

Copper, zinc, and iron bioleaching from polymetallic sulphide concentrate

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Abstract: Bioleaching of low-grade complex Cu–Zn–Pb–Fe–Ag–Au sulphide concentrate (of Majdanpek ore body, RTB Bor, Serbia) was carried out in an aerated bioleach reactor in the presence of mesophilic mixed bacterial culture of *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans*, and *Leptospirillum ferrooxidans*. A mesophilic acidophiles culture was isolated from the acidic solution of the underground copper mine of Bor, Serbia. The nutrient medium was 9K at pH 1.6. 87% of the particles were <10 µm in size, with a pulp density of 8% (w/v). Bioleaching efficiencies of 89% for zinc, 83% for copper, and 68% for iron can be achieved in the examined conditions. Kinetic analysis shows that the change in leaching corresponds to the Spencer-Topley kinetic model for diffusion-controlled topochemical reactions.

Key words: bioleaching; polymetallic sulphide concentrate; mesophiles; *Acidithiobacillus ferrooxidans*

1 Introduction

Bio-hydrometallurgical processing of complex low-grade non-ferrous metal concentrates has an important role in contemporary research on the possibility of achieving higher overall recoveries of metal values from such mineral resources [1–5]. High grade non-ferrous and noble metal ores are being exhausted, creating a need for the development of new technologies that could meet growing technological, economic, and ecological demands with regard to the available resources and capacities [6–10]. Chemical analyses of such resources in copper mines in Bor, Serbia, indicate that the presence of Zn, Cu, Pb, Ag, and Au is most common. The processing of complex raw materials with an average copper content of 2% in the concentrate using existing pyrometallurgical technology is not economically satisfactory. The processing of polymetallic concentrates by bioleaching can have commercial benefits compared to the conventional pyrometallurgical processing method. Compared to hydrometallurgy, zinc concentrate bioleaching has the advantage that it does not require roasting, a sulphuric acid plant, or washing of gaseous effluents, energy consumption and cost are low, and flow process is short [1,11].

Acidithiobacillus (A.) ferrooxidans, one of the most

important bioleaching microorganisms, bases its action on direct and indirect mechanisms. The first one refers to sulphur and sulphide oxidation by the bacteria attached to the particle surface. The latter is related to the oxidation of sulphur compounds by ferric ions resulted from the bacterial oxidation of ferrous ions. Although it is not easy to define the predominance of one or the other mechanism, the importance of cell attachment to the particles in order to carry out biooxidation is widely accepted [4,12].

Detailed study of *A. ferrooxidans*, an iron and sulphur oxidizing acidophile, showed that it grows much faster in the presence of ferrous ions than another mesophilic iron oxidizing chemolithotroph, *Leptospirillum ferrooxidans*. Besides that, some researchers proved that *A. ferrooxidans* grows best with a higher concentration of ferrous ions [13].

However, *L. ferrooxidans* is highly tolerant to acidic environments, and may enhance the regeneration of Fe³⁺ ions in acidic environments. That is why *L. ferrooxidans* is as important as *A. ferrooxidans* in the indirect leaching mechanism (over ferric ions). Furthermore, in some environments, *L. ferrooxidans* is to be found to a greater extent than *A. ferrooxidans* and it seems to be the dominant bacterium in industrial continuous-flow biooxidation tanks [14]. Some researchers have shown that the indigenous microorganisms which can be found in mineral raw materials are more efficient than

many of the consortia created in laboratories [15,16].

Polymetallic sulphide concentrates of Majdanpek ore body in RTB Bor Complex contain 8%–27% Zn, 2%–4% Cu, 4%–14% Pb (mass fraction), 170–500 g/t Ag, and 3.7–700 g/t Au. When using the existing pyrometallurgical technology of the copper smelter in Bor to process them, the formation of their oxides and thus the loss of these metals could not be avoided. This indicates that it is possible to use Pb–Zn sulphide concentrates only as a supplement to the feed for smelting, in order to correct the feed composition to make it suitable for further processing, and not as an independent concentrate.

The aim of this work is to present an experimental research on the bio-hydrometallurgical processing of complex sulphide concentrates in the pilot laboratory plant for bio-hydrometallurgical copper production of the Mining and Metallurgy Institute Bor, Serbia, in order to define the optimum process conditions for maximum utilization of useful components.

2 Materials and methods

2.1 Concentrates characterization

Polymetallic sulphide concentrate was taken from the ore deposit of Majdanpek ore body (Serbia). The sample contained 27.2% Zn, 3.7% Cu, 18.4% Fe, 4.6% Pb (mass fraction), 3.5 g/t Au, and 178.9 g/t Ag. From the results of chemical and mineralogical analysis of the concentrate, it can be seen that the treated sample is polymetallic Zn, Cu, Fe, Pb, Ag, and Au sulphide concentrate. Mineralogical analysis of the concentrate and bioleach residue was performed using the X-ray diffraction (XRD) Explorer model analyser (GNR) with Cu K α (0.154 nm). The operating conditions are 40 kV and 30 mA. The mineralogical XRD pattern is presented in Fig. 1, where it can be seen that the concentrate mostly

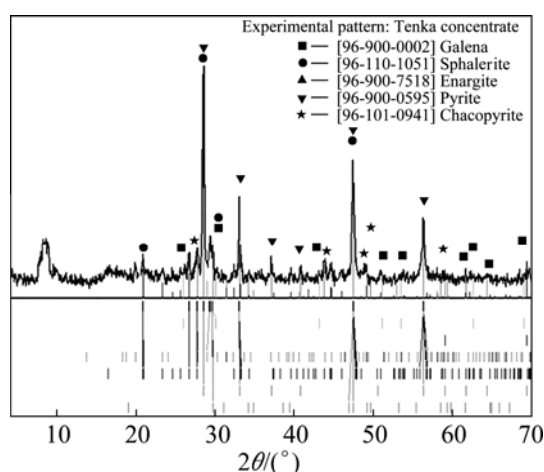


Fig. 1 XRD pattern for tested polymetallic sulphide concentrate

consists of sphalerite (ZnS), chalcopyrite (CuFeS₂), galena (PbS), and pyrite (FeS₂). The concentrate was milled and 87% of particles were <10 μ m in size.

2.2 Microbiological culture

Mesophilic mixed bacterial culture of *A. ferrooxidans*, *A. thiooxidans*, and *Leptospirillum ferrooxidans* was isolated from underground mine water of the Bor Copper Mine in Serbia. The mesophilic mixed culture is presented in Fig. 2. Bacterial growth was observed on an Exacta Optech binocular microscope with 1000 times magnification. A sample of mine water was taken from the ore body “Tilva Roš”.

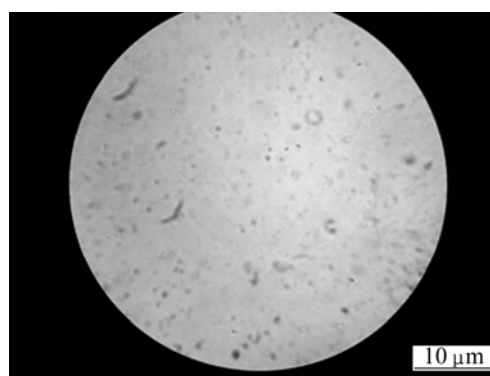


Fig. 2 Optical micrograph of mixed mesophilic culture with 1000 times magnification

2.3 Microbiological culture characterization

Characterization of microbiological species presented in RTB Bor resources (mine waters) was conducted using quantitative polymerase chain reaction (Q-PCR) analysis-based molecular equipment, and determination of their number was done within the EU FP6 BioMinE project by Bioclear (the Netherlands), applying the Q-PCR and T-RFLP methods [17]. The natural microbial population in RTB Bor mine waters is listed in Table 1, from which it can be seen that the relative presence of cultures which exist in natural mine habitats is not large.

Table 1 Quantification of microbial population using Q-PCR

Program for PCR analysis	Target – PCR	Bacteria population, cell/mL
P363P364	<i>Acidithiobacillus ferrooxidans</i>	2.3×10^4
P353P354	<i>Acidithiobacillus thiooxidans</i>	2.3×10^4
P071M041	<i>Leptospirillum ferrooxidans</i>	2.3×10^4

2.4 Analytical determinations

Ferrous and ferric ions concentrations were determined by titration with permanganate. This chemical analysis reliability is $\pm 5\%$. The value of

oxidation–reduction potential (ORP) was measured by Pt electrode in relation to a Ag/AgCl reference electrode (mV (vs Ag/AgCl)). The acidity of the solution was measured by combined pH electrode. Zinc, copper, and iron in solution were measured every seven days by absorption spectrometry (Perkin-Elmer 403) at the Mining and Metallurgy Institute Bor, Serbia. Expanded uncertainties of concentrations are $\pm 8.8\%$, $\pm 7.5\%$ and $\pm 10\%$ for zinc, copper, and iron, respectively. XRD analysis of the pulverized samples was conducted before and after the leaching process.

3 Results and discussion

The results of the dissolution of sulphides, including sphalerite, chalcopryrite, galena, and pyrite, by mixed mesophilic culture bioleaching were presented in this work. The analysis was done by applying the Q-PCR and T-RFLP methods [17]. For the treated sulphides, extended leaching time is required to achieve a high extraction degree using *A. ferrooxidans*, *A. thiooxidans*, and *Leptospirillum ferrooxidans* bacteria, which are active at temperatures in the range of 30–40 °C. These sulphides are much more easily dissolved by extremely thermophilic bacteria compared to mesophilic and moderately thermophilic bacteria. However, extremely thermophilic bacteria show higher sensitivity to solids content as well as to the particles granulation of the dissolved material. Thermophiles are intolerant even to the small concentration of silver. If the concentrate contains silver, it will have a negative impact on the thermophiles' growth [18]. Leaching by moderately thermophilic and extremely thermophilic bacteria requires higher energy consumption and corrosion-resistant equipment [19]. The chemical and mineralogical characterization of polymetallic concentrate was discussed in this work. For the test performed in the bioleaching reactor, a mixed mesophilic culture was used. The efficiency of extraction of Zn, Cu, and Fe was monitored simultaneously with the pulp ORP measurement, and the kinetics of the leaching process of all three metals was also examined.

3.1 Bacterial culture and nutrient

The culture isolated from acidic solution from underground exploitation of the Bor copper mine (Serbia) is mesophilic iron-sulphur oxidizing bacterial culture. Development of the culture was achieved in the testing laboratory of the Mining and Metallurgy Institute Bor, Serbia [20,21]. Development of mesophiles was achieved in 9K nutrient medium. The mineral salts of the 9K nutrient medium, produced by Lachner, are of p.a. quality and have the following composition: $(\text{NH}_4)_2\text{SO}_4$

(3.0 g/L), KCl (0.1 g/L), K_2HPO_4 (0.5 g/L), $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$ (0.5 g/L), $\text{Ca}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$ (0.01 g/L), $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$ (9 g/L). The acidity of the solution was adjusted to pH=1.8 with 1 mol/L H_2SO_4 . The bacterial concentration at the end of the incubation period was within the limit of 10^8 cell/mL, which corresponds to the literature data [22].

3.2 Culture adaptation

The bacterial culture prepared by isolation and growth was adapted for oxidation of polymetallic Zn–Cu–Pb–Fe–Ag–Au sulphide concentrate by processing in the 2 L volume glass reactor with magnetic stirring at 150 r/min and a temperature of 30 °C in the presence of (0.15%) CO_2 enriched air. The total solution volume was 1 L. The solution contained 5% inoculum with nutrient medium and 5 g/L polymetallic concentrate for culture adaptation. The initial pH value was adjusted to pH 1.6. The used 1 mol/L H_2SO_4 (produced by Molar) was of p.a. quality. The process was monitored by daily measurement of the pH value and ORP. Complete oxidation of ferrous ions was achieved in a period of 6 d. The value of ORP in that period gradually increased from 380 to 550 mV. In the period from 6 to 8 d, the ORP value remained at the maximum value of 550 mV.

3.3 Minerals characterization

Modal analysis of the tested sample (Table 2) shows that the content of basic sulphide minerals was 40.5% sphalerite, 10.6% chalcopryrite, 5.3% galena, and 32% pyrite. The chemical composition of the concentrate is presented in Table 3.

Table 2 Mineralogical components of concentrate

Mineral	CuFeS ₂	PbS	ZnS	FeS ₂	Other	Total
Mass fraction/%	10.6	5.3	40.5	32	11.6	100

Table 3 Chemical composition of concentrate

Element	Zn	Cu	Fe	Pb	$w(\text{Ag})/w(\text{Au})$ (g·t ⁻¹)	S_{tot}	Other	Total
Mass fraction/%	27.2	3.71	18.4	4.61	3.5	310	37.8	100

3.4 Particle size analysis

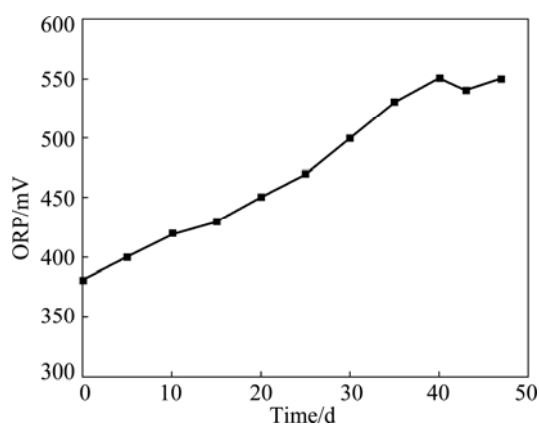
The concentrate was milled in the laboratory of the technical faculty in Bor in Siebtechnik vibrating ring mill. The concentrate was milled to 87% of particles <10 µm in size. The particle size of the concentrate after milling is presented in Table 4, where m indicates the mass fraction of the appropriate fraction and D is the cumulative undersize. The two finest fractions were used in the experiment.

Table 4 Particle size analysis of concentrate

$d/\mu\text{m}$	$m/\%$	$D/\%$
>30	7.40	100
30–20	3.70	93
20–10	1.85	89
10–5	5.56	87
5–0	81.48	81

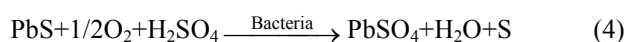
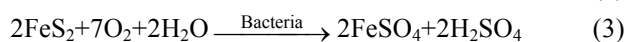
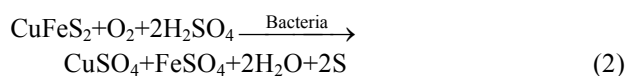
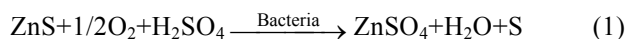
3.5 Laboratory bioleaching test

After adaptation by adding fresh quantities of polymetallic concentrate of 75 g/L, the total solids content of the pulp was 8% (w/v). The value of the redox potential ORP dropped to an initial value of 380 mV. The test was continued under the same conditions as during the culture adaptation in a 2 L glass reactor with a solution volume of 1 L at 150 r/min and a temperature of 30 °C. Air enriched with CO₂ (0.15%) was introduced into the reactor through an air diffuser. The acidity of the solution was corrected to pH 1.6 by adding 1 mol/L of sulphuric acid. Distilled water was added into the reactor to compensate for the evaporation of the process water. The potential versus the Ag/AgCl electrode was gradually increased from 380 to 550 mV, as presented in Fig. 3. The change in the ORP value was followed by the increase in the Zn, Cu, and Fe concentrations in the solution. After 40 d of mesophilic leaching, the extraction efficiency remained at the same level. In that period, by leaching of 80 g/L of concentrate, the final concentrations of 19.56 g/L Zn, 2.4 g/L Cu, and 10.45 g/L Fe were achieved. Chalcopyrite was dissolved at ORP values higher than 510 mV, while pyrite oxidation was only important when the ORP was higher than 450 mV, which is in agreement with the findings of some other researchers [23].

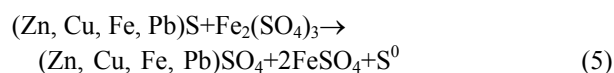
**Fig. 3** Graph illustration of oxidation-reduction potential (ORP) during bioleaching test

The following reactions describe the direct and indirect oxidation mechanisms of Zn–Cu–Pb–Fe sulphides. In the direct mechanism, metal sulphides can

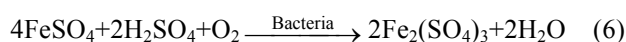
be oxidized by mesophilic microorganisms into soluble sulphates according to reactions (1) to (4):



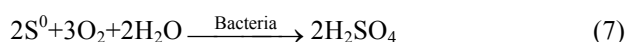
In the indirect mechanism of sulphide minerals oxidation, the sulphides oxidation by ferric ions proceeds according to the following reaction:



According to the presented mechanism, the dissolution of metals takes place by a cyclic process between reactions (5) and (6).



By formation of H⁺ ions during sulphur biooxidation, according to reaction (7)



the solubility and total recovery are increased.

In the sulphide areas, sulphuric acid is generated by indirect and direct bacterial attacks. By sulphuric acid generation, the acid balance is improved, which creates equilibrium in the system. Also, the reaction is exothermic, so it can be directed to increase the temperature, which improves the kinetics [24].

Distortion of the sulphide mineral crystal lattice occurs because of the much higher ionic radius of the sulphate ions. Thus, microbes gain access to new unreacted places [25].

3.6 Mineralogical analysis of solid residue

After the bioleaching process, the mass fraction of insoluble residue was 30% of the initial value. By bioleaching of polymetallic concentrate, Zn and Cu in the solution are converted into the sulphates, which can be further extracted by different extractants [26]. At the same time, Pb, Au, and Ag remain insoluble in the bioleach residue. By the application of the PLINT process, it is possible to obtain Au, Ag, and Pb from the bioleach residue [27]. XRD analysis of the solid residue, presented in Fig. 4, showed that the galena structure is converted into lead sulphate, which also dominates in the secondary beudantite, whereby it remains in the leach residue together with Ag and Au. Based on the mineralogical analysis of the concentrate and bioleach residue, it could be observed that the destruction of the sample crystal lattice occurred.

The fact that the leaching rate obtained by bioleaching with mixed cultures is higher than that obtained by leaching with pure culture indicates that the

influence of mineralogical composition is also important. Relevant information on ore mineralogical composition helps in understanding the interpretation of the microbial dissolution process [19]. Knowledge about the mineralogical composition of minerals in the ore is very important for understanding the biological processes of microbial dissolution, allowing for optimization of the process and processing method. The purpose for testing the mineralogical composition of the concentrate is to optimize the process parameters of bioleaching of complex sulphide concentrates using mixed mesophilic culture of *A. ferrooxidans*, *A. thiooxidans*, and *Leptospirillum ferrooxidans* with reference to the leaching of zinc and copper. The processing parameters of bioleaching processes are particle size, stirring speed, dissolution time, inoculum volume, pulp density, and pH value of the process.

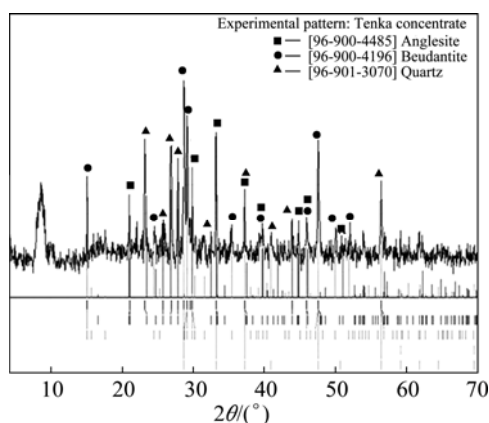


Fig. 4 XRD pattern for bioleach residue

The minerals supergene zone contains Zn, Cu, Fe, and Pb. This zone and the adjacent rocks also contain quartz minerals with relicts of present ore minerals including galena. Members of the solid solution series beudantite-segnite and lead jarosite represent a small part of a large group of natural compounds with alunite type structure. This alunite structure may also contain quartz. Under the influence of sulphuric acid, the decomposition of bedrock alunite occurs, whereby the beudantite can be extracted from galena, while quartz from such bedrock remains in the form of bioleach slurry.

Bioleaching experiments were performed in a glass reactor by using the mixed culture, which shows a higher leaching than the pure cultures [28]. In the incubation process in 9K nutrient solution, the number of bacteria reaches a value of 10^8 cell/mL. The acidity of the solution was adjusted to pH 1.6. The acidic condition is the bottleneck for the chemical regeneration of ferric ions from ferrous ions. Therefore, it is necessary to use the iron oxidizing bacteria *A. ferrooxidans* [3]. The ratio of ferric to ferrous ions in the bioleaching process is presented in Fig. 5. If the acidity of the solution was

lower, there would be a concern about jarosite appearing, which would precipitate copper in the slurry and further reduce the recovery from leaching [2,5].

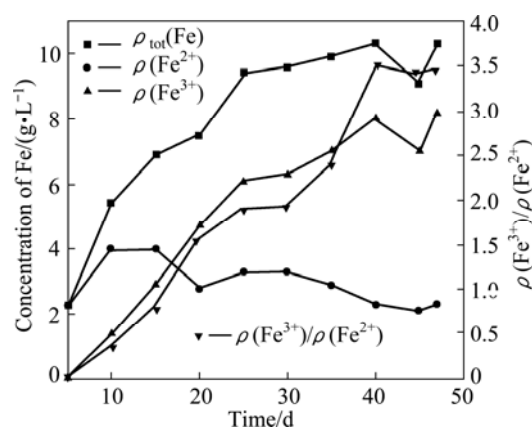


Fig. 5 Iron concentration released into solution with change of $\rho(\text{Fe}^{3+})/\rho(\text{Fe}^{2+})$ ratio and $\rho(\text{Fe}^{2+})$, $\rho(\text{Fe}^{3+})$ and $\rho_{\text{tot}}(\text{Fe})$ concentrations during bioleaching of concentrate by using mesophilic mixed culture at 30 °C

At the beginning of fresh sulphide minerals bioleaching, the ORP potential, φ_h , is very low, which corresponds to the highest concentration of ferrous iron in the leaching solution. This should not be interpreted as an ineffective situation. In fact, under these conditions, the reactor can show great bacterial activity and a high sulphide leaching rate. When the ORP potential, E_h , begins to increase, the concentrations of zinc, copper, and iron in the solution also increase. Under these conditions, the maximum increase in the ratio of $\rho(\text{Fe}^{3+})/\rho(\text{Fe}^{2+})$ over time also occurs. When the maximum value of the ORP potential, 550 mV, is reached, the highest content of metal leaching is also reached (Fig. 2), which has also been proven by some other researchers [29]. The change in the ratio of $\rho(\text{Fe}^{3+})/\rho(\text{Fe}^{2+})$ is shown in Table 5. It can be seen that the maximum value of the ions ratio reaches 3.5.

Table 5 Change in ferrous and ferric ions concentration as well as $\rho(\text{Fe}^{3+})/\rho(\text{Fe}^{2+})$ ratio at different time

Time/d	$\rho_{\text{tot}}(\text{Fe})/(\text{g}\cdot\text{L}^{-1})$	$\rho(\text{Fe}^{2+})/(\text{g}\cdot\text{L}^{-1})$	$\rho(\text{Fe}^{3+})/(\text{g}\cdot\text{L}^{-1})$	$\rho(\text{Fe}^{3+})/\rho(\text{Fe}^{2+})$
5	2.3	2.3	0	0
10	5.4	4.0	1.4	0.3
15	6.9	4.0	2.9	0.7
20	7.5	2.8	4.7	1.6
25	9.4	3.3	6.1	1.8
30	9.6	3.3	6.3	1.9
35	9.9	2.9	7	2.4
40	10.3	2.3	8	3.5
45	9.1	2.1	7	3.3
47	10.3	2.3	8.2	3.5

The solid phase content in the pulp was chosen to be 8% (w/v) because the density of the pulp must ensure the flow of CO₂ gas [4]. The experiment was conducted with particle size <10 µm. By reducing the particle size, the degree of leaching increases because the number of cells attached to the mineral increases. A particle size below 6.4 µm could have a negative impact on the microbial leaching performance [30]. If the particle size is additionally lowered, the oxygen supply would be reduced. For a larger particle size, the number of microbial attachments, and therefore the cells' ability to grow and develop, would be lower. Less metal would be exposed to leaching, which would reduce the contact between bacteria and minerals. Also, there would be a non-uniform distribution of sulphur, which is required for microbial growth [19].

The final values of zinc, copper, and iron recovery achieved by bioleaching are 89%, 83%, and 68%, respectively. Sphalerite (ZnS) has the lowest electrochemical potential and is easy to be oxidized. Chalcopyrite (CuFeS₂) has higher electrochemical potential and is more difficult to be oxidized, while oxidation of pyrite (FeS₂) is the most difficult, including bacterial oxidation [31].

3.7 Analysis of bioleaching kinetics

The fractions of zinc, copper, and iron extraction during the process of bioleaching as a function of time are presented in Fig. 6. One can see that the maximum metal leaching is achieved for a period of 40 d. When the bioleaching time exceeds 40 d, the degree of leaching does not increase any further. Since the particles are of nearly spherical shape with three equal geometric coordinates, they have the largest surface change while the process is occurring (assuming that the reaction rate is the same in all directions). Geometrical changes in this reaction type were studied by SPENCER and TOPLEY [32] using samples in which the particle radius changed linearly with time.

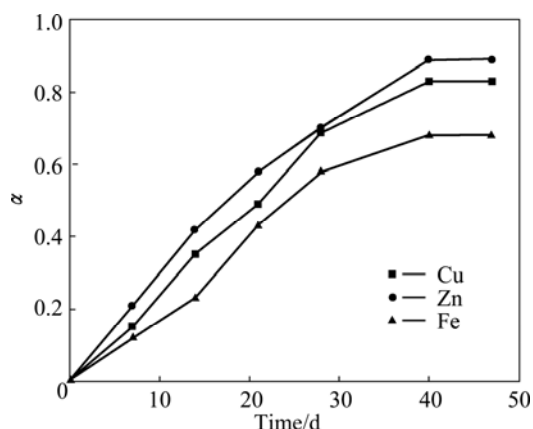


Fig. 6 Dependence of α -fraction of reacted Zn, Cu and Fe metals on time in 1 L solution at 30 °C with 8% pulp density

The usual criterion for the application of each kinetic equation in the kinetic process parameters calculation is its linearization in an appropriate coordinate system using the experimental results $\alpha=f(\tau)$. Namely, to determine the kinetic model, the leaching efficiencies $\alpha=f(\tau)$ have been introduced in equations corresponding to different possible reaction mechanisms. The best linearization was achieved by using the Spencer-Topley equation [33,34]:

$$1-(1-\alpha)^{1/2}=kt \quad (8)$$

where α is the mass fraction of metals extracted; k is the specific rate constant (s⁻¹); t is the reaction time (d).

The reaction rate is controlled by surface contact of the reactant with the product, indicating that the rate is controlled by geometry topochemical reaction.

A graphical representation of the experimental data in the coordinate system which corresponds to the Spencer-Topley equation is shown in Fig. 7.

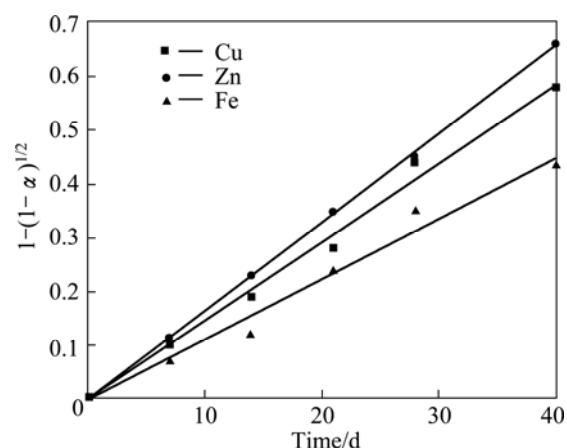


Fig. 7 Relationship between $1-(1-\alpha)^{1/2}$ and time for complex concentrate bioleaching according to data in Fig. 6

Good linearization exists for all three investigated metals. In all three cases, straight lines start from the origin of the coordinate system. The slopes of these lines correspond to the rate constants of the corresponding reactions (Table 6).

Table 6 Reaction rate constants for Cu, Zn, and Fe leaching at 30 °C

Element	k/s^{-1}
Cu	1.4×10^{-7}
Zn	1.6×10^{-7}
Fe	1.05×10^{-7}

The last measured values of α for all three metals (the last points on the curves presented in Fig. 6) are not taken into account during the linearization because saturation occurs in 40 d. By plotting the linearization it

is possible to assume that the bioleaching follows the proposed Spencer-Topley diffusion model.

The future investigation will be done with isolated culture of *Leptospirillum ferrooxidans* and *A. thiooxidans* without *A. ferrooxidans* at 40 °C. *L. ferrooxidans* has a higher affinity for Fe^{2+} than *A. ferrooxidans*. *L. ferrooxidans* can grow at stronger acidity levels and higher temperatures, whereby the percentage of the leached metals should be higher and the period of leaching time should be shorter [1,35–37]. But, it should be mentioned that the efficient microbial adaptation is usually a long-term process.

4 Conclusions

1) Mixed mesophilic bacterial culture of *A. ferrooxidans*, *A. Thiooxidans*, and *Leptospirillum ferrooxidans* is proved to be effective for leaching of a polymetallic sulphide concentrate from the Majdanpek ore body (RTB Bor, Serbia). Increasing pyrite content along with minimization of the pH leaching value minimizes jarosite precipitation.

2) Mesophilic mixed bacterial cultures can be used for bioleaching of polymetallic concentrate, whereby the efficiencies of extraction are 89% for Zn, 83% for Cu, and 68% for Fe.

3) The process of polymetallic sulphide concentrates bioleaching follows the Spencer-Topley equation for a topochemical reaction on particles in which all three dimensions are equally developed.

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多金属硫化精矿中铜、锌和铁的生物浸出

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摘 要: 利用嗜温混合菌 *Acidithiobacillus ferrooxidans*, *Acidithiobacillus thiooxidans* 和 *Leptospirillum ferrooxidans* 对低品位复杂 Cu–Zn–Pb–Fe–Ag–Au 硫化精矿在曝气生物浸出反应器中进行生物浸出。该菌种为从塞尔维亚 Bor 地下铜矿的酸性溶液中筛选出一种嗜热嗜酸菌。营养液为 pH 1.6 的 9K 营养液。87% 的矿物粒度大于 10 μm, 矿浆密度为 8%(w/v)。在测试条件下, 锌、铜和铁的浸出率分别达到 89%、83% 和 68%。动力学分析表明, 浸出过程与 Spencer-Topley 模型相符, 受局部反应扩散控制。

关键词: 生物浸出; 多金属硫化精矿; 嗜热菌; *Acidithiobacillus ferrooxidans*

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