Leaching Behavior of Hexavalent Chromium from Nickel Processing Residues: A Free Draining Column Study on Dry Tailings and Nickel Slag

Muhammad Sonny Abfertiawan[1*], Agventy Nuranis Edytya[2], Mindriany Syafila[1], Faiz Hasan[1]

[1]*Water and Wastewater Engineering Research Group, Faculty of Civil and Environmental Engineering, Bandung Institute of Technology, Bandung, Indonesia*

[2]*Bachelor of Environmental Engineering Program, Faculty of Civil and Environmental Engineering, Institut Teknologi Bandung, Bandung 40132, Indonesia*

Abstract

Nickel processing using High Pressure Acid Leaching (HPAL) and Rotary Kiln Electric Furnace (RKEF) generates large volumes of dry tailings and nickel slag that may release metals through leaching. This study evaluates their kinetic leaching behavior using Free Draining Column Leaching (FDCL) tests over 12 weekly cycles in five single and combined configurations. Dry tailings produced oxidative conditions under which hexavalent chromium (Cr^{6+}) reached 0.512 mg/L. In contrast, nickel slag generated alkaline and reductive conditions that suppressed Cr^{6+} mobility. The 50% tailings–50% slag mixture showed the lowest metal concentrations, highlighting the potential of slag-based co-disposal to mitigate chromium leaching risks.

Keywords: Dry tailings, free draining column leaching, chromium, mine waste management

Introduction

According to the Ministry of Energy and Mineral Resources (ESDM, 2023), Indonesia possesses approximately 17.7 billion tons of nickel ore resources, corresponding to 177.8 million tons of contained metal, with total reserves estimated at 5.2 billion tons of ore and 57 million tons of metal. National nickel production increased from 1.58 million tons in 2022 to 1.8 million tons in 2023, reflecting the rapid expansion of downstream nickel processing. To support this development, integrated utilization of limonite and saprolite laterite ores is increasingly promoted to supply raw materials for both nickel grade 1 and nickel grade 2 products, resulting in the continuous generation of large volumes of processing residues.

High Pressure Acid Leaching (HPAL) is commonly applied to process limonite laterite ores with nickel grades of approximately 1.1–1.4%, producing tailings as a major residual by-product (Gultom & Sianipar, 2020). In contrast, saprolite ores with higher nickel grades (Ni > 1.8%) are generally processed using Rotary Kiln Electric Furnace (RKEF) technology, generating substantial amounts of nickel slag (Setiabudi et al., 2012). These two processing routes produce waste materials with distinct physical and geochemical characteristics.

HPAL tailings may contain elevated concentrations of potentially hazardous elements, including Fe, Mg, Mn, S, and Cr prior to neutralization (Gultom & Sianipar, 2020). After dewatering processes such as filter pressing, tailings are commonly managed as dry tailings that may remain geochemically reactive when exposed to oxygen and infiltrating water. Nickel slag, although generally alkaline and classified as non-acid forming, may also undergo leaching under long-term weathering conditions. Under rainfall infiltration, both tailings and slag can release dissolved metals, posing potential risks to surrounding soil and water systems (Wang et al., 2024).

Evaluation of the leaching behavior of nickel processing residues is therefore essential to assess their environmental performance. Kinetic methods such as Free

Draining Column Leaching (FDCL) tests are widely used to characterize mineral reactivity, oxidation processes, and temporal changes in leachate quality under conditions that better represent field exposure than static tests (AMIRA International, 2002). Accordingly, FDCL testing provides a relevant approach for assessing the long-term leaching behavior of dry tailings, nickel slag, and their potential interactions under realistic hydrological conditions.

Methods

The kinetic test is conducted to observe the behavior of metals in leachate water. In this study, the kinetic test was carried out over 12 cycles, equivalent to 12 weeks. Each cycle used deionized water. The simulation of the kinetic test is shown in Fig 1

Kinetic tests aim for further geochemical identification based on previous physical, mineralogical, and static tests as well as based on SNI 6597:2021. The kinetic test was conducted with an acrylic reactor with a diameter of 15 cm and a total height of 35 cm. The kinetic test used 2–3 kg of dry tailing and slag samples, with the soil samples homogenized beforehand to a size of less than 75 µm. The leachate that passes through the samples will be tested for several parameters as listed in Table 1.

Results and Discussion

The kinetic tests presented in this study were conducted over 12 cycles (weekly cycles), and the samples analyzed included reactor 1 (100% dry tailings), reactor 2 (100% slag), reactor 3 (layering of 75% dry tailings and 25% slag), reactor 4 (layering of 50% dry tailings and 50% slag), and reactor 5 (mixing of 50% dry tailings and 50% slag).

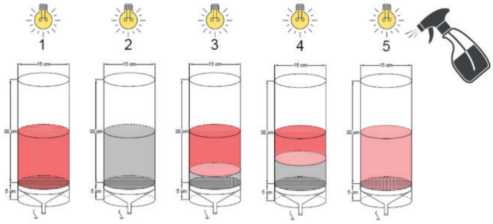

Figure 1 *Kinetic test simulation: 1) 100% dry tailing; 2) 100% slag; 3) 75% dry tailing & 25% slag (layering); 4) 50% dry tailing & 50% slag (layering); 5) 50% dry tailing & 50% slag (mixing).*

Characteristics of Deionized Water Used

The characterization of deionized water or distilled water in kinetic testing is necessary because this water serves as a neutral and pure dissolving medium that does not contain interfering ions which could affect the leaching or mineral dissolution reactions during testing. By ensuring that the characteristics of the deionized water, such as pH, conductivity, and initial ion concentrations, are very low or nearly zero, the kinetic test results will represent the true leaching rates of the samples without any additional interactions from ions already present in the water. This is crucial to obtain well-controlled leachate data.

Overall, the deionized water used was in a generally neutral condition based on the parameters tested, including pH, ORP, conductivity, salinity, DO, and TDS, indicating that it can accurately represent leachate water in the testing.

Temperature and Conductivity

The temperature graph in Figure 2a and the conductivity graph in Figure 2b are closely related, as ion mobility increases with rising temperature, allowing ions to move more rapidly, which indicates a faster electrical conduction process. The indicator in the process of conducting electricity can be assessed as conductivity. The measured leachate water temperature is around room temperature while the conductivity has decreased over time indicating that the ions in the leachate water are decreasing.

pH and ORP

pH and ORP parameters are related to each other and represented in the Pourbaix diagram to determine the chemical stability of an element or compound in water. Figure 3a shows that the pH of dry tailing tends to be neutral to alkaline, while the pH of slag is alkaline. These results are in line with the static test results which show that slag belongs to the NAF and dry tailing UC (tends to NAF). Then the ORP result in Figure 3b show that

***Table 1** Leachate water test parameters and analysis procedure.*

Parameters	Analysis Procedure	Standar Methods
TDS	Gravimetry	SNI 6989.3 : 2019
TSS	Gravimetry	SNI 6989.3 : 2019
Temperature	Thermometer	SNI 6989.23 : 2005
pH	pH meter	SNI 6989.11 : 2019
Oxidation Reduction Potential (ORP)	ORP meter	SNI 06-6989.2:2004
Conductivity	Conductivity meter	SNI 6989.1 : 2019
Total Cr	ICP-MS AAS	APHA 3125 SNI 6989.84 : 2019
Cr^{6+}	Spectofotometry	SNI 6989.71:2009
Other metals	ICP-MS AAS	APHA 3125 SNI 6989.84 : 2019

***Table 2** Characteristics of deionized water used on weekly cycle.*

Parameter	Value	Unit
pH	6,45	–
ORP	2,63	mV
Conductivity	0,01	µS/m
Salinity	0,01	psu
DO	7,5	mg/L
TDS	0	mg/L

the ORP value of dry tailing is higher than that of slag (negative value) which indicates that dry tailing tend to be oxidative and slag tends to be reductive.

TSS (Total Suspended Solid) and TDS (Total Dissolved Solid)

The TSS parameter shown in Figure 4a indicates a relatively high value only at the

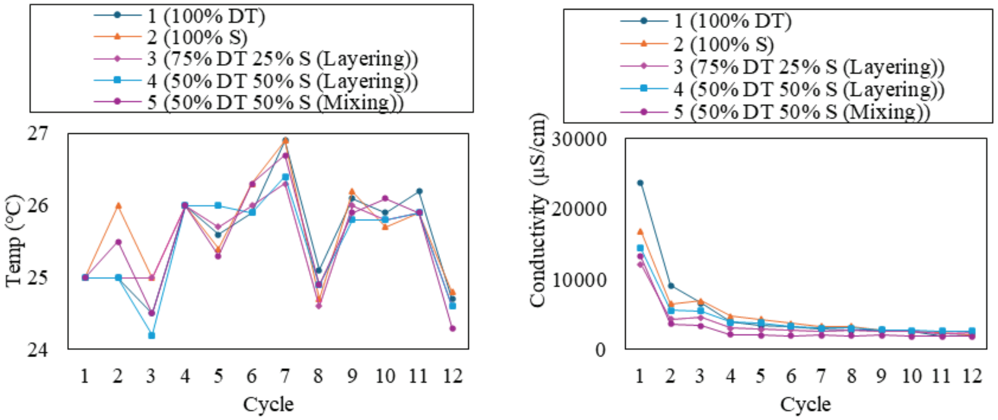

***Figure 2** Leachate water (a) temperature and (b) conductivity.*

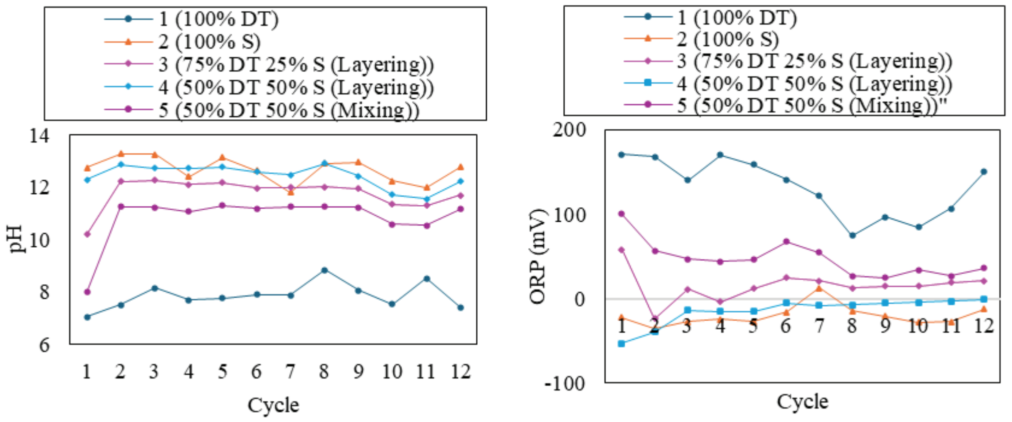

Figure 3 *Leachate water (a) pH and (b) ORP.*

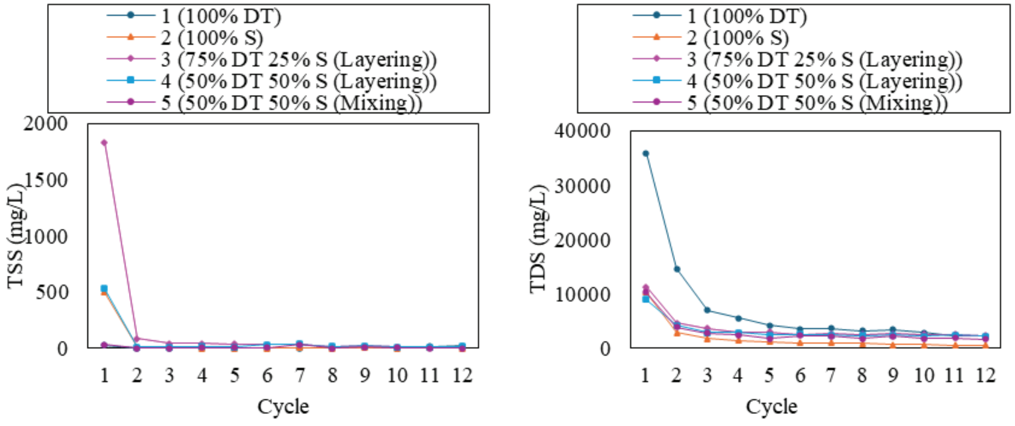

Figure 4 *Leachate water (a) TSS and (b) TDS test result.*

beginning, due to the release of fine particles during the initial dry condition of the sample. In the subsequent cycles, the TSS values are very low because a 10-micron filter paper was used during the kinetic test simulation to prevent fine particles (especially from the dry tailing) from being significantly leached into the water. Furthermore, the TDS parameter in Figure 4b shows a decreasing trend, as dissolved substances are gradually leached out over time.

Cr Metal Concentration

The most common oxidation states of chromium in the environment are Cr^{3+}, or trivalent chromium, and Cr^{6+}, or hexavalent chromium. Cr^{3+} species are more stable and less mobile, and they are less soluble in water compared to Cr^{6+}. Cr^{3+} tends to adsorb onto soil particles or organic matter and precipitate, whereas Cr^{6+} is highly soluble in water and more mobile, making it easier to spread in groundwater and surface water. Figures 5 shows an increase in total Cr and Cr^{6+} concentrations, with the peak Cr^{6+} concentration in reactor 1 occurring in week 9.

The concentration trends of total Cr and Cr^{6+} in the leachate show fluctuating values. This fluctuation is related to the properties of Cr_2O_3, which tends to be stable and therefore leaches into the environment gradually.

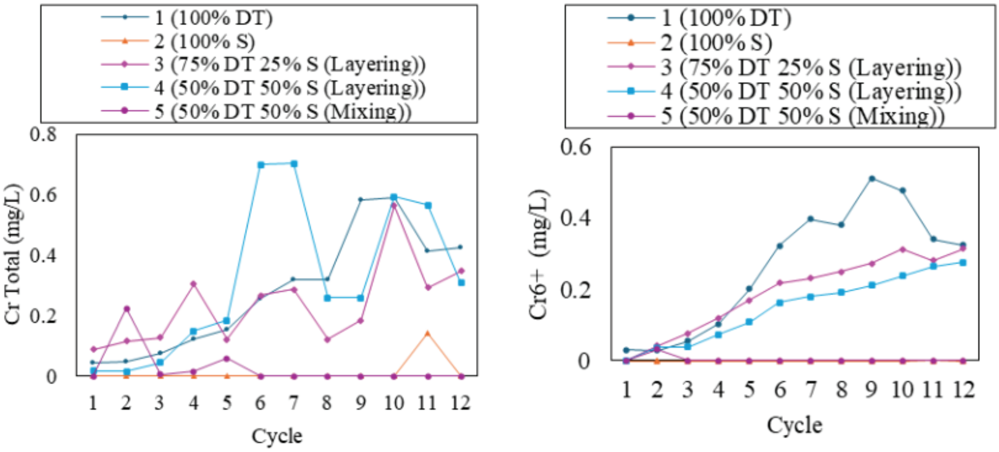

Figure 5 (a) Total Cr test result and (b) Cr6+ test result.

Table 3 Summary of pH, ORP, and Cr^{6+} concentrations in leachate.

Reactor	pH		ORP (mV)		Cr^{6+} (mg/L)	
	Min	Maks	Min	Maks	Min	Maks
1	7,05	8,85	75	171	0,028	0,512
2	11,80	13,28	-35	12,5	0	0,001
3	10,20	12,26	-23,5	58	0	0,314
4	11,55	12,90	-52,5	-1	0	0,275
5	7,99	11,29	25	100,5	0	0,032

Concentrations of Other Metals

The metal analysis focused on dissolved metals in accordance with the quality standards stated in the Indonesian Ministry of Environment Regulation No. 9 of 2009, except for chromium, which was analyzed separately. Before conducting periodic monitoring of these metals in each test cycle, an initial analysis was performed on the leachate from the first cycle (week 1) to determine the concentrations of dissolved metals using the ICP-MS method. Table 4 below presents a comparison between the dissolved metal concentrations and the quality standards.

Based on these results, it was found that the concentrations of dissolved Ni and Fe were still relatively high in the leachate. To further identify the behavior of these two metals, additional testing was conducted for Ni and Fe in the subsequent cycles.

Figure 6a above shows that dissolved nickel concentrations in the leachate were only detected in reactor 1 (100% dry tailings) and reactor 2 (100% slag) during the first week (cycle 1), while in reactors 3, 4, and 5, dissolved nickel concentrations remained at 0 mg/L throughout the testing cycles. The highest concentration of dissolved Ni was found in reactor 2, slightly exceeding the quality standard. For dissolved Fe testing in the leachate, Figure 6b shows that dissolved Fe was only detected in weeks one and two, with the highest concentration observed in reactor 2, exceeding the nickel mining wastewater quality standard.

Conclusions

Leachate from dry tailings exhibited neutral to slightly alkaline conditions (pH up to 8.55) and oxidative behavior (ORP up to 171 mV), whereas nickel slag produced strongly alkaline

Table 4 Comparison of week 1 leachate concentrations with quality standards.

Metals	Quality Standard (mg/L)	Reactor (mg/L)				
		1	2	3	4	5
Cu*	2	ND	0,03	ND	0,05	0,02
Cd*	0,05	ND	ND	ND	ND	ND
Zn*	5	0,19	0,05	ND	ND	ND
Pb*	0,1	ND	0,006	ND	ND	ND
Ni*	0,5	0,02	0,53	ND	ND	ND
Fe*	5	0,84	22,40	0,47	0,19	0,09
Co*	0,4	0,02	ND	ND	ND	ND

*) Dissolved Metals ND = Not Detected

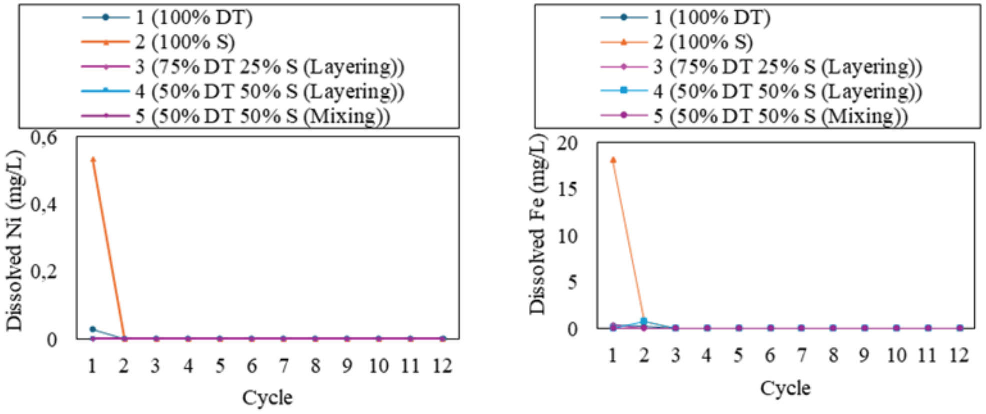

Figure 6 Dissolved (a) Ni and (b) Fe test result.

and predominantly reductive conditions (pH up to 13.28). Hexavalent chromium (Cr^{6+}) was more frequently detected in dry tailings leachate, reaching a maximum concentration of 0.512 mg/L. In contrast, the mixed system comprising 50% dry tailings and 50% slag showed the lowest concentrations of Cr^{6+}, total Cr, dissolved Fe, and dissolved Ni, all meeting mining wastewater quality standards. These results demonstrate that nickel slag effectively suppresses metal mobility and highlight its potential use in integrated waste management strategies to mitigate leaching risks from nickel processing residues.

Acknowledgements

This study was supported by the Bandung Institute of Technology through the Water and Wastewater Engineering Research Group (KK-RALC) and the Environment Department of Harita Nickel, Indonesia

References

AMIRA International (2002) ARD Test Handbook. Ian Wark Research Institute, New Zealand

ESDM (2023) Potensi Menjanjikan, Nikel RI Bakal Laris Manis Pikat Investor. https://www.esdm.go.id/id/media-center/arsip-berita/potensi-menjanjikan-nikel-ri-bakal-laris-manis-pikat-investor-. Accessed 20 Jan 2025

Gultom T, Sianipar A (2020) High pressure acid leaching: A newly introduced technology in Indonesia. In: IOP Conference Series: Earth and Environmental Science. Institute of Physics Publishing

Setiabudi A, Hardian R, Mudzakir A (2012) Karakterisasi Material : Prinsip dan Aplikasinya dalam Penelitian Kimia. UPI PRESS

Wang F, Li W, Wang H, et al (2024) The leaching behavior of heavy metal from contaminated mining soil: The effect of rainfall conditions and the impact on surrounding agricultural lands. Science of the Total Environment 914:. https://doi.org/10.1016/j.scitotenv.2024.169877