

Time-Dependent Effects of Grind Fineness on Gold Cyanidation Kinetics and Extraction

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Abstract

Finer grinding is commonly expected to improve gold cyanidation, but its effect over the full leaching cycle remains insufficiently understood. This exploratory study compared 48-h bottle-roll cyanidation of a low-sulfidation epithermal gold ore ground to 80% and 90% passing 75 μm (P80 and P90), using an initial sodium cyanide (NaCN) concentration of 1500 mg/L. A diagnostic leach test indicated that 89.0% of the gold was operationally cyanide-accessible. P90 required approximately 51% longer laboratory grinding time and produced faster early extraction than P80 (71.0% vs. 49.8% at 2 h), but this advantage diminished over time. At 48 h, P80 reached 94.0% extraction compared with 92.1% for P90, a small difference that should be interpreted cautiously given the 9.55% closure bias of the P90 mass balance. Model comparison using the small-sample corrected Akaike information criterion (AICc) most strongly supported the Crundwell-Godorr model for P80 and the Mintek model for P90. The results suggest that finer grinding mainly shifted gold extraction toward the early stage of leaching rather than increasing the extraction achieved within 48 h. A finer grind thus appears most useful when leach residence time is short. Replicated testing is required to confirm these single-run findings.

Keywords: Gold Cyanidation, Grind Fineness, Leaching Residence Time, Leaching Kinetics, Diagnostic Leach Test

INTRODUCTION

Cyanidation remains widely used for gold recovery, and feed particle size is an important operational variable because finer grinding generally increases surface area and can accelerate gold dissolution. However, faster dissolution does not necessarily result in higher extraction within a given leaching period, because gold accessibility can also depend on mineral association and liberation (Costa et al., 2022; Maganga et al., 2023).

Many previous studies have focused on endpoint recovery or individual kinetic parameters (Sari & Prayuditha, 2025; Habibah et al., 2025). Time-resolved grind studies are also available (Section II), but few have combined extraction-time profiles with size-by-size assays, diagnostic leaching, and model comparison for the same ore.

Finer grinding requires more comminution effort, and leaching residence time is limited by process capacity, so the benefit of finer grinding may be better judged over the whole leaching cycle than at a single endpoint.

The ore investigated in this study is a low-sulfidation epithermal (LSE) gold ore. LSE deposits are commonly associated with quartz-rich veins and relatively low sulfide contents (Simmons et al., 2005; White & Hedenquist, 1995; Hedenquist et al., 2000). Because no deposit-scale mineralogical

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characterization is available for the material investigated here, its cyanidation behavior is characterized operationally using diagnostic leach testing (DLT; Section IV.A).

The P₈₀ 75 µm target (80% passing 75 µm) is a reference grind commonly used in conventional carbon-in-leach/carbon-in-pulp (CIL/CIP) circuits treating free-milling ores, whereas P₉₀ 75 µm (90% passing 75 µm) is a finer alternative achievable with the same mill. Both this reference grind and the 48-h leaching period, which covers the upper end of typical industrial leach residence times (12-48 h), are consistent with common CIL/CIP practice (Marsden & House, 2006; Amwele & Groot, 2018).

This study compared bottle-roll cyanidation of the same ore ground to P₈₀ and P₉₀ 75 µm, with an initial NaCN concentration of 1500 mg/L chosen to keep cyanide non-limiting (Section III). The objective was to determine whether finer grinding provides a consistent extraction benefit or mainly changes the timing of gold extraction. The study combines time-resolved extraction profiles with feed size-by-size Au distribution, diagnostic leaching, and comparative kinetic modeling for the same ore to examine how grind fineness affects both extraction timing and the extraction reached within the tested leaching period.

LITERATURE REVIEW

Cyanidation of gold involves the formation of soluble aurocyanide complexes through the Elsner reaction, $4\text{Au} + 8\text{CN}^- + \text{O}_2 + 2\text{H}_2\text{O} \rightarrow 4[\text{Au}(\text{CN})_2]^- + 4\text{OH}^-$, and requires free cyanide and dissolved oxygen under alkaline conditions, typically at pH ≥ 10.5 (Marsden & House, 2006; Medina & Anderson, 2020). Particle size is an important variable affecting cyanidation kinetics (Sari & Prayuditha, 2025; Habibah et al., 2025), and bottle-roll testing provides a controlled bench-scale approach for evaluating leaching behavior (Sarempa & Isjudarto, 2016).

However, endpoint extraction alone cannot distinguish faster dissolution from differences in extraction achieved within the tested residence time. Ellis & Senanayake (2004) reported that a moderate grind (P₈₀ 45 µm) gave the highest gold dissolution during the first 2-8 h, whereas NaCN consumption increased markedly below P₈₀ 75 µm. Egan et al. (2016) found that gold dissolution increased with decreasing particle size. These findings are not fully consistent, because a finer grind can accelerate dissolution without improving final extraction.

Celep et al. (2025) found that grinding from d₈₀ 55 to 28 µm sped up gold dissolution during the first 8 h but lowered extraction after 24 h, which they attributed to greater sulfide reactivity, preg-robbing, and sulfide-ion passivation of gold surfaces at the finer size. Niu et al. (2025) reported that a 2.8% increase in the -38 µm fraction raised recovery by only 0.3%, while the grinding conditions strongly affected cyanide consumption.

Grind-size effects also depend on both liberation, controlled mainly by comminution, and cyanide accessibility, which is affected by mineral association and surface condition. Size-by-size assays provide information on the distribution of gold across particle-size classes (Egan et al., 2016), while DLT provides an operational estimate of gold accessibility and deportment through sequential selective dissolution (Guner et al., 2023). A previous study of an LSE ore from Mount Muro reported approximately 80% cyanide-accessible Au at P₈₀ $\approx$ 75 µm (Frideni et al., 2026).

The shrinking-core model (SCM) represents idealized regimes of film diffusion, product-layer diffusion, and surface reaction for a reacting particle population (Levenspiel, 1999; Dixon & Hendrix, 1993). Alternative formulations include the Two-Fraction model, which represents fast- and slow-reacting fractions (De Andrade Lima & Hodouin, 2005), the Mintek model (Wadnerkar et al., 2015), the mixed-potential Crundwell-Godorr model, and the Loveday model, which represents a continuous distribution of reactivity (Crundwell & Godorr, 1997; Loveday, 1975).

Candidate models can be compared using the small-sample corrected Akaike information criterion (AICc), ΔAICc , and Akaike weights (Burnham & Anderson, 2002). Such comparisons can

describe differences in extraction-curve behavior, but model fit alone does not establish a unique physical mechanism. Recent kinetic studies also report biphasic dissolution, with rapid early extraction followed by a slower stage in which the apparent controlling regime shifts ([Roostaei et al., 2026](#)).

RESEARCH METHOD

Two grind targets, P_{80} 75 μm and P_{90} 75 μm , were prepared from a common homogenized ore and evaluated by bottle-roll cyanidation at a matched initial NaCN concentration of 1500 mg/L (Table 1). This concentration was chosen to keep cyanide non-limiting, so that the baseline response to grind fineness could be observed; because it exceeds typical CIL/CIP levels, the results describe grind effects under cyanide-excess conditions.

Table 1. Summary of research methodology

Aspect	Procedure
Ore and sample preparation	A 35-kg ore sample was dried at 105 °C, crushed to -2 mm, homogenized for 4 h, and split for feed characterization, grind-size establishment, leaching (approximately 2.2 kg per test), and head assay.
Feed size-by-size assay	A split of the crushed (-2 mm) feed was dry-screened into 11 size fractions (+600 to <20 μm), and each fraction was assayed for Au to characterize gold distribution across particle-size classes before grinding.
Diagnostic leach test (DLT)	A single six-stage sequential DLT was performed on a head sample pulverized to P_{95} 75 μm , using 1000 mg/L NaCN and 24-h cyanide stages: CN1 (free), HCl + CN2 (carbonate), SnCl_2/HCl + CN3 (hematite/iron oxide), HNO_3 + CN4 (arsenopyrite), aqua regia (pyrite), and fire assay of the final residue (silicate). The ore supplier-specified protocol follows Lorenzen (1995) . Fine pulverization minimizes incomplete liberation, allowing residual gold to be interpreted in terms of operational mineralogical associations (Coetzee et al., 2011 ; Saba et al., 2011).
Grind-size establishment	A laboratory rod mill (26 cm long $\times$ 21 cm in diameter) produced P_{80} 75 μm after 21 min 48 s and P_{90} 75 μm after 32 min 58 s.
Bottle-roll leaching	Bottle-roll testing, a widely used bench-scale cyanidation test (Cetin et al., 2017 ; Sarempa & Isjudarto, 2016), was conducted in a 30 cm $\times$ 20 cm bottle rotating at 90 rpm, with 2.18- 2.24 kg of dry ore at 40% solids (w/w), pH maintained at 10.5-11.0, and an initial NaCN concentration of 1500 mg/L for 48 h. Lime and NaCN were added as required, and pH, dissolved oxygen (DO), free cyanide, and Au were monitored at 2, 4, 8, 24, and 48 h. Residues were filtered, dried, homogenized, split, and fire-assayed.
Head grade and analytical measurements	Triplicate head assays gave 2.20 g/t Au. Back-calculated heads were 2.17 g/t for P_{80} and 2.41 g/t for P_{90} , corresponding to closure biases of 1.36% and 9.55%, respectively. Gold extraction was calculated from the cumulative Au in solution relative to the total Au accounted for by the solution and final residue. A commercial laboratory analyzed solids by fire assay and solutions by atomic absorption spectrometry (AAS); its internal QA/QC records were unavailable.
Kinetic modeling	Seven kinetic formulations were fitted to each extraction series: three

	SCM variants (film diffusion, product-layer diffusion, and surface chemical reaction), Two-Fraction, Mintek, Loveday, and Crundwell-Godorr. Models were compared using R^2 , RMSE, MAE, AIC, Δ AIC, and Akaike weights (Burnham & Anderson, 2002).
Statistical treatment	Descriptive statistics were used where applicable. No inferential tests were performed because each grind target was tested in a single run.

FINDINGS AND DISCUSSION

Feed Characteristics, Gold Accessibility, and Grind Fineness

The crushed (-2 mm) feed was characterized before grinding by dry screening into 11 size fractions and assaying each fraction for Au. Au grade varied with particle size (Figure 1). The <45 μm fractions contained 3.08-3.25 g/t Au, about 1.7 times the weighted feed grade of 1.86 g/t, and the 106-150 μm fraction had the lowest grade (0.62 times the weighted grade).

The +600 μm fraction made up about 55% of the feed mass and held 49.7% of the Au at 1.69 g/t. Thus, nearly half of the Au in the crushed feed was associated with the coarse fraction, while the finest fractions were relatively rich in Au.

The weighted grade from the size-by-size assay was about 15% below the measured head grade (2.20 g/t), suggesting some sample heterogeneity (Section IV.D). These data describe the crushed feed only, not the P_{80} or P_{90} products.

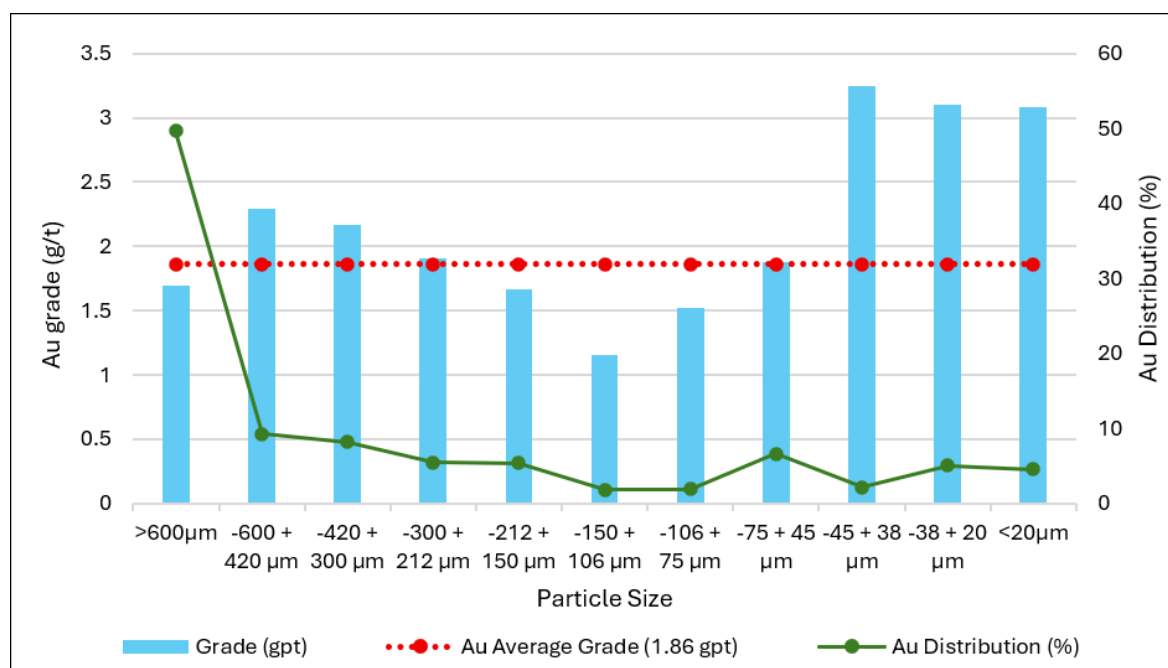


Figure 1. Size-by-size Au grade and Au distribution in the crushed (-2 mm) feed before grinding.

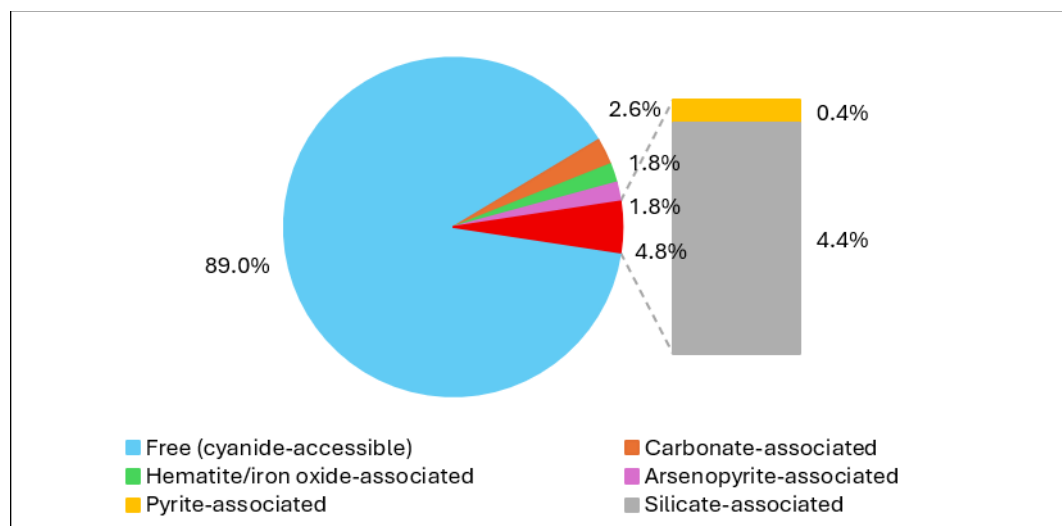


Figure 2. Operationally defined gold department of the head sample (DLT).

The DLT provided a complementary measure of Au accessibility. Its initial cyanidation stage dissolved 89.0% of the Au, with the remaining 11.0% distributed among carbonate (2.6%), hematite/iron oxide (1.8%), arsenopyrite (1.8%), pyrite (0.4%), and silicate-associated (4.4%) fractions (Figure 2), suggesting substantial but incomplete cyanide accessibility under the DLT conditions. This provides a contextual comparison with the approximately 80% cyanide-accessible Au reported for Mount Muro ore (Frideni et al., 2026), although differences in ore characteristics and test conditions limit direct comparison.

The DLT was run at P_{95} 75 μm with 1000 mg/L NaCN and 24-h cyanide stages, not under the bottle-roll conditions (P_{80} and P_{90} 75 μm , 1500 mg/L initial NaCN, 48 h). Both bottle-roll tests nevertheless exceeded the DLT cyanide-accessible fraction (92.1-94.0% vs. 89.0%) despite their coarser grind. This is plausibly related to the higher NaCN concentration and longer contact time in the bottle-roll tests and to subsample heterogeneity (Section IV.D), and it suggests that the DLT free-gold fraction is better treated as a conservative operational benchmark than as an upper limit of extractable gold.

The same homogenized ore was then ground to P_{80} 75 μm and P_{90} 75 μm . P_{80} was reached after 21 min 48 s of laboratory rod milling and P_{90} after 32 min 58 s, about 51% longer. The two products therefore differed in fineness but shared a common feed, allowing evaluation of the effect of additional grinding on the rate and timing of gold extraction.

Time-Dependent Cyanidation Response

The two grind targets produced distinct extraction trajectories over the 48-h leaching period (Figure 3). P_{90} showed a large early advantage, reaching 71.0% gold extraction at 2 h compared with 49.8% for P_{80} . This 21.2-percentage-point difference decreased to 16.6 percentage points at 8 h and 1.8 percentage points at 24 h, suggesting that the benefit of finer grinding diminished as leaching proceeded. At 48 h, the observed order was reversed, with P_{80} reaching 94.0% extraction compared with 92.1% for P_{90} .

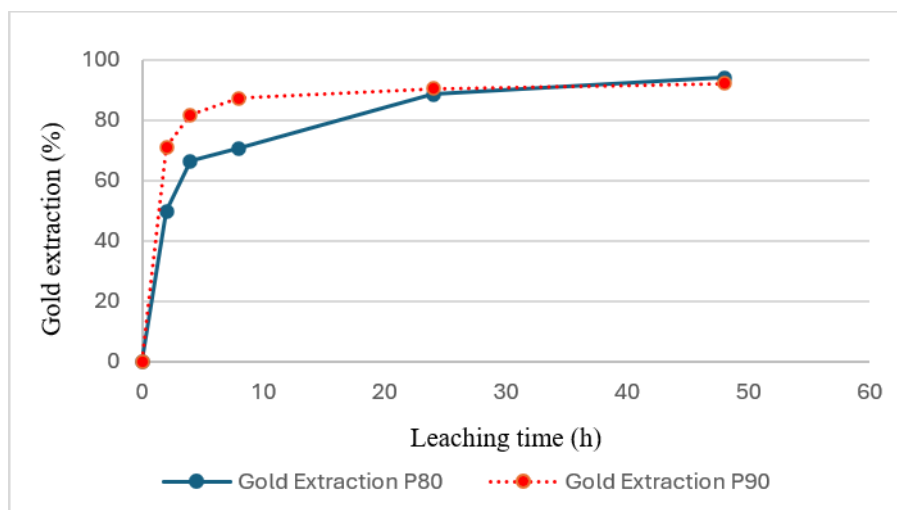


Figure 3. Gold extraction as a function of leaching time for P₈₀ and P₉₀.

The two profiles converged mainly because P₈₀ continued to extract gold. Between 8 and 24 h, P₈₀ extraction rose by 18.0 percentage points (about 1.1 percentage points per hour), while P₉₀ rose by only 3.1 percentage points (about 0.2 percentage points per hour).

The time-integrated response gives a complementary view. The trapezoidal area under the extraction curve (AUC) over 0-48 h was 4168.4 %·h for P₉₀ and 3901.4 %·h for P₈₀, reflecting the stronger early extraction of P₉₀ despite its lower 48-h endpoint.

Kinetic Modeling and Interpretation

Seven kinetic models were fitted to the extraction data and compared using AICc (Table 2; Figure 4).

For P₈₀, the Crundwell-Godorr model received the strongest support ($\Delta\text{AICc} = 0.00$; $w = 0.55$), followed by the SCM product-layer diffusion ($\Delta\text{AICc} = 1.22$; $w = 0.30$) and Mintek models ($\Delta\text{AICc} = 2.62$; $w = 0.15$). For P₉₀, the Mintek model was best supported ($\Delta\text{AICc} = 0.00$; $w = 0.67$), followed by Crundwell-Godorr ($\Delta\text{AICc} = 1.42$; $w = 0.33$). The three-parameter Loveday model was strongly penalized by the small-sample correction despite its high R^2 , and AICc could not be calculated for the four-parameter Two-Fraction model. With only five observations per grind target, the comparison is exploratory and describes the shape of the extraction profiles rather than a unique mechanism.

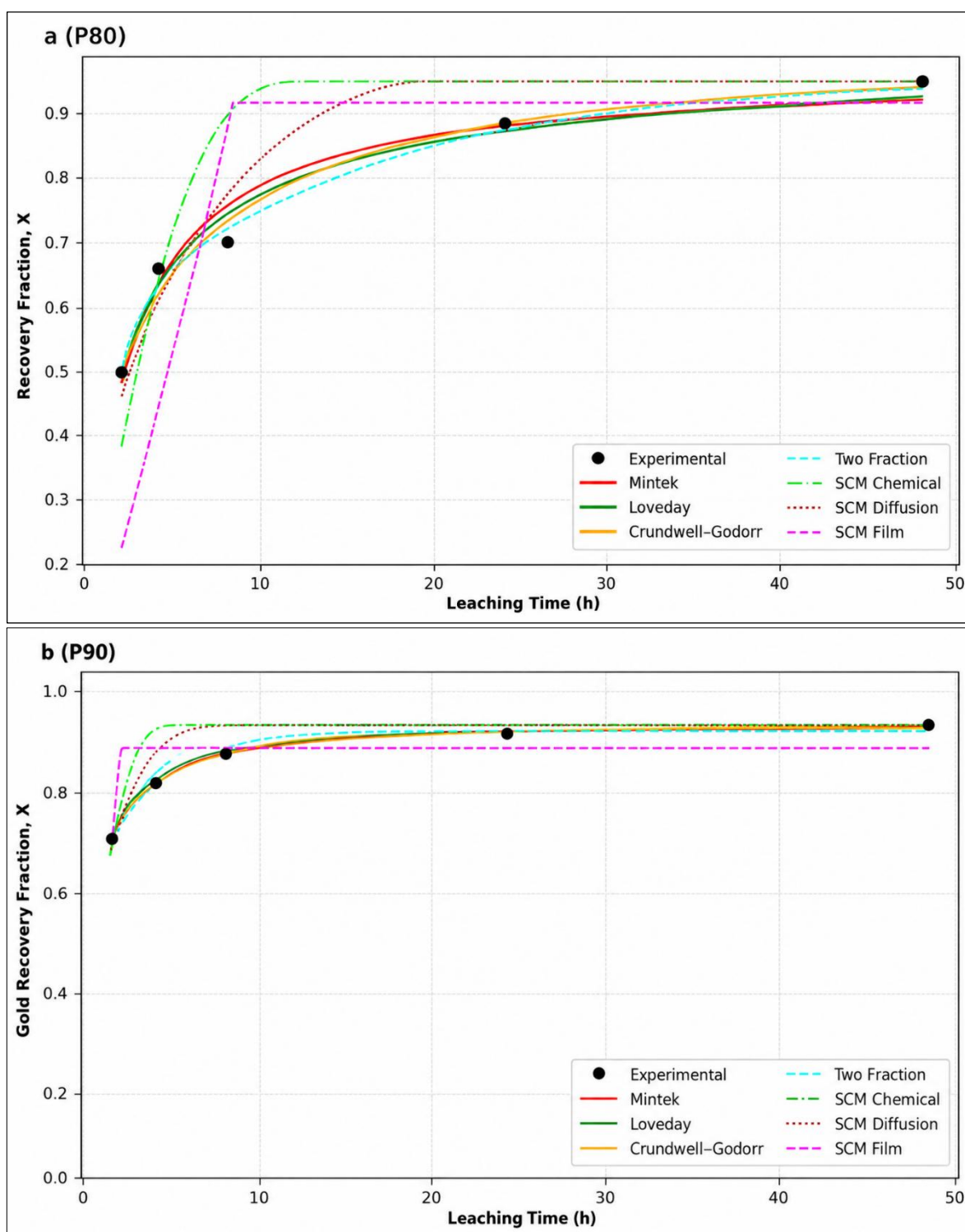


Figure 4. Fitted kinetic curves for seven candidate models against the observed extraction data for P₈₀ (a) and P₉₀ (b).

Mechanistically, the faster early response of P₉₀ is consistent with greater exposure of Au-bearing surfaces after finer grinding. The sustained later extraction under P₈₀ may instead reflect slower dissolution of less readily accessible Au-bearing particles in the coarser product. Confirming this would require size-by-size assays of the leach residues, which were not available for this study.

Table 2. Kinetic Model Comparison and AIC-based Model Selection for P₈₀ and P₉₀

Model	k	R ² (P ₈₀)	ΔAICc (P ₈₀)	w (P ₈₀)	R ² (P ₉₀)	ΔAICc (P ₉₀)	w (P ₉₀)
Crundwell-Godorr	2	0.976	0.00	0.55	0.994	1.42	0.33
Two-Fraction	4	0.988	n.d.	n.d.	0.987	n.d.	n.d.
Mintek	2	0.960	2.62	0.15	0.995	0.00	0.67
Loveday	3	0.972	20.79	<0.001	0.998	16.17	<0.001
SCM (product-layer diffusion)	1	0.898	1.22	0.30	0.846	11.57	0.002
SCM (chemical reaction)	1	0.581	8.29	0.01	0.620	16.08	<0.001
SCM (film diffusion)	2	-0.256	19.83	<0.001	0.779	19.23	<0.001

k = number of fitted parameters; w = Akaike weight calculated from ΔAICc (Burnham & Anderson, 2002); n.d. = not defined (AICc cannot be calculated for k = 4 with five observations). Negative R² indicates a fit poorer than the data mean.

Bulk solution chemistry was similar in the two tests: mean pH ($\pm$ standard deviation across sampling times) was 10.54 ± 0.07 and 10.56 ± 0.07 , and dissolved oxygen (DO) was 8.83 ± 0.36 and 8.73 ± 0.28 mg/L for P₈₀ and P₉₀, with no consistent trend between DO and extraction. Free cyanide stayed at or above 1050 mg/L NaCN, far above the stoichiometric requirement (<1 mg/L). Differences in Au accessibility linked to grind fineness are a more likely explanation for the contrasting trajectories than bulk solution chemistry.

Grinding Fineness, Endpoint Uncertainty, and Residence-Time Implications

Residual Au at 48 h accounted for about 6.0% and 7.9% of the back-calculated head for P₈₀ and P₉₀. For P₉₀, the measured (2.20 g/t) and back-calculated (2.41 g/t) heads differ by 9.55%, which may reflect sample heterogeneity, analytical variability, or both. Because extraction was calculated against each test's back-calculated head, the reported values are consistent with the Au mass balance (the measured head would give an apparent P₉₀ extraction of 100.9%), but a closure difference of this size limits interpretation of the small endpoint separation.

The 1.9-percentage-point difference is also sensitive to the residue assays. An increase of about 0.05 g/t in the P₈₀ residue grade (0.13 g/t), or a similar decrease in the P₉₀ residue grade (0.19 g/t), would remove it, while a 0.01 mg/L change in the solution assay shifts extraction by less than 0.1 percentage points.

Reagent consumption did not show a simple monotonic relationship with grind fineness. Total lime additions were high (3584 g/t for P₈₀ and 3268 g/t for P₉₀), mainly because of the initial dose needed to raise the slurry from its natural pH of 6.81 to above 10.5 (about 91% and 73% of the total, respectively); lime added after this conditioning was higher for P₉₀ (883.9 vs. 312.1 g/t).

NaCN consumption was higher for P₈₀ (1065.0 vs. 600.0 g/t), although finer grinding can increase the exposure of cyanide-consuming minerals (Ellis & Senanayake, 2004; La Brooy et al., 1994); a non-monotonic relationship has also been reported for Mount Muro ore (Habibah et al., 2025). The P₈₀ charge may have contained more cyanide-consuming minerals, consistent with the heterogeneity indicated by the head grades, but this could not be confirmed.

Reaching P₉₀ 75 μ m took about 51% more grinding time than P₈₀ 75 μ m, yet the extra grinding did not raise the observed 48-h extraction; its main effect was faster early extraction. Linear interpolation and the two models best supported by AICc (Mintek and Crundwell-Godorr)

consistently indicate that the P_{90} advantage fell below 5 percentage points after about 16-20 h, whereas the estimated crossover time ranged from about 35 h to beyond 48 h, so the crossover itself is poorly constrained by the data. Grind fineness and leaching residence time may be better evaluated together, as coupled process variables, than as independent operating parameters.

CONCLUSIONS

This exploratory study suggests that, for the ore tested, the effect of grind fineness on gold cyanidation was time-dependent and not uniformly beneficial. P_{90} 75 μm accelerated early extraction, whereas P_{80} 75 μm showed slightly higher extraction at 48 h (94.0% vs. 92.1%), a difference small relative to the P_{90} closure bias. The main observed difference was a shift in the timing of gold extraction, not higher extraction within 48 h. The DLT, feed size-by-size assay, and kinetic-model comparison provide context but do not identify a unique rate-controlling mechanism.

These results illustrate why grind targets may need to be judged against available residence time, not endpoint extraction alone. Under the conditions tested, the finer grind gave a clearly larger extraction (more than 5 percentage points) only during the first 16-20 h of leaching. These conclusions apply to cyanide-excess conditions (1500 mg/L NaCN). At the lower concentrations used in plant practice, cyanide could become partly rate-limiting, so the size and duration of the early advantage may differ.

LIMITATIONS & FURTHER RESEARCH

Each grind target was tested in a single run; the P_{90} test showed a 9.55% closure bias, and the commercial laboratory's internal QA/QC records were unavailable. The differences between the head, back-calculated, and feed-assay grades suggest possible coarse-gold heterogeneity in the 2.2-kg test charges, which gravity-recoverable gold (GRG) testing did not capture. The initial NaCN concentration was higher than in typical plant practice, and the leach residues were not characterized by size. The DLT and feed assay give contextual, not grind-specific, information; model discrimination was limited by the few observations, and grinding effort was expressed as milling time rather than specific energy.

Future work should include replicated cyanidation tests across a broader range of grind targets and cyanide concentrations, with denser sampling between 8 and 48 h. Grind-specific accessibility could then be examined using wet-screened residue assays and DLT under conditions aligned with the cyanidation tests, complemented by GRG testing, gold grain-size measurement, mineralogical characterization, and specific comminution energy measurement.

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