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A new procedure for recycling waste tailings as cemented paste backfill to underground stopes and open pits

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ABSTRACT

Waste tailings are increasingly being recycled as cemented paste backfill (CPB) for the cleaner production of mineral resources. In most cases, waste tailings cannot be fully recycled and the stability of underground stopes and open pits cannot be ensured. This research proposed a new procedure for recycling waste tailings as CPB to both underground stopes and open pits. Firstly, the physical, geotechnical and chemical tests required before the application of such procedure were discussed. Then, the new procedure was introduced in detail, including the process parameters determination and the backfill implementation. Finite element method and the three-zone theory were used to determine the process parameters. The application of this new procedure to an engineering instance, the Shirengou Iron Mine (SIM), was expatiated. The process parameters of recycling waste tailings as CPB in SIM were determined as follows. The solids content of CPB was 72%, the cement-tailings ratios were 1:8, 1:10, 1:20, the total height of open pit backfill was 80 m (with four backfilling stages), the stratification height was 1.5 m, and the cement-tailing ratios for four open-pit backfilling stages were 1:8 (stage 1 and 2), 1:10 (stage 3), and 1:20 (stage 4). It is shown that this new procedure achieved 100% recycling of waste tailings in SIM, which is of great environmental significance during mining operations. Harnessing such procedure extends recent efforts to recycle waste tailings as CPB, and can significantly promote the cleaner and safer production of minerals resources worldwide.

1. Introduction

The large-scale development of mining industry contributes trillions of dollars annually to the world economy through providing raw materials, such as metals, minerals and aggregates. Accordingly, it is critical that an efficient mining method is selected to improve profits and reduce the influence of volatile prices. Among all mining methods, open pit mining is by and large considered as the most efficient and economical method due to its higher recovery and production capacity (Bakhtavar et al., 2012). However, the transition from open pit to underground mining is often required during the mining operations as many near-surface deposits extend to ‘great depth’ (King et al., 2017). Such transition can facilitate the excavation of ore deposits, prolong the service life of mines and make full use of existing infrastructure and equipment (Macneil and Dimitrakopoulos, 2018).

Previous studies have mainly focused on the optimisation of the transition timing from open pit to underground mining (Bakhtavar et al., 2009; King et al., 2017), which is important for deposit excavation and cost saving. However, two important issues must be properly addressed in mines with such transition, namely the disposal of waste tailings, which is significant for the cleaner production in mining industry, and the stability of the underground stopes and open pits (USOP). Both issues have attracted worldwide attention as they may cause serious social and environmental consequences.

Waste tailings is a by-product generated during the production of minerals resources (Fig. 1a). It is estimated that more than 25 billion tons of waste tailings has been produced in China, resulting in approximately 12,000 tailings ponds (Sun et al., 2018; Xie et al., 2009). These tailings ponds destroy mining land resources, pollutes

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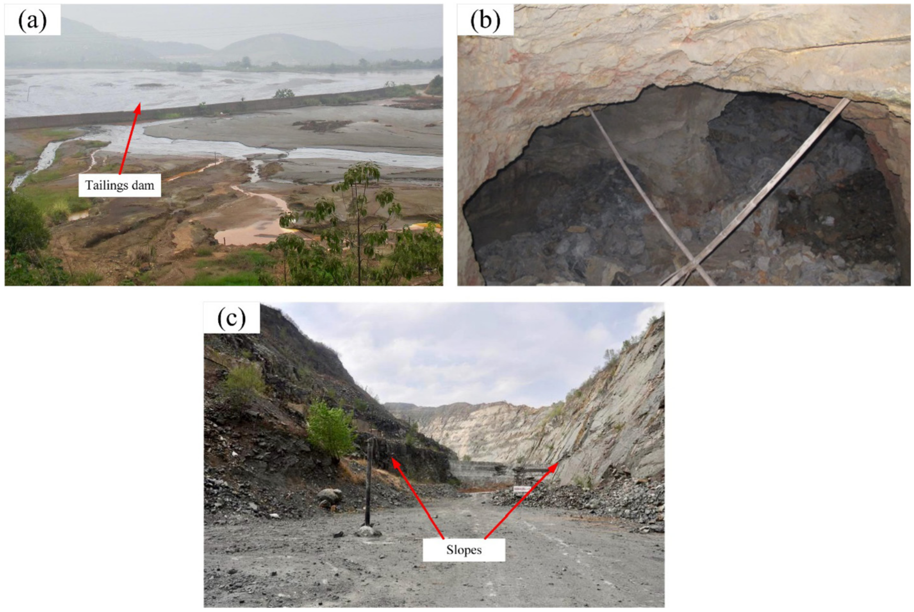

Fig. 1. Engineering photos of: **a** waste tailings, **b** underground stopes, **c** open pits.

the mining environment and causes potential accidents. There is, consequently, a pressing need for more safe and environmental-friendly disposal of waste tailings. In practice, recycling waste tailings as cemented paste backfill (CPB) to the underground stopes has been proved as the simplest, cheapest and most cost-effective method of waste tailings disposal (Benzaazoua et al., 2008; Chen et al., 2018; Fall and Benzaazoua, 2005; Helinski et al., 2010; Kesimal et al., 2003, 2005; Landriault et al., 1997; Qi et al., 2018a, 2018b; Wu et al., 2015a; Yilmaz et al., 2004, 2009). However, recycling waste tailings as CPB to the underground stopes consumes only 60–75% of waste tailings (Ercikdi et al., 2015), leaving 6.25–10 billion tons of waste tailings on surface in China alone. Similarly, backfilling open pits with waste tailings has been evaluated in the literature (Bryan et al., 2010; Gao et al., 2017; Landriault et al., 2001; Shuttleworth et al., 2005; Tariq and Yanful, 2013; Verburg et al., 2006; Villain et al., 2015; Yilmaz and Fall 2017), which consumes a small proportion of the produced waste tailings. Therefore, better disposal of waste tailings is very important for the cleaner production in mining industry.

The stability of the USOP is another major issue, especially for countries with the developed mining industry (Qi and Tang, 2018; Qi et al., 2018). Fig. 1b and c shows an example of the underground stopes and the open pits respectively. According to Xie et al. (2009), approximately 600 million cubic meters of underground stopes are generated annually in China as a result of mining. These underground stopes are often accompanied by instability issues that can trigger dangerous geologic hazards (Sun et al., 2018). For example, the stope collapse in Kangli Gypsum Mine, which occurred on November 6, 2005, in Xingtai City, Hebei province, China, resulted in 33 deaths (Ma et al., 2009; Qi et al., 2017). CPB has been proven to be an effective and widely-used method to prevent the stope failure in practice (Ercikdi et al., 2015). As for open pits, most of them are currently being left as mine voids or developed into pit lakes (Villain et al., 2013), which causes damages to the environment and increases the remediation costs. In-pit backfilling is one option for the restoration of the landscape as it minimises the occupied area of waste and reduces the extent of the contaminated area (Chapman et al., 1998; Gray and Gray, 1998; Younger et al., 2002). Though dry stacking of waste tailings has been widely used in open pits, it needs tailings dewatering system that increases the operational costs (Gomes et al., 2016). At present, there are only few studies on recycling waste tailings as CPB to open pits in the literature, which needs further investigation for improved recycling of waste tailing as CPB.

The main objective of this paper is proposing a new procedure for recycling waste tailings as CPB to the USOP. To the best of the authors' knowledge, this is the first time the USOP are considered as a whole system to be backfilled with CPB. The proposed procedure can reduce the residual waste tailings on surface and improve the stability of the USOP, leading to a cleaner and safer production of minerals resources. The remainder of this paper is organised as follows. Section 2 describes the materials and methods in this paper, including the study site, the experiments and the backfill procedure. Section 3 presents the results and discussion of the case study and Section 4 summarizes findings of this work.

2. Materials and methods

2.1. Study site

The engineering application of the proposed backfill procedure was performed in Shirengou Iron Mine (SIM), Heibei province, China. The mine is established in 1975 and the open pit mining is used at the beginning for the excavation of near-surface ore deposits. The length of the open pit is about 2,800 m (from north to south) and the width is about 230 m (from west to east). Since 2004, the mining method of SIM has changed from the open pit to underground mining due to economic considerations. Fig. 2 shows the transition from open pit to the underground mining in SIM. As shown, a number of underground stopes have been excavated beneath the open pit. The maximum strike length of the stope is larger 100 m with a width being larger than 10 m, which means the stability of the underground stopes needs to be carefully considered to prevent geological hazards.

Detailed information about the mining process in SIM is shown in Table 1. Fig. 3 illustrates the present situation of the open pit and the development system distribution. It can be seen that the open pit is divided into the south pit and the north pit by the line 18. The