Original Scientific Article • DOI: 10.2478/rmzmag-2021-0002

Received: June 22, 2021
Accepted: July 02, 2021

Copper tailings reprocessing

Pridobivanje bakra z deponij

Damjan Hann*
University of Ljubljana, Faculty of Natural Sciences and Engineering, Department of Geotechnology, Mining and Environment, Aškerčeva 12, Ljubljana, Slovenia
*Corresponding author: E-mail: damjan.hann@ntf.uni-lj.si

Abstract in English

Copper is widely used in the modern world. An excellent conductor of electricity, it is used in the electrical industry, in the construction industry because of its good corrosion resistance, and in the manufacture of heat exchangers in heating and cooling systems owing to its excellent thermal conductivity. Copper production has increased throughout the twentieth century, and this trend has continued over the last twenty years. The demand for copper is expected to increase significantly by the year 2030. Owing to the high prices of this metal and the lack of deposits, part of the demand can be met by extraction from copper-bearing tailings. In the past, owing to the lower level of technological development and lower copper prices, materials comparable in copper content to the copper ores mined today have ended up in tailings. Since these are already processed materials, the costs of mining, crushing and milling are largely eliminated, making them promising raw materials. The article presents the technological possibilities of reprocessing and also estimates the amount of copper that could be obtained worldwide in this way.

Keywords: tailings reprocessing, multi-gravity separator, flotation, copper

Abstract in Slovene

Baker v sodobnem svetu masovno uporabljamo. Kot odličen prevodnik električne energije je uporaben v elektro industriji, zaradi dobre odpornosti na korozijo v gradbeni industriji, zaradi odlične toplotne prevodnosti pa se ga uporablja za izdelavo toplotnih izmenjevalcev v ogrevalnih in hladilnih sistemih. Proizvodnja bakra je naraščala celotno dvajseto stoletje, trend pa se nadaljuje tudi v zadnjih dvajsetih letih. Do leta 2030 se pričakuje precejšnja rast povpraševanja po bakru. Zaradi visokih cen te kovine in pomanjkanja nahajališč je možno del potreb pokriti s pridobivanjem na jaloviščih, ki vsebujejo baker. V preteklosti so namreč zaradi nižje stopnje tehnološke razvitosti in nižjih cen bakra na jaloviščih končali materiali, ki so po vsebnosti bakra primerljivi z bakrovimi rudami, ki se odkopavajo danes. Glede na to, da gre za že procesirane materiale, stroški rudarjenja, drobljenja in mletja večinoma odpadejo, zato gre za zelo perspektivne surovine. V članku so predstavljene tehnološke možnosti glede reprocesiranja, ocenjena je tudi količina bakra, ki bi jo lahko na ta način pridobili globalno.

Ključne besede: reprocesiranje jalovišč, multi-gravitacijski separator, flotacija, baker

Introduction

In the past, prices for various non-ferrous metals were somewhat lower than they are today, and this is the main reason why the mining industry left significant amounts of those metals in tailings dams around the world. The prices of non-ferrous metals simply did not allow for too much engagement when it came to mineral processing and ore beneficiation. The second, equally important reason for the low efficiency of ore processing was the equipment, which was not as advanced as it is today.

Copper is considered one of the first metals ever mined and used by mankind, and it has contributed significantly to the improvement of society since the beginning of civilization [1]. More specifically, copper is a metal that has been in use for about 10,000 years [2], and there is no indication that it will be replaced by a similar material in the near future. The price of copper has recently peaked as concerns about supply disruptions and strong demand have raised expectations of a tight market. This key energy transition metal, which is also widely used in construction, is trading at around $10,000 a ton. The price is at its highest level since July 2011, when copper traded at about the same price. Analysts at Goldman Sachs expect copper prices to reach $15,000 per ton in 2025, driven by high demand, which is forecast to grow by almost 600% by 2030. The projected demand is likely to lead to a supply deficit and higher copper prices, which in turn are likely to trigger new investment cycles [3].

Notwithstanding the fact that copper has been used by humans for 10,000 years, as shown in Figure 2, a negligible amount of copper was mined before 1900. About half of the total amount of copper was produced by 1998, while another half was mined in the last 22 years. Total copper production from 1900 until the end of 2020 was about 740 million tons [5, 6].

In a situation in which global copper demand is growing and copper prices are steadily increasing, reprocessing copper tailings is becoming an increasingly logical decision [7, 8, 9]. In most of the copper tailings deposited in the last century, there is a sufficiently high content of valuable components so that the tailings can be economically exploited and considered a potential future resource [10].

Nowadays, the development of new technologies allows the exploitation of copper, which in the past was disposed of together with the tailings due to inefficient copper extraction processes. Another reason that enables the exploitation of copper tailings is the high price of copper on the world market. In the past, tailings, now considered a valuable source of metals, were treated as waste due to the low price of copper.

In the last century, the copper content of some tailings was as high as 0.75%, which means that these historic tailings may have a higher content than the current deposits, which mostly contain 0.2%–0.8% copper. However, as each individual deposit is at least a little different from all the others, and consequently so is the tailings dam, it is impossible to predict in advance the optimal procedure for reprocessing [7].

A significant and, above all, positive side effect of tailings reprocessing is the protection of the environment by eliminating or at least reducing exposure to hazardous substances.

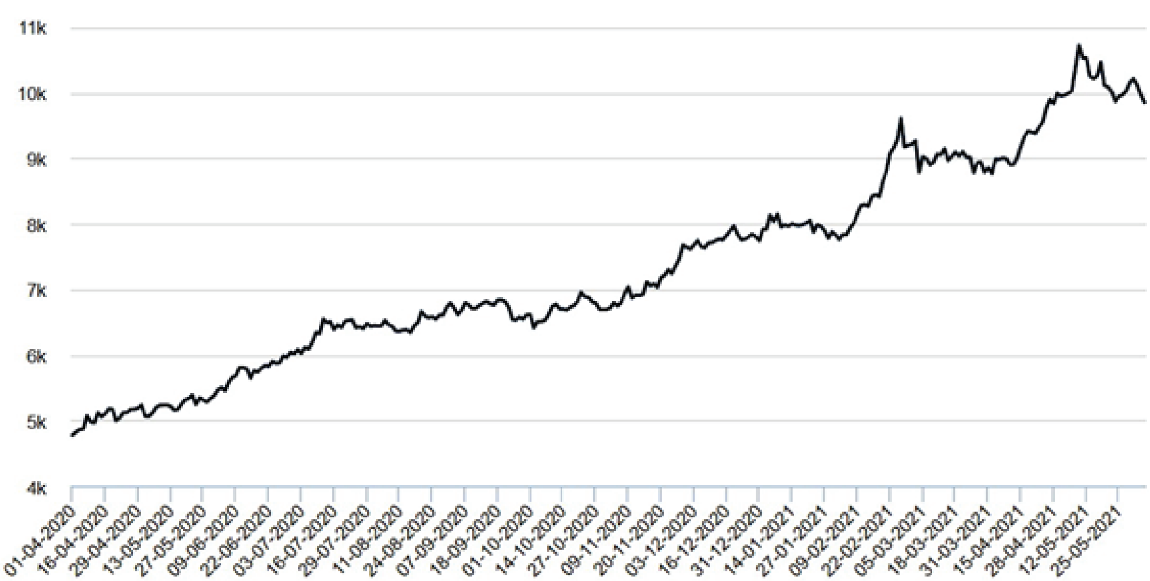

Figure 1: *Copper price on the London Metal Exchange since April 2020 (USD/t) [4].*

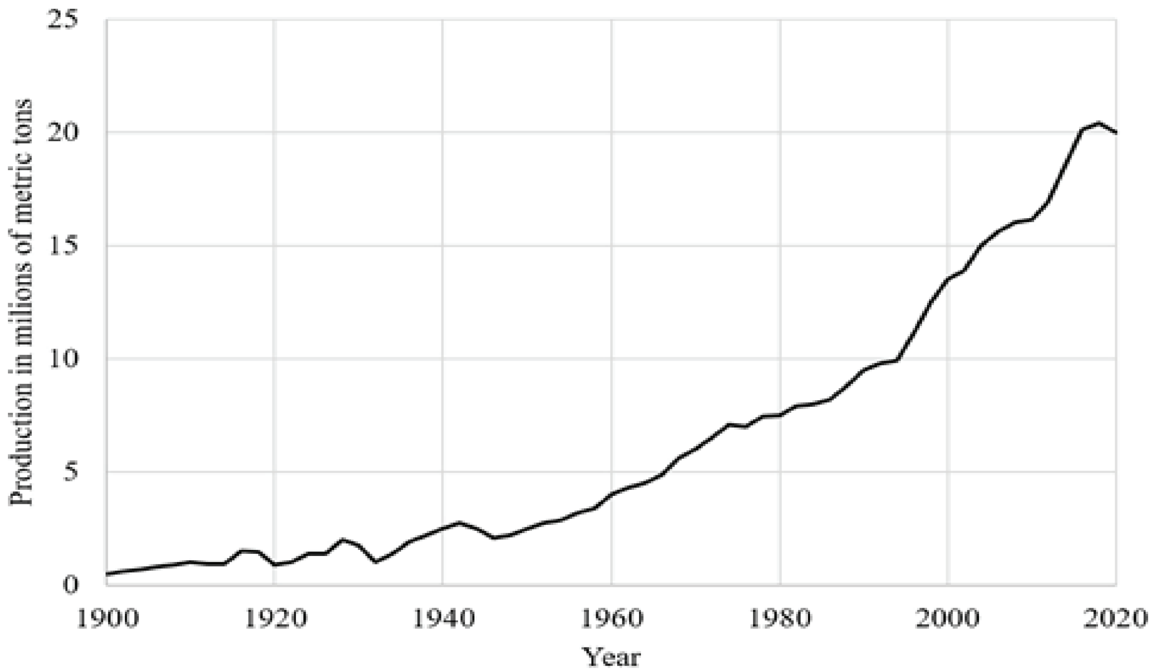

Figure 2: *Total copper mine production worldwide from 1900 to 2020 (adapted from [5, 6]).*

The economic balance of tailings reprocessing can also be improved through environmental protection if a government or community is interested in rehabilitating an area degraded by tailings and is willing to allocate funds to such a project. If heavy metals and other potentially harmful substances are removed from the material, the sale of the remaining material for everyday use in mass consumption can also be considered.

Since the material in the tailings dams is already accumulated in large quantities and has undergone mining and certain mineral processing such as crushing and grinding of the original ore, the costs are expected to be lower than those associated with extracting metals from the deposits.

In the exploitation of deposits, mining represents the highest cost [10] and together with the costs of crushing and milling in the case of a 100,000 t/day copper concentrator (Table 1), mining costs represent the largest part of all costs.

Owing to the many advantages of tailings retreatment, several tailings retreatment plants are already in operation around the world [10], and many more are expected to start producing copper in the near future.

Table 1: *Approximate relative costs of a 100,000 t/day copper concentrator [10].*

Item	Cost (%)
Crushing	2.8
Grinding	47.0
Flotation	16.2
Thickening	3.5
Filtration	2.8
Tailings	5.1
Reagents	0.5
Pipeline	1.4
Water	8.0
Laboratory	1.5
Maintenance support	0.8
Management support	1.6
Administration	0.6
Other expenses	8.1
Total	100

If metal minerals are to be extracted from ore or tailings, there are several chemical options. Minerals can be subjected to pyrometallurgy, which involves exposure to high heat; hydrometallurgy, which requires solvents; or electrometallurgy, which uses high electrical power, although combinations of different processes are also possible. By far the most common process among those mentioned is pyrometallurgy – or more specifically, smelting. All these processes are otherwise quite energy intensive. This is the main reason why smelting is not carried out until the copper ore has been concentrated to the maximum by mineral processing procedures, eg up to 25%. This also reduces transportation costs. Physical processes for separating valuable and gangue minerals are the exact opposite of chemical processes in terms of energy input [10].

This article presents various technological options for exploitation of tailings, which are expected to be rich enough in copper, according to the current copper price. It also reports the results of feasibility tests on the economic extraction of copper from tailings and gives an estimate of the amount of copper that could be extracted from tailings worldwide.

The idea for the research was triggered by the rising prices of non-ferrous metals, which made tailings reprocessing interesting. Large copper mines operating in the last century with the technology available at the time could not be as effective, so the copper content in tailings is likely to be high enough to be seen as a promising opportunity. Any feasibility testing or, in other words, demonstration of the viability of tailings should start with samples collected in the field. This should be followed by granulometric analysis and compositional analysis, for example XRF (X-ray fluorescence) analysis. Finally, enrichment of copper content using appropriate equipment, such as a multi-gravity separator or flotation cell, and redetermination of the composition of the tailings should follow.

Materials and methods

In copper mining, the concentration of ore is usually accomplished by a process called froth flotation [11], in which the valuable substance floats to the surface with the aid of air bubbles. Unwanted material, called gangue, sinks to the bottom and is removed. The concentration process can also be carried out using a variety of different techniques and technologies, including gravity-based methods, leaching, dense liquid separation, etc.

Sampling

In the past, many underground and open pit copper mines were in operation in Europe, so several sites with tailings dams are available for research purposes [12, 13]. Sampling was carried out at a tailings dam that had been created and filled in the second half of the previous century. Owing to the time period in which the tailings dam was formed, the copper content in the original ore, and the technology available at the time of copper extraction, the samples collected represent typical material suitable for copper tailings reprocessing. An excavator was used to obtain representative samples [14]. As it is characteristic for most bulk materials exposed to external forces over an extended period of time, oxidation occurred. Excavation of the material revealed that the material layers at a depth of about 1.5 meters and deeper are grey in colour and are not oxidised. Within the layers near the surface, the proportion of material that has been exposed to weathering increases, and there is a gradual transition in the colour of the tailings from grey to brown. In some cases, intact material occurs at depths as shallow as 0.5 meters. Samples were taken from both layers, and the total amount of almost one tonne of material was transported to the laboratory for examination.

The content of copper in the samples was determined by X-ray fluorescence (XRF), a technique that determines the presence of individual elements in a sample without damaging it. Samples of upper oxidised material and bottom unoxidised material were analysed separately for element content. It was found that the copper content in the samples taken from the upper part of the tailings was much lower than in the unoxidised samples, for which an average of 0.16% copper content was measured. As reported in [7], there is a reprocessing plant in Chile that extracts copper from tailings grading 0.12% to 0.27% Cu. Oxidised samples were consequently identified as not promising for reprocessing. The lower copper content in the upper layers is due not only to the weathering of the particles, but also to the continued downward movement of the heavier grains with water currents. Grains with a higher density, such as grains with some copper content (copper density is about 9 g/cm^3), definitely belong to this group of grains.

Granulometric analysis

Since the applicability of each method in mineral processing is highly dependent on particle size, granulation analysis was performed. Sieve analysis was carried out using seven different standard laboratory sieves [15] with aperture sizes: 32, 71, 125, 250, 500, 1,000 and 2,000 µm [14]. Before sieving, homogenisation, sampling [16] and drying of the appropriate amount of the tested material was performed. Table 2 shows the results of sieving analysis. The results and the graphical representation in Figure 3 show that the parameter d_{50} – mean particle size – is about 200 µm, while d_{90} is in the range of 450 to 500 µm.

Multi-gravity separator

Multi-gravity separators are separation systems that can be useful in applications such as upgrading industrial minerals, recovering precious metals, and recovering metal minerals such as copper minerals. They have proved their usefulness by enabling the production of high-grade concentrates at high recovery from low-grade tailings [10, 14, 17, 18].

As long as there is a sufficient difference in the specific gravity of the grains, this machine can separate a particular mineral or group of heavy minerals from a low-density gangue within a liquid suspension. For effective separation, there should be at least one SG (specific gravity) unit between the heavy and light particles. Nowadays, laboratory versions of multi-gravity separators up to full-scale industrial units with an ore processing capacity of 5 t/h are available on the market, which can treat even ultrafine particles down to a size of 1 µm.

The invention and further development of the multi-gravity separator, also known as an enhanced gravity separator, was inspired by a conventional shaking table. The physical basis and operating principle of both concentrators are quite alike. In the multi-gravity separator, centrifugal forces are used to increase the efficiency of separation of fine and ultra-fine particles. The centrifugal force acting on the grains is, in absolute value, much higher than the force of gravity in case of conventional shaking table; therefore, separation is easier to achieve. The forces acting on the particles can even reach up to 15 g and more.

Separately prepared and constantly stirred homogeneous feed slurry enters at the centre of the rapidly rotating conical drum. As shown in

Table 2: *Results of sieve test.*

Aperture size (µm)	Size interval (µm)	Sieve mass (g)	Cumulative pass (g)	Cumulative pass (%)	Cumulative oversize (%)
2,000	+2,000	13	2.81	97.19	2.81
1,000	1,000–2,000	4	0.86	96.33	3.67
500	500–1,000	11	2.38	93.95	6.05
250	250–500	143	30.89	63.06	36.94
125	125–250	193	41.68	21.38	78.62
71	71–125	54	11.66	9.72	90.28
32	32–71	24	5.18	4.54	95.46
0	0–32	21	4.54	0.00	100.00

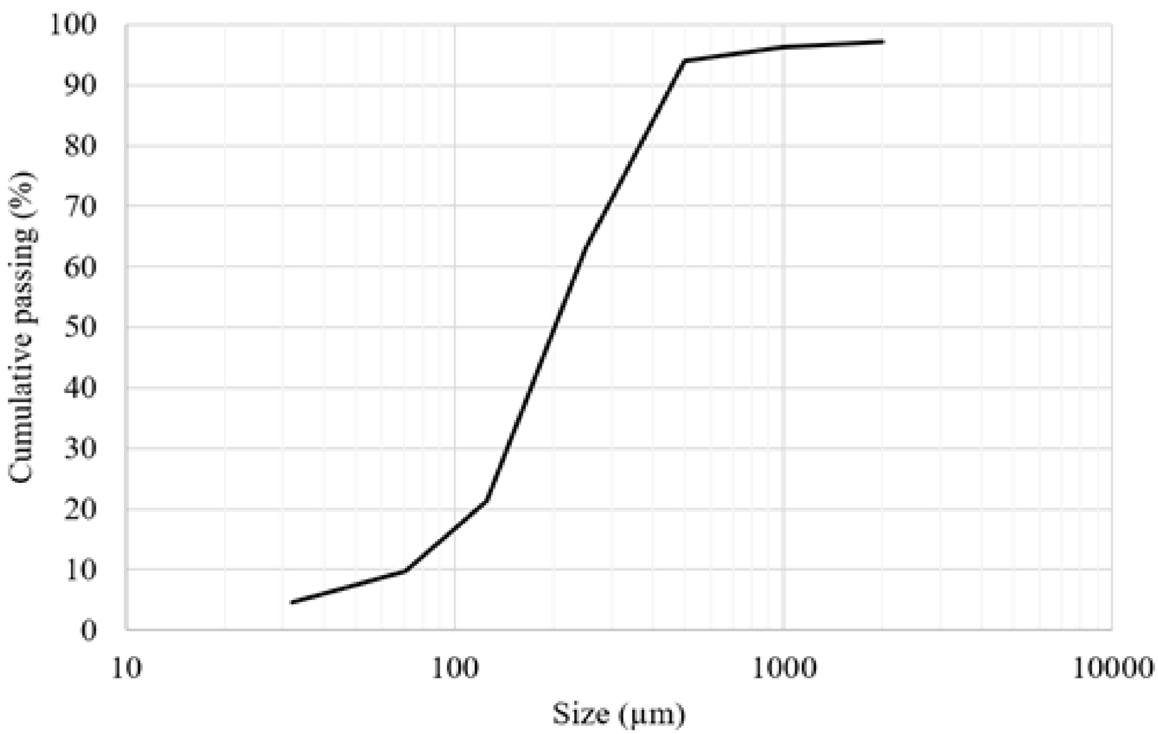

Figure 3: *Graphical interpretation of the sieve test.*

Figure 4, the drum rotates clockwise whilst being shaken by cyclic oscillation in the horizontal direction at 4–6 cps. After a few turns, the entering slurry is spread evenly over the entire surface on the inside of the drum. The light fractions begin to collect in the thin flowing film of water, which continuously ensures the movement of these particles in the direction of the far end of the drum. Particles with higher density are affected by the high centrifugal forces or so-called enhanced gravity and shear forces due to shaking. Consequently, they are squeezed through the pulp film and end up as pressed to the drum. The further movement of the heavy particles is controlled by the unique scraper system. Rotating scrapers direct heavy grains within the semi-solid layer to the concentrate outlet, which is in the opposite direction as the fine grains are discharged. The scrapers also rotate clockwise like the drum but at a slightly higher rpm (revolutions per minute).

Small quantities of wash water are added through the wash water inlet, which is located close to the concentrate outlet. The purpose of the wash water is to create a water film capable of carrying and bringing out the entrained light fraction into the tailings outlet and rinsing the dense grains just before they are discharged from the concentrator.

Flotation

The extent to which useful substance is lost to tailings during ore processing determines whether or not a deposit can be economically exploited. The proportion of losses depends partly on the natural characteristics of the ore deposit and partly on the technology used for extraction. More specifically, the losses depend, on the one hand, on the spatial distribution of the minerals in the ore and the mineralogy itself, and on the other hand, on the efficiency of the concentration [10]. As with other methods, technological progress in flotation brings new opportunities for the reprocessing of low-grade copper tailings.

Flotation is a process in which a useful substance is separated using chemical reagents in a three-phase system (solid, liquid and gas) by combining the grains with air bubbles to obtain a froth of concentrate as the tailings sink to the bottom.

The main problem with the flotation of tailings is the fact that the material has already been processed – crushed and milled – so that

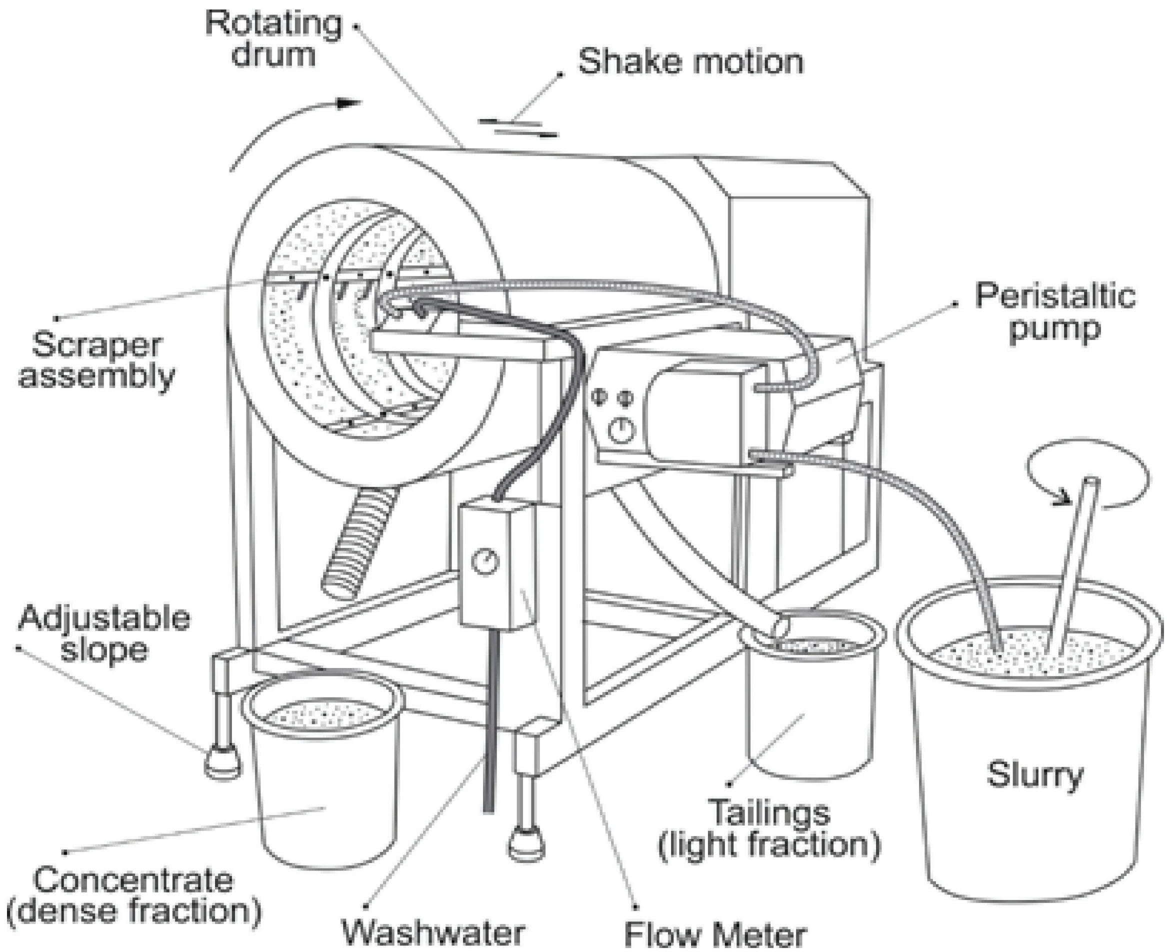

Figure 4: *Multi-gravity separator – MGS (adapted from [10, 14, 18]).*

the majority of particles are smaller than 100 or even 50 microns. Many different problems can arise in the flotation of such fine fractions, and the smaller the particles, the greater the problems. Particles with 1 mm^3, milled to 1 μm^3 particles, mean a huge increase in the number of bubbles required. In this case, the possibility of each particle being associated with an air bubble is small. Another problem is the huge increase in the amount of reagents required due to the increase in the specific area [7]. Therefore, if the particles in the tailings are very small, a method other than froth flotation should be used, based on a different physical basis.

Results and discussion

Since the multi-gravity separator (MGS) has many adjustable parameters, it is quite a challenge to find an optimal combination for a quality separation. Operating variables of the MGS are:

— shake amplitude
— shake frequency
— drum rotational speed
— drum angle of inclination
— wash water flow rate
— feed percent solids

During the test, the drum rotational speed, solids concentration, and wash water flow rate were adjusted while the other parameters remained constant. After each individual test, which lasted approximately five minutes, a small amount of concentrate was taken, and then a series of samples were heated to dryness. This was followed by elemental composition measurements, which showed that the combination of adjustable parameters plays a significant role when MGS is used for separation.

The upgrade factor, which is the relationship between the share of copper in the concentrate and the share of copper in the feed material, can be as low as close to 1. However, the concentration of copper when optimal conditions were reached was several times higher compared with the concentration in the feed material [14].

Tests with the MGS gave solid results, but to get even better results, the processing of the material with the multi-gravity separator would have to be combined with another physical process. Since today's knowledge of flotation far exceeds what we knew about this process decades ago, the flotation process could be used especially for coarser fractions.

Figure 5 shows the cumulative size distribution of the material from the copper tailings reprocessing plant in Chile, which has a d_{90} of 270 µm and was successfully processed in the flotation circuit [7]. Since the material considered in this work is quite similar in size to that processed in Chile, it would be useful to perform an additional test with flotation cells. Moreover, a batch process can be used.

From the combination of all the information obtained from the experiments and the information provided by other researchers on copper reprocessing, it can be concluded that the process line shown in Figure 6 would be successful for a tested material.

Taking into account the quantities of copper produced with low efficiency during the last century, the amount of material accessible on tailings dams, the oxidation of tailings, the efficiency of copper reprocessing and the average copper content within tailings, it is possible to give an estimate [Equation (1)] of the capacity of copper that can be recovered from tailings worldwide:

$$P = TP \times a \times b \times c \times d \times e \times f \qquad (1)$$

P = 737 million tons × 0.5 × 0.33 × 0.8 × 0.8 × 0.75 × 0.97 = cca 57 million tonnes
where the following abbreviations are used:

P: global potential of mining tailings for copper production
TP: total global historical production of copper
a: share of low-efficiency copper production, characteristic for the last century
b: ratio of copper content in original ore to copper content in tailings
c: share of tailings dams accessible for reprocessing

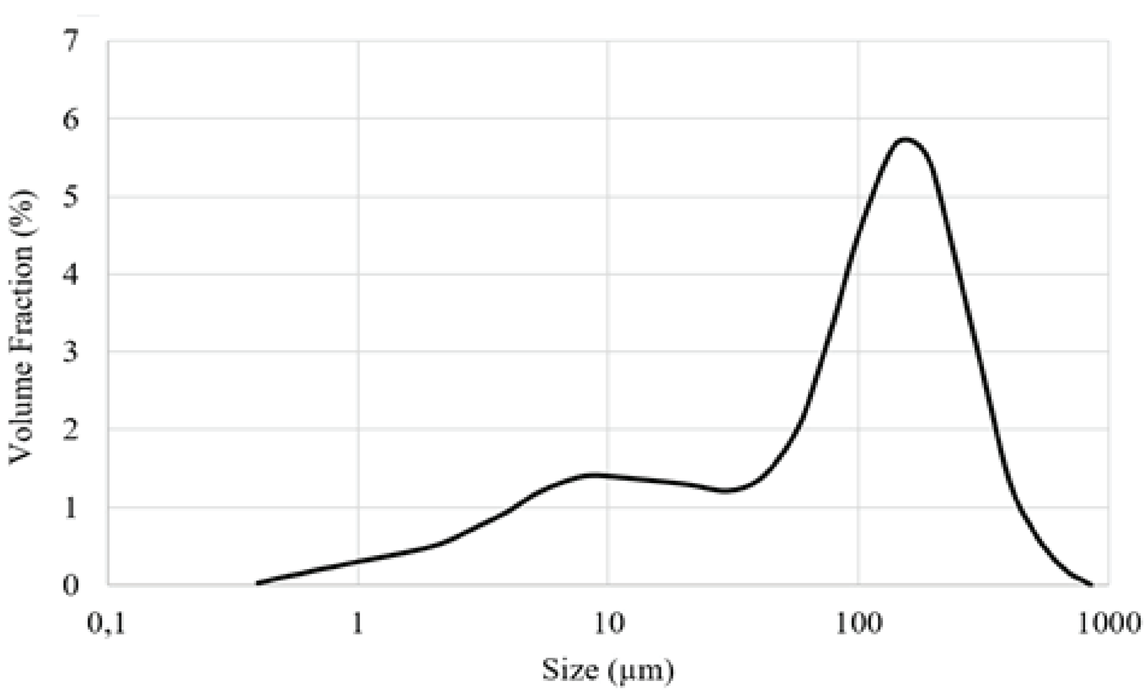

Figure 5: *Cumulative size distribution of feed material from a copper tailings reprocessing plant (adapted from [7]).*

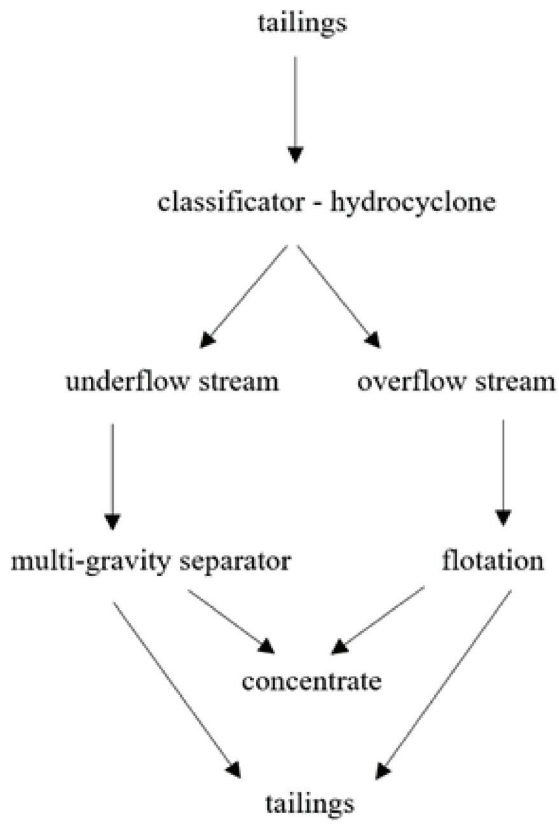

Figure 6: *Process line for copper tailings reprocessing.*

d: ratio of oxidised to intact tailings
e: efficiency of copper reprocessing (share of copper recovered from tailings)
f: share of tailinrgs not yet reprocessed

Given the current world copper demand (about 20 million tons per year), this potential corresponds to the same amount of copper produced from the deposits in about three years.

Conclusions

Despite the fact that the extraction and use of copper has a very long history, most copper has been mined in the 20th and 21st centuries. Copper consumption is increasing over the years, and the price of this commodity is growing accordingly. The extraction of copper accumulated in tailings dams around the world will be an increasing part of the mosaic of copper supply in the future.

At today's copper prices and processing technologies, reprocessing old copper tailings is generally economically viable and cheaper than recovering copper from deposits. Reprocessing tailings can withstand a slightly lower copper content, as there are no costs of excavation, crushing, or grinding.

Tests on samples of tailings have proved the usefulness of MGS in the reprocessing of copper tailings. However, MGS alone cannot provide sufficient recovery such that a concentrate could be prepared directly for smelting; instead, it must be combined with another process such as flotation.

The reprocessing of tailings not only brings additional amounts of copper into the supply chain, but also benefits the environment because the accumulated heavy metals burden the environment. Only copper reprocessing is discussed in this paper. Other metals are also accumulated within tailings dams in larger quantities and can be recovered profitably, which would also benefit the environment.

Acknowledgements

I would like to thank assistant Blaž Janc for helping me with the pictures.

References

[1] 'Copper – A Metal for the Ages', *U.S. Geological Survey, Mineral Resources Program*, https://pubs.usgs.gov/fs/2009/3031/FS2009-3031.pdf., pp.1-4, (accessed 24 May 2021).

[2] McHenry, C. (ed.), *The New Encyclopedia Britannica 3*, 15 edn., Chicago, Encyclopedia Britannica, Inc., 1992, pp.308-310.

[3] 'Copper Prices Hit Highest Level Since 2011' , *Eurometal*, https://eurometal.net/copper-prices-hit-highest-level-since-2011/, (accessed 22 May 2021).

[4] 'LME Copper Historical Price Graph', *London Metal Exchange*, https://www.lme.com/en-GB/Metals/Non-ferrous/Copper#tabIndex=2, (accessed 24 May 2021).

[5] 'Total Copper Mine Production Worldwide from 2006 to 2020', *Statista*, *https://www.statista.com/*

statistics/254839/copper-production-by-country/, (accessed 26 May 2021).

[6] 'World Production Trend of Copper', *U.S. Geological Survey*, https://commons.wikimedia.org/wiki/File:Copper_-_world_production_trend.svg. (accessed 26 May 2021.)

[7] Mackay, I. et al., 'Dynamic Froth Stability of Copper Flotation Tailings', *Minerals Engineering*, no. 124, DOI:10.1016/j.mineng.2018.05.0052018, pp. 103–107.

[8] Drobe, M. et al., 'Processing Tests, Adjusted Cost Models and the Economies of Reprocessing Copper Mine Tailings in Chile', *Metals*, vol. 11, no. 1, 2021, p. 103, DOI:10.3390/met11010103, (accessed 26 May 2021).

[9] Figueiredo, J. et al., 'Tailings Reprocessing from Cabeço do Pião Dam in Central Portugal: A Kinetic Approach of Experimental Data', *Journal of Sustainable Mining*, no. 17, 2018, pp. 139–144, DOI:10.1016/j.jsm.2018.07.001, (accessed 28 May 2021).

[10] Wills, B.A., Finch, J.A., *Wills' Mineral Processing Technology: An Introduction to the Practical Aspects of Ore Treatment and Mineral Recovery,* 8th edn. Oxford, Butterworth-Heinemann, 2016, pp. 1-23, DOI:10.1016/B978-0-08097053-0.00012-1 (accessed 27 May 2021).

[11] 'Processes: Copper Mining and Production', *European Copper Institute*, https://copperalliance.eu/about-copper/copper-and-its-alloys/processes/, pp. 1-3, (accessed 25 May 2021).

[12] Wirth, P., Černič Mali, B., Fischer, W., *Post-Mining Regions in Central Europe – Problems, Potentials,* Possibilities, Munich, Oekom Verlag, 2012, pp. 104-118.

[13] Uekoetter, F., *Mining in Central Europe – Perspectives from Environmental History, Munich, RCC Perspectives,* 2012, DOI:10.5282/rcc/5600, pp. 21-38, (accessed 28 May 2021).

[14] Kastivnik J., Venta A., *Report on Processing Test*, Ljubljana, Geološki Zavod, 2018, pp. 4-17.

[15] Stražišar, J., *Mehanska Procesna Tehnika I.* Ljubljana, Univerza v Ljubljani, 1996, pp. 27-30.

[16] Stražišar, J., Knez, S., *Vaje in Računski Primeri Iz Mehanske Procesne Tehnike*, Ljubljana Univerza v Ljubljani:, 2001, pp. 23-29.

[17] Enhanced Gravity Separator 911mpe-c-902, *911 Metalurgy Coporation*, https://www.911metallurgist.com/equipment/enhanced-gravity-separator/, pp. 1-20. (accessed 11 June 2021).

[18] Rao, G.V., Markandeya, R., Kumar, R. 'Modeling and Optimization of Multi Gravity Separator for Recovery of Iron Values from Sub Grade Iron Ore Using Three Level Three Factor Box Behnken Design', *International Journal of Mineral Processing and Extractive Metallurgy,* no. 2, 2017, pp. 46–56, DOI:10.11648/j.ijmpem.20170204.12. (accessed 28 May 2021).