Industrial Trial and Technical Scheme for a Novel Geofabriform Cofferdam Mine Backfill Method

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Abstract
To ensure a safe mining environment during pillar recovery in mines, a new mine backfill method known as the geofabriform cofferdam mine backfill method was proposed based on mining environment regeneration theory, and validated through field industrial experiments. The results indicate that the multi-point backfill mode can enhance the roof-contact effect of backfill when utilizing the cofferdam as the working platform for goaf backfill. The use of a geofabriform cofferdam can improve an unfavorable mining environment. Additionally, the geofabriform cofferdam mine backfill method could yield significant economic benefits, prevent ground subsidence, and contribute to enhanced ore recovery and environmentally sustainable mining practices.

Key words: mine pillar recovery, cofferdam, geofabriform, mine backfill, mining environment regeneration

Introduction
Mineral resources are essential for the development of human society. However, the negative environmental effects caused by mining, such as soil and water contamination, land subsidence, and disruption of biological diversity, are significant (Dudka and Adriano, 1997; Aryee et al., 2003). Modern mining operations actively strive to mitigate the potential environmental consequences of mining and to find effective approaches for the disposal of mine waste, including tailings, waste rock, mine water, and sludge (Wang et al., 2019; Ghoreishi-Madiseh et al., 2011). To maintain underground stability and increase ore recovery, the tailing-based backfill mining method is widely employed worldwide (Fang and Fall, 2018; Li et al., 2019). In most cases of mine filling, tailings serve as the primary aggregate for backfilling, representing the majority of solid waste generated by mineral processing. The utilization of tailings not only reduces costs associated with surface tailings storage but also helps prevent potential environmental issues (Sun et al., 2018). Consequently, scholars have shown interest in the utilization of mine solid waste over the past few decades, with their findings significantly contributing to green mining and clean production (Rahman et al., 2014).

For the purpose of cost savings, pollution emission control, or enhancing the strength of the filling body, researchers have continuously investigated additives, novel mine fill materials, and backfill techniques. Hassani et al. developed a lightweight foam mine fill material by incorporating pre-made foam into the backfill mixture using an air-entraining agent; this material reduces water consumption, improves rheology, and minimizes costs (Hassani et al., 2017; Hefni and Hassani, 2020). Kermani et al. (2015) added an alkali activator to tailing-based slurry, enhancing the mechanical properties of sodium silicate-fortified backfill (Gelfill). Wang et al. (2009) studied phosphogypsum-based cemented backfill techniques, considering gypsum as an aggregate. Field applications have shown that this technology not only protects the environment but also reduces land exhaustion and maintenance costs for gypsum piles (Wang et al., 2009; Zhou et al., 2020; Chen et al., 2018). Referring to the function of rebars in concrete, scholars have mixed fibers such as straw, steel, polypropylene, glass, and carbon fibers with tailing slurry to develop fiber-reinforced backfills, improving the stability of structures and ductility of the filling body in mine fills (Cao et al., 2019; Cao et al., 2021; Chen et al., 2020). Furthermore, unconventional backfill technology has been developed. For example, taking advantage of the extreme climate in cold regions, frozen backfill technology has been successfully implemented in the Polaris mine in the Zn-Pb District in the central Arctic islands of Nunavut, Canada (Dewing et al., 2006). Researchers have also conducted laboratory tests to investigate the mechanical behavior of frozen backfill (Cluff and Kazakidis, 2013; Jian and Fall, 2017; Hou et al., 2020).

Although the above-mentioned novel backfill materials or techniques have been proven to be effective in saving mining costs or improving the stability of stopes, a safe mining work environment is a prerequisite for backfilling (Hu et al., 2016). In other words, the conditions of the surrounding rocks have an important effect on the subsequent backfilling process (Chen et al., 2010). To ensure a safe mining environment for stoping and backfilling in a mine with broken ore bodies or surrounding rock, the concept of mining environment regeneration was proposed (Zhou et al., 2007). In this process, the unfavourable geological environment of the ore deposit can be transformed through geotechnical engineering technology, such as building artificial pillars, roofs, floors, or grouting (Chen and Zhao, 2017; Zhou et al., 2012). It is known that a cofferdam, as an artificial structure, is an efficient technology used for certain constructions within water (Kang et al., 2020). Enclosed cofferdams can prevent water from entering the working space and are commonly used in the construction or repair of bridges, oil platforms, pipelines, river crossings, and flood control (Xue et al., 2019). As a type of fluid, mine filling slurry must be confined in an enclosed space until it becomes cemented. Therefore, cofferdams could be used in conventional backfilling to provide an enclosed space.

Aiming to provide a safe mining environment for pillar recovery, the Changsha Institute of Mining Research Co., Ltd. proposed a novel backfill technology known as the Geofabriform Cofferdam Mine Fill (GCMF), supported by the twelfth Five-Year Plan for Science and Technology Development of China (Liu et al., 2018; Zhou et al., 2014). In the GCMF approach, the unfavorable mining environment is improved by constructing a cofferdam with geofabriform material. Subsequently, the goaf is filled while the cofferdam serves as the retaining wall. Finally, the pillar at the turning point of the cofferdam is stoped in a safe mining environment (Song et al., 2015; Zhou et al., 2015). It has been estimated that the direct economic benefit stimulated by the utilization of GCMF in trial mines exceeds $100 million so far. To encourage the widespread adoption of this environmentally friendly GCMF approach, the detailed processes of GCMF are presented in this technical note. It is expected that the GCMF approach could contribute to enhanced ore recovery and green mining practices.

Proposal of GCMF

Introduction of the GCMF approach

The construction of GCMFs can be regarded as a process of mining environment regeneration. The original mining environment comprises pillars and goaf, which pose relatively high risks for stoping due to fractured pillars or a fractured roof. To ensure a safe workspace for pillar stoping, the fractured pillars should be reinforced first. Subsequently, the adjacent irregular point pillars are connected by a special retaining wall (Figure 1).

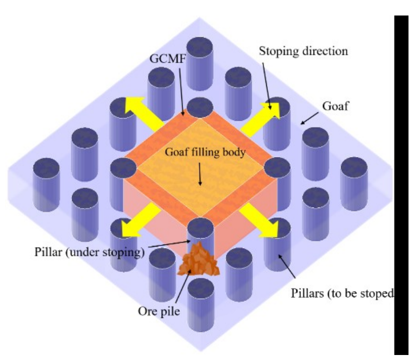

Figure 1. Three-dimensional structure of the GCMF approach (initial phase).

This special retaining wall is constructed using geofabriforms filled with cemented tailing slurry and can be considered a cofferdam. With the construction of the cofferdam, the stability of the goaf is continuously improved, providing a closed space to restrict the flow of filling slurry in the goaf. Consequently, a safe mining environment is created, and goaf filling can commence. Once a certain goaf is filled with cemented tailing slurry, the lateral cofferdam will be extended to adjacent pillars for the next pillar stoping (Figure 2).

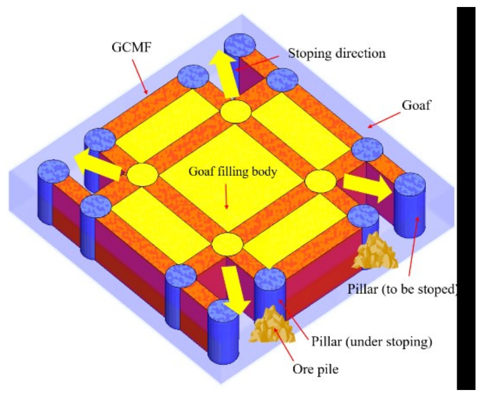

Figure 2. Three-dimensional structure of the GCMF approach (subsequent phase).

Blasting scheme

Blasting parameters play a significant role in the peak particle velocity of the surrounding rock and the production capacity of the stope. Mainly taking into consideration the stability of the workspace, two different blasting schemes can be used in pillar stoping (Figures 3 and 4). For the shorthole blasting scheme, an undercut is constructed in the bottom of the pillar first. Then, a drilling machine is fixed on the outer surface of the pillar to drill horizontal shortholes. Taking the outer surface of the pillar and undercut as the free surface for blasting, pillar stoping is completed. When the filling body shown in Figure 1 is constructed, the safety of the workspace is improved significantly. Therefore, to enhance the production capacity of the stope in one blast, the longhole blasting scheme can be used in the subsequent stope. As shown in Figure 4, an undercut roadway is constructed at the bottom of the pillar. Then, the undercut is taken as the workspace for drilling. Once the long fan blastholes are charged, blasting the longhole fan breaks the ore in the slice.

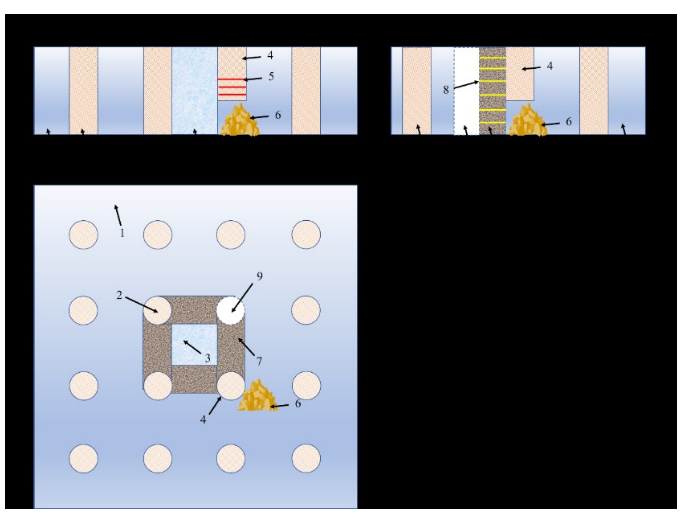

Figure 3. Sketch of the mining method with the shorthole blasting scheme.

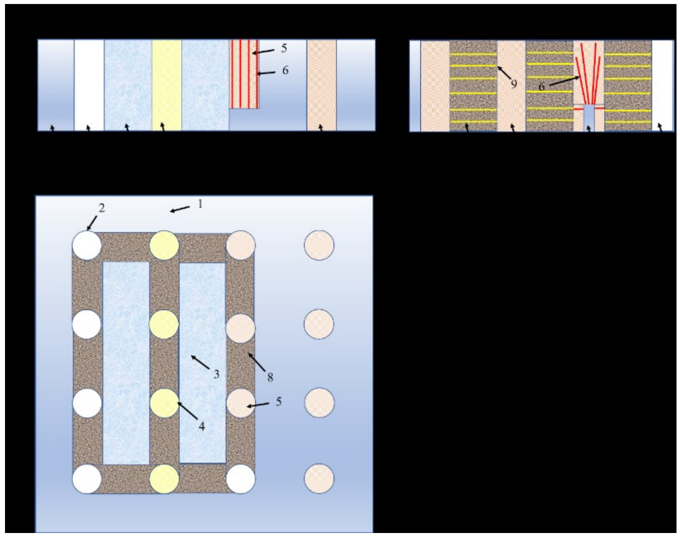

Figure 4. Sketch of the mining method with the longhole blasting scheme.

Advantages of the GCMF approach

The structural essence of the cofferdam is that of a retaining wall or artificial pillar, which is utilized to connect separate pillars and create a unified structure. The advantages of the GCMF approach can be summarized as follows:

- **Enhanced safety of the mining environment** Point pillars have limited ability to withstand roof and floor deformation. Pillars with multiple free faces may experience stress concentration leading to significant geodisasters. The GCMF provides a secure space for goaf filling and pillar stoping.
- **Increased ore recovery** In conventional pillar recovery, only pillars with good integrity can be stoped, resulting in considerable resource loss. With the GCMF approach, theoretically, all pillars can be stoped.
- **Improved effectiveness of roof-contact filling** Roof-contact filling is the final step in goaf filling. Typically, there is a gap between the top of the filling body and the stope roof, which does not effectively resist roof deformation. However, with the GCMF approach, the cofferdam provides a working platform for fixing filling pipes. Consequently, multiple filling pipes can be positioned for the last filling slice in the goaf. Additionally, the addition of cement expansion agents can significantly enhance the effectiveness of roof-contact filling.
- **Greater flexibility in GCMF layout** The spatial distribution of the GCMF can be adjusted according to site conditions. For instance, if the filling capacity is high and the surrounding rock is stable, the cofferdam can connect more pillars to enclose a larger goaf, resulting in more efficient production.

Proposal of GCMF

Engineering background

The Xianglushan tungsten mine, situated in Xiushui County, Jiangxi Province, China, is renowned for its high-grade deposits, boasting nearly 216,000 t of tungsten reserves. With a mean tungsten grade reaching 0.758%, the mine holds considerable economic value. Moreover, its annual scheelite output exceeds 8000 t. Some advantages, such as stable surrounding rock, a gentle ore body dip, and large thickness (with a mean ore body thickness of 18 m), contribute to highly efficient mining operations at the Xianglushan mine. Previously, the room-and-pillar mining method was the primary approach employed. However, due to the irrational mine planning in the early years of operation, significant irregular mine pillars were left (Figure 5) which had a considerably negative impact on work safety and the environment. The width of the goaf varies from 10–30 m, while the height of the mine pillars ranges from 10 –25 m. It is estimated that the ore within these pillars amounts to nearly ten million tons. On one hand, these pillars result in significant resource loss. On the other hand, recovering these pillars is challenging due to stress concentration-induced cracks in some of them (Figure 5). Additionally, roof areas in certain spots have collapsed, necessitating a considerable amount of time and cost for pillar reinforcement. In light of the GCMF approach, an industrial trial is being conducted at the Xianglushan mine, with the trial stope's location (Figure 6). The ore quantity within the trial stope is 31,500 t.

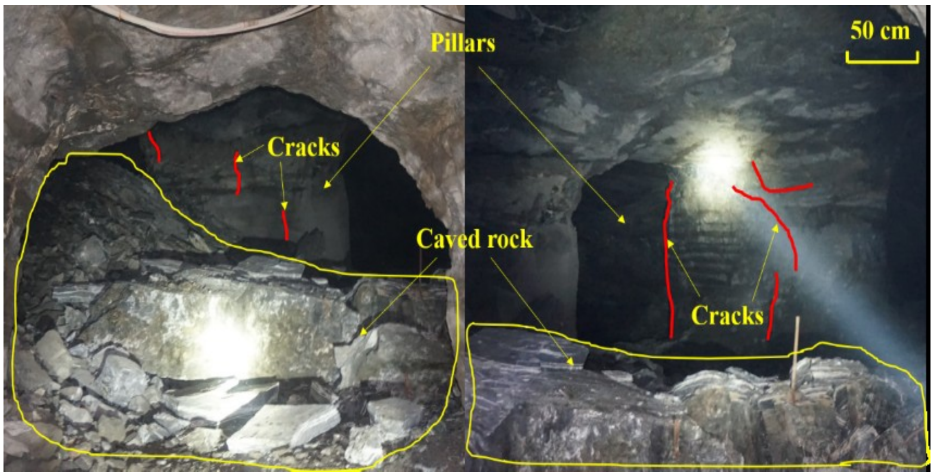

Figure 5. Roof falling and pillar damage induced by stress concentration.

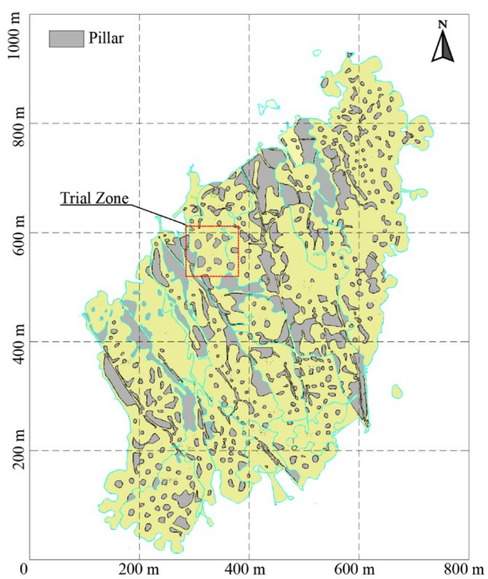

Figure 6. Distribution of mine pillars

Technical procedure of GCMF

Geofabriforms

Due to the stable surrounding rock and intact pillars in the trial stope, conventional stope preparation work was relatively easy. Therefore, the procedures for GCMF construction play a crucial role in pillar recovery. The cofferdam is constructed using customized geofabriforms, which are woven plastic bags primarily made from polypropylene (Figure 7). In this industrial trial, the lengths of the geofabriforms are 3, 5, and 10 m, and the selection of geofabriform type depends on the distance between two adjacent pillars. All geofabriforms have a width of 2 m and a height of 1 m. To maintain a high filling ratio, two slurry inlets are designed in each geofabriform. Belts are positioned along the flank of the geofabriform at intervals of 20 cm, which are used to secure the empty geofabriform along the bamboo fence or tubular steel.

Figure 7. Geofabriform for GCMF.

Scaffold

Because the geofabriform is flexible, it must be secured when filling slurry is injected into it. Therefore, a scaffold is utilized to control the shape of the GCMF and to gain access to heights and areas that would otherwise be challenging to reach during cofferdam construction (Figure 8). The scaffold structure comprises standards, ledgers, transom cross-bridging, and rock bolts. The intervals between the standards and transoms are both 1 meter. The angle between the cross-bridging and the floor remains at 45°. The distance between the ledgers in rows 1 and 2 is 2 m, providing space for geofabriform installation. The tubular steel in row 3 functions to enhance the stability of the entire framework. Additionally, the space between rows 2 and 3 serves as the working area for workers; a ladder is installed there, and preparation work for geofabriform installation can be conducted.

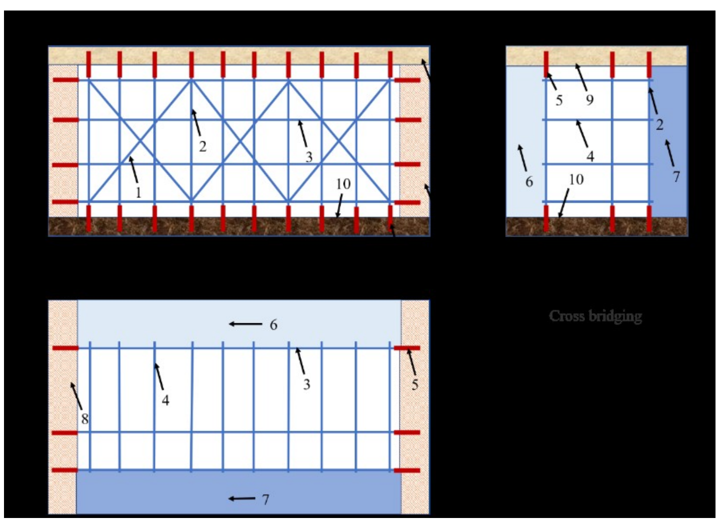

Figure 8. Structure of scaffold.

To further enhance the stability of the scaffold, boreholes are initially drilled in the pillars, roof, and floor at intervals of 1 m, with a depth of 0.7 m and a diameter of 42 mm. Subsequently, rock bolts, each 1 m in length, are installed in these boreholes and connected to the tubular steel using screw joints. The gap between the rock bolts and the borehole wall is filled with C15 concrete. The tubular steel is constructed from seamless steel, with a thickness of 3.5 mm and an outer diameter of 48 mm. Occasionally, deviations in the positioning of the rock bolts may occur due to poor borehole quality, making it challenging to connect these rock bolts directly to the tubular steel. In such cases, rebar is employed to weld them together. The structural scaffold effectively resists the deformation of the rock mass, greatly enhancing the safety of the working area. Moreover, most of the tubular steel and bamboo boards can be reused once the filling work is completed.

Geofabriform filling

Once the framework is assembled, bamboo fences are employed to restrict the movement of the geofabriform. As depicted in Figure 9, vertical bamboo fences are positioned both outside and inside the goaf, and they are secured to the tubular steel using iron wire. To reduce costs and lighten the framework, scaffold boards are also crafted from bamboo, allowing for easy relocation based on construction requirements. For safety considerations, the bamboo scaffold board boasts a thickness exceeding 30 mm and a length greater than three times the interval of the transom. This bamboo scaffold board is affixed to the transom using zinc-coated wire.

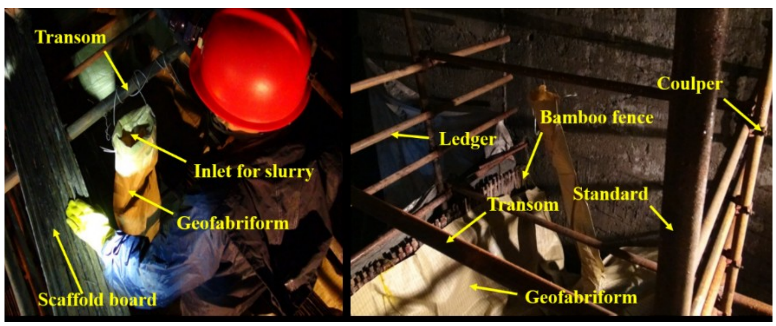

Figure 9. Scaffold structure and components.

Before filling, the geofabriform is carefully inspected to ensure proper fixation and absence of any holes. The filling pipe near the stope is constructed from a soft polyethylene pipe with a diameter of 180 mm, while the drainage pipe for water bleeding is made from a plastic corrugated pipe with a diameter of 40 mm. The filling pipe is cleansed with water for 5 min before the slurry injection process commences. The slurry composition primarily consists of tailings, water, and cement. In comparison to the slurry used for goaf filling, the slurry for the GCMF contains a higher cement content. The requirements for the unconfined compressive strength of the GCMF are outlined in Table 1.

Table 1. The requirements for the unconfined compressive strength of the filling body

Curing time (day(s))	GCMF	Goaf filling body
1	> 0.3 MPa	> 0.2 MPa
3	> 0.4 MPa	> 0.3 MPa
7	> 0.8 MPa	> 0.6 MPa
28	> 4 MPa	> 2.5 MPa

The strength evolution of the filling body is monitored through careful sampling at intervals of 1, 3, 7, and 28 days. The filling process and consolidation of the GCMF are depicted in Figure 10. Constrained by the bamboo fences and geofabriforms, the GCMF takes on a nearly rectangular solid shape with a smooth surface, which positively contributes to its stability.

Figure 10. GCMF filling and consolidation.

Goaf filling

The construction of the GCMF involves stratified filling, with each layer being 1 m in height. Therefore, it is essential to fill the gap between each layer of the GCMF with cement to prevent slurry leakage during goaf filling. Additionally, loose rocks must be cleared away from the floor and roof for safety reasons. Since the polypropylene bag may hinder the cementing of the goaf filling body to the GCMF, the surface of the geofabriform near the inside of the goaf should be removed before goaf filling. Furthermore, to further enhance the stability of the GCMF, it is connected to the goaf filling body using a wire rope (with a diameter ranging from 6–8 mm) (Figure 11).

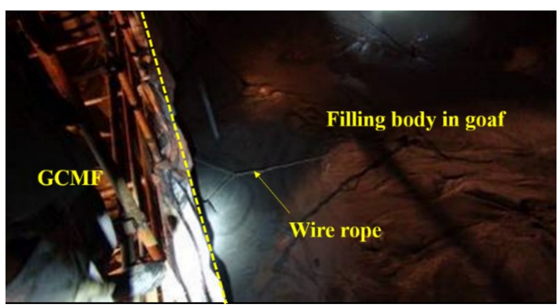

Fig. 11. Reinforcement between the GCMF and goaf filling body.

The wire rope is first wound around the GCMF, and its other end is secured to vertical tubular steel in the goaf. Once the slurry in the goaf sets and cements in place, the wire rope prevents the GCMF from collapsing. The filling pipe, fixed on the top of the scaffold, can be adjusted as needed for roof-contact filling, facilitating a multipoint filling mode. Additionally, the inclusion of a cement expansion agent (comprising calcium sulfoaluminate, calcium oxide, anhydrite, and aluminite powder) in the slurry enhances the roof-contact filling effect. Bleeding water drainage is facilitated by a three-dimensional reticular corrugated pipe, which is fastened to bamboo using wire (Figure 12). To alleviate pressure on the GCMF, the height of each filling slice in the goaf should not exceed 0.5 m. Subsequent filling can commence once the initial set of filling layers is completed, which typically occurs at least 24 hours later.

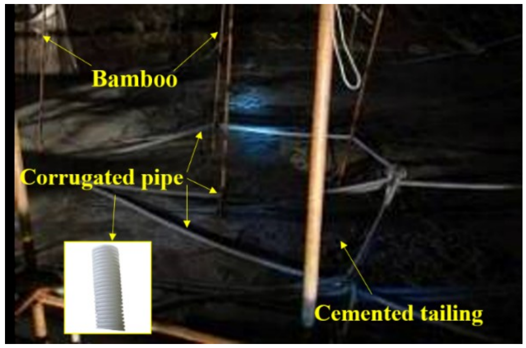

Figure 12. Drainage for bleeding water.

Since the GCMF acts as a secure barrier for goaf filling, the cemented tailing slurry used for goaf filling can have reduced cement content, as indicated by the strength requirements for the goaf filling body (Table 1). Field investigations have shown no leaks during the goaf filling process, and the strength of the filling body meets the specifications detailed in Table 1. Once the curing time for the goaf filling body reaches 3 days, the scaffold is removed from the industrial trial stope.

Pillar stoping

The shorthole mining method is employed for pillar stoping (Figure 13). Due to the intact surrounding rock, the existing haulage roadway near the trial stope remains suitable for ore transport. Therefore, the main preparation for stoping is relatively straightforward: constructing an undercut drift at the bottom of the pillar to be stoped. The undercut drift has a height and length of 2.8 m. Horizontal parallel boreholes, 4 m in length and 42 mm in diameter, are drilled from the outside of the pillar, with a row distance and borehole interval of 0.9 m each. Emulsion explosives, 36 mm in diameter and 200 mm in length, are utilized for rock fragmentation. The layer height of the caved ore is maintained at approximately 4 m, providing workers and drilling machines with a stable platform for subsequent borehole drilling.

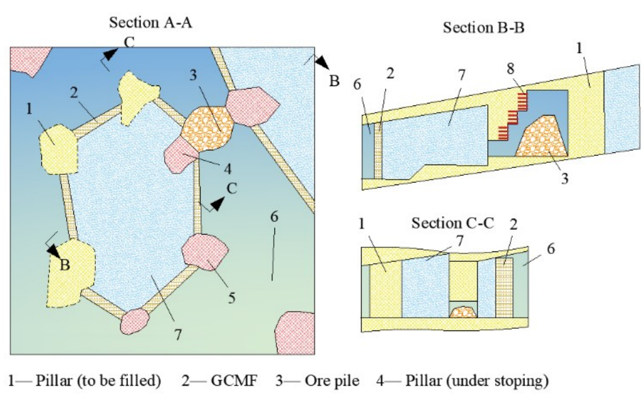

Figure 13. Mining method for irregular pillar stoping.

After conducting a thorough inspection of the air quality and loose rock in the trial stope, ore transportation commences. During ore transportation, the goaf is filled using the conventional cemented tailing backfill technique, as described earlier.

Analysis of industrial trial results

The industrial results are evaluated based on three factors: safety, cost, and production efficiency. During pillar stoping, the GCMF and goaf filling body exhibit good integrity, indicated by the absence of obvious boundaries between different filling slices, suggesting effective cementation. The costs associated with the industrial trial are detailed in Table 2, with the cost of the goaf filling body aligning with that of the conventional filling method in the Xianglushan mine. Although the cost of GCMF is slightly higher at 19 UCS/m^3 compared to traditional filling, the majority of ancillary facilities utilized in GCMF construction can be reused, resulting in significant cost savings. The production capacity of the trial stope ranges from 80–120 t/day. Additionally, the inclusion of 588.96 kg of cement expansion agent during the final roof-contact filling slice increases the roof filling rate from 50–90%, substantially enhancing the filling body's resistance to roof deformation. Considering its cost-effectiveness, safety benefits, and production capacity, the industrial trial of GCMF proves successful, indicating its potential for widespread application in other stopes.

Table 2. Technical-economic indicator of the industrial trial.

Cost of goaf filling (USD/m^3)	Cost of GCMF (USD/m^3)	Ore loss rate (%)	Rate of ore dilution (%)	Production capacity of trial stope (tons/day)
17	19	15~20	10~20	80~120

Conclusion

Based on the mining environment regeneration theory, the challenging mining conditions at the Xianglushan tungsten mine have been ameliorated through the implementation of the GCMF approach. The results of the industrial trial demonstrate that GCMF is a safe, cost-effective, and environmentally friendly backfill technology for point pillar recovery. Furthermore, the utilization of a multipoint filling mode, along with the incorporation of a cement expansion agent, notably improves the roof filling rate. With its potential to promote green mining, the GCMF approach is applicable to mines facing similar mining conditions.

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Data Availability

The data used to support the findings of this study are included within the article.

Disclosure statement

No potential conflict of interest was reported by the author(s).

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