A case study of mineral processing and metal extraction from typical Witwatersrand and greenstone tailings

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South Africa contains several abandoned Witwatersrand and Greenstone tailings facilities from over a century ago. Previously classified as waste, these deposits contain a high concentration of toxic elements, including heavy metals, sulphides and uranium. Moreover, they contain valuable commodities such as gold, silver, and base metals. A case study was conducted to evaluate the feasibility of refining these abandoned Witwatersrand and Greenstone tailings facilities. The case study determined that historic Witwatersrand and Greenstone sediments could be concentrated via flotation and size classification, resulting in a 70% average gold recovery in the flotation circuit. Pre-oxidation and cyanidation were also utilised to extract an average of 80% of the gold and a portion of the valuable base metals from the concentrate. Importantly, the resulting residue could be used in the production of construction materials. In conclusion, reprocessing these historic tailings can reduce environmental impact, support the mining industry, and generate revenue by repurposing valuable resources for construction materials.

INTRODUCTION

The activities associated with gold mining in the Witwatersrand (Wits) and Greenstone belt produced enormous amounts of tailings in the past 130 years. The majority of these tailings have historically been dumped at unsightly sites that are often environmentally damaging, visually unappealing, and occupy valuable land.

Given the large volumes of historic tailings generated by gold operations in South Africa, finding a use for these tailings would alleviate environmental problems while generating revenue. Using tailings from the Wits and Greenstone, the study determined their amenability to gold, sulphide and uranium concentration into a flotation concentrate stream to produce a stable residue suitable for manufacturing construction material. South African gold operations only target 40% of historic tailings dumps for reprocessing since the gold quality in the majority of the dumps is insufficient to allow for commercially viable recovery (Janse van Rensburg, 2016; Staden *et al.*, 2020). As a result, Mintek examined a potentially cost-effective flowsheet for mitigating the environmental impact of tailings while efficiently extracting gold. The scope of work included flotation amenability and optimisation, size classification, sulphide pre-oxidation, cyanidation, and residue leachability investigation to validate the suitability of the developed flowsheet.

Tailings re-treatment projects can typically explore flotation and size classification as a way to avoid 'whole stream' processing. Since the gold grade in Wits and Greenstone tailings gold grade is low, between 0.5 and 1 g/t, the projects would require large quantities of material to be economical at these low gold grades. Additionally, flotation has the advantage of allowing for the recovery of the majority of toxic minerals such as sulphides and uranium into a single stream resulting in flotation tailings that are acceptable for application in the construction industry (Janse van Rensburg, 2016).

The majority of gold mine operational sites' primary environmental concern is how to deal with large amounts of waste and minimise their long-term environmental impact while boosting long-term benefits and sustainability. Generating sustainable by-products encourages recyclability, and lowers the negative environmental and social effects of tailings while generating financial rewards. However, repurposing of historical tailings, produced by the gold mining industry into zero-emission concrete-based material depends on the type of ore extracted and the processing procedures performed on the ore.

Depending on the geology of the area, gold mine waste materials contain different minerals. For example; gold mine waste contains sulphide minerals such as pyrite (FeS_2), arsenopyrite (FeAsS), galena (PbS), chalcopyrite ($CuFeS_2$), and sphalerite ((Fe, Zn)S) (Kabata-Pendias and Pendias, 2001; Ramasala, 2018). These minerals contain trace elements such as arsenic (As), lead (Pb), zinc (Zn), nickel (Ni), cadmium (Cd), silver (Ag), cobalt (Co), chromium (Cr) selenium(Se), manganese (Mn), iron (Fe), boron (B), copper (Cu), vanadium (V) molybdenum(Mo), barium (Ba) and other trace elements (Kabatapendias and Pendias, 2001). Some of these trace elements at elevated concentration levels are poisonous to the environment and living organisms (Department of Water Affairs and Forestry, 1998; Lim *et al.*, 2009; Ramasala, 2018). The levels of trace elements in the leachate dictate the level of impact they will have on the environment and the natural water (Zyl *et al.*, 2001; Fashola and Ngole, 2016).

The study also investigated the environmental stability of both the Wits and Greenstone final residue after processing via the recommended flowsheet using the stability tests Toxicity Characterising Leaching Procedure (TCLP) and Synthetic Precipitation Leaching Procedure (SPLP) methods for the evaluation of environmental impacts of the envisioned final residue. These tests determined the leachable concentrations threshold of both samples according to the National Environmental Management Waste Act (NEM: WA) Act No.59 of 2008.

EXPERIMENTAL

The Wits and Greenstone tailings' process mineralogy offered options for enhancing the efficiency of the gold recovery circuit in a conventional tailing re-treatment operation. Mineralogy served as the foundation for the study since gold deportment is one component that affects gold extraction. The location and description of the gold-containing particles, as well as the gold speciation, grain size, and mode of occurrence, were all determined using gold deportment studies. This mineralogy study resulted in a thorough grasp of the mineralogical occurrence of the gold, enabling the development of a tailing reprocessing strategy that would increase the efficiency of gold extraction. As a result, Mintek carried out numerous experiments to determine the ideal conditions for enhancing gold recovery from the two tailings deposits.

Process Mineralogy

Chemical analysis

The Wits and Greenstone air-dried tailings sub-samples were analysed for gold, base metals uranium, total sulphur and total carbon. Table 1 shows the analytical methods and detection limits of each method used for the test work program.

Table 1. Analytical methods and their respective detection limits

Analytical method	**Package number and description**	**Analyte list**	**Determination limit**
Fire assay	FA7S: The standard fire assay with no high-temperature cupellation followed by the dissolution of the silver prill in aquaregia and analysis of the gold using AA.	Total gold	0.08 g/t
ICP-OES	ICP1: Ores and slags, fusion followed by acid dissolution in HCl/HNO3	Mg, Al, Si, Ca, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn & Pb	Lower limit 0.05%, Upper limit 40%
Combustion	Combustion ("LECO")	Total sulphur and total carbon	0.01%
XRF (X-ray fluorescence)	XRF: A non-destructive analytical method used to ascertain the elemental makeup of materials	Uranium	10 g/t

Mineralogy

The mineralogical analysis involved X-ray diffraction (XRD) and AutoSEM (MLA) to determine the mineralogical limits of each sample. XRD analyses were examined by the Bruker D8 Advanced powder diffractometer, with a Lynxeye detector and variable divergence and fixed-receiving slits, with Fefiltered Co-Kα radiation. The instrument was run from 4 to 80° 2θ with a counting time of 1 second per step to identify minerals using the Bruker EVA software package. XRD cannot detect crystalline minerals greater than 3 mass % and amorphous phases. However, the AutoSEM (MLA) was able to detect these discrete gold species, their mode of occurrence, mineral association, and liberation.

Particle size distribution and Assay-by-size of feed

Particle size distribution (PSD) and assay-by-size analysis of the flotation feed determined the gold deportment across the grain sizes in both samples. The samples were wet screened from 212 µm down to -25 µm filtered and dried, and then the mass of each size fraction was recorded, pulverised and submitted for analysis.

Flotation amenability

The basis of the efficiency of flotation consists of factors such as grade, degree of liberation, properties of interfaces, and operating variables. Flotation amenability using direct flotation evaluated the samples' amenability to upgrading by concentrating the gold associated with sulphide and oxide minerals. The test work programme used batches of 1 kg samples floated with potable Rand water in a 2 L cell using a Denver D12 flotation machine at an impeller speed of 1000 rpm.

The test work programme involved the collection of rougher kinetic concentrates, by scraping off the froth at 15 seconds intervals for a total of 30 minutes to investigate the particles of the same minerals that float at different rates because of different particle characteristics and cell conditions. Table 2 presents a summary of the reagent suite and test conditions used for the amenability tests based on the process mineralogy outcomes. The evaluation of the batch flotation tests was according to recovery obtained at a specified time. These reagents focus on the flotation of both oxide and sulphide gold particles while reducing the uranium and sulphur reporting to the tailings.

Table 2. Scoping flotation test conditions

Location	Reagents and dosages	Conditioning time	Float time	Cell size	Speed	Air rate
Rougher Conditioning				2.5 L	1200 rpm	
	160 g/t CuSO4	5 minutes				
	200 g/t SIBX	3 minutes				
	200 g/t Flottec 2800-02	3 minutes				
	70 g/t Sasfroth 10	1 minute				
Rougher Concentrates					1200 rpm	6.3 mL:/min
RC1			1 minute			
RC2			2 minutes			
RC3			4 minutes			
RC4			13 minutes			
RC5			10 minutes			

Flotation optimisation

The study also aimed to optimise and improve gold recovery to the flotation concentrate by applying low pulp density for both tailings to target the gold contained in the fines fraction. Investigation of carbon depression on the Greenstone tailings using dextrin at a dosing rate of 300 g/t was ineffective. Dextrin was not as effective as anticipated, as there was no improvement in carbon reporting to the flotation tailings stream. The study also assessed the possibility of rejecting the carbonaceous material in the Greenstone tailings, before gold recovery (carbon pre-float). The carbon pre-float was ineffective as it resulted in high gold losses of 19% and a low carbon rejection of around 7% instead of the targeted 80%. The tests thus far showed that the carbonaceous material in the Greenstone tailings sample appears as entrainments of fine gangue minerals, making chemical depression ineffective.

PSD and Assay-by-size of flotation products

The PSD and assay-by-size analysis of the flotation concentrates and tails determined the gold deportment across the grain sizes in both samples. The samples were wet screened from 212 µm down to -25 µm filtered and dried, and then the mass of each size fraction was recorded, pulverised and submitted for analysis.

Evaluation of flowsheet gold extraction efficiencies

Based on the process mineralogy, PSD and assay-by-size tests work findings, the flowsheet displayed in Figure 1 was established as an efficient flowsheet for the extraction of gold, uranium and sulphides to produce a residue that is stable for the manufacturing of construction material.

The study first investigated the flotation concentrate gold extraction efficiency and the influence of sodium cyanide (NaCN) addition and pre-oxidation using the standard bottle roll method. Cyanidation (Carbon in Leach 20 g/L carbon addition) of the concentrate at 2.5, 5 and 10 kg of NaCN per ton of ore showed the effects of increased sodium cyanide additions with partial pre-oxidation of sulphide minerals. Once the ideal NaCN addition was established, a composite sample made up of the concentrate and the size fractions of tailings that contained more than 0.5 g/t were produced. This composite was pre-oxidised for four hours and then leached using the conditions established during the NaCN scouting tests as shown in Table 3.

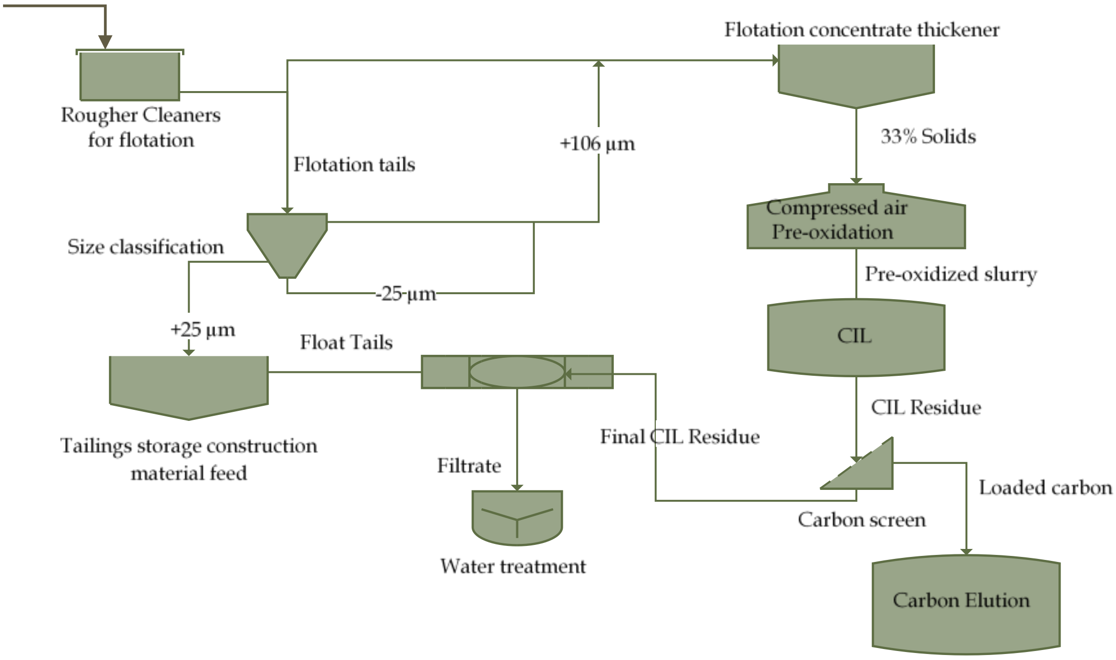

Figure 1. Conceptual flowsheet for the treatment of Wits and Greenstone historic tailings.

Table 3. Conceptual flowsheet carbon in leach (CIL) conditions

Ore grind size	90% -25 µm
Solids	33%
Water	66%
pH	10.5 to 11.5
Carbon addition	20 g/L
NaCN addition	2.5 kg/t
Peroxidation retention time	4 hours
Dissolved oxygen	6 mg/L
CIL retention time	24 hours

Environmental stability of final residue

The final residues of the Wits and Greenstone tailings treated via the recommended flowsheet were analysed to establish the amenability for brickmaking in terms of environmental impact and suitability using the TCLP and SPLP methods. The TCLP and SPLP tests provide information to support the evaluation of potential environmental risks related to the use of mining waste materials as soil amendment agents. These tests determine the leachable concentrations of the metals contained in each (Government of Western Australia Department of Environmental Regulation, 2015).

The procedure of the TCLP test simulates the worst-case scenario of the co-disposal of waste materials in municipal landfills (Hageman *et al.*, 2000; Al-Abed *et al.*, 2006). The tests involved end-over-end rotation for 18 hours with the extraction fluid used as a function of the alkalinity of the solid phase using a ratio of 1:20 solid-to-liquid (Hageman *et al.*, 2000). The standard TCLP method uses extraction fluid of either sodium acetate buffer solution having a pH of 4.93 ± 0.05 or an acetic acid solution having a pH of 2.88 ± 0.05 (Hesbach *et al.*, 2010).

The design of the SPLP method is to predict and determine the potential for leaching metals into ground and surface waters from which municipal solid waste is excluded (Hageman *et al.*, 2000). The procedure is time and resource intensive and 1:20 solid-to-liquid ratio, it provides a rigorous leach of the materials within 18 hours of agitation. The extraction fluid for the SPLP is a slightly acidified extraction fluid (of sulphuric and nitric acids 60/40 w/w) that was designed to simulate acid rain (Hageman *et al.,* 2000). The SPLP is likely to have higher suitability for use in acid rock drainage test work than the TCLP. Both procedures are described in the United States Environmental Protection Agency publication.

RESULTS AND DISCUSSION

Process Mineralogy

The chemical analysis shown in Table 4 confirmed the gold head grades to be 0.6 g/t for the Wits samples and 1 g/t for the Greenstone sample. Only the Wits sample contained uranium, thorium, and aluminium, while the Greenstone sample contained calcium. Both samples contained a significant amount of silica, iron and sulphur, which can all have a negative impact on gold extraction. Compared with the gold grade, these constituents are more significant and soluble during cyanidation, affecting gold dissolution by leaching simultaneously with gold and silver during cyanidation (Oraby, Eksteen and Tanda, 2017; Yliniemi *et al.*, 2018; Wu, Ahn and Lee, 2021). The samples also contained carbon, which can have a preg-robbing effect during cyanidation.

The chemical analysis indicated the presence of sulphur, anticipated to be iron sulphide minerals with a small content of base metal sulphides containing Ni, Co and Cu.

Table 4. Chemical analysis

Witwatersrand tailings	**Au**	**U**		**Th**	**Al**	**Fe**	**Si**	**Total C**	**Total S**
		g/t				%			
	0.58	42.7		9.76	3.44	2.98	36.3	0.13	1.36
Greenstone tailings	Au	Ca		Fe	Si	Total C	Total S		
	g/t			%					
	0.99	2.76		6.69	25.4	3.36	0.04		

PSD and Assay-by-size of feed

Figure 4 shows the PSD and assay-by-size analysis of the Wits and Greenstone tailings samples. The samples' PSDs showed that the Wits tailings contained more than 44% mass fraction in the finer fraction (25 µm) with 54% of the gold in the sample. The Greenstone tailings, on the other hand, showed that over 60% mass fraction is in the finer fraction with 73% of the gold in the sample.

The results indicate that the gold in both samples is already fine and at a suitable grind size for dissolution. During cyanidation, gold dissolution increases with decreasing particle size. This observation is due to the large contact surface associated with the fine particle size, which promotes rapid dissolution of the fine gold, preventing the passivation of the surface of the gold grains. This indicates that the effect of the pre-treatment could be size-dependent and may suggest the use of separate treatments for fine and coarse particles (Harris, 1990; Zhou and Cabri, 2004; Xu and Wang, 2015).

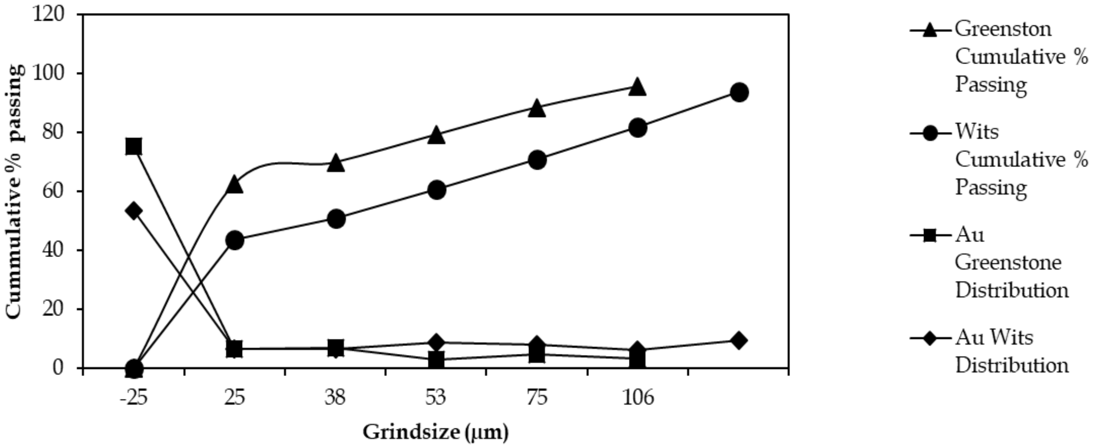

Figure 2. Feed PSD and assay-by-size results.

Mineralogy

The relative bulk mineralogy of the Wits and Greenstone tailings samples mainly consists of quartz, followed by chlorite, and mica (Table 5). The relative bulk mineralogy of the Greenstone tailings sample analysed mainly comprises quartz followed by intermediate proportions of chlorite. The Wits tailings also contained pyrophyllite and pyrite in minor quantities in the sample with gypsum occurring as a trace mineral. Pyrite accounted for all of the sulphur in the Wits sample.

Table 5. Wits and Greenstone tailings relative bulk composition of the analysed slimes sample

Wits			**Greenstone**		
Mineral name	**Chemical formula**	**Relative abundance**	**Mineral name**	**Chemical formula**	**Relative abundance**
Quartz	SiO_2	Predominant	Quartz	SiO_2	Predominant
Chlorite	$(Mg, Fe)_6(Si,Al)_4O_{10}(OH)_8$	Intermediate	Chlorite	$(Mg, Fe)_5Al(Si_3Al)O_{10}(OH)_8$	Minor
Mica	$KAl_2(AlSi_3O_{10})(F, OH)_2$	Minor	Mica	$KAl_2(Si_3Al)O_{10}(OH,F)_2$	Intermediate
Pyrophyllite	$Al_2Si_4O_{10}(OH)_2$	Minor	Clay	$Al_2Si_4O_{10}(OH)_2$-$Al_2Si_2O_5(OH)_4$	Trace
Pyrite	FeS_2	Minor			
Gypsum	$CaSO_42H_2O$	Trace			
Trace < 5 mass %, Minor 5-15 mass%, Intermediate 15-25 mass%, Major 25-50 mass%, Predominant >50 mass%					

Table 6 represents the gold liberation summary of both tailings samples. According to the gold mineral liberation and association study, approximately 90% by mass of identified gold grains in the Greenstone sample are completely liberated and therefore accessible for flotation or leaching, and only 10.2% by mass is completely locked. The main associations observed in the sample were with goethite at 12.5% and the remaining 87.5% of grains were associated with the free surface.

Approximately 33% by mass of identified gold grains in the Wits sample are completely liberated and therefore accessible for flotation or leaching and only 3% by mass observed grains of gold are completely locked. The main gold association observed in the Wits tailings was pyrite, occluding 64% of the gold grains. Therefore, pre-treatment of pyrite would expose the gold particle and positively affect the efficiency of cyanidation (Teague, Van Deventer, and Swaminathan 1999; Rabieh *et al.*, 2017).

Table 6. Gold mineral liberation data

Liberation characteristic	**Gold-free surface of particle**	**Wits tailings**	**Greenstone tailings**
Locked	0% (not exposed)	3.12	10.2
Partially exposed	0% < x <= 100%	64.0	-
Liberated	100%	33.3	89.8
Total			100.0

Flotation amenability

The scoping test results shown in Table 7 proved the amenability of Wits and Greenstone tailings to upgrading via direct gold flotation. The Wits tailings were upgraded to a cumulative grade of 1.99 g/t at a mass pull of 4.04% and gold recovery of 12% and if the residence time is increased to 30 minutes, the recovery increases to 71% and a grade of 2.5 g/t. Thus, a 1:4.2 ratio of feed to concentrate upgrade. However, 29% of the gold was lost to the tail stream and this was still too high for the tailing treatment process. Therefore, further tests were conducted using a more dilute pulp density to target the gold contained in the fines portion of the tailings material.

Table 7. Wits flotation amenability

Products	**Time (Min)**	**Mass (g)**	**Mass (%)**	**Grade**			**Recovery**		
				Au	**U**	**S**	**Au**	**U**	**S**
				g/t	**%**		**%**		
RC1	1	38.9	4.04	1.99	83.0	3.0	12.0	9.20	8.80
RC2	2	25.2	2.62	3.48	113	10.0	13.6	8.10	19.1
RC3	4	29.0	3.01	3.12	113	8.6	14.1	9.30	19.0
RC4	13	50.6	5.25	3.33	118	12.4	26.2	16.9	47.5
RC5	10	41.5	4.31	0.79	68.2	0.8	5.10	8.00	2.60
RT		777	80.7	0.24	22.0	0.1	29.0	48.4	2.90
Head (calc.)		962	100.00	0.7	36.6	1.4	100	100	100
Head (meas.)		1000		0.6	42.7	1.4			
% Variance		4%		15%	14%	1%			

The flotation amenability results shown in Table 8 showed that the Greenstone sample could be upgraded to 4.6 g/t at a mass pull of 8.8% and a recovery of 33.5% and if the residence time is increased to 30 minutes, the recovery increases to 72.2% and a grade of 3.0 g/t. Thus, a 1:3 ratio of feed to concentrate upgrade. The consistency of the total carbon grade shows that there is no association between gold and the carbonaceous material in this sample. However, the test achieved over 30% of carbon recovery into the product streams and this was still too high for the intended downstream processing. This led to the testing of carbon-depression for increased rejection of the carbonaceous material before cyanidation.

Table 8. Greenstone flotation amenability

Products	Time (Min)	Mass (g)	Mass (%)	Grade			Recovery		
				Au	C	S	Au	C	S
				g/t	%		%		
RC1	1	58.4	5.9	3.51	3.49	0.06	20.2	6.7	10.8
RC2	2	53.1	5.4	3.66	3.41	0.06	19.2	6.0	9.9
RC3	4	55.6	5.6	2.47	3.59	0.06	13.5	6.6	10.3
RC4	13	77.9	7.9	1.55	3.40	0.07	11.9	8.7	16.9
RC5	10	48.1	4.9	0.73	3.49	0.06	3.5	5.5	8.9
RT		699	70.4	0.46	2.89	0.02	31.7	66.5	43.2
Head (calc.)		992	100	1.02	3.06	0.03	100	100	100
Head (meas.)		1000		0.99	3.36	0.04			
% Variance		0.8%		4%	9%	7%			

Flotation optimisation

The results obtained from the Wits low pulp density test are summarised in Table 9. The low density of 20% (w/w) was effective in recovering some of the remaining gold in the tailings stream, reducing it from 29% to 26.4%. The test achieved a higher-grade product of 4.5 g/t, which is an enrichment ratio of 1:7.5. The low pulp density was beneficial in high particle dispersal, which resulted in better rheological and flotation outcomes.

Table 9. Wits low pulp density flotation test work results

Products	Time (Min)	Mass (g)	Mass (%)	Grade			Recovery		
				Au	U	S	Au	U	S
				g/t		%	%		
RC1	1	16.8	1.72	11.4	100	29.8	33.7	6.95	37.5
RC2	2	15.6	1.60	6.10	80.0	18.3	16.7	5.16	21.4
RC3	4	15.5	1.59	3.60	60.0	10.4	9.82	3.84	12.1
RC4	13	24.4	2.50	2.27	60.0	5.77	9.75	6.05	10.5
RC5	10	20.2	2.07	1.01	60.0	2.87	3.59	5.01	4.30
RT		883	90.51	0.17	20.0	0.22	26.4	73.0	14.2

Head (calc.)		975	100.00	0.58	24.8	1.37	100	100	100
Head (meas.)		1000		0.58	42.7	1.36			
% Variance		0.0248		0%	42%	1%			

The results obtained from the Greenstone carbon-depression test are summarised in Table 10. The test involved the addition of Dextrin as a carbon-depressing reagent at a high dosing rate of 300 g/t. The depressant addition test performed similarly to the amenability test, except that the mass pull in the carbon-depression test reduced to 5.9% while the gold recovery was still high at 68% with a negligible reduction in the recovery of the total carbon at 67% compared the amenability test that results in 67% carbon rejection.

Table 10. Greenstone carbon-depression flotation test work results

Products	Time (Minutes)	Mass (g)	Mass (%)	Grade			Recovery		
				Au	C	S	Au	C	S
				g/t	%		%		
RC1	1	58.4	5.9	3.51	3.49	0.06	20.2	6.7	10.8
RC2	2	53.1	5.4	3.66	3.41	0.06	19.2	6.0	9.9
RC3	4	55.6	5.6	2.47	3.59	0.06	13.5	6.6	10.3
RC4	13	77.9	7.9	1.55	3.40	0.07	11.9	8.7	16.9
RC5	10	48.1	4.9	0.73	3.49	0.06	3.5	5.5	8.9
RT		698.5	70.4	0.46	2.89	0.02	31.7	66.5	43.2
Head (calc.)		991.6	100.0	1.02	3.06	0.03	100.0	100.0	100.0
Head (meas.)		1000.0		0.99	3.36	0.04			
% Variance		0.8%		4%	9%	7%			

PSD and Assay-by-size of flotation concentrates and tailings

Figure 3 shows the PSD and assay-by-size analysis of the Wits flotation concentrate and tailing samples. The concentrate sample's PSD showed that the concentrate contained more than 85% mass fraction in the finer fraction (-38 µm) with 55% of the gold in the sample. While the flotation tailings showed that 55%, mass fraction is in the finer fraction with 64% of the gold in the sample.

Results showed that most gold particles in both feed samples report to the -50 µm fraction, with even distribution in the particle sizes larger than 25 µm. The tailings also contained a significant amount of gold in their -25 and +425 µm fractions.

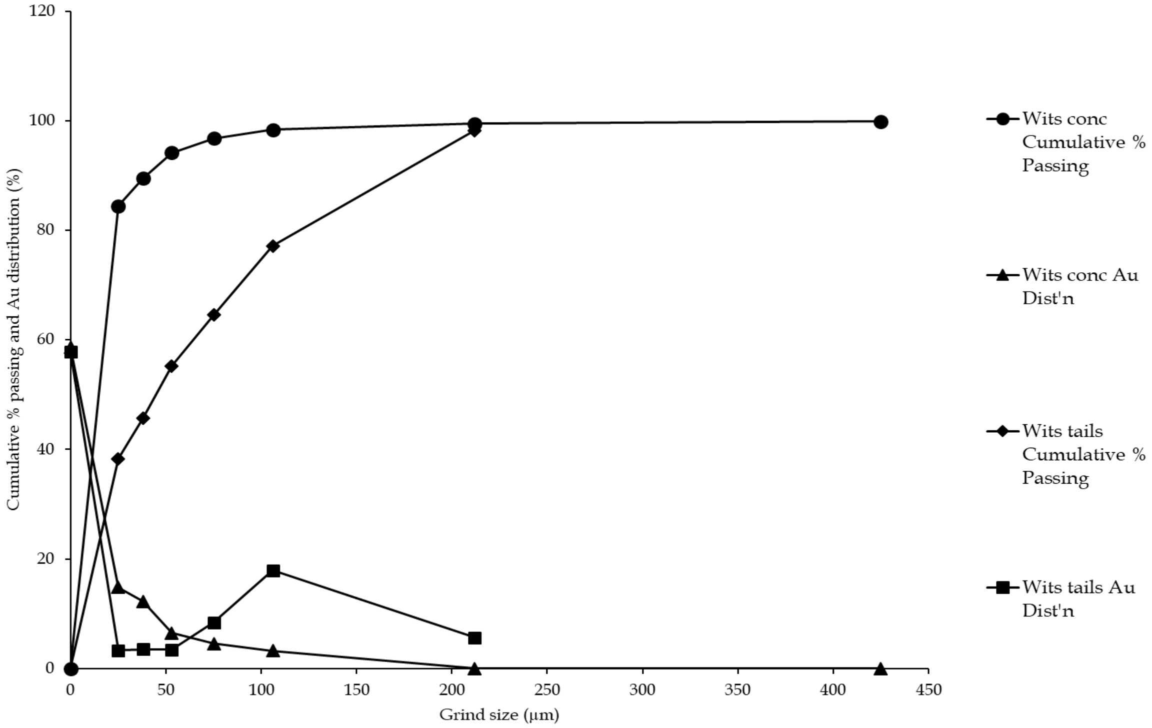

Figure 3. Wits concentrate and tailings PSD and assay-by-size results.

Figure 4 shows the PSD and assay-by-size analysis of the Greenstone flotation concentrate and tailings samples. The concentrate sample's PSD showed that the concentrate contained more than 50% mass fraction in the finer fraction (25 µm) with 65% of the gold in the sample. The flotation tailings showed over 50% mass fraction in the finer fraction with 65% of the gold in the sample.

Results showed that most gold particles in both feed samples report to the -50 µm fraction, with even distribution in the particle sizes larger than 25 µm. The tailings also contained a significant amount of gold in their -25 and +425 µm fractions.

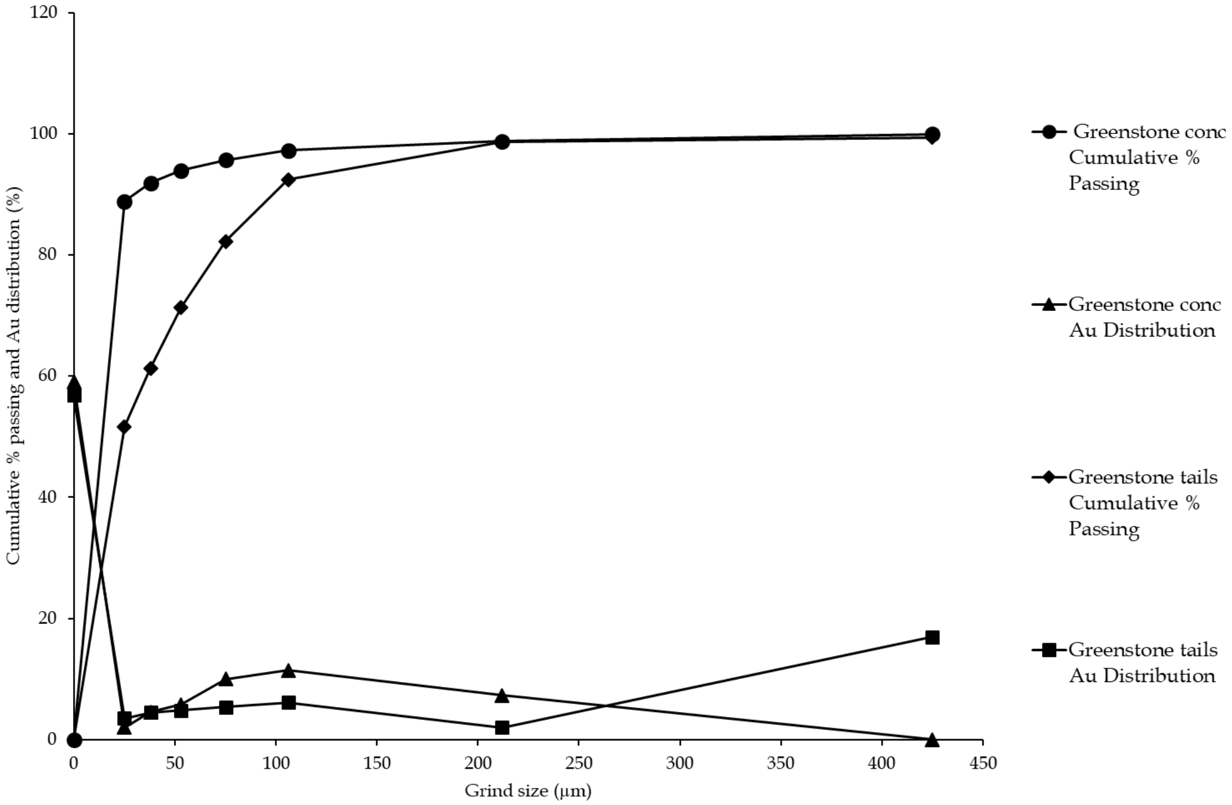

Figure 4. Greenstone concentrate and tailings PSD and assay-by-size results.

The PSD and assay-by-size analysis resulted in a decision to create a composite of the concentrate with the fraction of flotation tailings that contained a significant amount of gold (greater than 0.5 g/t). The Wits composite was a combination of the Wits flotation concentrate with the -25 and +106 µm fraction of the Wits flotation tailings resulting in a head grade of 3.07 g/t. The Greenstone composite was a combination of the Greenstone flotation concentrate and the -25 and +106 µm fraction of the Wits flotation tailings resulting in a head grade of 3.46 g/t.

Evaluation of gold extraction efficiencies

Cyanide scouting and baseline test of concentrates

The two concentrates were leached at three NaCN concentrations to evaluate their amenability to cyanidation and established the optimum NaCN addition for a maximum gold extraction. Figure 5 shows the gold extraction efficiencies, mass balance accountabilities and reagent consumption of the tests.

The maximum extraction from the Wits concentrate (79%) was obtained with a NaCN consumption of 0.43 kg/t. On the Greenstone sample, the highest achievable gold extraction was 87% with a NaCN consumption of 0.24 kg/t. The Greenstone concentrate required more CaO than the Wits concentrate to achieve the required pH of 10.5 to 11.0. The Greenstone concentrate contained a significant amount of carbonaceous material that consumed lime during cyanidation. The accountability of the Wits test work program was inadequate. This could be because the sample was not homogeneous, necessitating greater milling when analysing for total gold. The overall gold recovery, including flotation, was 51% for both Wits and Greenstone tailings. Leaching efficiency was favoured by lower cyanide concentrations in the case of the Greenstone concentrate, this could be due to the co-leaching of gangue minerals that act as cyanicides during cyanidation (Rees, 2000). Increasing NaCN addition was beneficial to the gold extraction efficiencies of the Wits composite.

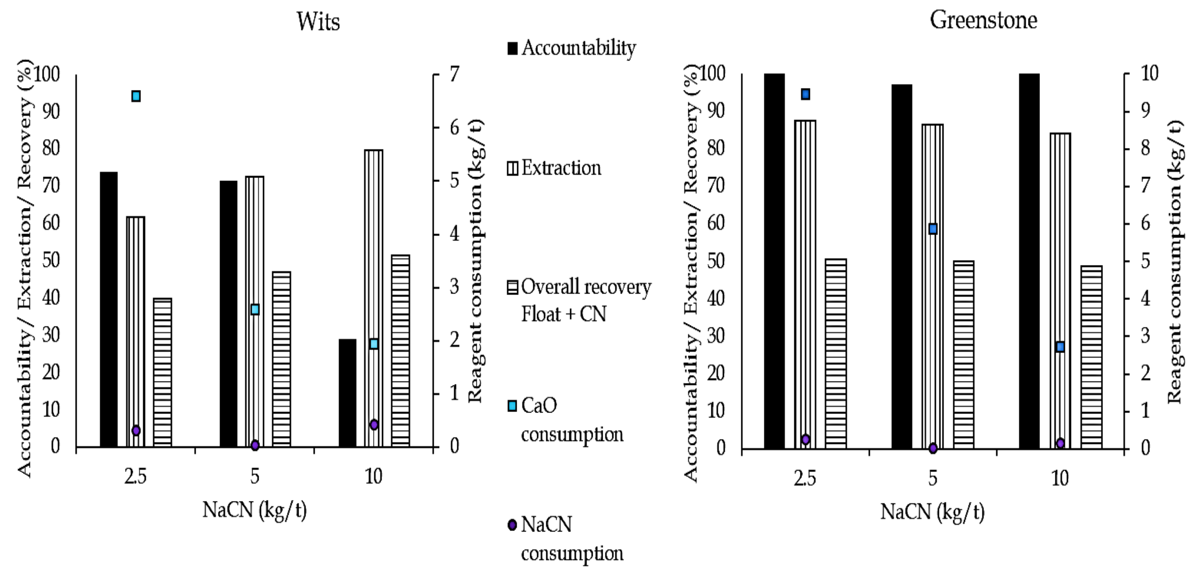

Figure 5. Baseline extraction efficiency of the concentrates.

Composite gold extraction efficiencies

The Wits (3.07 g/t) and Greenstone (3.46 g/t) composites were leached using conditions shown in Table 3 at a NaCN addition of 1.5 kg/t.

Figure 6 shows the gold extraction efficiencies of the two composite samples and the resultant mass balance accountabilities and reagent consumption. Both composite samples achieved an overall gold recovery of 50% (Flotation + CIL). The Greenstone composite had the highest CIL gold extraction of 85% while the Wits composite CIL gold extraction was 80%. The CaO consumption for the Greenstone leach was still high at 4.3 kg/t.

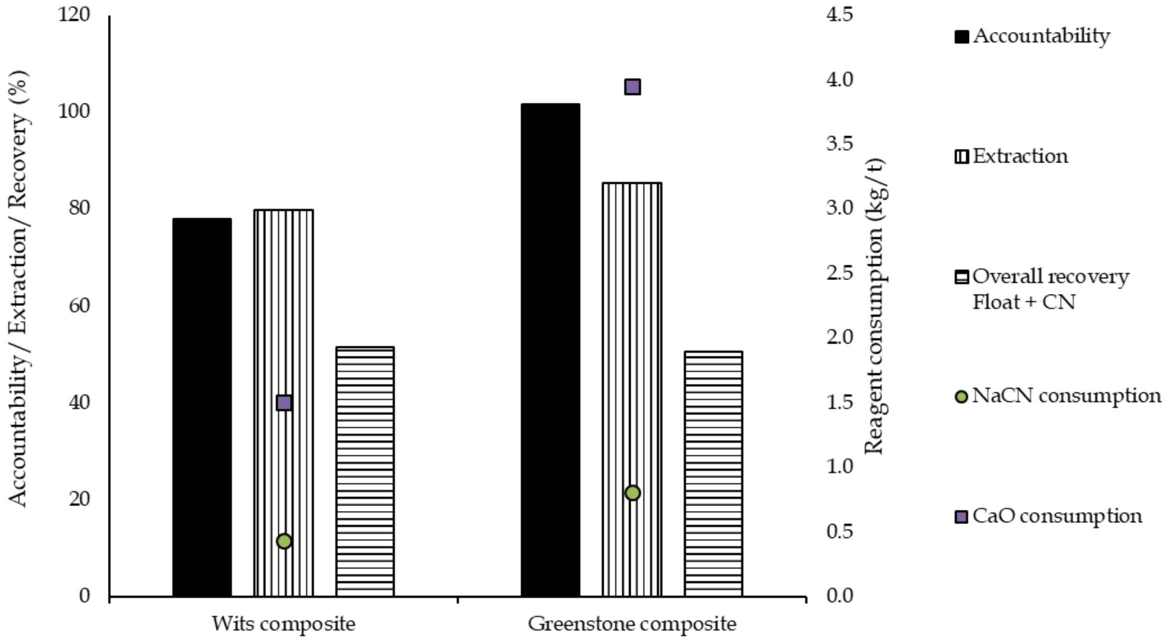

Figure 6. Gold extraction efficiency of the composites.

Environmental stability of final residue

The classification of waste material for disposal purposes helps in understanding the severity the material poses to the environment, i.e., whether the material poses a low risk (termed general waste) or a more significant risk (hazardous waste). The waste materials classification considers the waste type and waste risk profile. The analysed concentrations from the leachates generated from TCLP and SPLP methods indicate the hazardous properties and substances within the material; these are important to perceive the properties and the risk that the material poses for the environment if used for manufacturing of construction material.

Table 11 shows the outcomes of the environmental stability tests, of the final combined residues from flotation and cyanidation of the Wits and Greenstone tailings, alongside the leachable concentration threshold from the NEM: WA Act No.59 of 2008. The colour coding in Table 11 corresponds with the LCT levels. The results coded in green indicate that the concentration of the waste material is less than or equal to LCT0. The blue colour indicates that the concentration is above LCT1 but below LCT2, orange indicates that the concentration is above LCT2 but below LCT3 and the red colour indicates that they are above LCT3.

The classification of both Wits and Greenstone final residues categorised the materials as Type 3 waste, which requires a Class C containment barrier design landfill (or Class B or A). These waste materials are low-risk waste with some potential for contaminant release, the material requires proper control and continuous management to protect health and the environment (NEM: WA No.59 of 2008).

Table 11. Wits and Greenstone final residue leached concentrations of trace elements compared to the leachable concentration threshold from the NEM: WA Act No.59 of 2008

	Leach test method				**Leach concentration threshold**			
	Wits TCLP	**Wits SPLP**	**Greenstone TCLP**	**Greenstone SPLP**	**LCT0**	**LCT1**	**LCT2**	**LCT3**
	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L	mg/L
As, Arsenic	0.83	11.4	0.00	0.05	0.01	0.5	1.	4.00
B, Boron	0.00	0.00	0.00	0.00	0.50	25.0	50.0	200
Ba, Barium	0.00	0.00	0.00	0.00	0.70	35.0	70.0	250
Cd, Cadmium	0.00	0.06	0.00	0.01	0.003	0.15	0.3.	1.20
Co, Cobalt	0.26	3.78	0.15	0.05	0.50	25.0	50.0	200
Cr(VI), Chromium (VI)	0.06	1.59	0.07	0.12	0.10	5.00	10.0	40.0
Cu, Copper	0.18	2.51	0.17	0.13	2.00	100	200	800
Mn, Manganese	1.87	6.22	10.3	8.35	0.50	25.0	50.0	200
Mo, Molybdenum	0.00	0.00	0.08	0.08	0.07	3.50	7.00	28.0
Ni, Nickel	0.78	7.70	0.32	0.28	0.07	3.50	7.00	28.0
Pb, Lead	0.11	1.80	0.01	0.06	0.01	0.50	1.00	4.00
Se, Selenium	0.00	0.00	0.00	0.00	0.01	0.50	1.00	4.00
V, Vanadium	0.00	0.24	0.09	0.13	0.20	10.0	20.0	80.0
Zn, Zinc	1.16	6.84	0.69	0.50	5.00	250	500	2000

The SPLP method leached higher concentrations of elements compared to the TCLP leach test method due to the difference in the ionic strength of applied extraction fluids. However, the SPLP method was not designed for mining waste but rather for waste rock dumps (Hammarstrom and Smith, 2002) and is thus not considered further. Therefore, the classification of both residues was type 3 waste according to the TCLP test results shown in Figure 7. These waste materials can be incorporated into concrete and can be an environmentally beneficial practice but only when the waste materials are safely encapsulated within concrete and do not leach harmful substances into the environment; therefore can potentially provide several benefits, including reducing the use of natural resources and managing waste more sustainably.

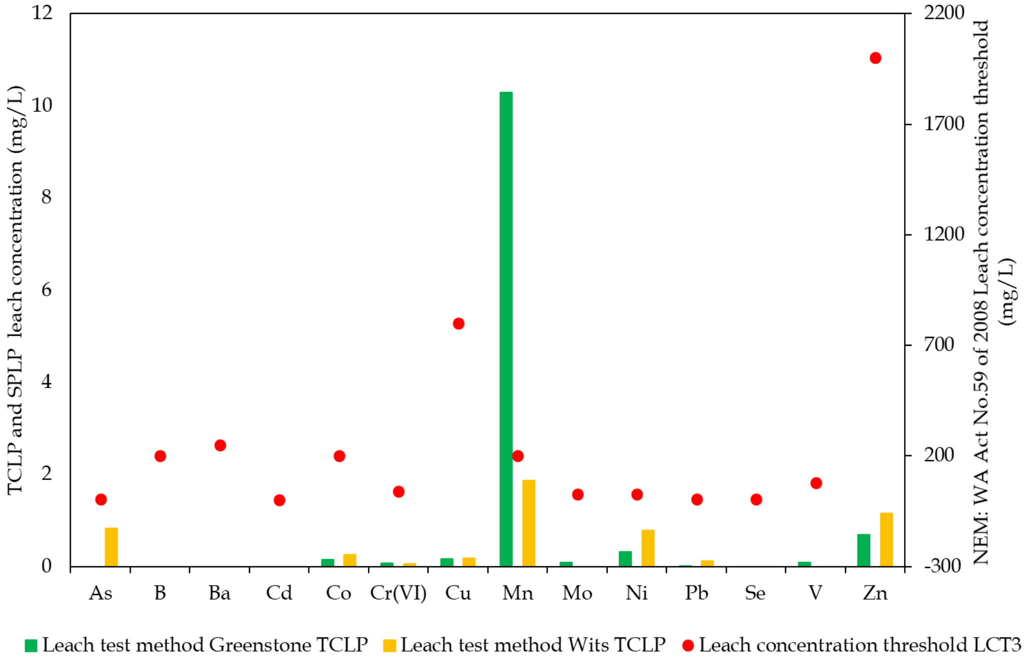

Figure 7. Final residues TCLP results.

CONCLUSIONS

The technology research completed for this scope of work evaluated a flowsheet focusing on gold, sulphide, and uranium extraction from gold tailings dumps, with the products being gold-loaded activated carbon and stable residues suited for construction material fabrication. The efficiency of the gold extraction process further supports the economics of the flowsheet; nevertheless, to further justify the adoption of the recommended flowsheet in a gold rehabilitation project, further design analysis for total capital and operational expenditure is required.

The final residues yielded type 3 waste of lower concentrations of heavy metals in the leachates; therefore, if the Wits and Greenstone tailings residue were to be utilised in manufacturing construction material it could be beneficial to the environment. However, it is of paramount importance to follow guidelines and regulations to ensure that this practice is carried out safely. Some considerations include:

1. Regulatory compliance: Always adhere to local, state, and federal regulations regarding the use of waste materials in concrete. Regulatory requirements can vary, and it is crucial to ensure that all applicable standards and permitting requirements are met.
2. Compatibility testing: Before incorporating waste materials into concrete, thorough testing should be done to ensure that the waste materials are compatible with the concrete mix and will not adversely affect the performance or durability of the concrete. This includes assessing factors such as strength, setting time, and workability.
3. Quality control and monitoring: Quality control measures and ongoing monitoring should be implemented to ensure that the concrete maintains its performance characteristics and that no leaching occurs over time.

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