1853.6×10^3 t, from 112.3×10^3 to 291.1×10^3 t and from 563.4×10^3 to 1493.8×10^3 t, respectively.

It can be drawn from the above data that the applications of non-explosive mechanized and intellectualized mining for low-waste and high-recovery exploitation and the implementations of circular economy and paste-like backfill for utilization of mine waste can significantly support the green mining in underground phosphate mine for fine exploitation, strata stability and environmental protection. Meanwhile, the

Table 1 Recovery and dilution rates of phosphate and utilizations of solid waste after performances of mechanized and intellectualized mining, circular economy and paste-like backfill in Kaiyang Phosphate Mine from 2011 to 2018

Year	Recovery rate/%	Dilution rate/%	Utilization of phosphogypsum/10^4 t	Utilization of yellow phosphorus slag/10^4 t	Utilization of waste rock/10^4 t
2011	79.71	5.40	48.67	11.23	56.34
2012	83.12	4.77	112.65	12.14	80.24
2013	85.31	4.52	142.45	16.18	102.45
2014	89.28	4.23	182.02	21.73	126.78
2015	92.35	4.37	185.17	29.88	147.74
2016	90.18	4.76	184.03	28.62	145.33
2017	90.31	4.85	181.42	26.81	146.41
2018	90.19	4.89	185.36	29.11	149.38

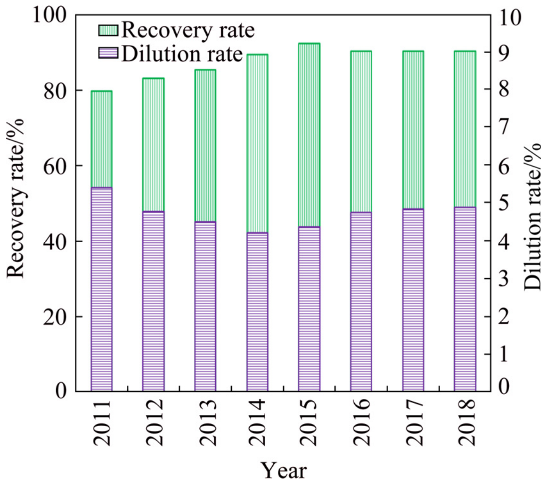

Fig. 18 Changes of recovery and dilution rates of phosphate in Kaiyang Phosphate Mine from 2011 to 2018

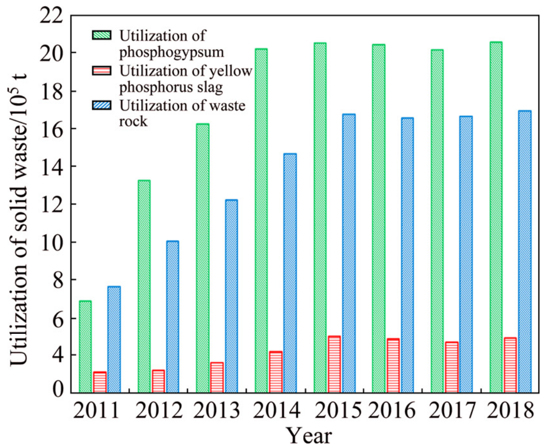

Fig. 19 Changes of utilizations of phosphogypsum, yellow phosphorus slag and waste rock in Kaiyang Phosphate Mine from 2011 to 2018

phosphate production in the Kaiyang Phosphate Mine increased from 2×10^6 to 8×10^6 t/a, the number of employees reduced from 4367 to 1199, the mining efficiency increased from 458 to 6672 t/a per capita, and the direct economic benefits of 418 million RMB have been created through the innovation of mining technology, circular economy and paste-like backfilling.

6 Conclusions

(1) Innovations of mining technologies were proposed by beneficial utilizations of unfavorable factors such as high geostress, high geotemperature and high mining depth to achieve green mining of deep underground minerals, which include non-explosive mechanized/intellectualized mining and in-situ leaching alternative to the drilling and blasting method as mining depth increases inevitably.

(2) Some measures of stress release or stress relief, such as reasonable excavations of some intersectant entryways, timely backfilling and flexible supports in mining stope and pre-excavations of slits and boreholes in orebody, should be conducted to change stress condition to improve the rock cuttability. Through the non-explosive mechanized and intellectualized mining, the recovery rate of phosphate increased over 90%, the dilution rate of phosphate ore decreased to near 5%, and the cutting efficiency of phosphate ore reached about 107.7 t/h, which meet the requirements of high-recovery, low-waste and high-efficiency exploitation of underground phosphate.

(3) A circular economy model and backfill system were proposed and constructed to conduct resource utilizations of solid waste, such as phosphogypsum, yellow phosphorus slag and waste rock. The utilizations of phosphogypsum, yellow phosphorus slag and waste rock increased to 1853.6×10^3 t/a, 291.1×10^3 t/a and 1493.8×10^3 t/a, respectively, which can reduce the environmental pressure in phosphate mine and phosphorus chemical industry.

(4) The green mining in the underground phosphate mine was achieved by the non-explosive mechanized and intellectualized mining for high- recovery, low-waste and high-efficiency exploitation and the circular economy

and paste-like backfill for resource utilization of mine waste, which was beneficial to fine exploitation, strata stability and environmental protection. The proposed mining methods, circular economy model and backfill technology can provide valuable information for achieving green mining of minerals in underground hard rock mines.

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基于非爆开采和固废资源化利用的硬岩矿山绿色开发

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摘 要：基于深部高地应力、高地温、高井深等灾害因素的“变害为利”，提出深部固体资源开采技术变革思路，实现深部固体资源的绿色开采。首先，通过深部硬岩可截割性实验研究和回归分析，获得能够有效改善非爆机械化破岩的应力诱导调控方法。其次，通过非爆机械化和智能化开采，实现以坚硬磷矿石为代表的深部硬岩连续化精准开采，确保贵州开阳磷矿资源的高回收率(大于 90%)、低废(贫化率 5%)、高效(开采效率 107.7 t/h)开采。最后，开发矿山循环经济新模式，构建矿山全固废充填系统，实现矿山固废资源化利用。连续实施后，2018 年开阳磷矿的磷石膏、黄磷渣、废石利用量分别达到 1853.6×10^3 t/a、291.1×10^3 t/a 和 1493.8×10^3 t/a。

关键词：硬岩矿山；非爆开采；固废充填；循环经济；固废资源化利用；绿色开采

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