

Article

The Impact of Pulp Temperature on the Flotation Performance of Copper-Lead-Zinc Sulphide Ore

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Abstract: Flotation performance can significantly be affected by seasonal variations due to the changes in water temperature and pulp temperature, type and concentration of dissolved ions in process water. Extreme temperature conditions could be the major factor affecting flotation performance and mask the influence of water chemistry. Therefore, the interactive effects of the temperature and water chemistry should be taken into consideration, particularly for mine sites experiencing extreme temperature conditions. In this paper, effects of temperature, sulphate (SO_4^{2-}), thiosulphate ($\text{S}_2\text{O}_3^{2-}$) and calcium (Ca^{2+}) ions on the flotation performance of a Cu-Pb-Zn complex sulfide ore were investigated using a statistical experimental design and modelling approach. The results were evaluated using ANOVA and regression analysis to determine the significant parameters and derive individual regression models for each flotation response using Design Expert software version 6.0.8. Individual regression models were developed for mass pull, water recovery, grade and recovery of the sulfide minerals using the statistically significant main effects and their interactions. The models were used to determine the concentration of the dissolved ions and pulp temperature required to achieve the maximum zinc recovery, maximum zinc grade or the optimum zinc grade and recovery. The results showed that the water chemistry (i.e., the concentrations of Ca^{2+} , SO_4^{2-} and $\text{S}_2\text{O}_3^{2-}$) affected the flotation performance significantly at low temperature (25 °C). At high pulp temperature (60 °C), however, the temperature was the dominant parameter and masked the effects of water chemistry. Details of the statistical experimental design, discussions of the effects of experimental factors and their interactions on flotation performance, and the development of regression models are presented in this paper.

Keywords: flotation; sulfide ores; water chemistry; temperature; statistical experimental design



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1. Introduction

Water reuse has become essential in mineral processing plants to minimize the use of fresh water. However, depending on the ore type and flotation chemistry, the water may be contaminated with different types of ions. It is therefore important to understand the effects of water chemistry on flotation performance, as the water quality can affect the efficiency of flotation of the desired minerals.

In the literature, there are several studies on the effect of water quality on the flotation performance of different ore types [1–10]. The effects of the major contaminating ions, such as calcium, magnesium, sulfate, thiosulfate, and residual organics are investigated using different experimental methods. The temperature of the process water is also considered to be a significant parameter affecting the dissolution and surface characteristics of minerals, water chemistry, and hence the flotation performance [11–19]. Seasonal variations and the grinding/regrinding processes can significantly change the water temperature in a process plant. The pulp temperature can reach up to 50 °C in the grinding mills and even in the flotation cells in the hot regions [9,12,15].

The water temperature affects both the pulp and froth properties in the flotation system and changes the hydrodynamics and kinetics of flotation [12–14]. The parameters that control particle-bubble interactions (except surface hydrophobicity) such as gas solubility and density, water surface tension and viscosity, bubble diameter, and rise velocity are all temperature dependent [20]. The rate of collector adsorption, hence the flotation kinetics is improved at moderate pulp temperatures (around 30–40 °C), particularly in the flotation of oxide and silicate minerals where long-chain oily collectors are generally used [13,21]. However, elevated pulp temperatures (>40 °C) may adversely affect the flotation performance through the desorption of the collector molecules from mineral surfaces, decomposition of the collector molecules, increasing dissolution of minerals, and the precipitation of sulfoxo complex species in the pulp [18,19,22]. Monde et al. [17] investigated the effect of tetrathionates on the flotation of a Cu-Pb-Zn sulfide ore at water temperatures of 25 °C and 60 °C. Chalcopyrite recovery is marginally affected by the tetrathionate ions and temperature. Chalcopyrite is the least affected mineral by water chemistry and flotation. Gonzalo and Forsenario [23,24] show that sulfate addition has a very small effect on the chalcopyrite flotation rate and recovery. On the other hand, galena and the secondary copper minerals are adversely affected by the presence of tetrathionate, sulfate ions and high temperature, due to probably higher rate of surface oxidation of these minerals. Bıcak et al. [22] showed that the pulp temperature between 20 °C and 60 °C can significantly affect the flotation performance of a Cu-Pb-Zn ore. High temperature increases the grade of bulk Cu-Pb and Zn concentrates due to reduced froth stability, i.e., lower water recovery and mass pull, and more efficient pyrite depression [23,24].

Changes in temperature in daily or seasonal (summer or winter) may influence water composition, either directly or indirectly, through chemical, physico-chemical and biological processes, e.g., mineral dissolution and oxidation, solubility of metal precipitates [12]. These processes may change water constituents in concentration and form. The pulp temperature may also affect the flotation performance through the change in mineral surface chemistry/hydrophobicity (due to mineral surface dissolution/oxidation, metal ion/hydroxide and reagent adsorption) and/or change in hydrodynamics (pulp viscosity, gas solubility, bubble size and velocity, froth stability, particle-bubble interactions). [25,26].

The pulp temperature is therefore a very important parameter when investigating the effect of water chemistry for a particular ore and plant conditions [27–29]. In this paper, the interactive effects of pulp temperature, dissolved Ca^{2+} , $\text{S}_2\text{O}_3^{2-}$ and SO_4^{2-} ions on the flotation performance were investigated using a Cu-Pb-Zn complex sulfide ore. A statistical experimental design method was used to determine the optimum experimental conditions and the results were evaluated using ANOVA analysis. Mathematical models were developed using linear regression analysis to estimate the flotation performance as a function of the pulp temperature and the dissolved ions. The main objective of this study was to develop a methodology that can be used for different types of ores and flotation plants. The mathematical models could be used to estimate the plant performance under various water chemistry and pulp temperature conditions and to develop alternative operational strategies to mitigate the negative effects of water chemistry and seasonal variations.

2. Materials and Methods

2.1. The Ore Sample

A complex copper-lead-zinc sulfide ore from a mine in the Iberian belt was used in the flotation tests. The chemical composition of the ore was given in Table 1. The ore is a massive sulfide ore with approx. 75% pyrite, 0.8% chalcopyrite, 1.2% galena, 9% sphalerite and trace amounts of secondary copper minerals and arsenopyrite. Iron oxides/carbonates and quartz are the major non-sulfide gangue minerals.

Table 1. Chemical composition of the major elements in the ore sample.

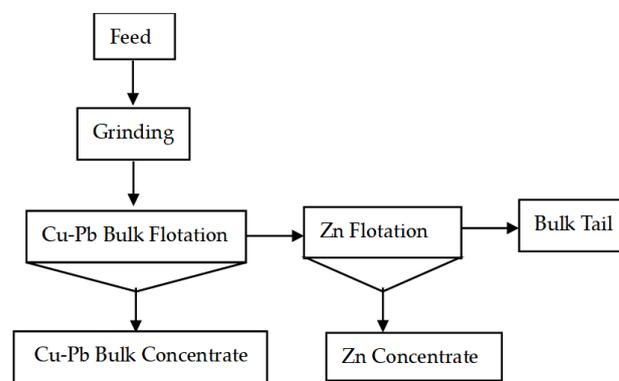
	Grade %				
	Cu	Fe	Pb	Zn	S
Ore	0.38	36.71	1.71	8.06	41.23

The ore is concentrated in a flotation plant producing a bulk Cu-Pb concentrate and a zinc concentrate. A bulk Cu-Pb concentrate is produced in the process plant due to the complex mineralogy of the copper and lead minerals. The main product of the flotation plant is the zinc concentrate. Given that effects of water chemistry and temperature were evaluated according to the performance of the zinc flotation section in this study.

A representative ore sample was taken from the feed belt of the primary grinding mill of the flotation plant. The ore sample was crushed in two stages to -2 mm by using a laboratory scale jaw crusher and a roller crusher. The crushed sample was homogenized and split into 2 kg sub-samples using a Riffle splitter. The sub-samples were packed in vacuumed bags and stored in a freezer to minimize surface oxidation of the sulfide minerals.

2.2. Flotation Tests

Batch scale rougher kinetic flotation tests were performed to investigate the influence of water chemistry and temperature on flotation performance. A bulk Cu-Pb flotation stage was applied to recover the copper and lead before the zinc flotation stage (Figure 1). The flotation conditions, i.e., reagent type and dosages and pulp pH, were similar to that used in plant scale operation. The test products were assayed for Cu, Fe, Pb and Zn using Thermo Fisher Scientific (Waltham, MA, USA) Niton XL series X-ray fluorescence (XRF).

**Figure 1.** Flowsheet of batch scale flotation tests.

The flotation tests were conducted using a modified Leeds flotation machine with 3 L cell volume. A 2 kg ore sample was used in each flotation test. The ore sample was ground to $d_{80} = 45$ μm using a ball mill with high chrome grinding media. 500 g/t sodium metabisulphite (SMBS) was used in the grinding stage to depress sphalerite and pyrite in Cu-Pb bulk flotation stage. The pulp was pre-aerated for 5 min before collector addition to simulate the hydrocyclone classification circuit of the plant and to increase the redox potential of the pulp to positive values for enhanced collector adsorption. Aero 3418A, a dithiophosphinate type of collector, was used in the experiments as copper and lead collector. After the pre-aeration, the pulp pH was measured as 6.5–7, which is the optimum range for effective depression of sphalerite and pyrite in the presence of SMBS [29]. In the zinc flotation stage, the pulp pH was increased to 9.5 with lime, and then 600 g/t copper sulfate (CuSO_4) and sodium isobutyl xanthate (SIBX) were used as activator and collector respectively. Methyl Isobutyl Carbinol (MIBC, 20 g/t) was used as the frother in both flotation stages. The condition times were 2 min for the collectors, 1 min for the frother,

10 min for the CuSO_4 . The total flotation times were 5 min in Cu-Pb flotation and 13 min in the zinc rougher flotation stage.

The pulp temperature was adjusted starting from the grinding stage using pre-heated water at the required temperature and maintained throughout the entire flotation test by heating the flotation cell. The flotation cell was wrapped with heating cable to heat the pulp and keep the pulp temperature constant.

The plant data and the previous studies on the same ore show that sulfate, thio-sulphate and calcium ions and the temperature were the major variables in the process water [3,24]. Therefore, synthetic process water samples having different concentrations of SO_4^{2-} , $\text{S}_2\text{O}_3^{2-}$, Ca^{2+} ions were prepared by using analytical grade $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, Na_2SO_4 and $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$. De-ionized water was used for preparation of the synthetic water samples. The amount of each chemical required for a given water quality was calculated and the chemicals were dissolved in a deionized water in the following order to prevent precipitation of the ions; $\text{Na}_2\text{S}_2\text{O}_3$, CaCl_2 and Na_2SO_4 . The chemical analysis of the water samples was performed by using ICP-OES (Thermo-Elemental Iris Intrepid) for the determination of the cations and Ion Chromatography (Dionex ICS-3000, ThermoFisher Scientific Waltham, MA, USA) for the determination of the anions.

The water chemistry and pulp temperature were adjusted as shown in Table 2. The range of ionic concentrations and pulp temperature were determined according to the plant data and the previous studies [3,9,24]. Effects of these parameters were tested at two levels. Factorial design with center points repeats was used for the experimental design method [18]. In the center point experiments (Exp No 17 to 20), the concentrations of the ions and temperature were taken as the average of the low and high levels. The relationship between the independent variables and observed responses were evaluated using multiple regression in Design Expert software version 6.0.8.

Table 2. The experimental design used in the flotation tests.

Exp No	Ca^{2+} (ppm)	SO_4^{2-} (ppm)	$\text{S}_2\text{O}_3^{2-}$ (ppm)	T, °C
1	300	1500	200	25
2	1000	1500	200	25
3	300	4500	200	25
4	1000	4500	200	25
5	300	1500	700	25
6	1000	1500	700	25
7	300	4500	700	25
8	1000	4500	700	25
9	300	1500	200	60
10	1000	1500	200	60
11	300	4500	200	60
12	1000	4500	200	60
13	300	1500	700	60
14	1000	1500	700	60
15	300	4500	700	60
16	1000	4500	700	60
17	650	3000	450	42.5
18	650	3000	450	42.5
19	650	3000	450	42.5
20	650	3000	450	42.5

The flotation performance was evaluated based on the mass pull, water recovery, grade and recoveries of Cu, Pb, Zn and Pyrite. The recoveries in the zinc flotation stage were calculated in reference to the feed to the zinc rougher flotation (i.e., the Cu-Pb rougher flotation tail). The water recovery and mass pull relationship are generally used to evaluate the froth stability [9,23,26].

The flotation test results were evaluated using ANOVA analysis at 95% level of confidence. To ensure the reproducibility of the results, standard deviation was calculated using the center points repeat tests (Exp No 17–20) (Table 3).

Table 3. Standard deviations of STD 17,18,19 and 20 tests (R: %Recovery, G: %Grade).

Std. Dev.	Mass Pull %	Water Rec %	Recovery (%)				Grade (%)			
			Cu	Py	Pb	Zn	Cu	Py	Pb	Zn
Zn Flotation Stage	6.55	2.32	7.26	8.81	4.29	4.63	0.03	3.63	0.18	1.90

3. Result and Discussion

3.1. Flotation Tests

Effects of process water chemistry and temperature on the performance of the zinc flotation were discussed in the paper. The test results, mass pull, water recovery, zinc grade and recovery, and pyrite recovery are illustrated in Figures 2–4 respectively. In batch flotation tests, water recovery and mass pull indicate the changes in the froth phase and froth stability. The temperature significantly affected the mass pull and hence the grade of the zinc concentrate. The mass pull was about 50%–60% at 25 °C and decreased to around 20% at 60 °C. The low mass pull at high temperature was due to the reduced pyrite recovery (Figure 4). Pyrite recovery was around 60% for most of the tests at 25 °C temperature and decreased down to 20% at high temperature regardless of water chemistry. The zinc recovery was less affected at the high temperature, but the zinc grade increased considerably (Figure 3).

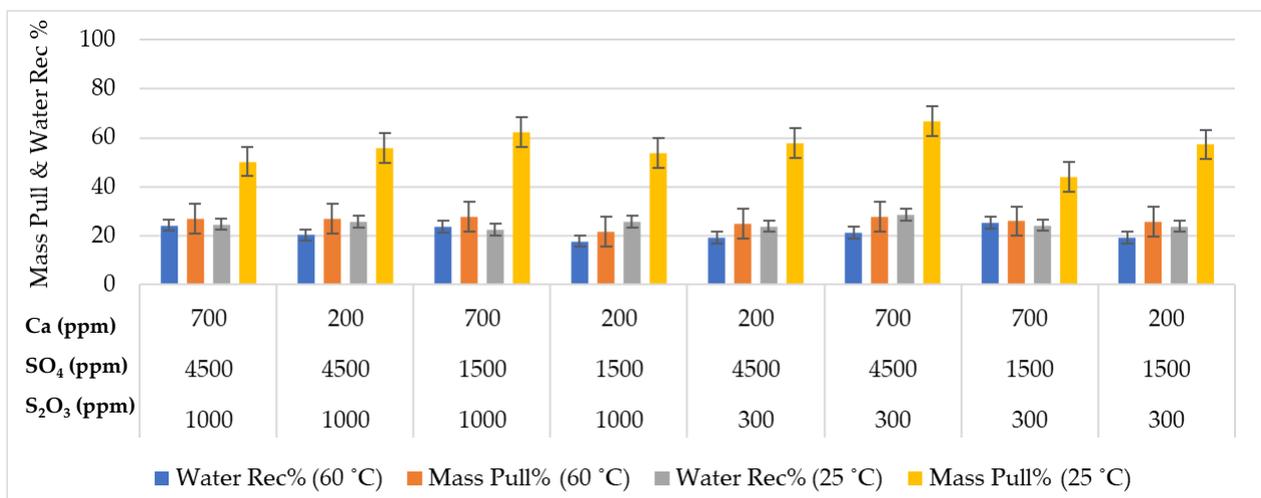


Figure 2. Effects water chemistry and pulp temperature on the water recovery and mass pull.

The pulp temperature affects both the froth stability and surface characteristics of the minerals. In general, an increase in temperature results in a decrease in the viscosity of water and water recovery, thus increasing the drainage of gangue particles in the froth phase [17]. Higher concentrate grades should be expected at high temperatures without negatively affecting the recovery. In this study, the water recovery and hence the froth stability were not significantly affected by the pulp temperature in most of the tests. The

low pyrite recovery at high temperature was therefore attributed to the reduced pyrite floatability and enhanced froth drainage characteristics.

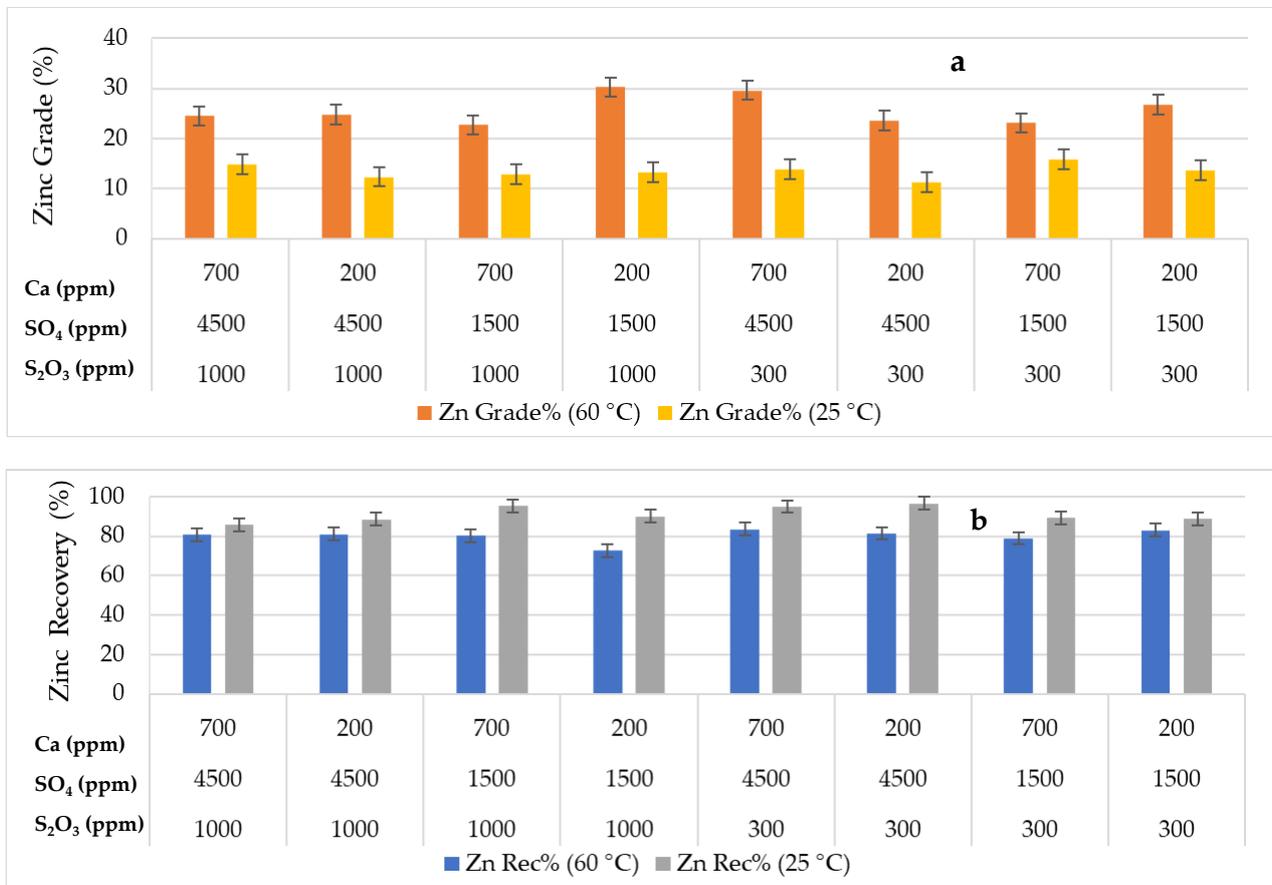


Figure 3. Effects water chemistry and pulp temperature on the zinc grade (a) and recovery (b).

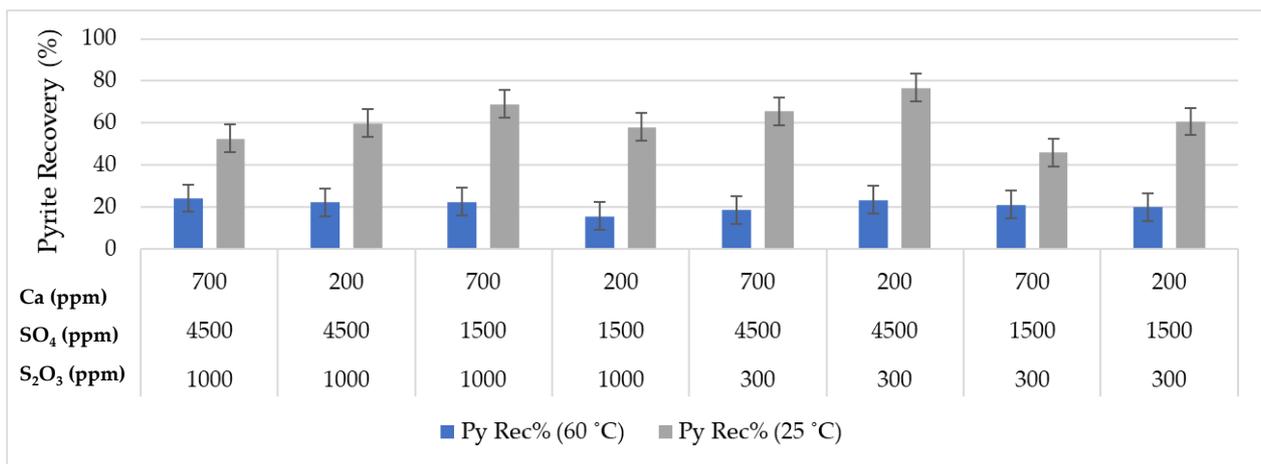


Figure 4. Effects water chemistry and pulp temperature on the pyrite recovery.

Monde et al. [18] show that temperature variation between 5 °C and 65 °C bears no effect on the decomposition of xanthate. Effects of high temperature on xanthate adsorption is considered to be mineral and ore specific. High temperature (50–60 °C) enhances xanthate adsorption on chalcopyrite, particularly at high dosages, but has a negative effect on adsorption on pentlandite. [18,27,28]. This is attributed to weaker floatability and rapid surface oxidation of pentlandite than chalcopyrite. Similar effects of high temperature

were observed between flotation recoveries of pyrite and copper activated sphalerite. Copper ions form a CuS_2 film at the surface of sphalerite particles, and they show similar flotation performance to that of chalcopyrite in the presence of xanthate [29]. Given that the sphalerite recovery was less affected than pyrite at high temperature.

The influence of water chemistry, i.e., concentration of Ca , SO_4 and S_2O_3 ions on flotation performance was clearly observed at 25 °C. The zinc grade of the concentrate was only affected by the water chemistry at 60 °C. The mass pull and zinc recovery were around 25% and 80% respectively in all the tests performed at 60 °C, except the test at high calcium concentration and low sulfate and thiosulfate concentrations (Figure 5). The low zinc recovery in this test was due to reduced froth stability, i.e., low water recovery and mass pull.

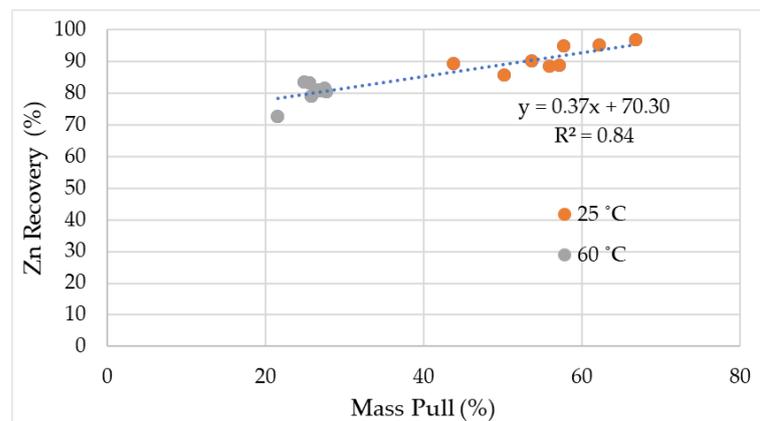


Figure 5. Zinc recovery as a function of mass pull at 25 °C and 60 °C.

Figure 5 shows the zinc recovery as a function of mass pull. The water chemistry had a stronger influence on the mass pull and hence zinc grade and recovery at low temperature. The mass pull varied between 44% and 67%. The large variation in the mass pull affected the zinc grade and recovery (Figure 6). The lowest mass pull was obtained in the presence of high thiosulfate concentration, which depresses pyrite effectively. The zinc recovery was not affected significantly in this test, but in the test with the highest concentrations of calcium, sulfate and thiosulfate, high ion concentration may enhance formation of colloidal calcium-sulfoxy compounds on mineral surfaces [18].

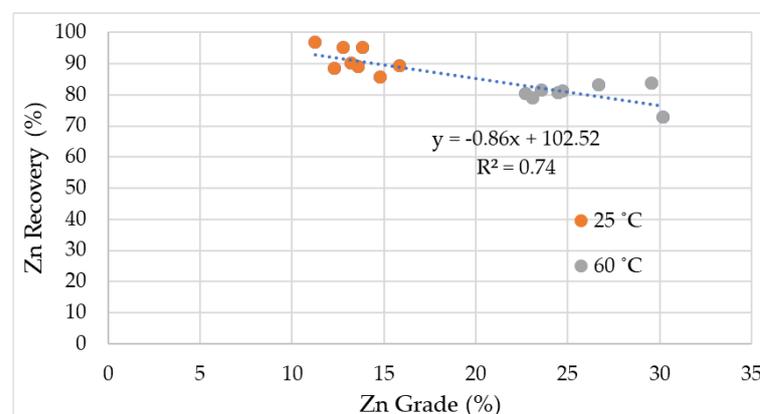


Figure 6. Grade vs. recovery of zinc at 25 °C and 60 °C.

3.2. Statistical Evaluation of the Effects of Flotation Temperature and Anion Concentrations on Flotation Performance

Effects of dissolved ions (Ca^{2+} , SO_4^{2-} , $\text{S}_2\text{O}_3^{2-}$) and temperature on flotation performance were statistically evaluated using Design Expert 6.0.8 software. The significance of

each parameter on mass pull, water recovery, recovery and grade of copper, zinc, lead and pyrite was evaluated using ANOVA analysis at 95% level of confidence.

Table 4 shows a typical regression model for the zinc recovery using all the variables and their interactions. Model F-value of 2.09 implies the model is not significant relative to the noise. There is a 29.82% chance that a “Model F-Value” could occur due to noise. “Prob > F” values of less than 0.05 indicate that model terms are significant. In this case, D (Temperature) was the only significant model term for zinc recovery. There were some model parameters and interaction effects with “Prob > F” values between 0.05 and 0.10. Therefore, 90% level of confidence was used to include more parameters for the model development to increase the prediction power of the models. In spite of that there were many insignificant model terms (not counting those required to support hierarchy), and hence model reduction was performed to improve the models.

Table 4. Effects of main parameters and Anova Results for Zinc Recovery.

Source	Sum of		Mean		F	
	Squares	DF	Square	Value	Prob > F	
Model	670.4361	15	44.69574	2.088397	0.2982	not significant
A (Ca ²⁺)	32.48389	1	32.48389	1.517802	0.3057	
B (SO ₄ ²⁻)	12.22862	1	12.22862	0.571379	0.5046	
C (S ₂ O ₃ ²⁻)	0.269591	1	0.269591	0.012597	0.9177	
D (T)	480.6573	1	480.6573	22.45859	0.0178	
AB	22.03202	1	22.03202	1.029441	0.3850	
AC	18.69274	1	18.69274	0.873414	0.4190	
AD	0.216075	1	0.216075	0.010096	0.9263	
BC	16.19368	1	16.19368	0.756646	0.4484	
BD	5.351833	1	5.351833	0.250063	0.6514	
CD	0.003898	1	0.003898	0.000182	0.9901	
ABC	15.94497	1	15.94497	0.745025	0.4515	
ABD	57.93601	1	57.93601	2.707045	0.1985	
ACD	6.192822	1	6.192822	0.289358	0.6280	
BCD	1.088195	1	1.088195	0.050846	0.8361	
ABCD	1.144502	1	1.144502	0.053477	0.8320	
Curvature	0.1776	1	0.1776	0.008298	0.9332	not significant

The same ANOVA analysis was done for all of the flotation responses. Table 5 shows the *p*-values for goodness of fit of the regression models. The bold numbers show the significant model parameters. The temperature was a significant parameter for all the flotation responses. Interaction of the different parameters significantly affected the water recovery, copper, lead and zinc grades of the concentrate and the copper recovery.

The model reduction studies were performed according to the values given in Table 5. The parameters having >0.10 values were not included in the model development. However, it must be noted that the main effects which were not significant but exist in the interaction effects were also included as part of hierarchical regression analysis in the model development.

The model reduction studies performed on the copper recovery (RCu) is given below as an example. D and ABD were significant effects for copper recovery (Table 5). Although A and B and their interaction effects were not significant, they had to be included in the model development as described above. According to the ANOVA results of the reduced model given in Table 6, the reduced model is significant.

Table 5. The *p*-values of the model parameters of the flotation responses.

Factor	Prob > F Value for Zn Circuit									
	Mass Pull	Water Rec	R Cu	R Pb	R Zn	R Py	GCu	GPb	GZn	GPy
Model	0.0790	0.3930	0.1949	0.3045	0.2982	0.0807	0.0078	0.0057	0.0308	0.0997
A (Ca²⁺)	0.8752	0.9342	0.4905	0.5798	0.3057	0.8383	0.7085	0.1520	0.7872	0.8673
B (SO₄²⁻)	0.5151	0.5945	0.6854	0.9329	0.5046	0.4529	0.5413	0.1382	0.6688	0.6077
C (S₂O₃²⁻)	0.7266	0.3816	0.8813	0.3105	0.9177	0.8557	0.1561	0.0467	0.2610	0.3733
D (temp)	0.0027	0.0541	0.0099	0.0223	0.0178	0.0028	0.0003	0.0002	0.0010	0.0035
AB	0.3344	0.6130	0.6559	0.4349	0.3850	0.3073	0.0448	0.5785	0.8419	0.9817
AC	0.3501	0.9013	0.3463	0.1852	0.4190	0.4216	0.0494	0.6438	0.9098	0.8175
AD	0.9286	0.7989	0.5175	0.6200	0.9263	0.7779	0.7460	0.5615	0.9402	0.9697
BC	0.6381	0.4114	0.5550	0.9675	0.4484	0.6833	0.1544	0.0851	0.3630	0.7585
BD	0.7734	0.4862	0.8931	0.5826	0.6514	0.7564	0.1765	0.9520	0.7206	0.9319
CD	0.3521	0.0619	0.9301	0.3376	0.9901	0.3672	0.0072	0.1204	0.0499	0.2173
ABC	0.3801	0.3796	0.7707	0.4936	0.4515	0.4518	0.3025	0.0706	0.2051	0.8884
ABD	0.2561	0.3879	0.0810	0.1789	0.1985	0.2004	0.0432	0.5757	0.1974	0.2625
ACD	0.4689	0.8758	0.9640	0.7989	0.6280	0.4998	0.0782	0.1582	0.5839	0.6370
BCD	0.8268	0.7722	0.3466	0.6831	0.8361	0.7295	0.2560	0.4710	0.8409	0.7427
ABCD	0.7212	0.6299	0.9056	0.7214	0.8320	0.7290	0.8522	0.1497	0.4207	0.8674
Curvature	0.4593	0.9888	0.6371	0.5217	0.9332	0.4083	0.0520	0.1109	0.8607	0.6861

Table 6. Analysis of variance of table for the reduced model of the copper recovery.

Source	F Value	Prob > F	
Model	11.02631	0.0003	significant
A	1.110743	0.3145	
B	0.360981	0.5601	
D	62.11856	<0.0001	
AB	0.439635	0.5210	
AD	0.967917	0.3463	
BD	0.038665	0.8477	
ABD	12.14763	0.0051	
Curvature	0.495192	0.4962	not significant

Standard deviation, mean, predicted and adjusted R squared values which show the consistency of the model are summarized in Table 7. “Adeq Precision” measures the signal to noise ratio, and a ratio greater than 4 is desirable. The reduced model has an adequate precision value of 9.7. Therefore, the model given in terms of actual factors in Equation (1) can be used to calculate the copper recovery in the zinc flotation section. Figure 7 shows the comparison of the actual vs. predicted copper recovery values calculated using Equation (1). The predictive power of the model is statistically satisfactory and can be used to navigate the design.

Table 7. Standard Deviation and Sum of Square of Copper Recovery for reduced model.

Std. Dev.	5.393149	R-Squared	0.875261
Mean	61.44702	Adj R-Squared	0.795882
Pred R-Squared	0.639887	Adeq Precision	9.705738

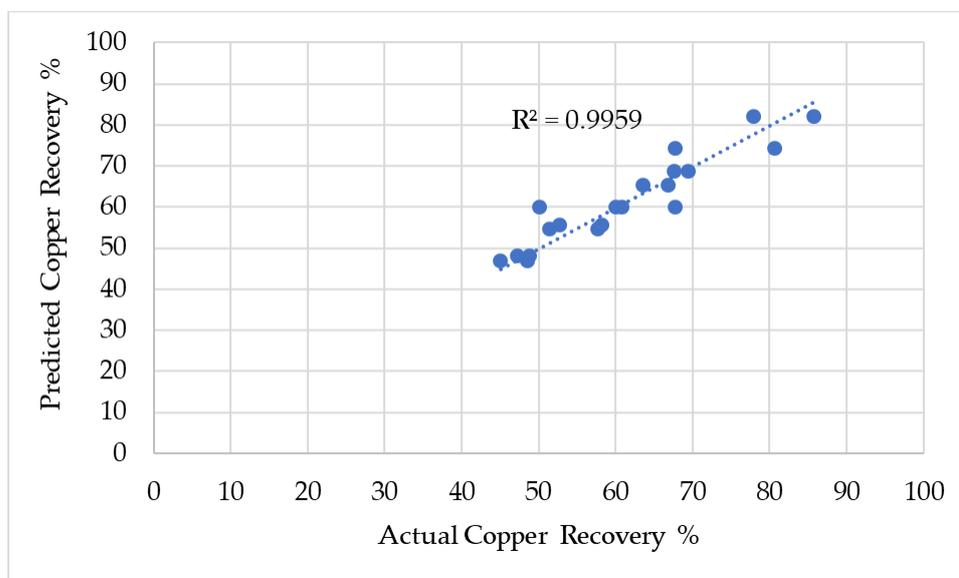


Figure 7. The actual vs. predicted copper recovery calculated using Equation (1).

$$RCu = 47.68 + 0.06A + 0.016B + 0.28D - 2.3 \times 10^{-5}AB - 1.3 \times 10^{-3}AD - 3.4 \times 10^{-4}BD + 5.11 \times 10^{-7}ABD \quad (1)$$

Similar model reduction studies were performed to develop statistically significant models for all the flotation parameters. Table 8 shows the *p*-values of the model parameters, the correlation coefficient (*R*²) and the precision values of the reduced models. All the reduced models are significant with the selected effects and can be used for optimization studies.

Table 8. The *p*-values of the reduced models.

Prob > F Values of the Reduced Models										
Factor	Mass Pull	Water Rec	R Cu	R Pb	R Zn	R Py	GCu	GPb	GZn	GPy
Model	<0.0001	0.0003	0.0003	0.0002	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
A (Ca ²⁺)	-	-	0.3145	-	-	-	0.7854	0.1658	-	-
B (SO ₄ ²⁻)	-	-	0.5601	-	-	-	0.6505	0.1472	-	-
C (S ₂ O ₃ ²⁻)	-	0.1762	-	-	-	-	0.2331	0.0284	0.1322	-
D (temp)	<0.0001	0.0007	<0.0001	0.0002	<0.0001	0.0001	<0.0001	<0.0001	<0.0001	<0.0001
AB	-	-	0.5210	-	-	-	0.0522	0.6375	-	-
AC	-	-	-	-	-	-	0.0599	0.6970	-	-
AD	-	-	0.3463	-	-	-	0.8140	-	-	-
BC	-	-	-	-	-	-	-	0.0755	-	-
BD	-	-	0.8477	-	-	-	0.2624	-	-	-
CD	-	0.0011	-	-	-	-	0.0020	-	0.0023	-
ABC	-	-	-	-	-	-	-	0.0568	-	-
ABD	-	-	0.0051	-	-	-	0.0496	-	-	-
ACD	-	-	-	-	-	-	-	-	-	-
BCD	-	-	-	-	-	-	-	-	-	-
ABCD	-	-	-	-	-	-	-	-	-	-
R ²	0.88	0.71	0.88	0.56	0.65	0.87	0.96	0.94	0.94	0.88
Adeq Precision	14.27	8.32	9.71	6.06	7.32	13.96	13.94	18.44	18.44	14.69

The coefficients of the equations based on actual factors are given in Table 9. Since the values of the main effects are large (e.g., SO_4^{2-} ranges between 1500 ppm and 4500 ppm), the equations have relatively small coefficient numbers. The coefficient numbers show that the mass pull and water recovery decrease with increasing the temperature, indicating lower froth stability and more selective flotation. Hence, copper, lead and zinc grade of the concentrate increases at high pulp temperatures. Calcium and sulfate ions increase the copper recovery and grade of copper and lead in the zinc rougher concentrate. The zinc recovery is negatively affected by high pulp temperature, presumably due to lower mass pull, but the zinc grade increases. Most of the ore sample is pyrite, and it is depressed effectively at high pulp temperatures. This was attributed to improved froth drainage and faster pyrite oxidation at high temperature.

Table 9. Coefficient Estimates of the reduced models for all the flotation responses.

Factor	Coefficient Estimates									
	Mass Pull	Water Rec	R Cu	R Pb	R Zn	R Py	GCu	GPb	GZn	GPy
Intercept	77.50	33.73	47.683	74.763	98.94	89.637	−0.076	−0.2473	−0.651	74.8
A-Ca			0.0571				7×10^{-5}	1.2×10^{-3}		
B-SO4			0.0162				3×10^{-5}	4.4×10^{-5}		
C-S2O3		−0.014					2×10^{-4}	1.7×10^{-4}	0.012	
D-T	−0.86	−0.276	0.28	−0.27	−0.31	−1.15	0.016	0.06	0.50	−0.44
AB			-2×10^{-5}				-7×10^{-8}	-4×10^{-7}		
AC							3×10^{-7}	-3×10^{-6}		
AD			−0.001				-8×10^{-6}			
BC								-3×10^{-7}		
BD			-3×10^{-4}				-1×10^{-6}			
CD		3.9×10^{-4}					-1×10^{-5}		-3×10^{-4}	
ABC								9.5×10^{-10}		
ABD			5×10^{-7}				3×10^{-9}			

The models are now available to determine the operating conditions for specific targets, such as the maximum zinc recovery, or zinc grade or both. Table 10 shows the values of the main effects to achieve the target grade and recovery values. Mass pull, water recovery and grade and recoveries of the copper, lead and pyrite are also calculated but not included in the table due to space restrictions. The maximum zinc grade could be obtained at the highest temperature and calcium, moderate sulfate and minimum thiosulfate ion concentrations tested in this work. For maximum zinc recovery, the temperature should be reduced to 25 °C. The models suggest that the optimum zinc grade and recovery are 24.77% Zn and 82.35% respectively and they could be obtained at about 53 °C, moderate calcium, high sulfate and low thiosulfate concentrations. The models can also be used to predict the zinc grade and recovery for a given temperature and water chemistry.

Table 10. The zinc grade and recovery calculated under different concentrations of ions and temperature using the reduced models.

Target	Ca ²⁺ (ppm)	SO ₄ ^{2−} (ppm)	S ₂ O ₃ ^{2−} (ppm)	T (°C)	RZn	GZn
Max. GZn	977.86	1944.52	200.00	60.00	80.15	27.81
Max. RZn	851.17	1779.56	494.58	25.00	91.11	13.62
Optimum RZn & GZn	493.53	3685.57	200.00	52.99	82.35	24.77
Moderate Temp.	359.80	1678.92	200.00	42.50	85.63	20.22

4. Conclusions

Effects of process water chemistry (Ca^{2+} , SO_4^{2-} , $\text{S}_2\text{O}_3^{2-}$) and temperature on the zinc flotation performance of a Cu-Pb-Zn complex sulfide were investigated by using a statistical experimental design and modelling approach. The results were evaluated to derive individual regression models for each flotation response.

The results showed that the pulp temperature was the most effective parameter affecting the flotation performance. Copper, lead and zinc grade of the concentrate increases at high pulp temperatures. Pyrite is depressed effectively at high pulp temperatures. This may have attributed to improved froth drainage and faster pyrite oxidation at high temperature. At higher temperature, the zinc grade increased due to better pyrite depression and froth drainage characteristics resulted in lower mass pull. Influence of the dissolved ions (Ca^{2+} , $\text{S}_2\text{O}_3^{2-}$ and SO_4^{2-}) on the flotation performance was masked at 60 °C pulp temperature.

Individual regression models were developed using the statistically significant main effects and their interactions for each flotation response. Then, the models were used to determine the concentration of the dissolved ions and pulp temperature required to achieve the maximum zinc recovery, maximum zinc grade or the optimum zinc grade and recovery. This approach could effectively be used to predict effects of the changes in water chemistry and pulp temperature in a flotation plant and provide a guidance to the plant metallurgist for better control of water chemistry and seasonal variations.

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