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Proceedings of

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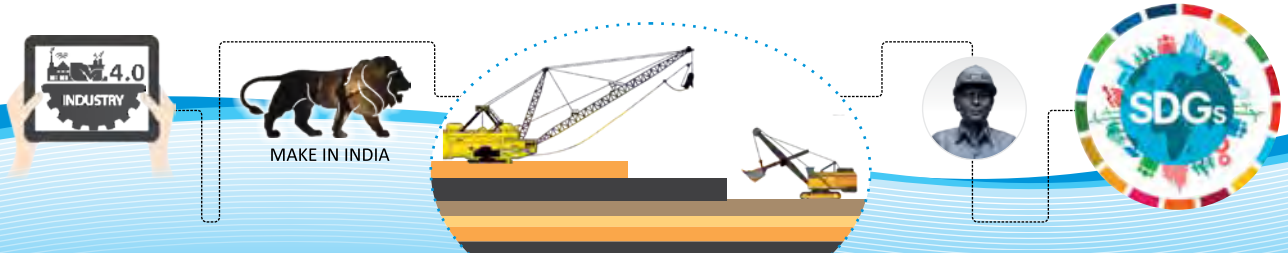
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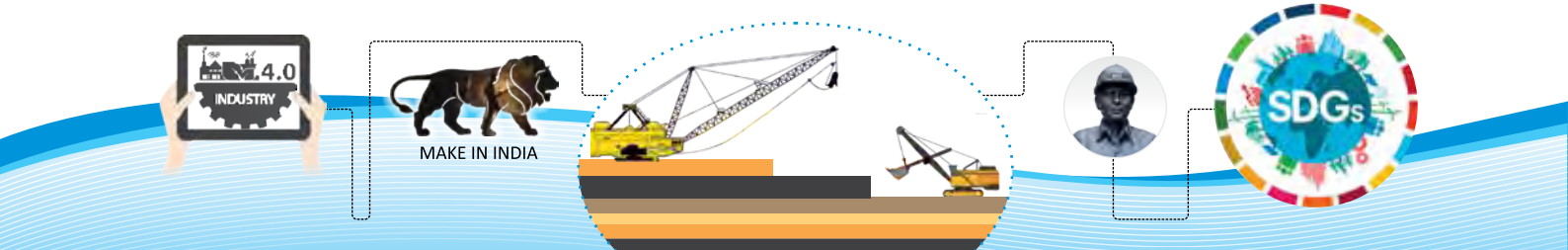


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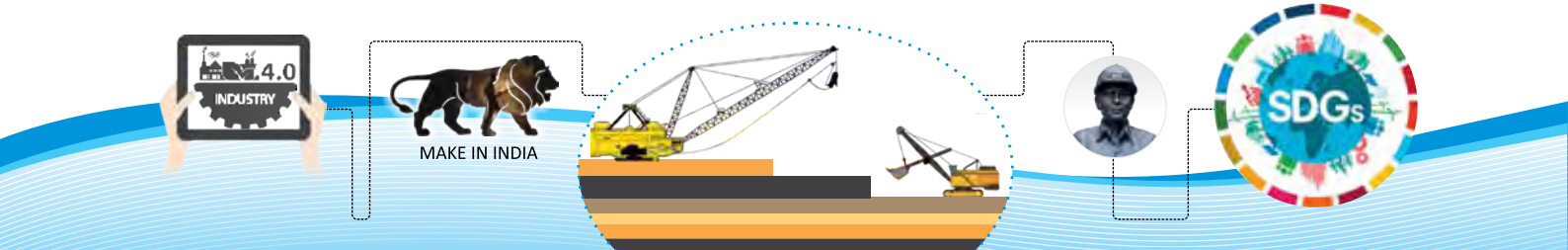


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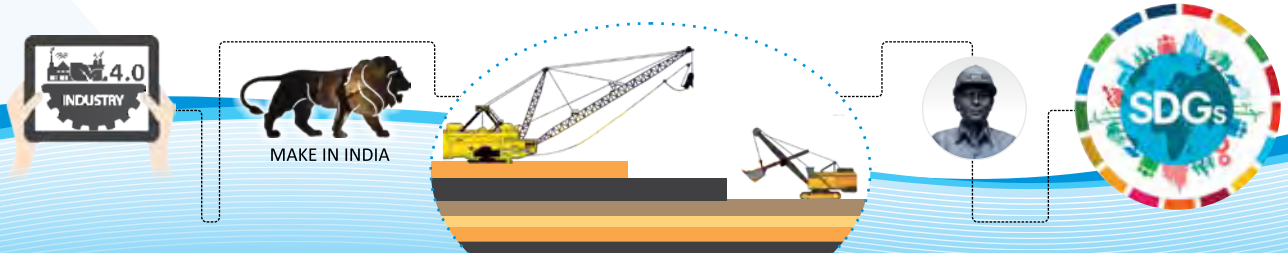
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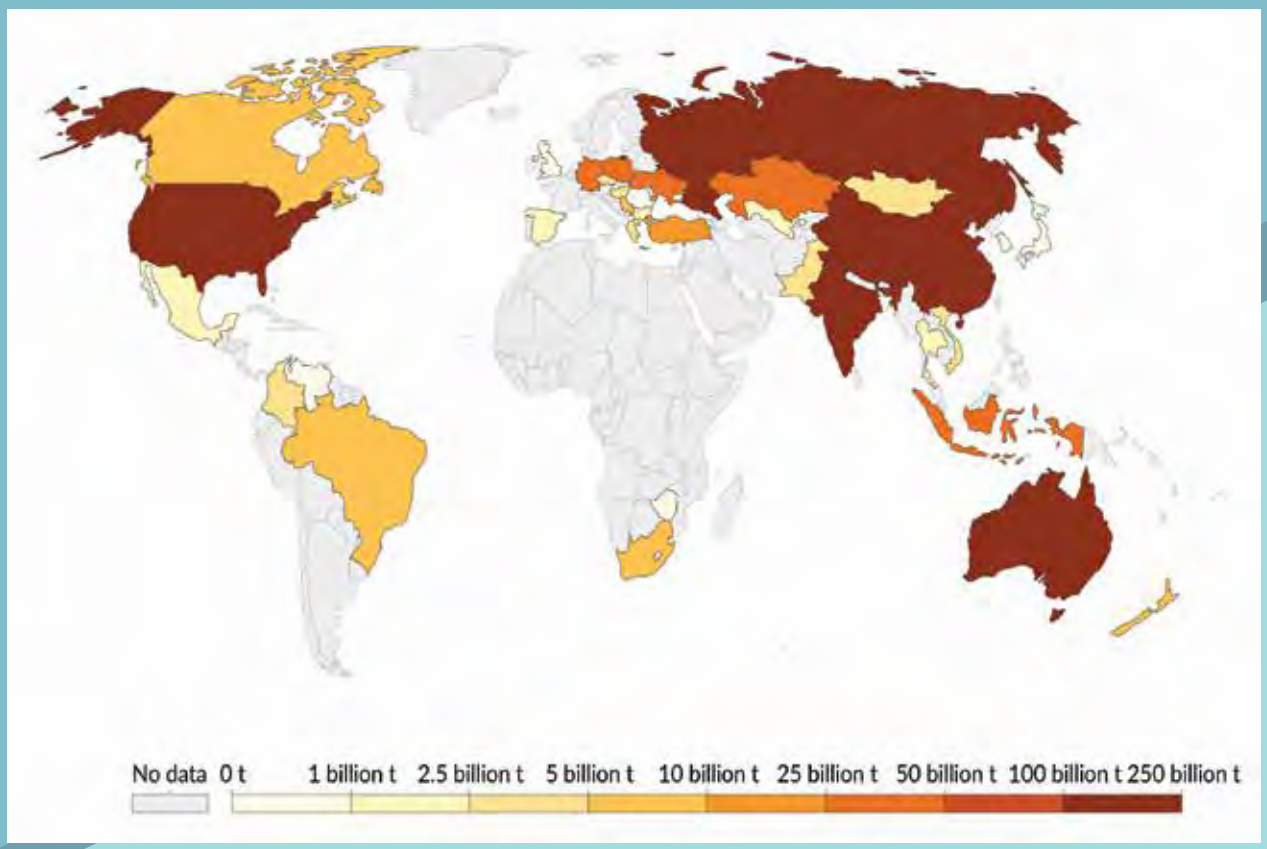
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CHAPTER 1



Source: BP Statistical Review of World Energy

INTERNATIONAL RECEIPTS

Sustainable approach for sulfidic mine tailings: Integrated paste technology

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***Abstract* — Sulfidic mine wastes are problematic since they contain reactive minerals rich in heavy metals, such as pyrite. These wastes can lead to serious environmental problems and high tailings management costs if not appropriately managed. There is a need for long-term approaches for transforming these wastes to move toward zero environmental footprint, such as 'how can they create new economic value, minimize its environmental impacts and diminish liability from mining waste?'. One practical solution is to employ paste backfill technology which allows operators to store, backfill or recycle wastes as secondary resource, innovative and environmentally sound system. Paste backfilling technology for underground mine backfill and surface tailings disposal applications has recently gained a great popularity mainly due to increased tailings usages, reduced rehabilitation costs and environmental impacts, and enhanced ore extraction and security conditions. This paper aims at introducing the concepts of underground paste backfill and surface paste disposal for sustainable mining and backfilling operations.**

Keywords*— *Tailings; environmental impact; paste technology; sustainable mining

I. INTRODUCTION

A large amount of mining wastes such as waste rocks and processing tailings, which have no economic value and can be considered environmentally harmful, are produced from mining industries every year [1]. Essentially, these wastes contain sulfide minerals that tend to form acid mine drainage when exposed to air and in the presence of water [2]. Waste rock is a coarse material that does not contain mineralization during the extraction of mines or that cannot be enriched according to the current economic and technical conditions but has to be produced due to the operation and has not been subjected to any processing other than excavation [3]. The tailings, on the other hand, is a fine-grained constituent that remains after precious minerals are recovered by different ore preparation and enrichment methods, is detrimental to the environment due to heavy and toxic metals they contain, and has no economic value [4]. New technologies are constantly being developed to reduce waste generation and to dispose of it effectively. One of the most ideal methods considered for mining waste disposal is to control them at source [5]. For sustainable management, one way of good management of mine wastes is to fill some of the hazardous wastes (up to 60%) into underground production rooms known as stopes and to apply paste technology, where the remaining waste (40%) is safely stored on the surface as an effective waste disposal system [6]. The low-cost and effective tailings management technique needed in the mining industry pushes mine wastes to be considered as an important raw material source both within their own structure and in different fields [7]. In this view, the cemented paste backfill (CPB) method, which allows effective ground support and waste reduction for most modern underground mines, has newly been used frequently in most modern mines [8,9]. Besides, innovative waste disposal systems are proposed by mines around the world to replace conventional methods. The basic principle of these systems is to use dewatered wastes and to store the wastes above ground in a relatively dry paste form [10,11]. The mining industry continues to face many challenges due to its potential environmental impacts. With increasing social awareness, increasing government pressure on waste disposal alternatives, and the scarcity of available spaces for waste disposal, these challenges are becoming increasingly difficult to meet [12]. In this concept, Fig. 1 discusses an exemplary mine life cycle established to effectively manage mining waste in a sustainable way.

In recent years, one of the strategic topics in the mining sector, as in many important sectors, is sustainability [13]. Sustainability has been defined by the UN Commission on Environment and Development as 'the ability of humanity to achieve development by meeting their daily needs without compromising the ability of future generations to meet their needs'. With the Kyoto protocol, protecting the environment, reducing CO_2 emissions, using alternative raw materials have become medium and long-term goals by many countries. Waste management in the mining industry is an important issue that needs improvement in terms of sustainability [14]. In order to achieve this, it is essential to consider and use wastes as alternative raw materials in other sectors such as construction and civil engineering [15-17]. Certainly, paste integrated solutions offer a number of technical, operational, financial and environmental benefits for safe disposal and management of harmful mining waste [18]. The key benefits of implementing paste technology for underground backfill application are: reduced amount of binder for equivalent strength, reduced amount of water in the backfill, reduced labor requirements, relatively fast fill settlement and mining cycle, reduced maintenance and improved mining operations [19,20]. The main benefits of implementing paste technology for surface disposal application are: less tailings storage space, water consumption, rehabilitation and shutdown costs, and operational risk [21]. Paste is a solid, non-precipitating and flowing material that exhibits negligible bleeding when

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settled under its own weight. The paste has a flow resistance of 200 kPa and a slump of up to 25 cm [22]. Depending on underground and surface paste technology application, sand and cement can be added to paste backfill without impairing the flow and strength properties [23].

CPB is a high-density, engineered, and fluidized mixture consisting of total or finely discarded and filtered processing tailings (75-85wt.% solids), hydraulic binder required to bind solids and liquids (2-9wt.%), and mixing water (15-25wt.%) required to transport the paste material to underground mined out stopes under gravity or with the aid of a pump [24-26]. It is used in underground mines to re-fill mined out stopes. The quality and behavior of CPB is controlled not only by its internal factors such as tailings, cement and water [27-30], but also by external factors such as transport, placement and curing conditions [31]. Many studies have been so far carried out on CPB materials in the lab [32-34] and field conditions [35]. Due to relatively difficult and risky nature of field tests, different experimental setups have recently been discussed to describe the field behavior of CPB material in a controlled laboratory medium [36,37]. Surface paste disposal (SPD) has recently been proposed as a serious alternative to traditional tailings dam application for surface tailings disposal in the mining industry [38,39]. SPD, derived from the CPB system used for underground metalliferous mines, can be applied with and without cement [40]. Note that as SPD system is a relatively new alternative for paste tailings management, it is less utilized by modern mines worldwide. The Bulyanhulu mine (Tanzania) was the first gold mine to adopt this system [41,42]. Non-cemented paste backfills have a solid content of up to 75wt%, corresponding to a slump value of 20-25 cm. Dewatered mine tailings are placed sequentially in 30 cm layers (each formed in 5 days) which are allowed to dry before placing the next layer. As a result, it is believed that the efficient utilization of paste tailings for both aboveground storage and underground backfill purposes will bring a new light to the sustainable waste management practice for most modern mines worldwide.

II. MATERIAL AND METHODS

A. Laboratory and field tests

In this study, two different experimental sets were used to examine the CPB and SPD applications. A new laboratory equipment was designed and used in the tests to carry out the consolidation tests of CPB, as demonstrated in Fig. 2. This device has been developed for in-situ paste tailings settling, curing and stress conditions to be well studied at laboratory. The laboratory equipment consists essentially of three parts: i) an upper loading plate to apply vertical stress up to 800 kPa, ii) a transparent sample box (D × H: 10 × 20 cm), and iii) a lower drainage hole to collect drainage water. system. Further information on this innovative laboratory equipment can be found elsewhere [36,37,43].

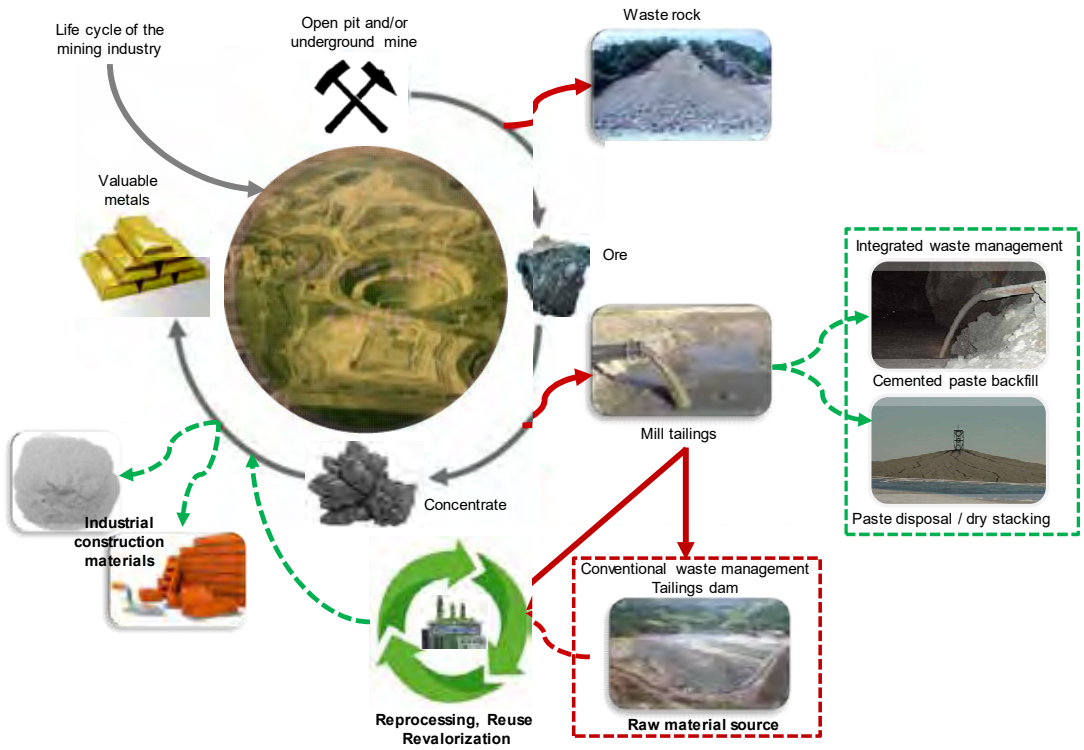
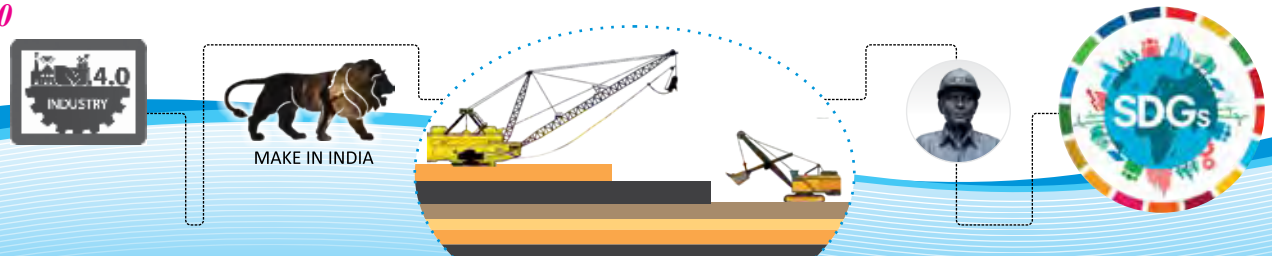


Fig. 1. Schematic of the life cycle of the mining industry: ore, waste, concentrate and raw materials



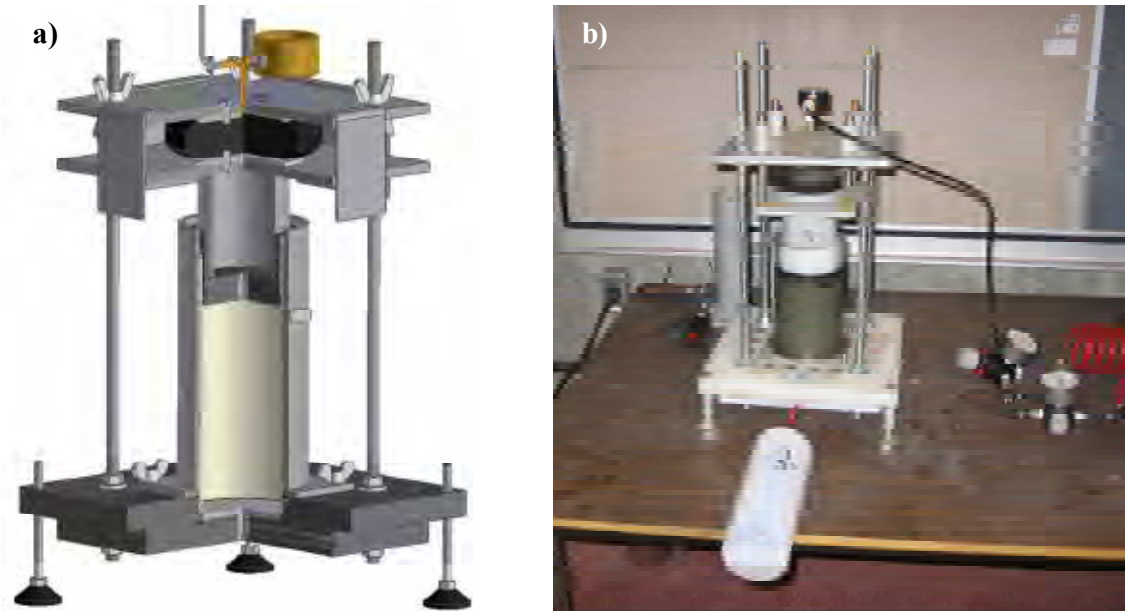
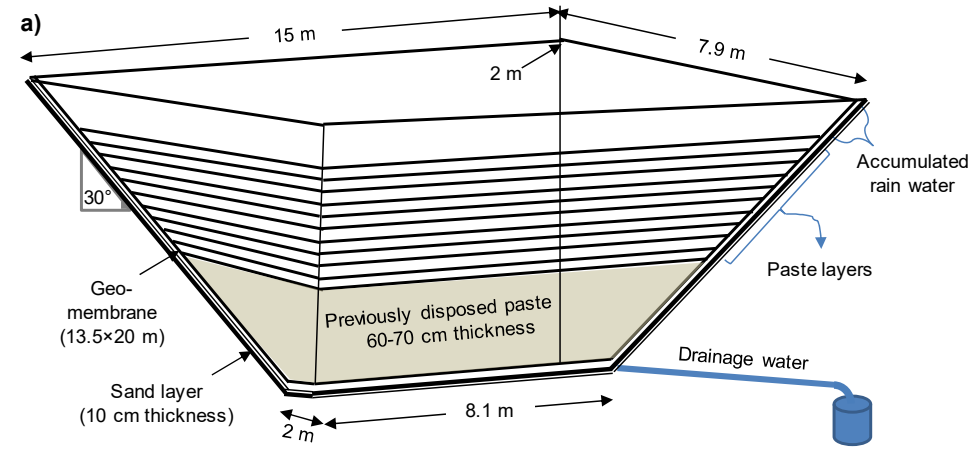


Fig. 2. Laboratory setup developed to measure underground backfill performance: a) schematic; and b) application



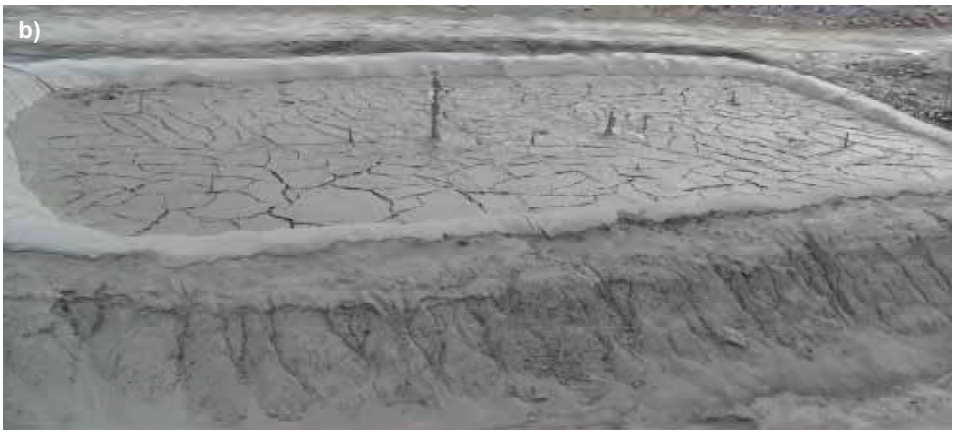


Fig. 3. Field setup developed for the aboveground paste tailings storage system: a) schematic and b) application

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In addition to underground paste backfill, some of mining wastes (approximately 40%) are stored in the aboveground tailings dams. For long-term/permanent disposal of mining wastes in surface tailings dams, above-ground engineering structures such as valley and/or slope dams and specially constructed tailings dams are used. Paste tailings are usually stored on land but can sometimes be filled in abandoned opencast mines. In this study, SPD application was examined with two mini experimental cells (Fig. 3). The first cell is called cemented cell, partially filled with 2% by weight low cement waste, while the second cell is completely filled with cement-free waste and is called a non-cemented cell. A total of 10 different layers of paste material were placed in each cell. More information on this innovative field test can be found elsewhere [39].

B. Paste tailings characteristics

One of the most important distinguishing features of the paste is the particle size distribution of the solids. The paste mass should contain fine particles to ensure sufficient water retention. At least 15% by weight of a typical paste should be below 20 µm. Thanks to the colloidal water holding feature of fine-grained particles, mixtures that do not decompose and show typical paste flow characteristics are provided. The size distribution of the tailings sample was measured by the wet method using Malvern Mastersizer particle size distribution device (Fig. 4). The tailings have a water content of 25%, a specific gravity of 3.3, a specific surface area of 2.5 m^2/g, a total porosity of 48.7%, a dry unit weight of 23.6 kN/m^3, 1.3% It has liquidity and plastic index values of 4.8%.

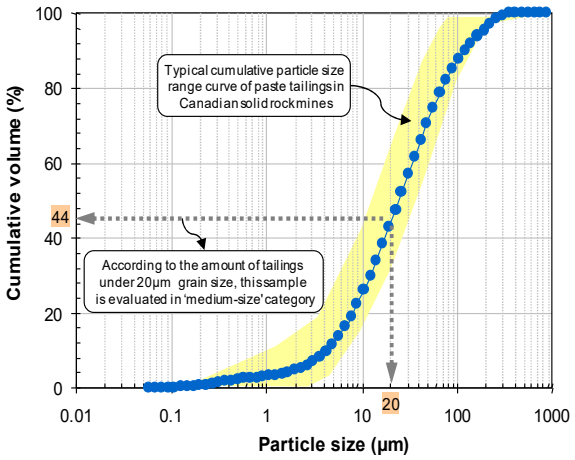


Fig. 4. Size distribution of the studied processing tailings sample

In this study, the mineralogical composition of tailings was investigated by using Bruker AXS D8 Advance XRD and Hitachi® 3500-N SEM-EDX equipment (Fig. 5). X-ray diffractometry (XRD) results illustrate that tailings contain abundant quartz (53.5%) and pyrite (27.5%). Moreover, energy dispersive X-ray spectroscopy integrated scanning electron microscope (SEM-EDX) results show that tailings contain sulfur (S: 29.2%) and iron (Fe: 22.3%) as the two main elements that cause acid and sulfate production. Silicon (Si: 13.5%), aluminum (Al: 7.3%) and calcium (Ca: 0.4%) were found in the tailings.

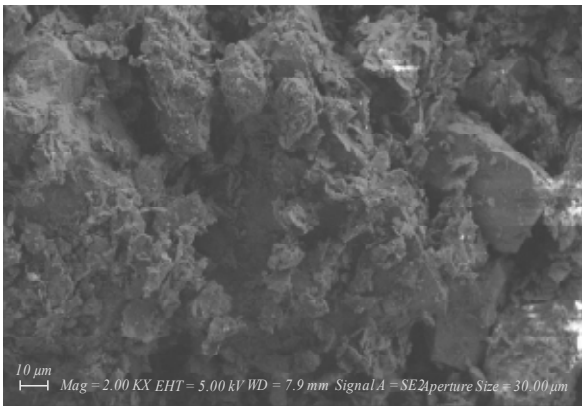


Fig. 5. SEM micrograph of the studied processing tailings sample

For CPB applications, a cement mixture consisting of 20%:80% Portland cement CEM I and ground blast furnace slag (Slag) was used, while only CEM I was used for SPD applications. Cement content of 4.5% and 2%, respectively, was used for both underground mine backfill, and surface paste disposal purposes. The chemical properties of binder and mixing water are listed in Table I.

Tap water and tailings pore water were used as mixing water. pH, redox potential (Eh) and electrical conductivity (EC) were measured by using a Benchtop pH/ISE Meter Orion Model 920A coupled with a Thermo Orion Triode combination electrode (Pt-Ag-AgCI). The measured pH, RP and EI values of void water and tap water were determined as 9.3, 152 mV and 7.6 mS/cm, 8.1, 425 mV and 0.3 mS/cm, respectively.

C. Sample preparation conditions

To better examine the effect of curing conditions, various backfill samples were prepared by using a cement content of 4.5%. To obtain a homogeneous mix consisting of tailings, binder and mixing water, all these ingredients were carefully blended by using a Hobart mixer for 12 minutes. After the mixing process, the slump of the backfill was adjusted to 18 cm by adding mixing water. The prepared samples were first placed in both transparent and plastic containers and then placed in the curing chamber with 80% relative humidity and 80% ambient temperature. A vertical stress up to 400 kPa was gradually applied to backfill. This pressure value depicts underground production room (stope) with a total height of 18 m. Here, the wet unit weight of CPB samples is taken as γ: 23.1 kN/m^3. SPD samples were prepared at the above ground paste backfill facility and transported to the site with a ready mix truck. Tailings, whose slump was measured in the range of 20-29 cm, were placed in previously prepared mini cells in the field in thin layers of 10 cm.

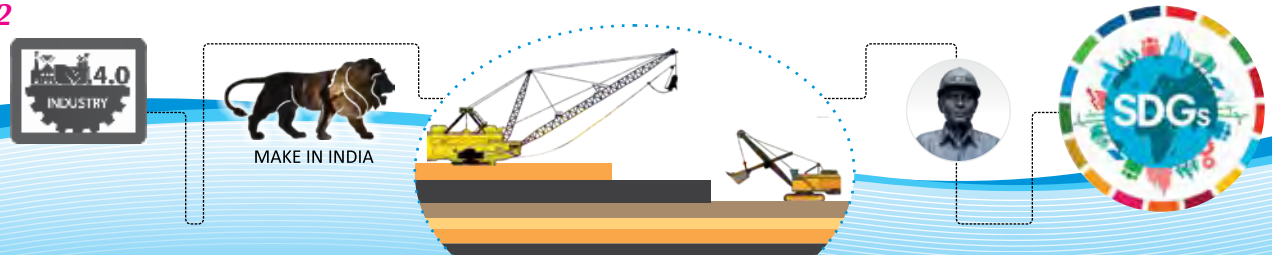


TABLE I. CHEMICAL COMPOSITIONS OF HYDRAULIC BINDER AND MIXING WATER USED IN THIS STUDY

Element	Detection limit (mg/L)	CEM I %100 (mg/L)	Slag %100 (mg/L)	CEM I: Slag/ %20:80 (mg/L)	Tailings pore water (mg/L)	Tap water (mg/L)
Al	0.010	2.57	5.42	4.44	0.21	0.01
Ba	0.001	0.01	0.15	0.03	0.05	0.01
Ca	0.030	47.0	22.45	30.6	559	40.9
Fe	0.006	1.71	0.38	0.45	0.01	0.06
K	0.003	0.69	0.42	0.46	0.29	0.84
Mg	0.001	1.33	6.81	3.73	1.83	2.27
Mn	0.002	0.03	0.75	0.14	0.01	0.01
Na	0.004	1.57	1.49	1.51	0.05	0.01
S	0.033	1.47	1.31	1.34	1630	46.0
Si	0.020	9.12	16.9	14.5	0.89	0.90
Ti	0.002	0.15	0.37	0.29	0.01	0.02
Zn	0.005	0.03	0.01	0.01	0.11	0.10

After each paste layer application, the layer of placed tailings was flattened with the help of the Topcon RL-H3C rotary laser. For the cement cell, only the first layer was filled with 2% cementitious tailings and the remaining 9 layers were filled with non-cemented tailings. Cement type CEM I was used. Sensors were placed in layers 2, 4, 7 and 9 to monitor the quality and behavior of the paste tailings layers.

D. Strength and geotechnical tests

Compression tests, 50 kN load capacity and 1 mm/min. was performed only on CPB samples using a press with a deformation rate. A total of three specimens were tested to reach an average strength value. To determine the water content of samples, they were oven dried at 45°C for 3 days. This temperature was chosen to ignore the dehydration of cement composites. No strength test was performed for SPD specimens. Geotechnical index tests were performed on representative specimens that broke after strength testing. Initially, only the water content and specific gravity values of tailings backfill samples were determined. Then, these two important experimental data and other remaining parameters (void ratio and saturation degree) were calculated.

III. RESULTS AND DISCUSSION

A. Effect of infill placement conditions on strength

Fig. 6 shows the change in uniaxial compressive strength of CPB containing 4.5% cement as a function of curing time. Different paste backfills (consolidated, drained and non-drained) were compared with each other at 7, 14 and 28 days. In general, it can be said that the consolidated backfills provided much better strength than other backfills, regardless of the curing time. The compressive strength (2.9 MPa) of the consolidated CPB during the 28-day curing period is 50% higher than that of the drained fillings (1.5 MPa). The main reason for this is the decrease in the void ratio of the consolidated fillings due to stress and an effective hydration product formation. Another reason for the higher strength of consolidated paste backfills is the drainage of excess water from the sample due to the consolidation loads applied during the curing period. Drainage of the free water present in fresh backfills first provides a decrease in the void ratio of paste backfill and then an increase in the strength.

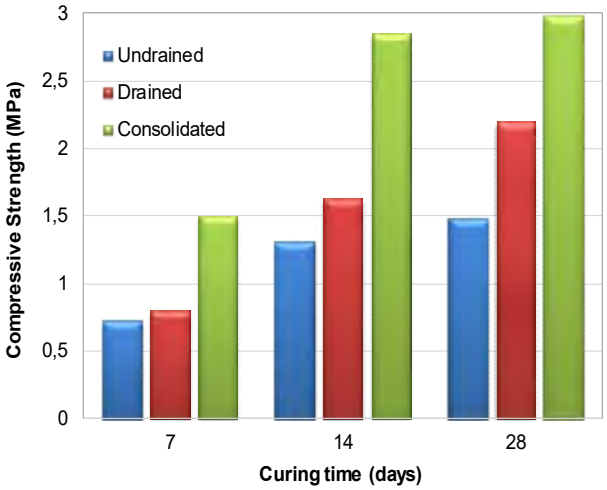


Fig. 6. Curing time-compression strength relationship for CPB samples

B. Effect of infill stope height on strength

Fig. 7 shows the uniaxial compressive strength evaluation of samples taken from different heights in a stope (mineralized production room) containing 4.5% by weight cemented paste backfill at different curing times (7, 14 and 28 days). In a given sphere, the strength of the fill increases proportionally with the increasing stope depth. This trend follows the same trend as geo-static compressive stress ($\gamma \times h$). The strengths of the fill at stope depths of 0, 4, 8, 12, 16 and 20 m during the 28-day curing period are 1.6, 2.1, 2.5, 2.6, 2.7 and 2.9 MPa, respectively. It proves that the strength of these back-filled stopes increases from the top to the bottom due to the consolidation effect. For a curing period of 7, 14 and 28 days, the strength of backfill at the base of the stope was 81%, 64% and 51% higher, respectively, than the strength of backfills located above the stope. The density of consolidated filling increases with increasing stope depth, thus reducing void ratios as a result of stress during curing. This is because the lower the void ratio, the closer the backfill solid grains are to each other, and therefore the lower the friction angle formed and the stronger the backfill strength.

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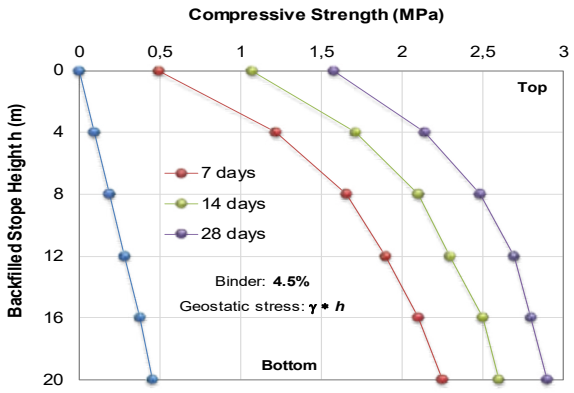


Fig. 7. Stope height-compressive strength relationship for CPB samples

C. *Effect of paste tailings layers on volumetric water content*

Fig. 8 shows the assessment of the measured volumetric water content in paste tailings layer 1, 3, 5, 8 and 10 in cemented or non-cemented mini cells. For the first layer, the volumetric water content of the cemented cell (0.46) is lower (0.46) than that of non-cemented cell (0.48). Paste tailings layers except the first layer show relatively the same trend. That is, the volumetric water content of the non-cemented cell is always low compared to that of the cemented cell. The main reason for this is that it acts as a leak-proof cover with the cement applied in the first layer, allowing neither water nor oxygen permeability. In addition, when the paste layer is applied, the water content will increase as the material contains water in the first case, but after a certain period of time, the volumetric water content will decrease with the effect of settling (there is also the effect of evaporation).

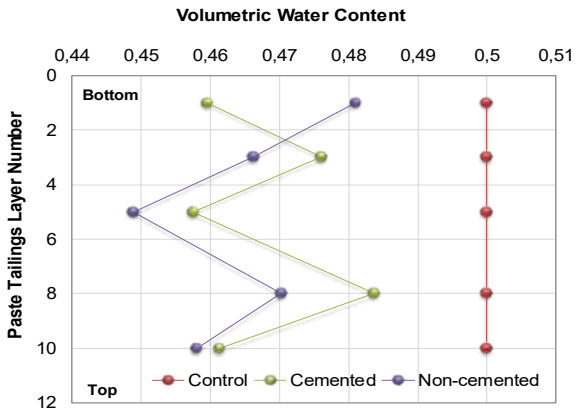


Fig. 8. The relationship between paste layer thickness and volumetric water content for SPD samples

D. *Effect of fill placement conditions on saturation degree*

Fig. 9 shows the evolution of the observed saturation degree depending on curing time for different cementitious paste backfill samples. The degree of saturation decreases over time regardless of the sample being tested. The highest decrease in saturation degree was obtained from consolidated cementitious paste backfill. During the 28-day curing period, the degree of saturation of consolidated paste backfills (86%) is lower than both drained backfilling (88%) and non-drained backfilling (93%) coastal. It is noteworthy that the variation in saturation degree of non-drained paste backfills is limited (between 93-95%) for a certain curing time.

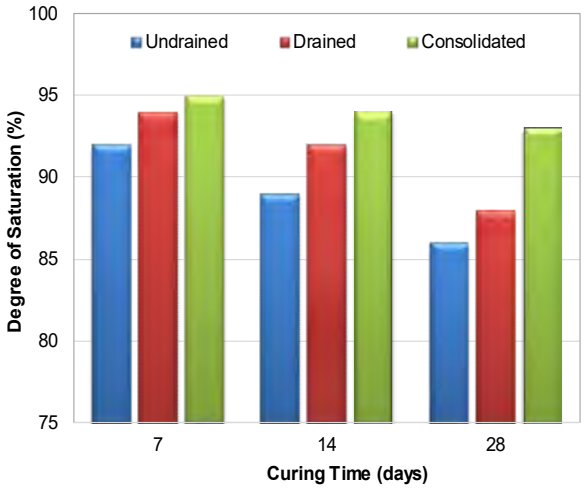


Fig. 9. Saturation degree-curing time relationship for SPD samples

IV. CONCLUSIONS

This paper presents the results of studies designed for both underground paste backfill and surface paste disposal applications. Numerous laboratory and field testing were performed on paste tailings from a metallic Canadian mine. Laboratory research includes mechanical and geotechnical tests on consolidated, non-drained and drained backfills with 4.5% cement by weight, at curing times of 7, 14 and 28 days, while field research includes the volumetric water content and degree of saturation of tailings placed in cemented and non-cemented cells. Based on different laboratory and field test results, the following conclusions can be drawn:

- Compared to other types of paste backfills (drained and non-drained), the most ideal CPB mixtures are obtained from consolidated paste backfills.
- The application of consolidation stress to laboratory-made paste fills during curing mimics the placement and in situ conditions of CPB for an efficient backfill design for mines.
- The addition of cement to paste tailings layers applied in the mini field cells plays an important role in the quality and behavior of the SPD application.
- The SPD method can be well applied to conventional tailings impoundments (called tailings dams) for the optimal tailings disposal and to significantly reduce future reclamation costs.

These results show that consolidated backfill produced using a new laboratory equipment can be appropriately used for cost- and performance-effective paste backfill in place of both drained and non-drained paste backfill prepared using conventional molds. In addition, the proposed new approach for safe surface disposal of hazardous paste tailings enables operators to reduce costs linked with waste management. As a final point, additional studies are underway to confirm the benefits of underground paste backfilling and aboveground paste disposal techniques.

