D.Q. DENG
F. F. JIANG
Y. DUAN
and
L. PENG

Solid waste management in urban mines based on resource reutilization mode of cleaner production

Tailing-cement filling is used in Laixin iron mine for improved protection of the Earth's surface, prevention of surface collapse, and sustainable development. The tailing is composed of over 40% particles with a diameter of –20 μm and is thus classified as extremely fine tailing. A proportioning test proves that the tailing is difficult to combine with cement. However, using cementation powder as the filling additive can significantly improve strength, and the rock stratum is steadily supported. The filling slurry is prepared as follows: tailing filter cakes are mixed with tailing slurry, and a slurry is produced from the mixture by using a compressor before placing sand in pipelines. The filling slurry exhibits stable properties and superior strength and can be used in industrial applications. In this study, the tailings of fine particles are used as backfill materials to fill the goaf, and this usage effectively solves the problem of tailing disposal. The solution ensures safe and efficient mining of urban mines and helps protect the ecosystem and lithic drainage. Furthermore, it helps achieve friendly development among mines, cities, and the ecosystem.

Keywords: *Solid waste management; lithic drainage; environmental protection; urban mines; goaf.*

1. Introduction

The city scale expands as urban construction grows. Thus, enterprises surrounding cities should maintain good environmental reliability to provide a favourable ecosystem for urban development. Only by doing this can a coordinated and harmonious mutual development between cities and enterprises be achieved. However, cities are sensitive to surrounding industrial pollution. The negative influence of this pollution is experienced within a short period and harms dense populations. For example, several chemical, building material, and smelting and mining enterprises discharge various wastes in the production process. Fortunately, local governments and enterprises are supervising these industries to achieve healthy development. Enterprises are also upgrading their technology and techniques to minimize waste discharge and are seeking for optimal means of waste disposal (Swati Sinha Babu et al., 2013; O. Morton-Bermea et al., 2008).

During the production of mineral products, mines peripheral to cities also produce a large amount of solid waste and numerous goafs; they exert environmental effects by producing goafs in mining, tailings from site selection of metal mines (M. Fall et al., 2010; D.Q. Deng et al., 2017; Bayram Ercikdi et al., 2010), and coal gangues discharged from coal mines (Hu Bing Nan, 2012; X. Querol et al., 2008). These substances damage the environment. Therefore, methods to avoid or minimize negative influences have become important concerns for most urban mines.

Similar to several mines peripheral to cities (Wang Shun-cai et al., 2008; Huang Wen-jun et al., 2012; Yang Zhi-qiang et al., 2014), Laixin iron mine is located in a densely populated suburb of Eastern China with a developed economy. The hydrogeological conditions of the mine are complicated, and the mine is abundant in water (Xu Jia-fu., 2012). However, a part of ore-rocks are unstable (Zhang Guo-lian et al., 2008; Wang Hong-yong et al., 2010; Li Wen-xiu et al., 2010). The cut-and-fill stoping method can prevent surface subsidence and ensure bio-safe disposal of solid waste. Such a disposal procedure is essential to the survival and development of mines. This process requires a set of reliable and efficient filling slurry preparation and transport systems to transport backfilled waste to the goaf (Liu Jian-feng, 2016; Xu Jia-fu, 2014; Lou Guang-wen, 2012). The mechanical properties of fillings added with cementing materials meet the requirements of mining techniques and can stably support the surface rock stratum to avoid collapse.

Messrs. D.Q. Deng, Institute of Mining Engineering, Guizhou Institute of Technology, Guiyang, Guizhou 550003, E-mail: ustbb20070025@126.com; F. F. Jiang, State Key Laboratory of Geomechanics and Geotechnical Engineering, Institute of Rock and Soil Mechanics, Chinese Academy of Sciences, Wuhan, Hubei 430071, University of Chinese Academy of Sciences, Beijing 100049, E-mail: jiangfeifei17@mails.ucas.ac.cn; Y. Duan, Institute of Mining Engineering, Guizhou Institute of Technology, Guiyang, Guizhou 550003, E-mail: 119203867@qq.com and L. Peng, Changsha Institute of Mining Research Co., Ltd., 410012 Changsha, China. E-mail: 183278576@qq.com

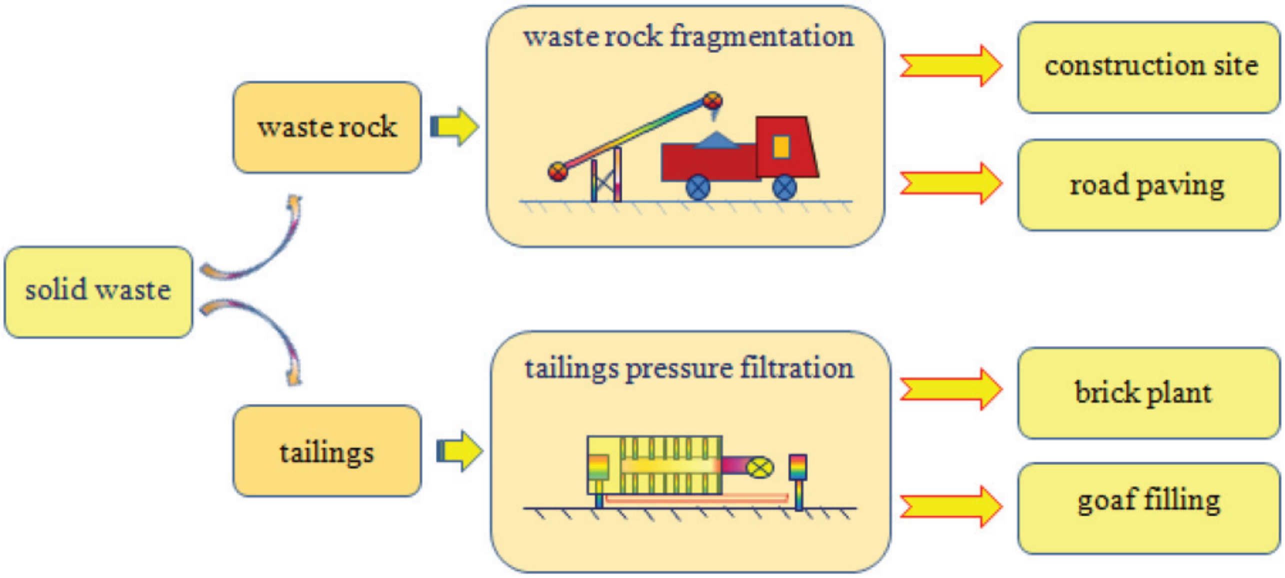


Fig.1 Disposal mode of solid waste in Laixin iron mine

2. Disposal mode of solid waste in Laixin iron mine

The deposits in Laixin iron mine are deep, and the geological conditions where deposits lie are complicated and changeable. Moreover, some deposits are crushed, and part of them are powdered oxide ores. Thus, the minerals in this mine are special. As a typical mine peripheral to cities, Laixin iron mine exerts profound effects on the urban environment. Therefore, waste (e.g., goafs, waste rock, and wastewater) from its production process should be discharged properly to avoid pollution and damage to the surrounding environment.

On the basis of its features and after analyzing the useful elements and means of market supply, the solid waste from Laixin iron mine is disposed as resources. Drifting waste rocks and tailings, which account for 20% and 80% of the total solid waste, respectively, are reused or sold. All of the drifting waste rocks are transferred to the Earth's surface and smashed into powder to be sold to construction and transportation industries.

The major tailings for disposal are divided into two parts; 47% of the total (which is approximately 37.6% of solid waste) is sold to a brickyard nearby as a brick-making material, and the other 53% of the total (approximately 42.4% of solid waste) is used to fill the goaf in the pit. The disposal mode is shown in Fig.1. A filling test should be conducted for effective protection and utilization of iron ores to ensure safe mining and avoid surface collapse.

3. Materials and method

3.1 Properties of tailings

Waste disposal in Laixin iron mine is unique. In this study, the tailing slurry was transferred by a pump to a filter press in a filter workshop to be made into filter cakes that contain 80%–85% water. Multi-draw was used to ensure the representativeness of samples. The sample cakes were dried for subsequent use. After a series of tests and analyses, tailing density was measured to be 2,610 kg/m^3, and its bulk density was 1,510 kg/m^3. The content of –20 μm particles in the tailings reached 40.4%, and that of –75 μm particles reached 76%. These measurements show that the tailings are fine enough to form a structural fluid. Chemical analyses revealed that the content of SiO_2 was 30%, which is lower than that in similar mines at home and abroad.

However, the sum content of CaO, MgO, and Al_2O_3 was as high as 37%. The demolding of filter cakes in the filter press is displayed in Fig.2, and the stocking state is shown in Fig.3. The basic physical property indicators are presented in Table 1.

Fig.2 Filter cakes

Fig.3 Stocking cakes in the cake bin

TABLE 1: INDICATORS OF MATERIAL PROPERTIES

Materials	Specific gravity	Compacted volumetric weight (t/m^3)	Loose volumetric weight (t/m^3)	Porosity (%)
Tailings	2.61	1.51	1.15	42.15
Cement	3.09	1.39	1.19	55.02
Cementation powder	3.18	1.41	1.21	55.66

3.2 Properties of cement

PC32.5 cement was used as the basic cementing material. The indicators of its physical properties are shown in Table 1.

3.3 Properties of cementation powder

Cementation powder was utilized for comparison with cement. Its indicators are also shown in Table 1.

3.4 Water

Laboratory tap water at room temperature was used. Its pH value was 7. The water was added gradually, and the addition stopped when the slurry showed good fluidity. This concentration was used as the preparation concentration for corresponding tests on concentration and proportion.

3.5 Preparation of filling slurry

The tailing was mixed with cement and cementation powder and stirred in an agitator to produce a slurry with good fluidity. The slump range was 25-28 cm without separation or delamination.

3.6 Filling body mechanical strength test

With a concentration of 57%, the slump of the filling slurry was 26-27 cm when pipeline gravity transport was possible. Thus, 57% filling slurry in different proportions was prepared to produce a sample with a size of 7.07×7.07×7.07 cm^3. After some maintenance, the uniaxial compressive strength of the samples was tested. Table 2 shows the test results. Comparative analysis revealed that the strength of the filling body was significantly improved when cementation powder was used as the cementing material. The strength of the filling body decreased when cement was utilized as the cementing material. Consequently, cementation powder was selected.

3.7 Industrial application of cemented-tailing filling materials

Continuous production is generally adopted in the filling system of Laixin iron mine, in which only goafs need filling. After preparation in the pit, the tailing slurry is transported to the mill plant, and the backfill pulp added with cementation powder is transferred to the goaf. The procedure is shown in Fig.4. The filter cakes are cut into pieces and mixed with low-content tailing slurry in a steel filling tank that is as large as 100 m^3. The mixture is made into a thick, stable slurry by using an air compressor. As shown in Fig.5, the tailing slurry in the bin is mixed with cementation powder, and the mixture is stirred in an agitator to form a paste-like fluid, which is used to fill the pipeline and ultimately flows into the goaf. The pipeline transfer of the filling slurry is shown in Fig.6.

In the process of underground filling, the filling retaining wall is made of wood, geotechnical cloth, and nylon filter cloth of different sizes that screens the water in the filling slurry, thus speeding up the hardening process. One or two filter pipes can be installed on the wall according to the size of the stope and the concentration of the filling slurry. The

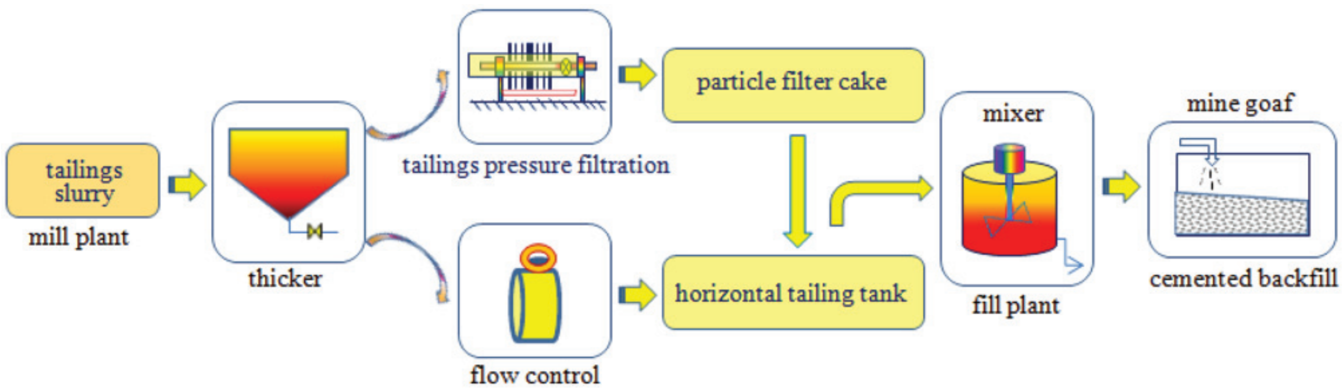
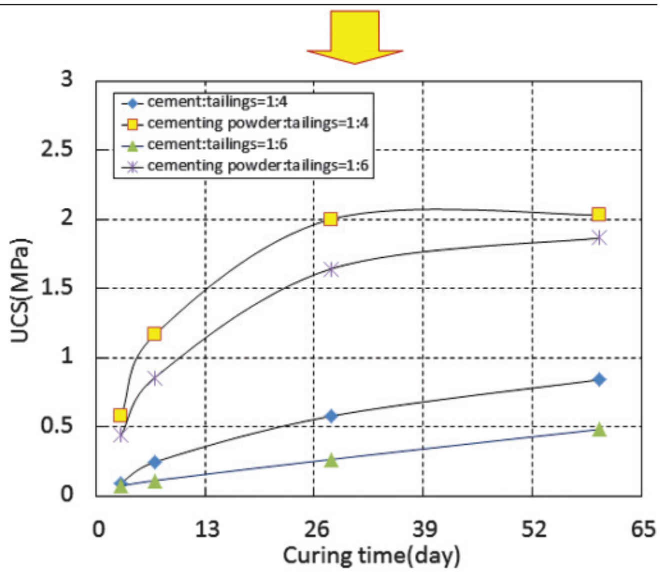


Fig.4 Filling system process flow

TABLE 2: PARAMETERS OF THE UNIAXIAL COMPRESSIVE STRENGTH OF THE BACKFILL

Materials proportion	Volumetric weight(g/cm^3)	No.1 cement:tailings =1:4	No.2 cementing powder:tailing=1:4	No.3 cement:tailings =1:6	No.4 cementing powder:tailings=1:6
Uniaxial compressive strength (MPa)	1.664	1.681	1.658	1.672	
	3d	0.096	0.583	0.075	0.439
	7d	0.247	1.167	0.113	0.857
	28d	0.579	2.002	0.266	1.643
	60d	0.842	2.033	0.483	1.866



filter pipes can be as deep as the goaf for an optimal drainage rate, and the hydration reaction can be implemented fully to achieve the desired cementing effect. The structure of the wood retaining wall is shown in Fig.7.

When the goaf is ready to be filled up, roof contact filling should be conducted several times to prevent voids from separation. After on-site tests, performing forced roof contact filling several times is good. The contact between the roof and the backfill should be as large as possible to improve the tight-filling rate. The backfill can prevent the roof from sinking, so damages caused by rock strata movement are avoided. The roof contact is shown in Fig.8.

Fig.5 Slurry making through an air compressor

The reutilization mode of solid waste disposal in Laixin iron mine achieved the benefits of improved environmental protection, harmonious development, and noticeable

Fig.6 Pipeline transfer of filling slurry

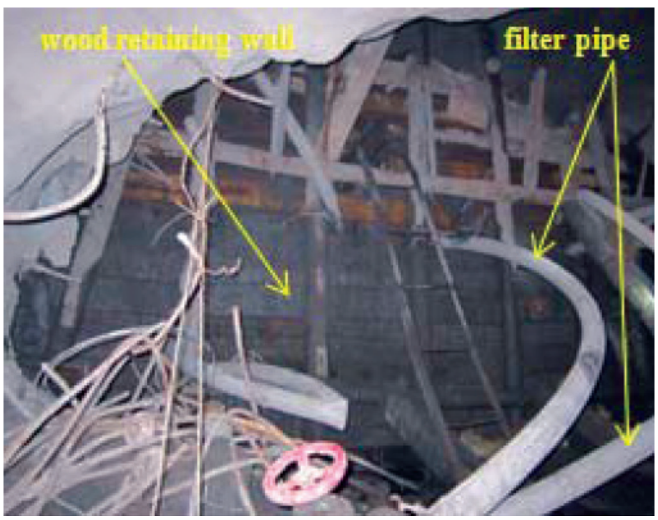


Fig.7 Wood retaining wall

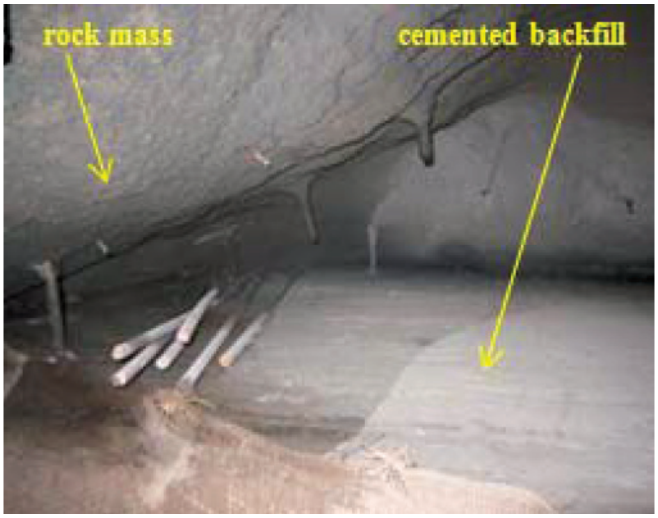


Fig.8 Good roof contact in the goaf

economic returns. Filling the goaf with solid waste avoids air pollution caused by dust and smoke. Moreover, the underground water and the ecosystem on the ground (including cities, rivers, and plants) are under effective protection. As a typical urban mine with a dense population, Laixin iron mine produces a good ecological protection effect through the successful disposal of solid waste (Fig.9).

4. Results and discussion

Physico-chemical analysis indicated that the content of SiO_2 in the tailings was low (only approximately 30%), whereas that in other similar mines is mainly 45%-75%. Thus, the SiO_2 content in Laixin iron mine is lower than that in similar mines at home and abroad (Yin Shenghua et al., 2012; Bayram Ercikdi et al., 2009). The contents of CaO, MgO, and Al_2O_3 in the tailings of Laixin iron mine add up to 37%, which is much higher than that in other mines (Deng Dai-qiang et al., 2009). The specialty of chemical components results in special physical properties. Samples were dried and smashed into the original particle size. During this procedure, high pressure was required, and scattering the particles became difficult, which meant that the tailings had strong viscidity. In addition, the setting was slow, as proven in the slurry-making process.

The tailings were mixed with cementation powder or cement. The mixtures were added with running water to produce a test specimen. Uniaxial compressive strength was measured after maintenance. The measurement results showed that the specimen made from 57% tailing slurry and cementation powder with tailings (1:4) after maintenance for 3, 7, 28, and 60 d had the highest uniaxial compressive strength, which was much higher than that of the specimen made from 57% tailing slurry and cementation powder with tailings (1:4). At a cementing material–tailings ratio of 1:6, the strengths of the two specimens became similar. The cementing effect of cementation powder was much better than that of cement. Thus, cementation powder was selected as the cement filling material.

The low content of SiO_2 in the tailings, fine particles, and poor permeability of tailings made the combination with cement, whose hydration was affected, difficult and resulted in a backfill with poor strength. In addition, the high contents of CaO, MgO, and Al_2O_3 weakened the cementing effect of cement. The filling body added with cementation powder remarkably improved in terms of strength. The uniaxial compressive strength test revealed that a few water drops were precipitated when the tailings–cementation powder specimen was compressed, whereas no water drops were noted when the tailings–cement specimen was compressed.

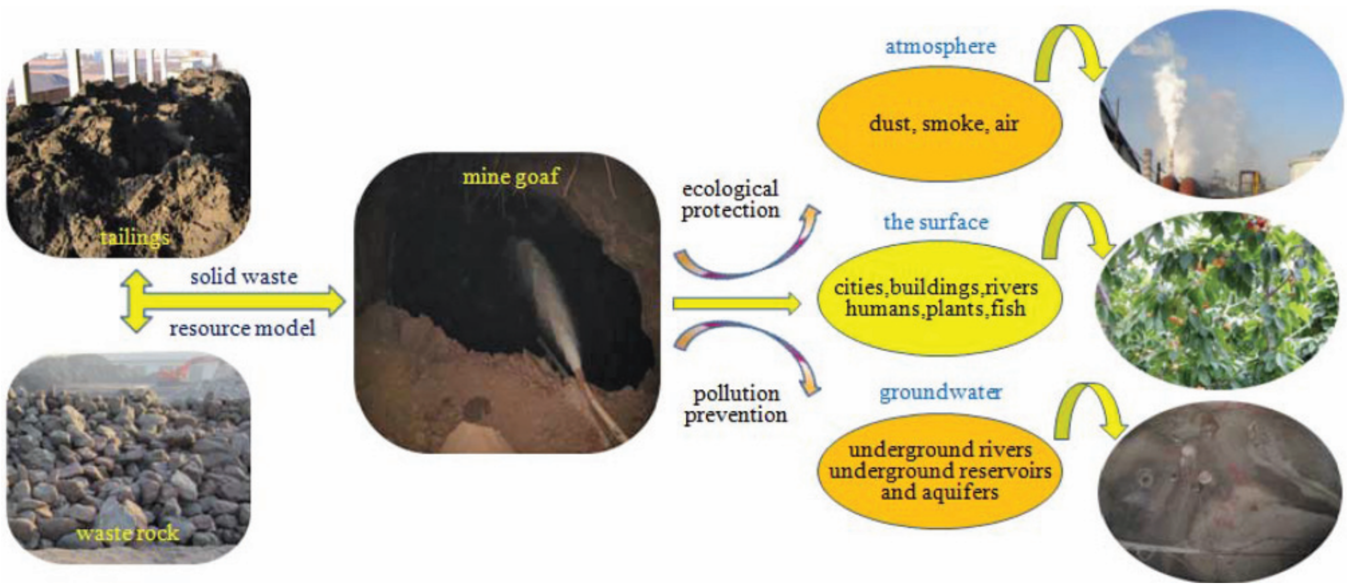


Fig.9 Favourable effect of the recycling mode of solid waste disposal

These findings indicate that the filling body with tailings–cementation powder had several properties of high-water materials. However, long-term on-site application showed that the filling body had good mechanical stability. The proportion of tailings and cementation should be adjusted according to engineering locations and mining steps to meet the requirements of different mining methods.

Compared to the filling technique used in other mines, the technique used in Laixin iron mine possesses different characteristics. Most of the other mines are located in Gobi Desert or mountainous under-populated areas, whereas this mine is near a large city with a dense population. No condition for building a tailing pond is available, which is also not allowed by policies. Thus, harmless disposal is the only solution. In the process of filling the goaf in this mine, the tailings are smashed into pieces through machines and transported to the tailing tank before mixing with low-concentration tailing slurry. Then, the mixture is compressed to produce a slurry, which is added with cementation powder. After the mixture is placed into the pipeline, it flows into the goaf automatically. The filling slurry is dehydrated in the goaf and hardened to form a large backfill. After the hardened backfill fills up the entire goaf and participates in the geological tectonics, it supports the surrounding rocks, closes the rock cracks, and prevents the weak rock mass from expanding, consequently controlling the ground pressure, protecting the Earth's surface, and preventing Earth collapse.

5. Conclusions

Harmless disposal of solid waste and environmental protection are important for underground metal mines peripheral to cities. Thus, the feasibility of harmless disposal should be studied according to the conditions of mines to identify the best disposal mode of solid waste. For energy conservation, emission reduction, and clean production, the filling method is adopted in Laixin iron mine. Most of the tailings are used to fill up the goaf, and some are compressed and sold. This procedure is a good example of zero discharge, so building a tailing pond is unnecessary. Thus, harmonious development of the mine and the city is achieved.

The special physico-chemical property of tailings in Laixin iron mine (high sum content of CaO, MgO, and Al_2O_3 and low content of SiO_2) and fine tailing particles lead to a poor combination of cement with the tailings. However, cementation powder can speed up the hardening of the filling slurry and greatly improve the strength of the backfill. Thus, the requirements of mining are satisfied, surrounding rocks are effectively supported, and underground water channels are closed.

For long-term industrial applications, the fine particles with large specific surface areas result in low concentrations of filling slurry to form a structural fluid that is thick and has a good levelling property after flowing into the stope. Owing to either drift stoping with backfill or sublevel open stoping with subsequent backfilling, the tight-filling ratio and exposure of backfill sections show a favourable wholeness. The homogeneity and physico-mechanical properties of the filling body create good conditions for controlling rock strata movement and safe backstopping.

The underground water enrichment problem is common in mines in Shandong Peninsula, China, where underground water is abundant. Therefore, water control in the mines of this area is a challenge to be solved. The filling method used in Laixin iron mine safeguards a stable lithic drainage and avoids large-area exposure of the lithic drainage while controlling the ground pressure from the rock stratum. As a result, water supply and river feeding are protected from any negative influence. The local ecosystem is well preserved and developed, and a friendly interaction among mines, cities, and the ecosystem is achieved in heavy-water areas.

Acknowledgements

This research is supported by National Natural Science Foundation of China (Grant No. 51764009) and the Guizhou Province Science and Technology Support Plan Project ((Grant No. [2018]2836).

Author contributions

D.Q. Deng wrote the main text of the manuscript. F.F. Jiang and L. Peng collected and analyzed the data. All authors reviewed and commented on the manuscript.

Additional information

Competing interests: The authors declare that they have no competing interests.

References

1. Sinha Babu Swati, Datta, Soumyendra Kishore, (2013): The relevance of environmental Kuznets curve (EKC) in a framework of broad-based environmental degradation and modified measure of growth–a pooled data analysis. *International Journal of Sustainable Development & World Ecology.* 20(4), 309-316.
2. Morton-Bermea O., Hernández-Álvarez E., González-Hernández G., Romero F., Lozano R., Beramendi-Orosco L.E., (2008): Assessment of heavy metal pollution in urban topsoils from the metropolitan area of Mexico City. *Journal of Geochemical Exploration.* 101(3), 218-224.
3. Fall M., Célestin J.C., Pokharel M., Touré M., (2010): A contribution to understanding the effects of curing temperature on the mechanical properties of mine cemented tailings backfill. *Engineering Geology*. 114 (3), 397-413.
4. Deng D.Q., Liu L., Yao Z.L., Song K.I.-I.L., Lao D.Z.,

(2017): A practice of ultra-fine tailings disposal as filling material in a gold mine. *Journal of Environmental Management.* (196), 100-109.

5. Ercikdi Bayram, Cihangir Ferdi, Kesimal Ayhan, Deveci Haci, Alp Ýbrahim., (2010): Utilization of water-reducing admixtures in cemented paste backfill of sulphide-rich mill tailings. *Journal of Hazardous Materials.* 179(1), 940-946.
6. Nan Hu Bing., (2012): Backfill Mining Technology and Development Tendency in China Coal Mine. *Coal Science and Technology*. 40(11), 1-5, 18.
7. Querol X., Izquierdo M., Monfort E., Alvarez E., Font O., Moreno T., Alastuey A., Zhuang X., Lu W., Wang Y., (2008): Environmental characterization of burnt coal gangue banks at Yangquan, Shanxi Province, China. *International Journal of Coal Geology*. 75(2), 93-104.
8. Wang Shun-cai, Cao Wei-qing, Kang Rui-hai., (2008): Full Tailings Cemented Filling Technology in Nanjing Lead-zinc-silver Mine. *Nonferrous Metals*. 60(2), 107-109.
9. Huang Wen-jun, Liao Qiu-guang, Liu Wan-yun, et al., (2012): Coagulation Aid in the Study of Flocculation Sedimentation for Unclassified Tailings Backfilling in Donguashan Copper Mine. Jiangxi Chemical Industry. (3), 25-29.
10. Yang Zhi-qiang,Gao-qian,WangYong-qian, et al., 2014. On the Technological Progress and Prospects of Paste Backfilling in JinchuanNickel Mine. *Journal of Xuzhou Institute of Technology* (Natural Sciences Edition). 29(3), 1-8.
11. Xu Jia-fu., (2012): Underground curtain grouting near ore body technique and application in iron ore mining. *China Mining Magazine.* 21(12), 78-81.
12. Zhang Guo-lian, Zhao Xing-dong, Yang Yu-jiang., (2008): Numerical Simulation of Back Sublevel Fill Stoping with Parallelogramic Stope Structure. *Journal of Northeastern University* (Natural Science). 29(5), 722-725.
13. Wang Hong-yong, Chang Xing-jian, Liu Jing-shan, Zheng Fei., 2010. Research on stope caving-in mechanics and controlling method. *IM&P.* 39(6),25-27.
14. Li Wen-xiu, Liu Xin-qiang., (2010): Application of Sublevel Filling Method to Soft Rock Strata in Laixin Iron Mine. *Chinese Journal of Rock Mechanics and Engineering.* (S2). 3749-3754.
15. Liu Jian-feng., 2016. Selection of Water Control Solutions for Heavy-water Deposit of Laixin Iron Mine. *Mining Engineering.* 14(3), 21-24.
16. Xu Jia-fu., (2014): Optimization of the filling system in Laixin Iron Mine. *Mining Technology*. (6), 22-25.
17. Lou Guang-wen., (2012): The transformation of full tailings filling system in Laixin iron mine. *Modern Mining.* (4), 90-92.
18. Yin Shenghua, Wu Aixiang, Hu Kaijian, Yong Wang, Yankai Zhang., (2012): The effect of solid components on rheological and mechanical properties of cemented paste backfill. *Minerals Engineering.* 35(3), 61-66.
19. Bayram Ercikdi, Ferdi Cihangir, Ayhan Kesimal, Haci Deveci, Ýbrahim Alp., (2009): Utilization of industrial waste products as pozzolanic material in cemented paste backfill of high sulphide mill tailings. *Journal of Hazardous Materials.* 168(2), 848-856.
20. Deng Dai-qiang, Gao Yong-tao, Kang Rui-hai, Zhu Wei-ya., (2009): Mechanics Properties of Cementation Powder-tailing Backfill Material. *Journal of Shihezi University* (Natural Science) 27(1), 88-91.