

Research Article

Gold Recovery from Cyanide-Based Leach Solutions Using Zinc Cementation: A Case of Small-scale Gold Mining in Zimbabwe

Rachiel Bvurire¹ , Kupakwashe Lindsay Mahamba² , Yemurai Vengesa¹ , Sharrydon Bright¹ , Hlanganipai Ngarivume^{3,*} 

¹Department of Mining, University of Zimbabwe, Harare, Zimbabwe

²Department of Metallurgical Engineering, Gwanda State University, Filabusi, Zimbabwe

³Department of Metallurgy, Zimbabwe School of Mines, Bulawayo, Zimbabwe

Abstract

The small-scale gold mining sector (SSGM) in Zimbabwe is a significant contributor to the country's economy, at 12% of total exports. Although official output figures are rising, the general belief is that most of the small-scale gold production is unaccounted for, as it only reports gold produced from amalgamation and carbon adsorption, which the Government monitors through Statutory Instruments. However, gold produced from unregulated methods often ends up in illicit gold trading, with Zinc cementation being one of the unregulated gold recovery methods that small-scale gold miners rampantly abuse due to its ease of filtration and low cost. Governing legislation or Statutory Instruments for control of Zinc cementation are non-existent, creating easy loopholes for abuse and strong links to illicit financial flows. This study investigates the feasibility of regularising Zinc cementation as a gold recovery method for small-scale operations in Zimbabwe, ensuring effective monitoring and surveillance. Optimum parameters for Zinc cementation were determined experimentally. The determination of optimum parameters for Zinc cementation was done using a 2³ fractional factorial design and gold deportment analysis was conducted using samples from a small-scale gold mine located on the early Precambrian, Bulawayan, andesitic and dacitic meta-volcanic geological formation in Zimbabwe's Matabeleland mining region. The influence of free cyanide concentration, dissolved oxygen concentration and pH on gold recovery was evaluated. Experimental work showed the feasibility of using Zinc Cementation as a possible recovery route for gold in SSGM with optimum parameters of: - pH value 11.5, free cyanide concentration 0.05g/L and dissolved oxygen concentration of 0.5ppm. The analysis showed that pH and Oxygen concentration increase gold recovery by a factor of 40%, with pH having the most significant effect on gold recovery. The study concludes that Zinc Cementation for small-scale hydrometallurgical gold extraction is an effective recovery method and should be regularised by the Government through a Statutory Instrument for easier monitoring and surveillance. Further studies on various ores from different provinces are recommended to incorporate diverse mineralogical differences into the design. Additionally, setting up a pilot plant to refine the metallurgical plant requirements for controlling zinc cementation is suggested.

Keywords

Zinc Cementation, Gold, Cyanide, Leaching, Small-scale Mining

*Corresponding author: hngarivume@gmail.com (Hlanganipai Ngarivume)

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1. Introduction

Twenty to thirty million of the world's poorest population receive employment and income from the small-scale gold mining (SSGM) sector worldwide, which employs ten times as many people as large-scale mining and sustains the lifestyles of five times as many. In recent years, Zimbabwe's SSGM industry has grown to be one of the nation's economic pillars and a significant source of revenue [1]. The industry has grown significantly in importance to the President's goal of making Zimbabwe an up-per-middle-income country by 2030, with the SSGM industry contributing about 12% of the total exports. More than half of the nation's gold deliveries are now accounted for by the small-scale mining sector. Due to Zimbabwe's geology, some deposits cannot be economically mined by large conglomerates. Therefore, the government, through the Minister of Mines and Mining Development (MMMD), is prioritising small-scale mining operations to increase the country's mineral production.

In recent years, the country has witnessed a decline in gold deliveries to Fidelity Gold Refinery (FGR), particularly from the small-scale mining sector. Gold deliveries in September 2020 fell by 73% to close at 1.36 tonnes compared to 2.8 tonnes for the same period the previous year [1]. Although official production figures have been rising, it is generally believed that the majority of SSGM production remains unaccounted for, resulting in significantly understated official output figures. Smuggling is believed to be responsible for approximately 50% of the losses in small-scale gold production [2-4].

According to the stipulated legal flowsheet for gold production, only carbon adsorption and electrowinning (elution) are required for gold recovery processes following ore leaching. Although there are other contributors to the reduced gold declarations, the Zinc cementation process is a significant route used in Zimbabwe for illegal bullion trading, resulting in the country losing expected revenue from gold mining.

This study investigates the feasibility of regularising Zinc cementation as a gold recovery method for small-scale operations in Zimbabwe, aiming to ensure effective monitoring and surveillance by determining the optimum parameters for Zinc cementation suitable for hydrometallurgical small-scale gold extraction.

The Zinc Cementation method is typically applied to solutions obtained from heap leaching, solid-liquid separation steps following grinding and leaching, from carbon stripping eluates, as well as solutions obtained through intensive cyanidation. Cementation (i.e., reductive precipitation), a conventional recovery process whereby Au ions are reduced to metallic Au via electron transfer, can be employed by using zero-valent base metals (i.e., cementing agents) [5]. The Merrill-Crowe process is still applicable for some specialized metallurgical applications despite the potentially higher cap-

ital and operating expenses [6].

The following key phases follow leaching/cyanidation in the Merrill-Crowe Process [7]:

- 1) Solid-liquid separation using vacuum filtration or counter-current decantation thickeners.
- 2) Increasing the pregnant leach solution's clarity to about 1ppm solids.
- 3) The cleared solution is de-aerated using tightly packed Crowe towers while under vacuum.
- 4) Using a mixing cone, powdered Zinc or Zinc shavings are added.
- 5) The pipeline facilitates precipitation between the press feed pumps and filter presses.
- 6) Filtering the metals that have precipitated in a filter press.
- 7) Dore formation in the refinery after smelting.

Depending on how much mercury and base metals are present in the product, it may be calcined, retorted or dried before being refined [6, 8, 9].

The schematic reaction mechanism for Zn cementation is illustrated in Figure 1.

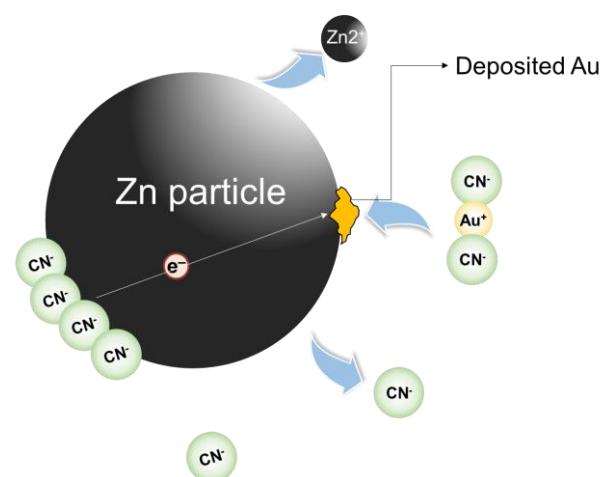
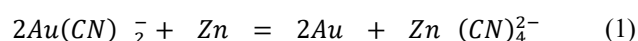


Figure 1. Schematic representation of the mechanism of Zn Cementation [7].

The following overall response is a representation of how gold is reduced by Zn metal:



The effectiveness of Zn dissolution in the filtered pregnant leach solution determines how well precious metals are cemented. In the absence of sufficient free cyanide and the presence of dissolved oxygen, Zn will dissolve on its own and occasionally generate Zn hydroxide, which passivates Zn surfaces and clogs filters.

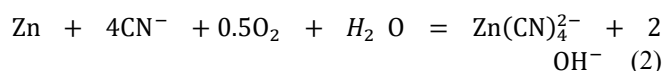
The pH of the pregnant solution significantly affects the redox potential, which changes from positive to negative with increasing alkalinity. This may be advantageous if the cementation reaction's rate is not totally controlled by diffusion [10]. According to studies, gold cementation is essentially steady between pH values of 8 and 11; however, increasing the pH to a range of 11.5 to 11.9 results in a noticeable improvement.

The high cost of chemicals is one of the most significant difficulties in the cementation stage. Zn passivation is a detrimental effect caused by the decrease in cyanide concentration. When this happens, the process's regulating step might be altered, and more Zn powder will need to be added to bring the gold cementation up to par [11]. In reality, the cementation rate is only affected by the free cyanide concentration if it falls below a minimum specific value that is based on the gold concentration and pH [8].

Because the reaction for oxygen reduction competes with the gold reduction, the presence of dissolved oxygen in the clarified solution lowers the precipitation kinetics and efficiency. The effect becomes noticeable in diluted Aurro-cyanide solutions at ambient temperatures, as those used in Zn cementation, when the concentration of dissolved oxygen rises above 0.5 to 1.0 mg/L. Therefore, to lower dissolved

oxygen before precipitation, solutions must be deaerated. It has been suggested that inefficient removal of oxygen in the vacuum deaeration tower is a significant problem in many Merrill-Crowe systems, resulting in excessive Zn consumption under these conditions. Research has shown that as the level of oxygen is increased, especially at higher concentrations of cyanide, the solubility of Zn is substantially increased. In fact, about 50% of the Zn is dissolved when 0.5 mg/l Oxygen and 0.5 g/l NaCN are present [12].

The relevant chemical reaction is:



2. Materials and Methods

The sampling procedure involved selecting quantities of the test material at a designated plant in Matabeleland North, Zimbabwe, to evaluate the bulk material. Rotary splitting was employed to obtain a homogeneous sample. The samples were dried and weighed, then subjected to various analyses outlined in Table 1 below.

Table 1. Summary of metallurgical test work.

Testwork	Process	Laboratory Equipment
Gold deportment Analysis	Particle size distribution, Fire Assay and AAS finish	Dickie & Stockler Laboratory Pulveriser ME 137
Gold Head Grade Determination	Fire assay with AAS finish	Analytic Jena Nova 800 Analyser
Ore Characterisation	X-Ray Diffraction	XRD-Bruker D2 Phaser (2 nd Gen) Diffract Commander
Elemental Analysis	X-Ray Fluorescence	Niton Innov X XRF Analyser
Leachability Tests	Bottle Roll	Analytic Jena Nova 800 Analyser, Bottle Roller
Zinc Cementation Testwork	Zinc Cementation	Reactor vessel (schematic shown)

As presented in Table 2, all reagents used in the study were analysed for purity, and distilled water was used as the solvent.

Table 2. Reagents for Zn cementation experiments.

Material	Source
Zn dust	Reditek Industrial
Reagent-grade NaCN	Pipeline Marketing
Reagent-grade NaOH	Pipeline marketing
Reagent-grade Lime	Reditek Industrial

Material	Source
Reagent-grade PbNO ₃	Pipeline marketing
Distilled water	Pipeline marketing
Reagent-grade Sodium sulfide	Pipeline marketing

To simulate the Merrill-Crowe Process, the experimental tests were conducted by utilising the experimental device schematised in Figure 2 below:

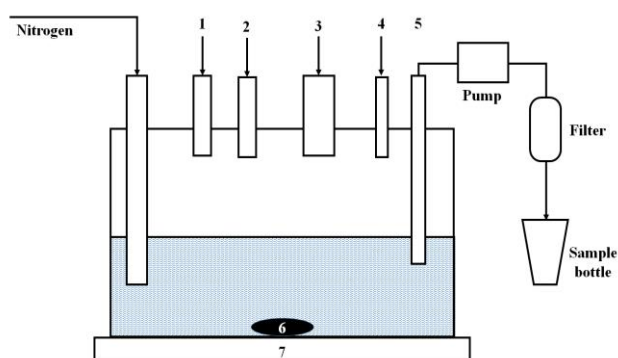


Figure 2. Schematic of experimental device for Zn Cementation.

The device was mainly composed of: -

- 1 = transfer tube for adding Zinc
- 2 = transfer tube for adding Pb(NO₃)₂ and Sodium Sulfide
- 3 = oxygen meter probe
- 4 = tube for air escaping
- 5 = glass tube for solution withdrawal
- 6 = magnetic follower
- 7 = magnetic stirrer
- 8 = gas dispersion tube/vacuum.

For each experimental run, 500ml of pregnant leach solution was added to the reactor vessel, and the vacuum pump was connected for 2 hours to remove oxygen (de-aeration). Sodium sulfide was immediately added to the holding vessel. Thereafter, Zn dust and lead nitrate were added to the reaction vessel. The magnetic stirrer was kept at around 240 rpm at room temperature and pressure. Aliquots were extracted at

3-hour intervals over 12 hours and analysed for gold values using AAS.

Tables 3 and 4 show the details of the 2³ fractional factorial experimental design, which was utilised to analyse the effect of:

- 1) Cyanide concentration,
- 2) Dissolved Oxygen concentration, and
- 3) pH on the gold recovered from Zn cementation.

Factorial designs are used to analyse the effects of different factors on a process's optimisation. It establishes which variables have the most significant impacts on the answer, as well as how the effect of one variable varies with the amount of the other variables [13]. Reduced experimentation was employed to achieve optimal overall process optimization using a factorial design, which provides greater accuracy in calculating the significant factor impacts and interactions of various factors. The regression analysis, statistical computations, and optimization calculations were performed using Minitab® Statistical Software. Table 3 shows the uncoded values for the three factors at 2 levels (high and low).

Table 3. Independent variable experimental ranges and levels.

Levels	pH	[O ₂] (ppm)	[CN ⁻] (ppm)
-1	10.5	0.5	0.05
1	11.5	2	0.2

Table 4 presents the 2³ fractional factorial experimental design generated by Minitab with uncoded units and centre points.

Table 4. 2³ Fractional factorial design (with centre points, actual experimental values).

StdOrder	RunOrder	CenterPt	Blocks	pH	[CN ⁻]/g/L	[O ₂]/mg/L
5	1	0	1	11	0.2	1.25
1	2	1	1	10.5	0.05	2
4	3	1	1	11.5	0.2	2
7	4	0	1	11.5	0.125	1.25

StdOrder	RunOrder	CenterPt	Blocks	pH	[CN ⁻]/g/L	[O ₂]/mg/L
3	5	1	1	10.5	0.2	0.5
2	6	1	1	11.5	0.05	0.5
6	7	0	1	11	0.125	2
8	8	0	1	11	0.125	1.25

The parameters in Table 5 remained constant throughout the experimental runs.

Table 5. Constant Parameters for Zn Cementation [6].

Parameter	Specification
Zn concentration	2 grams/Litre
Temperature	25°C
Lead Nitrate	1ppm
Sodium sulfide	5g/dm ³
Time	12 hours with sampling at 3-hour intervals

3. Results

In ASM, recoveries from gravity concentration (amalgamation) and leaching are usually less than optimum due to failure to determine the particle size that brings about sufficient liberation of the mineral particle. In this research, gold deportment analysis was carried out, and the results are presented in Figure 3.

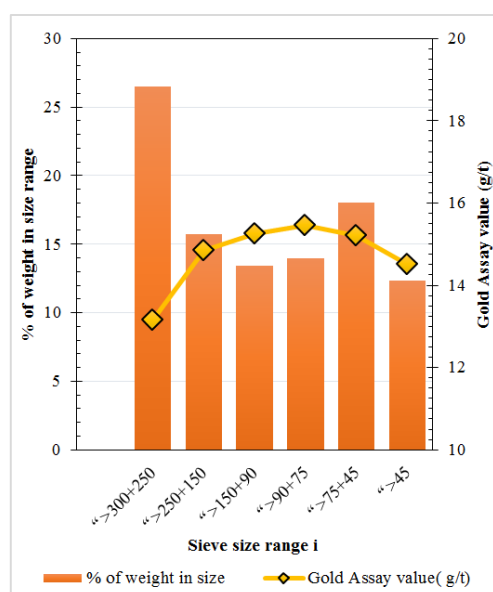


Figure 3. Gold Deportment Analysis.

The highest assay value (15.5g/t) was found at the aperture size of 75µm. However, as shown in Figure 3, the sample was too coarse, as over 26% of the sample was retained on the 250µm sieve. Control steps to remedy this are to further grind before leaching and subsequent Zn cementation to obtain optimum metal recoveries and prevent metal losses.

It can be observed from Figure 3 that 80% of the sample was >260µm, showing the need for further grinding to ensure sufficient liberation of the gold in downstream processes.

3.1. Gold Head Grade Determination (Fire Assay with AAS Finish)

For the determination of the head grade, a fire assay was conducted using a Lamcast fusion furnace with an AAS finish, and the results are presented in Figure 3. The head grade of the sample was determined to be 16.05g/t.

3.2. Leachability Tests (Bottle Roll)

Amenability of the ore to leaching was tested using the bottle roll technique to simulate the leaching process. A residence time of 48 hours was used to ensure effective leaching, after which 99.87% gold was recovered. This concurs with literature on free milling ores, where over 95 % can be recovered using conventional cyanidation [8].

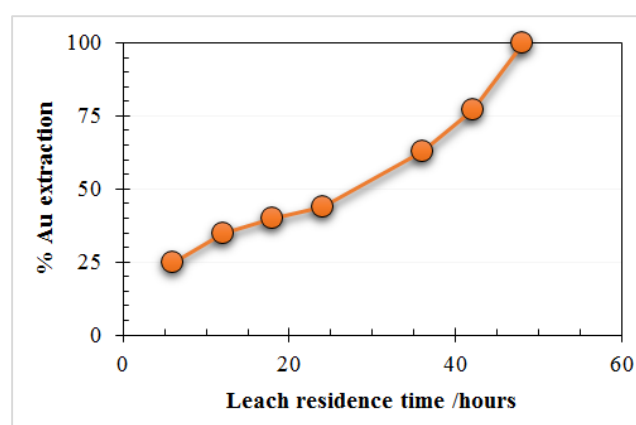


Figure 4. Leachability Tests: Gold leaching profile [7].

3.3. Ore Characterisation (X-Ray Diffraction)

The XRD Bruker Diffract Commander was used to determine the mineralogical characterisation of the ore. Figure 5 shows the results, where Quartz (SiO_2) was the predominant mineral in the sample, indicating that this was a free milling

ore, which is an ore where approximately 95% can be extracted by leaching/ cyanidation when the ore is pulverised to a P80 of $75\mu\text{m}$, without incurring prohibitive reagent cost and consumption [7]. Albite was also detected in the sample, but the aluminium and sodium in the mineral did not seem to have any adverse effect on the leachability of the sample.

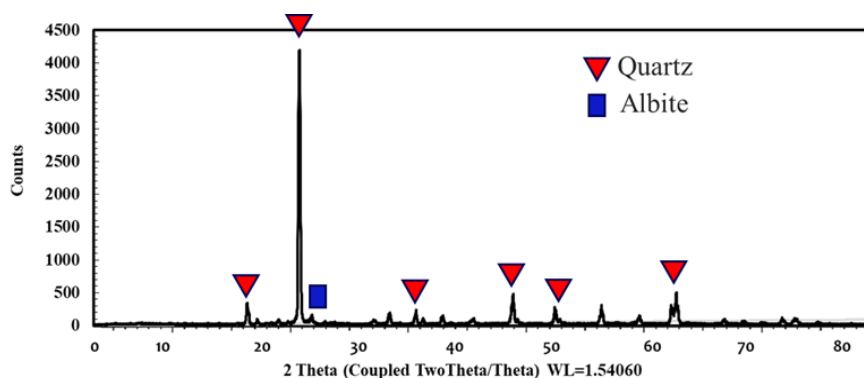


Figure 5. Mineralogical Characterisation with XRD.

3.4. Elemental Analysis (X-Ray Fluorescence)

To obtain the elemental compositions, a representative sample was analysed at a local laboratory, and the results are tabulated in Table 6.

Table 6. Elemental analysis of the ore sample.

Element	Concentration	Units
Si	11.4	%
Fe	1.7	%
Ca	1.1	%
As	8	ppm
Cr	51	ppm
Co	5	ppm
Cu	39	ppm
K	8313	ppm
Mn	159	ppm
Ni	48	ppm
Pb	28	ppm
Sb	330	ppm
Sn	190	ppm
Sr	56	ppm
Ti	709	ppm
V	22	ppm

Element	Concentration	Units
Zr	100	ppm

The results showed that this was a silica-based sample, concurring with XRD results. No other element showed concentrations which could be detrimental to gold recovery through leaching and Zn cementation, such as Sulphur, Arsenic, Antimony, Copper, or Iron [8].

3.5. Zinc Cementation Testwork with 23 Fractional Factorial Design

The initial pH values and concentrations for dissolved Oxygen and free cyanide in the testwork were chosen in alignment with the Pourbaix diagrams for cyanidation to avoid the passivation challenge [8]. The goal was to identify the conditions that resulted in the highest gold recovery without causing operational challenges. The results from the factorial experiments were analysed using Minitab® Statistical Software.

The design summary is shown, showing the confounding of the main effects and the design generators as well as centre points in Figure 6 where:

A = pH

B = Free cyanide concentration

C = Dissolved Oxygen concentration

* NOTE * Some main effects are confounded with two-way interactions.

Design Generators: C = AB

Design Summary

Factors: 3 Base Design: 3, 4 Resolution: III
 Runs: 7 Replicates: 1 Fraction: 1/2
 Blocks: 1 Center pts (total): 3

Alias Structure

I + ABC
 A + BC
 B + AC
 C + AB

Figure 6. Design Summary.

Table 7 shows the standard deviation of the residuals (S), which is 2.473, indicating that the data was more spread out in the experimental work. The R-sq value of 98.38% represents the proportion of variation in the response that the experimental model can explain, also known as the coefficient of determination. The remaining 1.62% of variation cannot be explained by the model and is considered random. The adjusted R-sq (R-sq (adj)) of 95.14% is the modified R-sq value preferred by statisticians. The difference between R-sq and R-sq (adj) is only 3.24%, with a significant difference suggesting the presence of insignificant factors in the model. The predictability of the model for new observations was not

evaluated in this case; therefore, R-sq (pred) was not provided.

Table 7. Model Summary.

S	R-sq	R-sq (adj)	R-sq (pred)
2.47300	98.38%	95.14%	*

Table 8 presents the percentage of gold recovered from the Zn Cementation process, along with the fits and residuals. It can be observed that the highest cementation was obtained at high pH, as indicated by the centre point values for free cyanide and dissolved oxygen concentrations. Fits are the values predicted using the model or regression equations. The residuals refer to the differences between the observed and fitted values.

Table 8. Results of the Fractional Design, Including Fits and Residuals.

RunOrd	CentPt	pH	[Free Cyanide]	[Oxygen]	Au (%)	FITS1	RESI1
1	0	11	0.2	1.25	75.09	75.943	-0.853
2	1	10.5	0.05	2	69.3	69.3	0
3	1	11.5	0.2	2	68.26	68.26	0
4	0	11.5	0.125	1.25	84.01	84.01	0
5	1	10.5	0.2	0.5	48.88	48.88	0
6	1	11.5	0.05	0.5	78.73	75.943	2.7867
7	0	11	0.125	2	74.01	75.943	-1.933

The regression equation in uncoded units is presented herein:

$$\text{Gold Recovered}(\%) = -106.8 + 17.05\text{pH} + 1.56[\text{Oxygen}] - 120.6[\text{Free Cyanide}] + 8.33\text{CentPt} \quad (3)$$

This is the model that Minitab® used to predict the response for several settings of the factors.

The factorial regression table presented in Table 9 shows

the effects of the 3 factors being examined at a 95% confidence level ($\alpha = 0.05$). In coded coefficients, the values in the “effect” column show the magnitude of main effects and interactions on gold recovered by Zn Cementation. It can be observed that pH has the most significant effect, at 17.05, followed by dissolved Oxygen concentration, with an impact of 2.33. Free Cyanide concentration has an adverse effect of -18.08.

Table 9. Factorial Regression Table- Coded Coefficients.

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
Const		67.61	1.24	54.68	0.000	

Term	Effect	Coef	SE Coef	T-Value	P-Value	VIF
pH	17.05	8.52	1.24	6.89	0.020	1.00
[O ₂]	2.33	1.17	1.24	0.94	0.445	1.00
[CN ⁻]	-18.08	-9.04	1.24	-7.31	0.018	1.00
Ct Pt		8.33	1.89	4.41	0.048	1.00

However, pH has a corresponding p-value of 0.02, which is less than α (0.05), as well as the Free Cyanide concentration with a p-value of 0.018. This indicates that the 2 factors are considered significant at a 95% Confidence level. The dissolved oxygen concentration has a corresponding p-value of 0.445, which is greater than 0.05, indicating that it is not considered a significant effect at a 95% Confidence level.

The standard error of coefficients (SE Coef) is small for all factors, showing that the estimates of the coefficients are

precise. The T-values are the values of the t-distribution for each factor. In this case, the larger t-values indicate a more substantial possibility that the effects are statistically significant, with corresponding smaller p-values [14]. The variance inflation factor (VIF) is low, with a value of 1, indicating independence between the factors and no correlation. A value of 10 or more would have demonstrated the need to omit one of the factors due to correlation.

3.5.1. Analysis of Variance (ANOVA)

Table 10. Analysis of Variance (ANOVA).

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	4	742.028	185.507	30.33	0.032
Linear	3	623.051	207.684	33.96	0.029
pH	1	290.532	290.532	47.51	0.020
[O ₂]	1	5.452	5.452	0.89	0.445
[CN ⁻]	1	327.067	327.067	53.48	0.018
Curv	1	118.976	118.976	19.45	0.048
Error	2	12.231	6.116		
Total	6	754.259			

Table 10 summarises the Analysis of variance (ANOVA) for the experiment, which uses the F-distribution to calculate p-values [14]. As there are 7 total experimental runs, the total degrees of freedom are 6. Each effect has one degree of freedom. The p-values are the same as those for the factorial regression table, indicating that pH and free cyanide concentration are significant factors in the model. The model sum of squares is calculated from the equation, which is in coded units:

$$SS_{Model} = SSA + SSB + SSC + SS_{curvature} + SS_{error} = 754.259 \quad (4)$$

By plotting the data means for the 2-level design to examine how the factors influence the response of gold recovered and whether the variables interact, a cube plot (Figure 6) was generated. The corner points of the cube plot represent the average re-sponses for each corner. The highest yields are obtained at various levels of the 3 factors as shown in the cube plot [14].

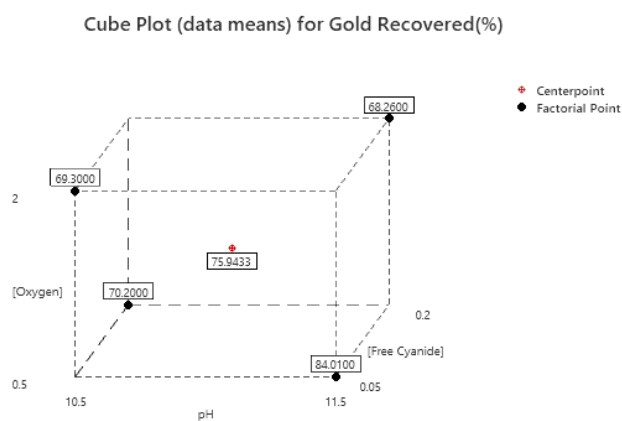


Figure 7. Cube plot for gold recovered.

3.5.2. Normal Plots of Standardised Effects

The normal probability plot of standardised effects is presented in Fig 7. In this plot, points that do not cluster closely around the line typically indicate significant effects. Unimportant effects tend to be smaller and placed around zero.

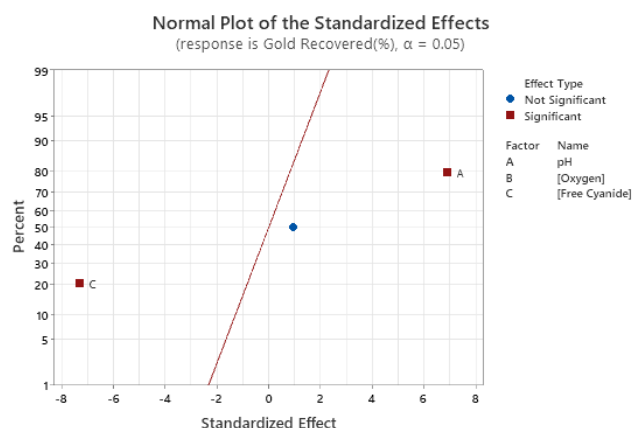


Figure 8. Normal Plot of Standardised Effects.

Regarding gold recovery, it is shown that factors A and C, marked in red, lie away from the straight line, indicating that they are significant at a 95% Confidence Level. Factor B lies close to the line and is not significant at this level of significance. Hence, pH and Free Cyanide concentration are the most critical factors affecting gold recovery using Zn Cementation. This concurs with the p-values in Table 10, which are 0.05.

3.5.3. Pareto Chart of Standardised Effects

The Pareto chart in Figure 8 was used to further analyse the effects of the factors from the Normal plot by determining the magnitude and importance of their impact on gold recovery using Zn Cementation. The Pareto chart displays the absolute value of the impact and draws a reference line (t-value limit), indicating the 95% confidence interval (CI). Any effect that

extends past the t-value limit is potentially significant.

In this case, the t-value limit is 4.303. Effects A and C were higher than this t-value limit at $\alpha = 0.05$, implying they are significant factors in Zn Cementation. Factor B had a t-value lower than the limit and was deemed insignificant at this stage. The p-values for Factor A and C were relatively lower than α .

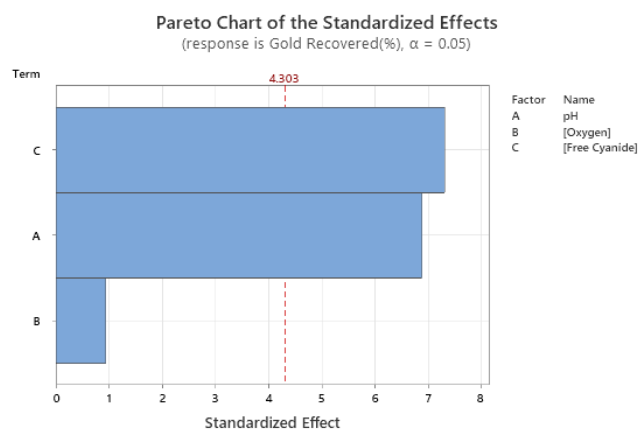


Figure 9. Pareto Chart of Standardised Effects.

3.5.4. Residual Plots

Figure 9 shows four graphs: a standard probability plot for residuals, a plot of residuals versus predicted values (fits), as well as histograms and plots of residuals versus observation numbers. All plots are satisfactory with a few outliers.

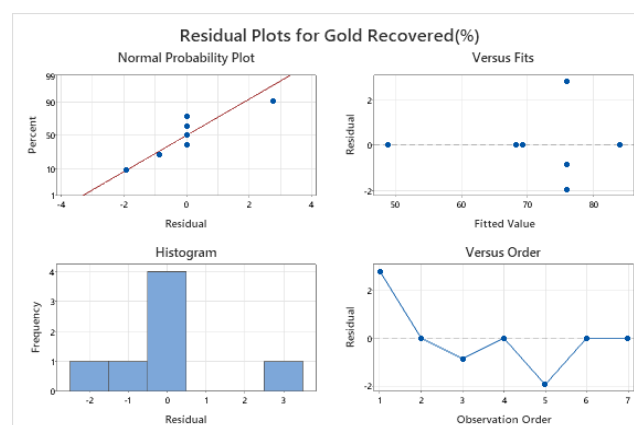


Figure 10. Residual Plots for Gold Recovered.

3.5.5. Main Effects Plot

The main effects of every factor on gold recovered were established by ANOVA. The main effects plot in Figure 10 helps visualize the 3 factors that affect the response, in this case, the gold recovered from Zn cementation. At a 95% confidence level, pH and Oxygen concentration have a positive effect on gold recovery. pH was found to have the highest impact on gold recovery, followed by dissolved Oxygen

concentration. Free cyanide has a negative effect on the gold recovery, concurring with the literature [8, 7, 12].

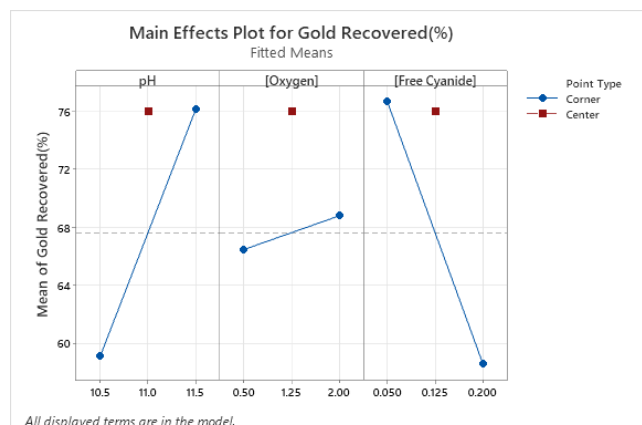


Figure 11. Main Effects Plot.

3.5.6. Interaction Plot for Gold Recovered

An interaction plot details the impact of changing the settings of one variable on another [15]. The interactions in the study were examined through the interaction plots in Figure 11. There was no interaction between pH and free cyanide concentration as the lines were parallel to each other. The interaction between dissolved oxygen concentration and pH was strong, as the lines were not parallel to each other [14]. It can be observed that the interaction between Oxygen and free cyanide is very strong, as shown by the converging lines in the plot. However, the plots showed that the 3 variables need to be optimised separately, as not all interactions occur at high levels.

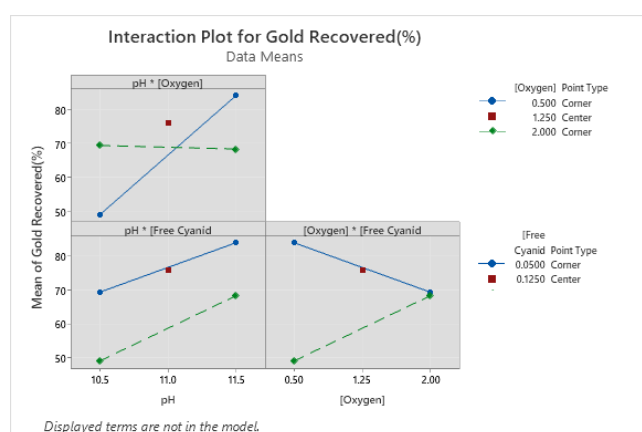


Figure 12. Interaction Plot for the effects on [CN⁻], pH and [O₂] on gold recovered.

3.5.7. Factorial Surface Plots

The regression model in Equation 1 was used to generate contour and response surface plots [15]. The response surface

plots in Figures 12, 13, and 14 provide a 3-3 dimensional view of the response surface [15]. The plots are very useful for optimising the response and will assist in modelling the equipment design. As shown, the responses have a curvature, which arises from the interaction between the selected factors in question.

Surface Plot of Gold Recovered(%) vs [Oxygen], [Free Cyanide]

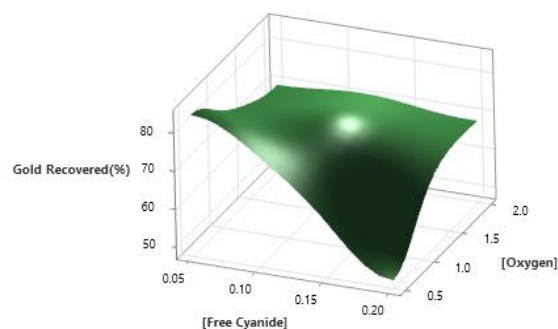


Figure 13. Surface plot of Gold Recovered vs [O₂], [CN⁻].

Figure 12 shows that the interaction between dissolved oxygen and free cyanide concentration causes the plane to twist, re-sulting in curvature of the response surfaces. Low free cyanide concentration and low dissolved Oxygen levels bring the highest cementation of gold on Zn [12].

The interaction at high pH level and low [Oxygen] level brings about the highest cementation of gold, concurring with the literature [8, 7].

Surface Plot of Gold Recovered(%) vs pH, [Oxygen]

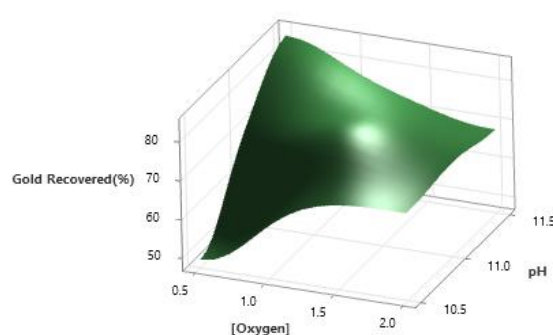


Figure 14. Surface Plot of gold recovered vs pH, [O₂].

It can be observed from Figure 13 that the interaction of dissolved oxygen and free cyanide concentration resulted in the lowest cementation at high levels of free cyanide and low pH levels. This is because passivation of Zn surfaces occurs

from the formation of Zn Hydroxide and inhibits the cementation of gold [11, 6].

Surface Plot of Gold Recovered(%) vs pH, [Free Cyanide]

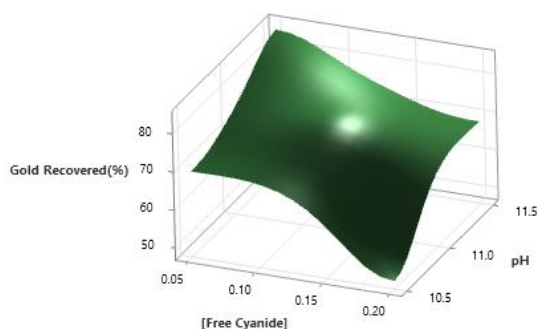


Figure 15. Surface Plot of Gold Recovered vs pH, [CN⁻].

Minitab® therefore enabled the design of the fractional factorial experiment, as well as the analysis of the results from the experimental design using various methods. It can be observed clearly that there is a need to optimise the responses to obtain higher values of gold recovered at a 95% confidence level, as literature and plant data have shown that recoveries as high as 95% can be achieved in Zn Cementation [9].

All parameters for leaching and milling will be maintained as in literature [8].

4. Conclusions

The following conclusions were drawn from the study:

- 1) Experimental work showed the feasibility of using Zn Cementation as a possible recovery route for gold in SSGM with optimum parameters of: - pH at 11.5, free cyanide - 0.05g/L, and dissolved oxygen concentration of 0.5 ppm.
- 2) These parameters can be recommended for small-scale mining operations.
- 3) Regularising Zinc Cementation for effective monitoring and surveillance is possible in Zimbabwe.

Abbreviations

SSGM	Small-scale Gold Mining
ppm	Parts per Million
MMMD	Ministry of Mines and Mining Development
FGR	Fidelity Gold Refinery
Zn	Zinc
AAS	Atomic Absorption Spectrophotometry
XRF	X-Ray Fluorescence
XRD	X-Ray Diffraction
CtPt	Centre Point

DF	Degrees of Freedom
Adj SS	Adjusted sum of squares
Adj MS	Adjusted Mean Squares
F-value	Ratio of variance between sample means to the variance within samples
P-value	probability of observing sample data as extreme or more extreme than what was actually measured assuming the null hypothesis is true

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Author Contributions

Hlanganipai Ngarivume: Funding acquisition, Methodology, Software, Writing – review & editing

Rachiel Bvurire: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Software, Writing – original draft, Writing – review & editing

Kupakwashe Lindsay Mahamba: Formal Analysis, Writing – review & editing

Yemurai Vengesa: Formal Analysis, Supervision

Sharrydon Bright: Formal Analysis, Methodology, Supervision, Writing – review & editing

Funding

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Zimbabwe School of Mines (Business Development and Innovation Department)

Data Availability Statement

The data sets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Conflicts of Interest

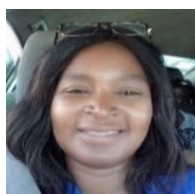
The Authors declare no conflicts of interest.

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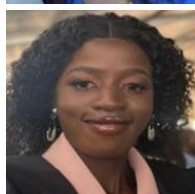
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Biography



Rachiel Bvurire is a Principal Metallurgical Engineer with the Ministry of Mines and Mining Development, Zimbabwe. She completed her Master's degree in Advanced Mineral Processing and Extractive Metallurgy from the University of Zimbabwe in 2023. Rachiel is passionate about small-scale mining in the country and is a keynote speaker for several events on environmental awareness, climate change, skills transfer, knowledge sharing, and technical capacitation of Small-scale miners. She is also an Australia Awards Alumni, with a certificate in Mining Governance from the University of Queensland.



Kupakwashe Lindsay Mahamba is a Senior Lecturer at the Department of Metallurgical Engineering, Midlands State University, Zimbabwe. She completed her Master's degree in Advanced Mineral Processing and Extractive Metallurgy from the University of Zimbabwe in 2023. Previously, she chaired the Department of Metallurgical Engineering at Gwanda State University, Zimbabwe. Kupakwashe is an enthusiastic researcher who has written articles on Hydrometallurgy. She is currently studying the Brimms course with the University of British Columbia.

Yemurai Vengesa is a senior lecturer at the University of Zimbabwe, Mining, Chemical, and Metallurgy Department, and the Electrical Engineering Department. She completed his PhD in Materials Engineering from Bu Ali Sina University in 2022, and her Master of Engineering in Materials Engineering from the University of Science and Technology Houari Boumediene in 2013.



Sharrydon Bright is a metallurgical engineering professional with a diverse background in academia, research, and industry. Possesses over 12 years of experience with a strong technical foundation in metallurgical engineering and mineral processing. He is a dedicated and innovative researcher passionate about developing sustainable and safe mineral processing methods, with a focus on reducing carbon emissions and promoting environmentally responsible practices. He completed his Master of Engineering degree from Hokkaido University, Japan, in 2021 and is a member of The Minerals, Metals & Materials Society (TMS).



Hlanganipai Ngarivume is an experienced metallurgical engineer with over 15 years of experience. He has worked as a process engineer, metallurgy process auditor, tailings dump evaluation consultant and metallurgy lecturer. Hlanganipai was the lead engineer for several projects, including the auger drilling sampling campaigns of How Mine's old tailings dumps (2021) and Freda Rebecca's old tailings dumps (2020). He has conducted training of plant operators, attendants and supervisors with companies such as Anglo-American Platinum (Unki Mine) and Metallon Gold Zimbabwe (How Mine). Currently, he is the head of the metallurgy department at the Zimbabwe School of Mines.

Research Field

Rachiel Bvurire: Mineral Processing, Hydrometallurgy, Pyrometallurgy, Mining legislation, Electrometallurgy, Process Simulation, Environmental Conscious Manufacturing

Kupakwashe Lindsay Mahamba: Mineral Processing, Hydrometallurgy, Electrometallurgy, Process Simulation, Environmental Conscious Manufacturing

Yemurai Vengesa: Mineral Processing, Materials Engineering, Nanotechnology

Sharrydon Bright: Mineral Processing, Hydrometallurgy, Electrometallurgy, Pyrometallurgy, Critical Metals Recovery, Process Simulation, Carbon footprint reduction in mining

Hlanganipai Ngarivume: Mineral Processing, Hydrometallurgy, Electrometallurgy, Process Simulation, Environmental Conscious Manufacturing, Plant Design