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Original Research

Circular use of fine-grained tailings to underground mine wind walls

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ABSTRACT

Mining activities tend to generate various waste including tailings, waste water and waste rock. Efficient management and disposal of these waste materials are critical to minimize their environmental impact and ensure the sustainable operation of mining activities. A huge number of tailings are produced all around the world each year. Generally, part of the tailings is used for underground backfilling and another part is discharged to the tailings dam. The former can provide underground support while the latter tends to cause some environmental problems because the tailings are generally mixed with some chemicals. Regarding this, enhancing the circular use of tailings is crucial to guarantee the sustainable mining engineering. In this study, the feasibility of using fine-grained tailings to make non-burning hollow bricks for underground windbreaks is investigated. A two-stage experiment was implemented where the first stage experiment indicated the threshold of water content, the ratio of cement and tailings and the ratio of fine-grained and rod-mill tailings. In addition, it can be indicated that the addition of polyethylene fibers would increase the compressive strength of hollow bricks in some extent. The second-stage experiment was conducted with no rod-mill tailing added and it can be found that when the ratio of cement and tailings is equal or higher than 1:6, fiber content is more significant in improving brick strength but when this value is lower, the ratio of cement is more important than fiber factors. When the ratio of cement and fine-grained tailings is 1:8 with 0.5 g/kg and 12 mm polypropylene fiber added, the hollow brick is capable of achieving strength of 1.4 MPa for 28 days curation with the price of 0.50 RMB/block. This proportioning scheme is the least expensive while meeting the strength of the windbreak wall for the Fan Kou lead—zinc mine. Finally, it can be indicated that the usage of fine-grained tailings to make underground windbreak wall is feasible and thus provide a new scenario to circular usage of tailings. In addition, other proportioning schemes proposed in this study perhaps can meet more engineering requirements so as to provide more alternatives for circular use of tailings.

1. Introduction

Mining engineering is a notable field that centers on the extraction, processing and utilization of minerals derived from the Earth (Hartman & Mutmansky, 2002). During the mining process, not all of the extracted material can be utilized, resulting in the formation of leftover material called tailings (Kossoff et al., 2014; Wang et al., 2014). Generally, the tailings are mixed with some chemical reagents which depend on the flotation process. Tailings generated by the mining industry constitute a significant portion of industrial waste. Therefore, effective management and disposal of tailings are essential to minimize their environmental impact and ensure the long-term sustainability of mining operations (Adiansyah et al., 2015; Reid et al., 2009). According to 2021 statistics, China produces approximately 16.49 billion tons of tailings annually, yet only 312 million tons are utilized, resulting in a meager comprehensive utilization rate of 18.9% (Li et al., 2023). Indiscriminate disposal of tailings poses grave threats to production safety and environmental pollution (Lazorenko et al., 2021). Over the past few decades, a lot of tailings have been discharged into

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tailings dams and the resulting issues have been reported a lot (Azam & Li, 2010; Dong et al., 2020; Kossoff et al., 2014), such as floods (Sharma & Al-Busaidi, 2001), underground water pollution (Sharma & Al-Busaidi, 2001) and slope slide. Given the colossal volume of tailings produced, the recycling of this waste has emerged as a pressing topic (Martins et al., 2021). One of the most popular methods to reuse tailings is backfilling (Chen et al., 2020, 2021; Li et al., 2021; Lu et al., 2020; Yang et al., 2020). Backfilling refers to the process of filling underground or excavated areas or voids with tailings or waste rock to provide support, stability and safety to the mine workings. Over the past few years, many studies about using tailings for backfilling have been conducted. For instance, Fall and Pokharel (2010) tested 200 cemented paste backfilling (CPB) specimens with different sulfate content and curation temperatures with different maintenance times to explore the coupled influence of sulfate and temperature on the strength of CPBs. And it can be found that when the curing temperatures is larger than 20 °C and sulfate concentrations up to 15,000 ppm, the strength of CPB would get positive impact at early (28 days) and late (90, 150 days) curing times. However, it should be noted that the high temperature is not always conductive to backfilling operations, since the boundary heating plays a negative role in exacerbating backfill instability over a certain incubation period (Tao et al., 2022). This sheds light on the challenges associated with backfill processes in high-temperature mining environments. Bian et al. (2021) valuated the effect of sulfate on the yield stress and viscosity of CPB through various experiments. The results indicated that when the initial sulfate content increased, the yield stress would decrease while the viscosity would increase which indicated that too many sulfates would influence the backfill transport systems. Chen et al. (2018) conducted a series of experiments to explore the influence of polypropylene (PP) fiber on the compressive behavior and microstructural properties of fine-grained CPB. The results showed that PP fiber can enhance the overall strength performance of CPB and bridge the cracks. However, the treatment of fine-grained tailings has always been tough in practical application, since they tend to need more cement to achieve underground mining strength requirement. In addition, sulfate content in fine-grained tailings may be higher and cause lower fluidity. Therefore, some alternatives to consume tailings are necessary.

Concurrently, there is a growing demand for diverse construction materials in the construction industry. Researchers have acknowledged that employing industrial waste as raw materials in construction not only enhances waste utilization and sustainability but also reduces construction costs (Xi et al., 2020; Zhang et al., 2022). Blocks serve as the primary material for various housing constructions. Conventional clay blocks typically necessitate significant quantities of clay for firing. However, the availability of natural resources required for traditional clay brick production is highly limited. Over the past 50 years, the construction brick industry in China has decimated approximately 1.3 billion square meters of arable land. Moreover, the production of no-bake blocks often demands substantial amounts of natural aggregates, resulting in a certain level of environmental pollution during the extraction process (Yang et al., 2009). Presently, the escalating prices and diminishing production of natural aggregates, driven by environmental policies in different nations, underscore the importance of utilizing greener and more cost-effective raw materials for brick manufacturing (Söderholm, 2011). Some tailings contain abundant quartz minerals, with particle sizes resembling those of natural sand, thereby enabling their incorporation as fine aggregates in concrete, akin to river sand or manufactured sand. Several researchers have discovered that the utilization of different tailings, including iron tailings, copper tailings, and lead–zinc tailings, for brick production not only guarantees the desired mechanical properties but also improves the sustainability characteristics of the material (Chen et al., 2011; Roy et al., 2007; Sheikh & Reza, 2017). Zhao et al. (2009) utilized low-silicon tailings to make load-bearing bricks by pressing and autoclaving process where the weight of the tailings accounts for 83% of the weight of the brick. The highest strength can reach 16.1 MPa and 3.9 MPa for compression and bending, respectively. Roy et al. (2007) proposed to combine Portland cement, black cotton soils, red soils and gold mill tailings to make bricks. When the tailings are combined with cement, the bricks with 20% cement and 14-day curation would be recommended. Sheikh and Reza (2017) employed the geopolymerization technique to produce copper mine tailings-base non-burning bricks. The basic procedure is to mix tailings with an alkaline solution and provide some compression pressure to form the bricks. The impact of four factors on the physical and chemical properties of bricks are investigated including sodium hydroxide solution concentration, water content, forming pressure and curing temperature. It can be found that it is feasible to make bricks with the suitable preparation conditions. de Freitas et al. (2018) evaluated the feasibility of reuse of steel slag and iron ore tailings to produce solid brick. The produced brick can reach a lowest flexural strength of 2 MPa and the mean weight is similar to some ecological bricks. Meanwhile, the produced bricks can consume a large amount of slag in Brazil in the practical application. Furthermore, certain tailings such as lead–zinc tailings exhibit a volcanic ash effect, actively engaging in the hydration reaction of concrete and resulting in the formation of a robust and compact cementitious structure (Li et al., 2023). Inspired by these findings, this study proposed the utilization of fine-grained tailings from the Fan Kou lead–zinc mine, for the production of non-burning hollow bricks used for underground windbreak walls to enhance tailings utilization efficiency and mitigate environmental pollution. The mechanical properties of the hollow blocks were tested based on different proportioning schemes and the influence of content of tailings, cement, and fibers on the mechanical properties of the hollow blocks were evaluated. And then the corresponding cost of each proportioning scheme was given, providing valuable insights into the circular use of fine-grained tailings. To the best of the author's knowledge, this study is the first one to propose to utilize fine-grained tailings to produce hollow blocks by a vibration method and further utilize hollow blocks to construct underground windbreak wall in the mine.

2. Research background

This study is mainly based on tailing treatment issues in the Fan Kou lead–zinc mine, situated in the northeastern Guangdong Province of China. There are three main sources of underground backfilling, i.e., fine-grained tailings, graded tailings and rod-mill tailings where the rod-mill tailings are the coarse sand below 3 mm by grinding waste rock and used with the graded tailings or fine-grained tailings to increase the backfilling strength. The general production process of fine-grained and graded tailings can be seen in Fig. 1. The original tailing slurry is extracted by pumping Station #1, and then all tailings slurry is fed to Concentrator #1, the bottom flow part is graded by desliming cyclone and sent to ceramic filter to produce graded tailing cake. The cyclone overflow and ceramic filter overflow are returned to Concentrator #1. The overflow of Concentrator #1 goes to Concentrator #2, the bottom flow is further concentrated and supplied to produce fine-grained tailing cake. A small part of fine-grained tailings is directly used for filling, however, there are still lots of fine-grained tailings discharged into the tailing dam resulting in some environmental issues. In addition, the fine-grained tailings tend to be hard to generate desirable backfilling strength and thus cannot meet the

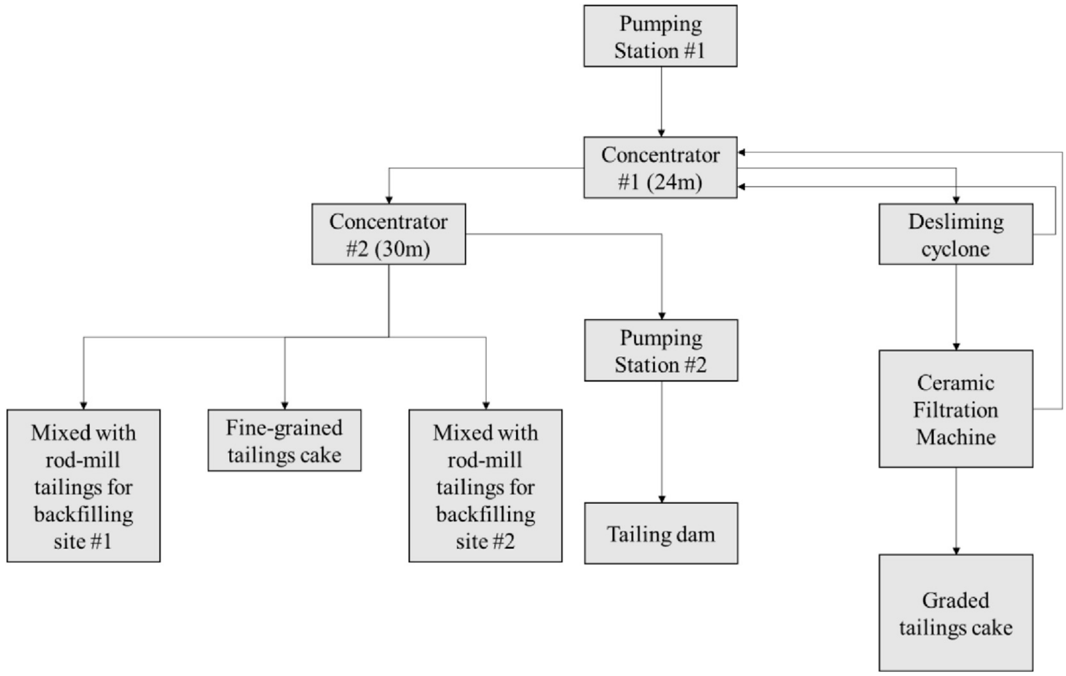

Fig. 1. The general tailing production process of the fine-grained and graded tailings in the Fan Kou lead–zinc mine.

requirement of some mining operations. Regarding this, the Fan Kou lead–zinc mine further proposed the combination of fine-grained tailings and fiber materials. This approach aims to enhance the strength of filling body, improve tailings utilization efficiency and thus mitigate environmental pollution concerns. However, the addition of fiber materials into the filling slurry would decrease the slurry fluidity and thus lead to pipeline blockage which would induce a huge economic loss to the mine. To solve this issue, this study proposes circular use of fine-grained tailings to underground mine windbreak walls to reduce the pressure of tailings discharge and generate economic benefits for the mine.

3. Materials, equipment and testing procedure

3.1. Materials

The fine-grained tailings are the main investigation objective in this study. The auxiliary materials include Hailuo cement, rod-mill tailings, polypropylene (PP) fiber and water. Where Hailuo cement is a kind of widely used cement in the Fan Kou lead–zinc mine and can meet the requirements of minimum strength of 42.5 MPa with the standard 28-day curation. Rod-mill tailings are obtained by grinding waste rock and mixed with tailings to enhance the brick strength. To measure the particle distribution of fine-grained tailings and rod-mill tailings, the test was completed using LS13320 Laser Particle Size Analyzer. The general particle distribution of fine-grained tailings and rod-mill tailings can be seen in Fig. 2.

It can be found that the median particle size of fine-grained tailings is about 25.31 μm and the cumulative percentage 10, 30, 60 and 90 corresponds to 3.206 μm, 9.819 μm, 33.01 μm and 92.1 μm, respectively. According to the test report, the particle inhomogeneity coefficient is 10.3 and the curvature coefficient is 0.911. In general, the desirable particle inhomogeneity coefficient is not less than 5, and the curvature coefficient is between 1 and 3. It can be considered that the material grade and the degree of compactness is good. Therefore, it can be said that fine-grained tailing grade is general. For rod-mill tailings, it can be seen that the median particle size is about 131.8 μm and the cumulative percentage 10, 30, 60 and 90 corresponds to 39.78 μm, 76.43 μm, 146.8 μm and 339.9 μm, respectively. The particle inhomogeneity coefficient is 3.69 and the curvature coefficient is 1.0. According to the aforementioned standard, it can be seen that the grade distribution is not desirable.

The chemical composition analysis of tailings in this study employed X-ray fluorescence spectrometry (XRF) for semi-quantitative analysis. The results are shown in Table 1.

From the XRF chemical composition test results, it can be seen that the main metallic elements in the tailings are Fe, Ca and Al, with little heavy metals, and the metallic elements contained in both tailings are similar but different ratio. The main non-metallic oxides in the tailing sand are SiO_2, whose contents in fine-grained and rod-mill tailings are 27.10% and 24.60%, respectively; the main metal oxides include Al_2O_3, Fe_2O_3, MgO, CaO and K_2O, and the contents of other metal oxides are low. The high content of SiO_2, Al_2O_3 and CaO in the tailings is beneficial to the preparation for building materials. But the high content of S elements is not conducive to the strength development. Regarding this, a certain amount of polypropylene (PP) fiber can be considered to improve the overall performance of the materials (Chen, Shi, et al., 2021; Sohaib et al., 2018; Tang et al., 2007). In this study, three PP fibers with length of 9 mm, 12 mm and 19 mm are chose and investigated. The general properties of PP fibers can be seen in Table 2.

3.2. Equipment and testing procedure

The equipment used for the production of fine-grained tailing hollow bricks in this study is a kind of non-burning vibration brick machine produced by Xinfa Brick Company, Henan, China. It is easy to operate and produces bricks by vibration molding with common two-phase electricity. Each operation can produce two hollow blocks with the same component and size. The size of the mold is 19 cm in height, 39 cm in length and 19 cm in width and the cross-sectional area of each mold is 366.45 cm^2, excluding the two solid

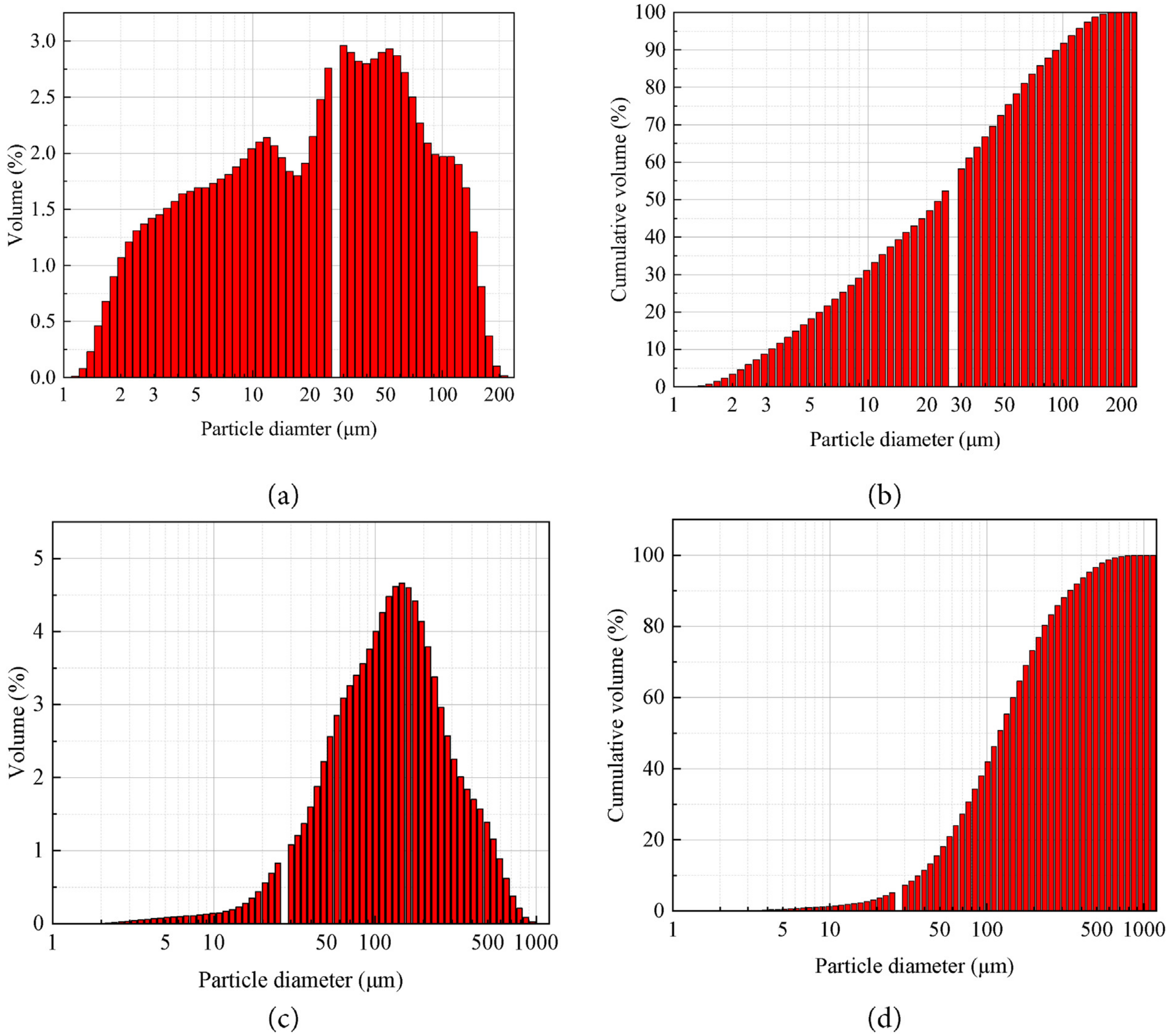

Fig. 2. Particle diameter of fine-grained and graded tailings: (a) particle diameter distribution of fine-grained tailings; (b) cumulative particle diameter distribution of fine-grained tailings; (c) particle diameter distribution of rod-mill tailings; (d) cumulative particle diameter distribution of rod-mill tailings.

Table 1
Chemical analysis results of tailings.

Samples	Results (%)										
	Al_2O_3	SiO_2	MnO	Fe_2O_3	MgO	CaO	K_2O	TiO_2	P_2O_5	S	Cu
Fine-grained tailings	9.11	27.10	0.01	23.70	1.40	22.6	2.19	0.26	0.08	11.90	0.032
Rod-mill tailings	5.21	24.60	0.28	22.50	1.63	32.0	1.18	0.24	0.06	10.70	0.013
Samples	Sr	Cr	Ni	Zn	Pb	Ba	Cl	F	Zr	As	Rb
Fine-grained tailings	0.014	0.056	0.012	0.430	0.883	0.07	0.01	–	0.007	0.098	0.006
Rod-mill tailings	0.022	0.076	0.009	0.448	0.47	0.061	0.019	0.337	0.007	0.084	0.004

Table 2
General properties of PP fibers.

Fiber shape	Bundled monofilament	Tensile strength	>486 MPa
Specific gravity	0.91	Modulus of elasticity	>4.8 GPa
Acid and alkali resistance	Very high	Fiber diameter	18–48 μm
Thermal conductivity	Very low	Water absorption	None
Low temperature resistance	Strong	Tensile limit	>15%

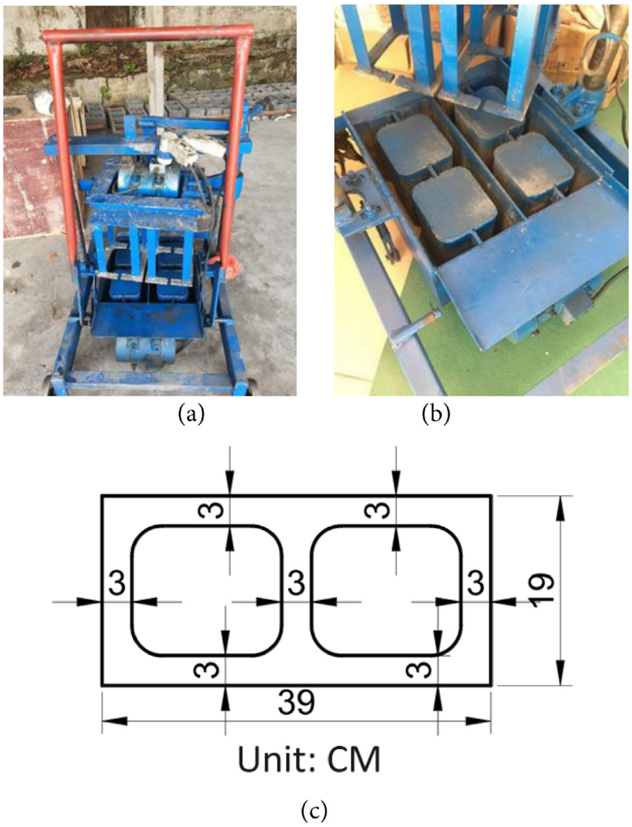

Fig. 3. The appearance of vibration brick machine. (a) The general appearance of vibration brick machine; (b) the general appearance of the mold; (c) the cross section of the mold.

parts as shown in Fig. 3. The brick machine is equipped with two vibrators at the top and bottom, and the vibrator is the ZW55 single-phase vibrator produced by Wenxian Wuzhou Motor Factory, China, whose specific specifications are shown in Table 3.

The general production progress including: sampling, drying, grinding, stirring, vibration molding and curing as can be seen in Fig. 4. In addition, all bricks are watered every day until the eighth day. To mimic the practical production environmental, the bricks are cured in a natural environment with the temperature range of 20–30 °C.

To explore the feasibility of usage of fine-grained tailings to make hollow bricks, this study involves two stages. The first stage involved some trial tests to determine a general proportion to ensure the formation of hollow bricks and conduct a general evaluation for different materials. In the second stage, the proportioning scheme from the first stage is used as a basis to determine schemes with lower cement and rod-mill tailings consumption and higher consumption of fine-grained tailings. PP fiber is added to enhance the strength of the hollow blocks and further reduce cement and rod-mill tailings consumption. The 28-day uniaxial compressive strength from two same component specimens was tested and the average value was taken as the final test result. The tests were conducted using a 2000 kN hydraulic universal testing machine (CHT4305), as shown in Fig. 5 (a). Since the surface area of the hollow block exceeds the area of the pressure transducer, a steel plate was placed to both the upper and lower surfaces of the hollow block. Additionally, for the hollow blocks with uneven upper and lower surfaces, a grinding machine was used to polish them. This process ensured complete touch between the upper and lower surfaces of the hollow blocks and the steel plate during the stress tests, as depicted in Fig. 5 (b). The test was continued until the specimen was fully damaged.

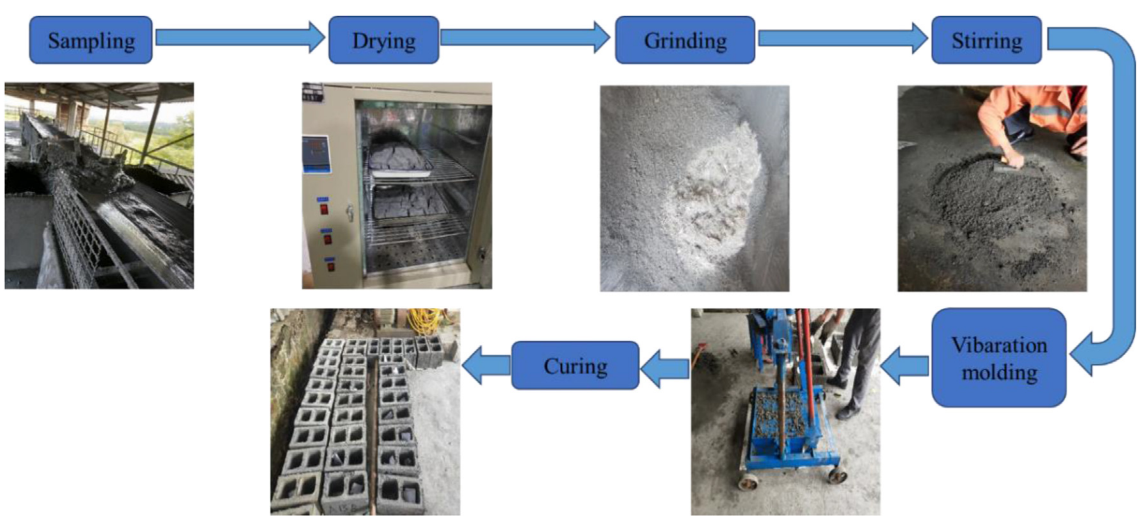

Fig. 4. The general production progress of fine-grained tailings hollow bricks.

Table 3
ZW^{55} single-phase vibrator specifications.

Working power	550 W	Vibration frequency	48 Hz
Working voltage	220 V	Excitation force	2.6 kN
Working current	1.6 A	Weight	11 kg
Phase	Single-phase	Factory	Wenxian Wuzhou Motor Factory

(a) (b)

Fig. 5. The compressive strength tests for hollow bricks: (a) the compressive strength testing machine; (b) the polishing process.

4. Results

4.1. Mechanical properties

The water content is a significant factor for the formation of non-burning bricks. Therefore, precise control of the water content is crucial for the production of hollow bricks. Since it is the first to explore the feasibility of usage fine-grained tailings to produce hollow bricks in the Fan Kou lead–zinc mine and the properties of tailings in different mines vary a lot, the ratio of water content needs to be validated by testing and observing. For the ratio of water, if it is excessive, then it will cause the materials to have a high slump, leading to deformation of bricks as shown in Fig. 6(a). If the water ratio is low, the cement cannot undergo sufficient hydration reaction, reducing the bonding strength between the materials and thus causes collapse as shown in Fig. 6(b). Some trial tests were conducted at first, it can be found that the formation of hollow bricks is desirable with water content 23%.

Therefore, in the following experiments, the 23% water content is used for all specimens. The detailed proportioning scheme and resulting compressive strength in the first stage can be seen in Appendix in Table A1. At first, the influence of cement-talings ratio (CTR) and the ratio of fine-grained and rod-mill tailings (RFR) was tested, and it can be found that when the CTR is constant, when the RFR is equal to 4:4, the scheme can produce the highest compressive strength compared with RFR equal to 3:4 and 2:4 as shown in Fig. 7. It can be explained that the strength formation requires some number of fine-grained tailings since their sizes are smaller than rod-mill tailings and fill the voids in the cement mortar and making the concrete more compact, in addition, fine aggregates help to disperse the cement particles and prevent them from clumping, thus distributing the cement more evenly throughout the concrete which helps to improve the reactivity of the cement and enhances the strength of the bricks. When the CTR is constant, the RFR equal to 2:4 brought higher strength than RFR equal to 3:4; this perhaps is due to the experimental error because only two specimens were made for each proportioning scheme. When the RFR is constant, lower CTR induced lower brick strength because more hydration reaction could provide more strength.

(a) Deformation (b) Collapse

Fig. 6. (a) Deformation and **(b)** collapse.

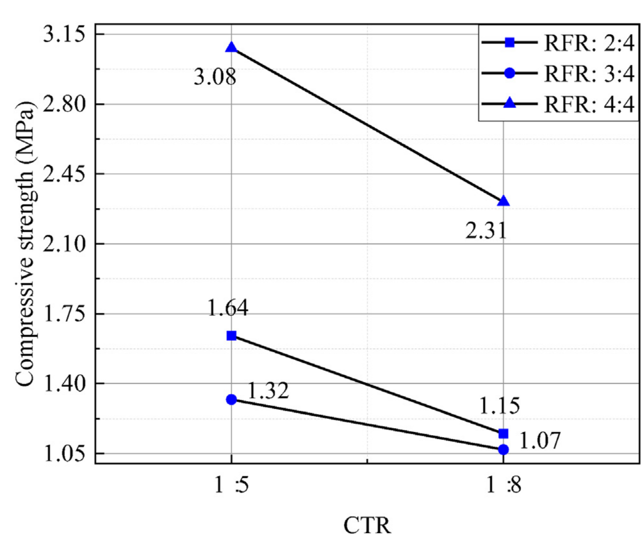

Fig. 7. The influence of CTR and RFR on the brick compressive strength.

When the CTR is equal to 1:8, the compressive strength shows a decreased trend with the increased RFR from 4:4 to 7:4. However, when the RFR continues to increase, no obvious trend can be observed from the tests. It can be indicated that the addition of a certain number of rod-mill tailings would bring a positive influence on the compressive strength due to the high strength and rigidity of coarse rod-mill tailings, they can disperse and transfer stresses in some extent, providing greater resistance. But when few rod-mill tailings are added, it may not have a significant impact on compressive strength. This phenomenon has been shown in Fig. 8. In addition, it can be found that when the materials are not mixed with rod-mill tailings, bricks can still be formed. To explore the limitation of the ratio of fine-grained tailings in all materials, a lower CTR was tried. However, when the value of CTR is lower than 1:12, it would be hard to form a brick. Therefore, 1:12 seems to the limitation of CTR. To investigate the influence of PP fibers, three groups of lower CTR tests were chose and PP fibers with 19 mm in length and 3 g/kg were added into the materials. It can be indicated that the compressive strength increases a lot when the rod-mill tailings are added and the CTR is equal to 1:8, but when the CTR is too low, i.e., 1:12, the addition of PP fibers cannot affect the brick strength as shown in Fig. 9. However, the ductility of the bricks can be enhanced because of the tensile effect of fibers. As shown in Fig. 10, PP fibers can effectively delay the generation and development of concrete cracks.

The tests conducted in the first stage indicated.

(a) The rod-mill tailings seem to be not necessary for the formation of fine-grained hollow blocks.
(b) The addition of PP fibers did not affect the formation of hollow blocks and brings some positive influence on the increase of hollow brick strength.
(c) The concentration could be set at about 77%, ensuring successful formation of the hollow bricks.
(d) The minimum CTR is about 1:12 when no rod-mill tailing is added to ensure the formation of hollow bricks.

According to the proportioning test of the first stage, it is known that the hollow blocks can still be formed without the addition of rod-mill tailings. The proportioning scheme for the second stage was designed according to the orthogonal proportioning test, considering three influencing factors: the CTR, fiber content, and fiber length. And two orthogonal tests with 3 factors of CTR, fiber content and fiber length, and 3 levels of CTR, fiber contents and fiber length are designed, with a total of 9 groups, as shown in Tables A1 and A3 in the Appendix. The single factor analysis can be seen in Tables 4 and 5.

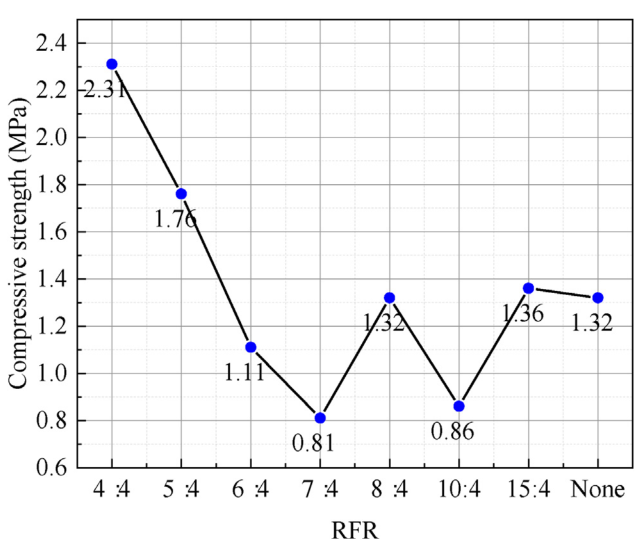

Fig. 8. Compressive strength trend with 1:8 CTR and different RFR.

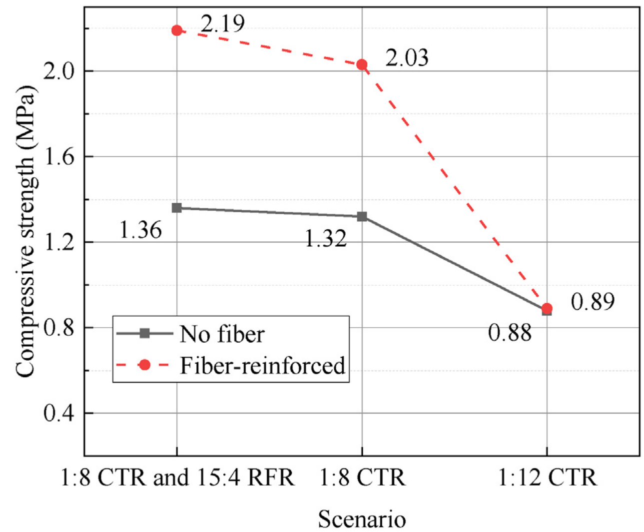

Fig. 9. Comparisons of compressive strength of no-fiber and fiber-reinforced hollow bricks.

From the single factor analysis of the orthogonal test 1 in Table 4 and Fig. 11, it can be seen that the order of strength influence of each factor level is A1>A2>A3, B3>B1>B2, C3>C1>C2. The range $R_A = 1.07$, $R_B = 2.23$, $R_C = 1.59$, the larger the value of R_j (j = A, B, C) means that the corresponding factor has a greater influence on the strength of the test sample. Therefore, it can be indicated that when the CTR is between 1:4 and 1:6, the order of importance of the factors affecting the compressive strength of hollow bricks is: fiber content (B) > fiber length (C) > CTR (A). From the single factor analysis of the orthogonal test 2 in Table 5 and Fig. 12, it can be seen that the order of strength influence of each factor level is A1>A2>A3, B2>B3>B1, C2>C1>C3. The range $R_A = 1.53$, $R_B = 0.99$, $R_C = 0.45$, it can be indicated that when the CTR is between 1:7 and 1:12, the order of importance of the factors can be ranked as: CTR (A) > fiber content (B) > fiber length (C). These results show that when the CTR is equal or higher than 1:6, fiber content plays a more important role in improving brick strength while when the CTR is lower and CTR is more significant than fiber factors.

4.2. Market potential

Based on the unit price of each material, the material costs required for the hollow blocks were derived as shown in Table 6. As a result, the corresponding price can be calculated as shown in Table A4 in the Appendix. It can be found that the proportioning scheme of group A14 requires the lowest material cost of 0.26 RMB/block and 0.88 Mpa compressive strength, which corresponds to the proportioning scheme of 1:12 CTR; the proportioning scheme of group A20 requires the highest material cost of 1.05 RMB/block and 4.23 Mpa compressive strength, which corresponds to the proportioning scheme of 1:4 CTR, 19 mm PP fibers of 3 g/kg.

According to the requirements of the Fan Kou lead−zinc mine, the hollow bricks will be used to build the unground windbreak wall instead of previous common hollow bricks as shown in Fig. 13. The main function of windbreak wall in the mine is to control ventilation and separate work areas. As we can see in Fig. 12, a piece

Fig. 10. The effect of PP fibers to crack development of bricks.

Table 4
Single factor analysis based on orthogonal test 1.

CTR (A)		Average compressive strength (MPa)	
		Mean value (MPa)	Range (MPa) (R)
A1	1:4	2.62	1.07
A2	1:5	2.27	
A3	1:6	1.55	
Fiber content (g/kg) (B)		Average compressive strength (MPa)	
		Mean value (MPa)	Range (MPa) (R)
B1	0.5	1.57	2.23
B2	1	1.32	
B3	3	3.55	
Fiber length (mm) (C)		Average compressive strength (MPa)	
		Mean value (MPa)	Range (MPa) (R)
C1	9	1.96	1.59
C2	12	1.44	
C3	19	3.03	

Table 5
Single factor analysis based on orthogonal test 2.

CTR (A)		Average compressive strength (MPa)	
		Mean value (MPa)	Range (MPa) (R)
A4	1:7	2.4	1.53
A5	1:8	1.553	
A6	1:12	0.87	
Fiber content (g/kg) (B)		Average compressive strength (MPa)	
		Mean value (MPa)	Range (MPa) (R)
B1	0.5	1.16	0.99
B2	1	2.15	
B3	3	1.51	
Fiber length (mm) (C)		Average compressive strength (MPa)	
		Mean value (MPa)	Range (MPa) (R)
C1	9	1.68	0.45
C2	12	1.96	
C3	19	1.51	

of green canvas is fixed by wooden boards to block the windbreak flow. When the ventilation is need, the wooden boards can be moved to open a gap. It can be assumed that the maximum height of the windbreak wall is 4.5 m, the average height of the hollow blocks is 19 cm and the average weight of the hollow blocks is 18 kg, then the highest part of the windbreak wall needs to be stacked with 24 hollow blocks, and the pressure required for the lowest hollow block is 0.136 Mpa, in addition, due to the complex underground conditions, the hollow blocks may be eroded by wind and water, and may also be affected by blasting vibration, so in view of

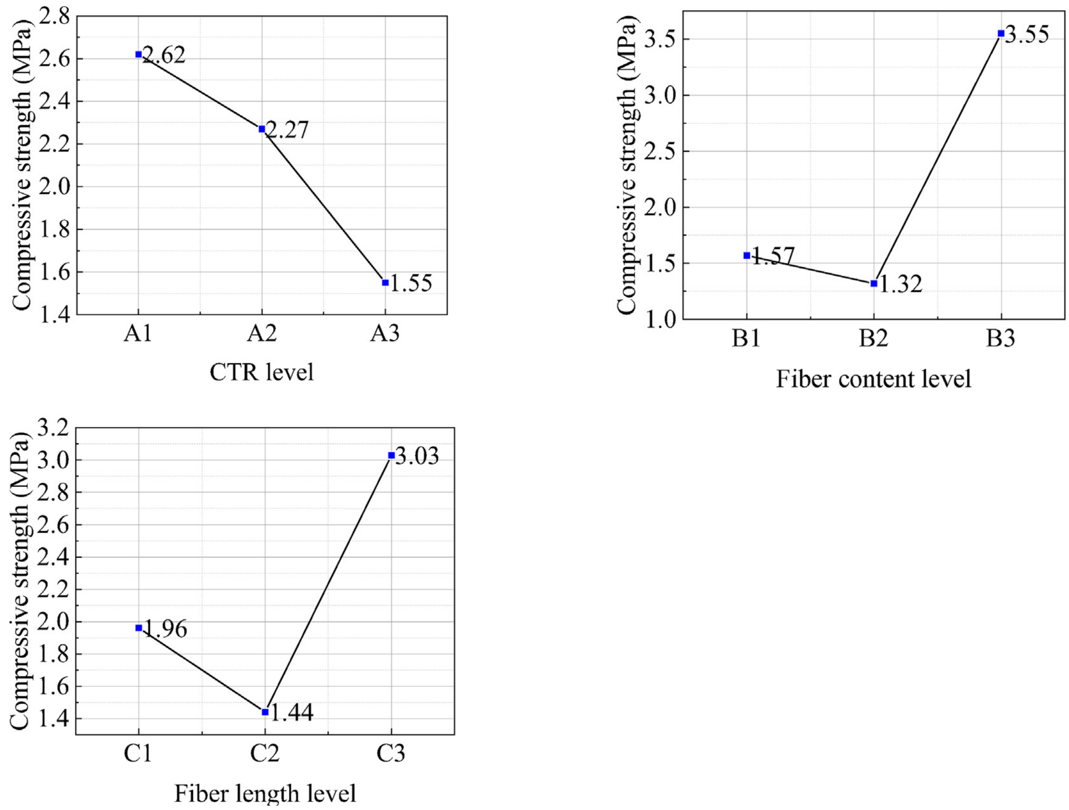

Fig. 11. Single factor analysis of the average UCS based on orthogonal test 1.

safety, the safety factor is set to 10, that is, the compressive strength of the hollow blocks should meet more than 0.136 $\times$ 10 Mpa, that is, 1.36 MPa. According to this requirement, the proportioning scheme which can meet the compressive strength requirements and corresponding cost for each block are shown in Table 7.

From the above table, it can be seen that most of the ratios of this project can meet the requirements of constructing underground windbreak wall, but considering the harsh underground conditions, the durability and toughness of hollow blocks with added polypropylene fiber can be improved. Therefore, the schemes with PP fibers will be given priority. Based on the consideration of material cost and the capacity of consumed fine-grained tailings, A31 can be considered as the best scheme as marked in Table 7.

Based on the aforementioned discussion, it can be concluded that the use of fine-grained tailings to product hollow bricks for the underground windbreak wall is feasible. In addition, some schemes can reach higher compressive strength which probably can be used for other cases.

5. Discussion

Tailings, which are waste materials produced during mining activities, require careful management in the context of lead–zinc ore production. Various methods are employed for tailings disposal, including tailings storage facilities, dry stacking and deep tailings injection. These approaches aim to minimize the environmental impacts associated with tailings and, whenever feasible, recover valuable metal elements. Stringent measures are implemented during the tailings management process to regulate the release of tailings and prevent contamination of soil, water sources, and ecosystems.

A pivotal strategy discussed in this study involves harnessing tailings for the creation of hollow blocks, with the overarching aim of optimizing tailings circular utilization from a resource-driven perspective. The adoption of technologies resonates with resource efficiency and environmental conscientiousness, constituting a sustainable solution for tailings management. Firstly, by substituting fine aggregates with tailings, the demand for natural sand, a non-renewable resource, can be reduced. Maximizing the utilization of tailings as a substitute for sand in concrete block production not only conserves resources, but also safeguards the ecological integrity of river systems. Compared to traditional sand mining and processing, the use of tailings as a substitute material has the potential to lower carbon emissions. Conventional sand and gravel extraction, coupled with their processing, incurs substantial energy consumption and contributes to challenges like riverbank erosion and water quality deterioration. Tailings, on the other hand, have already undergone extraction and concentration, rendering them readily accessible on-site. Consequently, the production of blocks utilizing tailings may require less energy input for manufacturing and transportation when compared to traditional sand-based alternatives.

Moreover, it is imperative to acknowledge that tailings possess the potential for harboring hazardous elements, and improper handling and disposal can engender environmental contamination. Particularly concerning are scenarios where lead–zinc tailings are exposed to the elements in open-air sites or contained within

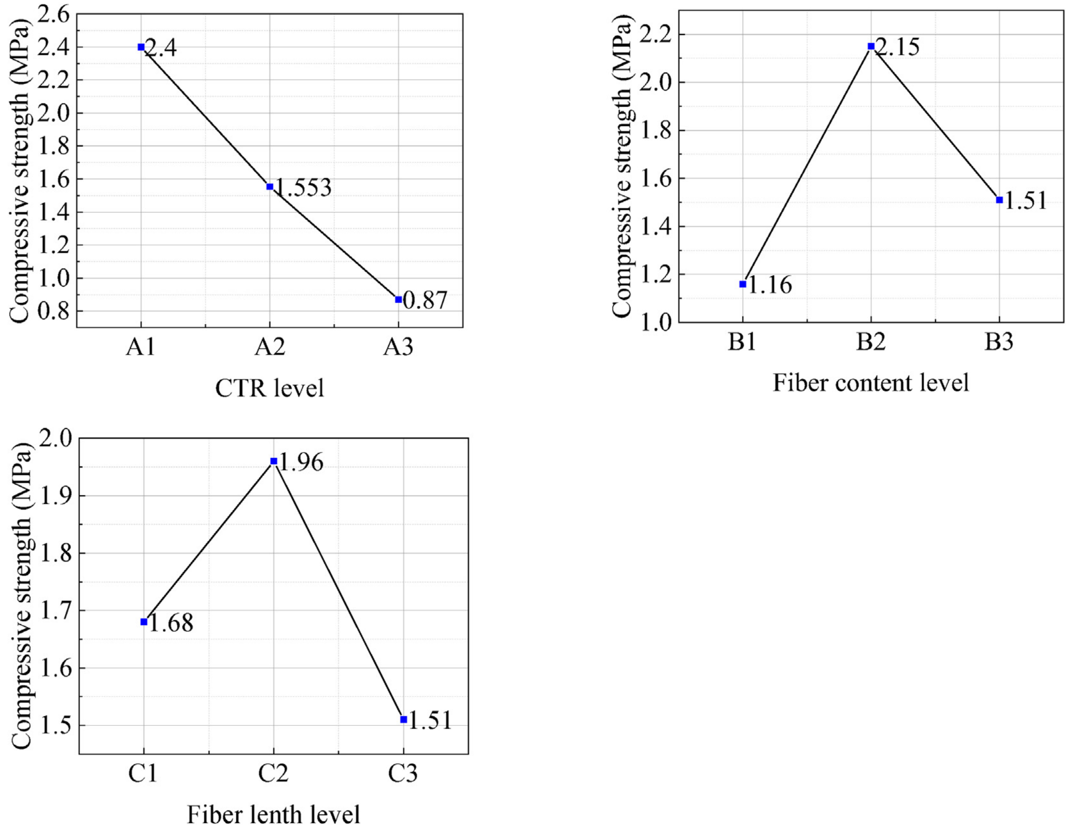

Fig. 12. Single factor analysis of the average UCS based on orthogonal test 2.

Table 6
The unit price of each material.

Material	Price (RMB/ton)
Hailuo cement	370
Fine-grained tailings	0.3
Rod-mill tailings	35
PP fibers	7000
Water	4

Fig. 13. A typical underground windbreak wall in Fan Kou lead−zinc mine.

tailings dams. Rainwater infiltration can transport pollutants into groundwater or nearby water bodies, culminating in water pollution. The ingress of heavy metals into the soil can ensue through processes like weathering, dissolution, and infiltration, triggering soil pollution. The practice of open dumping may foster the generation of dust laden with fine particles and noxious chemicals. These minute particles and substances can be disseminated by wind, precipitating air pollution and detrimentally affecting the air quality in the vicinity. Consequently, in most instances, the management of tailings generated during lead−zinc ore production entails their confinement within specialized tailings facilities. These facilities, however, demand substantial land allocation and stringent oversight to avert soil and water contamination.

By integrating tailings into block production, a potential materializes to reduce the spatial demands imposed by tailings storage facilities while concurrently immobilizing hazardous components within the blocks themselves. This approach not only mitigates land occupation but also curtails the jeopardy of water interaction and potential discharges originating from tailings storage facilities. Through this innovative avenue, the hazards inherent to tailings can be effectively managed and their ecological repercussions minimized.

Our block preparation process is conducted on-site, providing test data that is more representative of real-world applications compared to laboratory-prepared blocks, thereby offering practical relevance. However, we acknowledge the limitations of the testing conducted thus far. Currently, only the mechanical properties of the blocks have been tested and confirmed for practicality. Considering that the blocks will be utilized in windbreak walls, which are directly exposed to the external environment, the durability of the blocks must also be considered. Therefore, we recommend that in the next phase, the material's durability performance be examined in relation to factors such as alkalinity, acidity, chloride ions, and other environmental considerations to address any potential.

Table 7
The properties of hollow bricks that meet the requirement.

Number	CTR	RFR	Fiber length (mm)	Fiber content (g/kg)	Average compressive strength (MPa)	Price/per block (RMB)
A1	1:5	2:4	–	–	1.64	0.84
A5	1:5	4:4	–	–	3.08	0.95
A6	1:8	4:4	–	–	2.31	0.61
A7	1:8	5:4	–	–	1.76	0.54
A13	1:8	–	–	–	1.32	0.38
A15	1:8	15:4	19	3	2.19	0.63
A16	1:8	–	19	3	2.03	0.55
A18	1:4	–	9	0.5	2.45	0.84
A20	1:4	–	19	3	4.23	1.05
A22	1:5	–	12	1	1.87	0.79
A23	1:5	–	19	3	3.96	0.97
A24	1:6	–	9	3	2.46	0.78
A27	1:7	–	9	1	3.14	0.59
A28	1:7	–	12	3	2.38	0.75
A29	1:7	–	19	0.5	1.69	0.54
A31	**1:8**	—	**12**	**0.5**	**1.4**	**0.50**
A32	1:8	–	19	1	2.33	0.56

Note: Cement-talings ratio (CTR); Ratio of fine-grained and rod-mill tailings (RFR).

6. Conclusions

Over the past few years, the treatment and reuse of tailings in mining engineering has been a popular topic. Currently, the cemented paste backfilling is an effective approach. However, for fine-grained tailings, it tends to consume too much cement and is hard to achieve satisfactory backfilling strength resulting in a huge amount of tailings accumulation and discharge. The resulting environmental problems need to be solved. Regarding this, this study conducted a few dozen of proportioning schemes to explore the feasibility of using fine-grained tailings to produce hollow bricks for underground windbreaks. It can be found that it is feasible to make fine-grained tailings-based hollow bricks by vibration. According to the results from the first-stage experiment, it can be found that the concentration to ensure the formation of hollow bricks is about 77%. The rod-mill tailings are not necessary for the formation of fine-grained based hollow bricks. And when no rod-mill tailing is added, the minimum CTR is about 1:12. The addition of PP fibers can produce some positive influence on the increase of hollow brick strength, however, it cannot make obvious effect when the CTR is too low, i.e., equal to 1:12. The second-stage experiment was conducted based on fiber-reinforced proportioning schemes, and then it can be indicated that when the CTR is equal or higher than 1:6, fiber content is more significant in improving brick strength while when the CTR is lower, CTR is more important than fiber factors. Finally, it can be concluded that using fine-grained tailings to make underground windbreak walls is feasible and the best proportioning scheme is the ratio of cement and tailings equal to 1:8 with 12 mm and 0.5 g/kg PP fiber added since it meets the strength requirement of underground windbreak wall and need lowest cost. These efforts hold practical value and theoretical significance in achieving sustainable mine development. However, there are some shortcomings need to be addressed in the future study, at first, the influence of some other factors on the brick strength have not been investigated, such as water content, curation time and brick density. Secondly, some other properties of bricks like durability, tensile strength and flexural strength should be tested since the underground mine condition is complicated and the brick properties might can be influenced by underground water and seismic wave shock. Finally, some proportioning scheme that can produce higher compressive strength perhaps can be considered used for pavement works, however, the potential influence on the environment should be further investigated.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

Table A1
The first stage compressive tests of hollow bricks

Number	CTR	RFR	Fiber length (mm)	Fiber content (g/kg)	Average compressive strength (MPa)
A1	1:5	2:4	–	–	1.64
A2	1:8	2:4	–	–	1.15
A3	1:5	3:4	–	–	1.32
A4	1:8	3:4	–	–	1.07
A5	1:5	4:4	–	–	3.08
A6	1:8	4:4	–	–	2.31
A7	1:8	5:4	–	–	1.76
A8	1:8	6:4	–	–	1.11
A9	1:8	7:4	–	–	0.81
A10	1:8	8:4	–	–	1.32
A11	1:8	10:4	–	–	0.86
A12	1:8	15:4	–	–	1.36
A13	1:8	–	–	–	1.32
A14	1:12	–	–	–	0.88
A15	1:8	15:4	19	3	2.19
A16	1:8	–	19	3	2.03
A17	1:12	–	19	3	0.89

Note: Cement-talings ratio (CTR); ratio of fine-grained and rod-mill tailings (RFR).

Table A2
The compressive strength performance of the second-stage experiment based on orthogonal test 1

Number	CTR	RFR	Fiber length (mm)	Fiber content (g/kg)	Average compressive strength (MPa)
A18	1:4	–	9	0.5	2.45
A19	1:4	–	12	1	1.18
A20	1:4	–	19	3	4.23
A21	1:5	–	9	0.5	0.97
A22	1:5	–	12	1	1.87
A23	1:5	–	19	3	3.96
A24	1:6	–	9	3	2.46
A25	1:6	–	12	0.5	1.28
A26	1:6	–	19	1	0.91

Note: Cement-talings ratio (CTR); ratio of fine-grained and rod-mill tailings (RFR).

Table A3
The compressive strength performance of the second-stage experiment based on orthogonal test 2

Number	CTR	RFR	Fiber length (mm)	Fiber content (g/kg)	Average compressive strength (MPa)
A27	1:7	–	9	1	3.14
A28	1:7	–	12	3	2.38
A29	1:7	–	19	0.5	1.69
A30	1:8	–	9	3	0.93
A31	1:8	–	12	0.5	1.40
A32	1:8	–	19	1	2.33
A33	1:12	–	9	1	0.98
A35	1:12	–	12	3	1.22
A36	1:12	–	19	0.5	0.40

Note: Cement-talings ratio (CTR); ratio of fine-grained and rod-mill tailings (RFR).

Table A4
The unit price for fine-grained tailings based hollow bricks

Number	CTR	RFR	Fiber length (mm)	Fiber content (g/kg)	Average compressive strength (MPa)	Price/per block (RMB)
A1	1:5	2:4	–	–	1.64	0.84
A2	1:8	2:4	–	–	1.15	0.68
A3	1:5	3:4	–	–	1.32	0.83
A4	1:8	3:4	–	–	1.07	0.59
A5	1:5	4:4	–	–	3.08	0.95
A6	1:8	4:4	–	–	2.31	0.61
A7	1:8	5:4	–	–	1.76	0.54
A8	1:8	6:4	–	–	1.11	0.66
A9	1:8	7:4	–	–	0.81	0.63
A10	1:8	8:4	–	–	1.32	0.48
A11	1:8	10:4	–	–	0.86	0.46
A12	1:8	15:4	–	–	1.36	0.47
A13	1:8	–	–	–	1.56	0.38
A14	**1:12**	—	—	—	**0.88**	**0.26**
A15	1:8	15:4	19	3	2.19	0.63
A16	1:8	–	19	3	2.03	0.55
A17	1:12	–	19	3	0.89	0.44
A18	1:4	–	9	0	2.45	0.84
A19	1:4	–	12	1	1.18	0.87
A20	**1:4**	—	**19**	**3**	**4.23**	**1.05**
A21	1:5	–	9	0	0.97	0.62
A22	1:5	–	12	1	1.87	0.79
A23	1:5	–	19	3	3.96	0.97
A24	1:6	–	9	3	2.46	0.78
A25	1:6	–	12	0	1.28	0.66
A26	1:6	–	19	1	0.91	0.69
A27	1:7	–	9	1	3.14	0.59
A28	1:7	–	12	3	2.38	0.75
A29	1:7	–	19	0	1.69	0.54
A30	1:8	–	9	3	0.93	0.63
A31	**1:8**	—	**12**	**0**	**1.4**	**0.50**
A32	1:8	–	19	1	2.33	0.56
A33	1:12	–	9	1	0.98	0.42
A35	1:12	–	12	3	1.22	0.54
A36	1:12	–	19	0	0.4	0.33

Note: Cement-talings ratio (CTR); ratio of fine-grained and rod-mill tailings (RFR).

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