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Sibanye Gold Limited: Cooke Operations

Geochemical Report for the Millsite TSF

Project Number:

SIB4276

Prepared for:

Sibanye Gold Ltd

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EXECUTIVE SUMMARY

Sibanye Gold Limited (SGL) is planning to reclaim the Millsite TSF, process it through the Cooke plant and then deposit the resultant tailings in one or more of the surface pits which they are currently using to deposit reclaimed Dump 20 tailings.

This study examines the geochemical characteristics of the Millsite TSF material in order to understand the impacts that this material may have on the groundwater resources in the vicinity of the disposal sites and to guide the management process where required. A number of geochemical results were obtained from the metallurgical test work programme to understand the Millsite tailings geochemical properties. Samples were also independently taken and the following findings are made based on the geochemical study conducted on 8 samples from the Millsite TSF:

- The mineralogy is dominated by silica, constituting 33.1 to 93.1% by weight. The difference in the samples mineralogy is suspected to be due to the tailings being sourced from different ores and have been deposited on the TSF over many years. One sample is also enriched in haematite. Pyrite was only detected in one of the 8 samples (Sample 6), at a concentration of 0.6% by weight meaning that the pyrite content is low.
- Sulphide-S was detected in only one sample in significant quantities at 0.62% which is in line with the mineralogy results. The rest of the samples have approximately 0.25% which is slightly less than the 0.3% benchmark required to generate acid sustainably. Since pyrite was only detected in Sample 6, the 0.25% sulphide-S should therefore be present in other Fe containing minerals.
- The average neutralisation potential is 1.3 kg CaCO₃/tonne, while the average acid potential is 17.9 kg CaCO₃/tonne. This means that the average net neutralisation potential (NNP) is -16.7 kg CaCO₃/tonne, indicating that the samples are potentially acid generating.
 - One sample (Sample 5) is unique whereby the NNP is 9.5 kg CaCO₃/tonne. Considering this together with its relatively high paste pH (6.9) and low sulphide content (0.01%), the sample is different from the rest and not potentially acid-generating.
 - The neutralisation potential ratio (NPR) of the samples (excluding Sample 5) was quantified at 0.01, which further confirms that the tailings material is likely to be acid generating. The geochemistry of Sample 5 is excluded from the rest of the samples as its NPR is 30.5 and falls in the non-acid generating category. This sample is an exception and overall Millsite TSF can be classified as potentially acid generating.

- A solid-phase total concentration analysis shows that a number of elements are found at higher concentrations than they are usually encountered in the crustal rocks, out of which arsenic can be considered as the main elements that should be looked at from an environmental perspective. Noteworthy is the scarcity of uranium in the tailings. This is because uranium had been previously extracted and its concentration in the tailings is below the detection limit.

Sulphur species were also analysed by Mintek (2013) on 8 different samples from the Millsite TSF. The sulphide-S was found at higher concentrations than those conducted during this study. The concentration ranged between 0.3 and 0.7%, with the average of 0.6%. This is a clear indication that there is sufficient sulphide to generate acid.

The mine void is generally acidic but is expected to be neutral to alkaline in the vicinity of the pits where the reclaimed tailings (which is high in pH of around 10-11) is being deposited. The tailings material is treated with lime in the metallurgical plant and is generally deposited at high pH values. The samples were therefore leached under neutral (distilled water) and acidic (synthetic precipitation leach procedure, SPLP) solutions to reflect the mine void groundwater under a range of pH conditions.

- The distilled water leach test shows that under neutral pH the following elements can be released from the tailings at concentrations in excess of the WUL limits :
 - Ca in all samples, except in Sample 3;
 - EC in samples 3, 5, and 8;
 - Fe in samples 3, 4, 6, 7 and 8;
 - Mn in samples 1, 3, 4, 7 and 8;
 - Although As is found at higher concentrations in the solid phase (as observed using the multi-element analysis), it is inert in neutral solvent and its solubility is below the detection limit of 0.02 mg/L; and
 - The concentration of U is below the detection limit of 0.004, which is way below the WUL limit of 0.07 mg/L.
- The SPLP leach test shows that under acidic conditions the following metals can be released at concentrations in excess of the WUL limits :
 - Ca and Fe in all samples;
 - Mn in all but Samples 2, 5 and 6;
 - There is no arsenic limit provided in the WUL. However, it is expected to leach to some extent if acidic environment prevails. This is particularly true for Sample 5 where the As concentration is 2.6 mg/L; and
 - As was the case with the distilled water leach result, the concentration of U is below the detection limit of 0.004.

The geochemical results from the Millsite TSF have been compared to previous work conducted on Dump 20 tailings material to evaluate if Millsite is more of an environmental concern than Dump 20. The result shows that the two tailings have similar acid generation potential. The metals expected to leach under neutral or acidic conditions are also generally similar.

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LIST OF ABBREVIATION

ABA	Acid-base accounting
AMD	Acid mine drainage
AP	Acid potential
BPS	Booster pump station
EIA	Environmental impact assessment
EMP	Environmental management plan
NEM:WA	National environmental management: waste act
NNP	Net neutralisation potential
NP	Neutralisation potential
NPR	Neutralisation potential ratio
SGL	Sibanye Gold Limited
SPLP	Synthetic precipitation leaching procedure
TSF	Tailings storage facility
WUL	Water use license
XRD	X-ray diffraction

1 Introduction

Sibanye Gold Limited (SGL) has existing operations supplying its Cooke Plant with ore from reclaimed sand and tailings. This ore feed currently comes from reclamation of Dump 20, Lindum Dump as well as the Cooke Shafts 1, 2 and 3 situated in the West Rand District, Gauteng Province (the Cooke Project). A Mining Right (MR 09/2008) is in place in respect of the farms Randfontein 247 IQ, Waterval 174 IQ, Rietvalei 241 IQ, Uitvalfontein 244 IQ, and Middelvlei 255 IQ. The East Reef Millsite area is situated on the farm Uitvalfontein 244 IQ. This Mining Right authorises mining on the farms for a period of 30 years ending on 6 May 2039. SGL also holds a converted Mining Right (MR 09/2008) to mine gold, uranium, silver, nickel and pyrite which is valid until 17 December 2037.

For the surface operations, SGL is currently reclaiming gold from Dump 20 which consists of a mixture of sand and slimes material as well as the Lindum slimes dam. The Dump 20 project entails the mechanical reclamation of sand which is transported by train to the Cooke Plant as well as the hydraulic reclamation of the Dump 20 slimes tailings residue and hydraulic transportation of the mixture from the existing Dump 20 booster station to the existing Cooke Plant for gold recovery, via a dedicated pipeline. The resultant residue tailings are disposed of into several open cast mining pits, namely the Millsite, Battery 1 & 2, Porges, SRK 2 & 3 and Training open pits. These open pits formed part of the historical Lindum Reefs Operations which were previously dormant and required rehabilitation.

The Dump 20 resource is nearing its end and SGL now intends to reclaim the Millsite Tailings Storage Facility (TSF) which is located adjacent to SGL's Water Treatment Plant and Dump 20. The focus of this document is on the inclusion of the Millsite TSF into the existing Cooke Operations and the specific activities to be undertaken.

The Millsite deposit consists of dams 38, 39, 40 and 41 under the Mining Right GP 30/5/1/2/2 (173) MR, MR 09/2008 and 190/2008.

SGL commissioned Digby Wells Environmental (Digby Wells) to conduct an Environmental Impact Assessment (EIA) and provide an Environmental Management Plan (EMP) for the proposed reclamation and deposition of re-processed tailings material.

As part of this EIA, Digby Wells conducted a geochemistry study to evaluate the characteristics of the Millsite TSF tailings by conducting acid-base accounting and leachate tests.

Acid mine drainage (AMD) and metal leaching are widespread phenomenon affecting the quality of water at many South African mines. To operate a mine in an informed, environmentally responsible manner, the metal leaching and AMD potential of all the materials excavated, exposed or otherwise disturbed must be understood and managed to prevent metal leaching and AMD through prediction and design, avoiding long-term mitigation and risk wherever possible.

Sulphide minerals are the primary sources of acidity and dissolution of metals from mine wastes, and their measurement is a critical requirement in drainage chemistry prediction. This study focused on the multi-element composition, mineralogical composition, Acid Base Accounting (ABA) and leachate tests to evaluate the AMD generation and metal leachate concentrations of the reprocessed tailings materials.

The hydraulic reclamation activity to be followed is identical to the current approved activities for Dump 20 and Lindum. An existing Booster Pump Station (BPS) is currently in place at Dump 20 which will remain and be utilised for the reclamation of the Millsite TSF and pumping it to the Cooke plant. A finger screen will be put in place at the toe of the Millsite TSF from where the slurry material will enter a sump. A drain pipe will be put in place from the sump to a vibrating screen prior to entering tank from where it will be pumped in a slurry pipeline that will convey the tailings to the BPS at Dump 20. This slurry pipeline will be a 450 mm diameter pipeline with a 6mm rubber lining.

The residue is to be deposited into the open pit voids at the rate of 400 000 tons/month. Cyanide destruction will take place in the Cooke Plant before the residue is deposited.

2 Objectives

The objectives of the study are to:

- Evaluate the acid generation and/or neutralisation potential of the Millsite tailings;
- To identify and measure the concentration of different sulphur species present, in light with their potential to oxidise and generate acid;
- Identify the mobilisable metals that will leach under acidic and neutral environmental conditions;
- Compare the Millsite leachate quality with the groundwater quality WUL limits associated with the pit deposition;
- Compare the Millsite tailings geochemistry with Dump 20 (which has been reclaimed in the past); and
- Identify the source-term concentration that will be used as an input into the groundwater simulation model.

3 Methodology

Eight samples of approximately 2.5 kg of the tailings were collected for acid-base accounting (ABA) and leachate tests under static conditions. The location of the sampling points is illustrated in Figure 3-1.

Samples 1 and 2 were collected from the top 0.5 m of the TSF to represent the oxidised (weathered) part. The remaining 6 samples (Samples 3 to 8) were collected from the fresh and saturated sections at a depth of approximately 1 m from surface.

The initial terms of reference included waste classification to be conducted as per the National Environmental Management: Waste Act 59 of 2008 (as amended by the National Environmental Management: Waste Amendment Act 26 of 2014) (NEM:WA). The objective of a waste classification is to determine the waste type as per the NEM:WA standards and specify the type of liner required to dispose the tailings on. However, SGL is intending to deposit the reclaimed tailings into the open pit voids that are interconnected with the underground mine voids. There is no need of liner requirements and hence waste classification is deemed unnecessary.

The collected samples were sent to M&L Laboratory in Johannesburg for analysis of the following parameters:

- **Mineralogical examination** – X-ray diffraction (XRD) was utilised to identify the major and minor minerals in the tailings. XRD allows for the measurement of the crystal structures to identify the mineralogical composition to determine whether any reactive elements will lead to environmental risks through the study of the various minerals;
- **Acid-base accounting (ABA) and Sulphur Speciation** – these were conducted by evaluating the acid generation and acid neutralisation potential of the samples. The amount of the various sulphur species in the tailings was also analysed to determine their oxidation states since mine acid is primarily generated from sulphide sulphur;
- **Net Acid Generating (NAG) testing** – this was conducted to provide an indication of the behaviour of the samples under oxidising conditions (reaction with hydrogen peroxide), using a standard NAG test method; and
- **Static leach testing** – would provide an indication of the readily leachable components present in a samples by exposing the samples to a leachate extraction. Two tests were conducted in this study:
 - As specified in the NEM:WA Regulations (2013), a reagent (distilled) water was used to leach the samples at a 1:20 solid to water ratio (i.e. 5% reagent water extraction) was prepared and analysed by the laboratory. This analysis will be used to characterise the mobile metals that could be released from the tailings if a neutral pH conditions prevails; and
 - The samples were also exposed to the Synthetic Precipitation Leaching Procedure (SPLP). The test was conducted under acidic environment of pH 4.2. The pH of the mine void is generally acidic but is expected to be neutral in the vicinity of the pits where the reclaimed tailings (which is high in pH of around 10-11) is being deposited. The leaching of the samples under neutral and acidic solution was conducted with the intention of reflecting the mine void water under a range of pH conditions.

- **Total Concentration Analysis** - Total concentration values were determined by *aqua regia* digestion as stipulated in the NEM: WA Regulations (2013). The objective of the total concentration analysis was to provide a measure of the solid-phase levels of various mineral-forming elements that may be of environmental concern. Combined with the metal leachate test, these levels allow the calculation of metal depletion times and can be used as a screening tool to detect constituents which occur in anomalously high concentrations and may, under unfavourable geochemical conditions, be of concern as a constituent in AMD.

The geochemical results of the Millsite TSF have been compared to previous work conducted on Dump 20 to evaluate if the Millsite is more of an environmental concern than Dump 20. In 2012 three samples were analysed from Dump 20 for ABA and leachate assessments. The samples were collected from the sand residue, slime residue and composite sample (sand residue mixed with underground tonnage). In the discussions to follow, these samples are labelled as Dump 20 Sand, Dump 20 Slime and Dump 20 Composite; and have been compared with the Millsite TSF geochemistry.

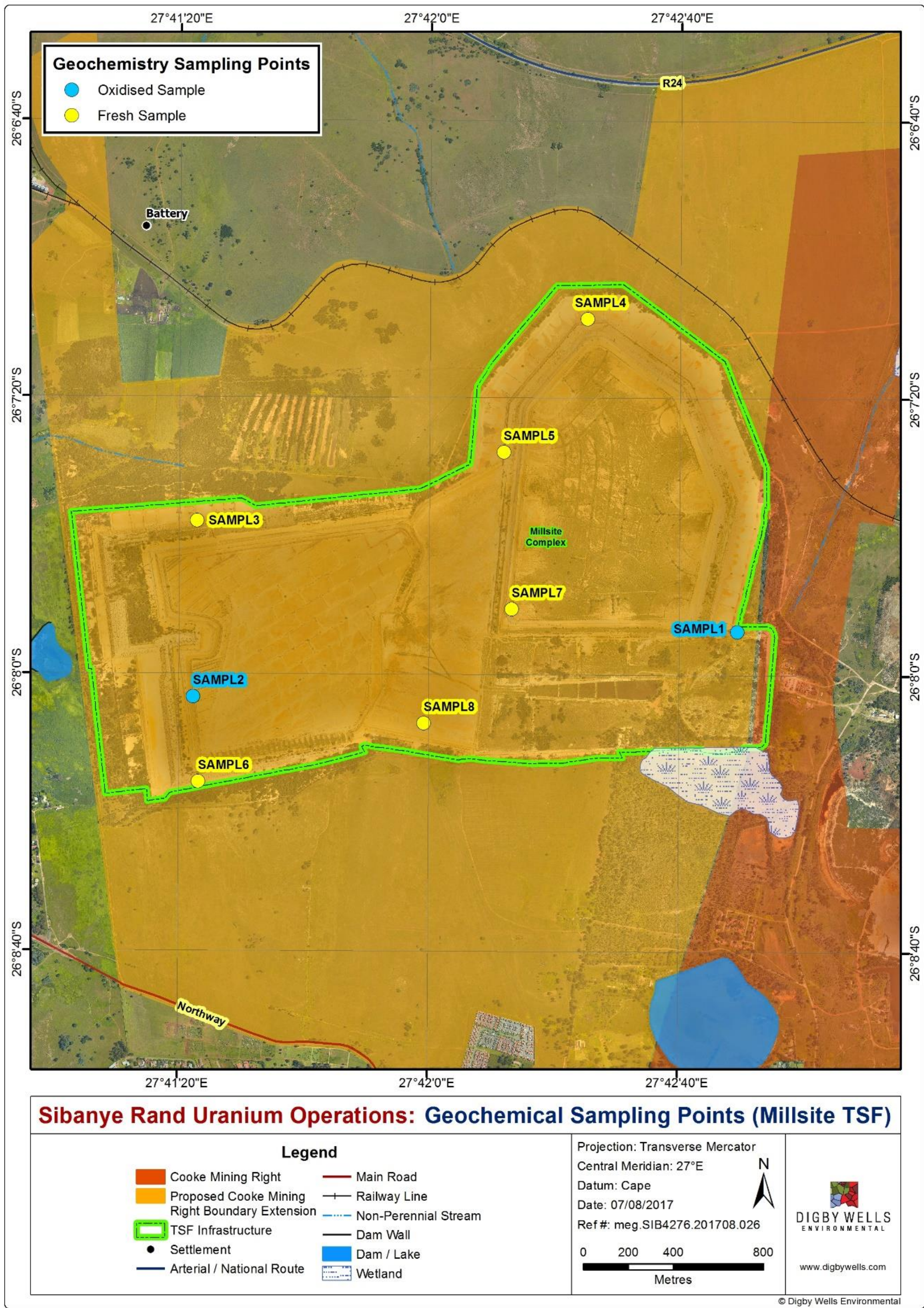


Figure 3-1: Location of the Tailings Sampling Points

4 Investigation Results

4.1 Mineralogy

Identification of the mineralogy of the tailings is necessary for determining the potentially leachable metals and the acid generating and neutralizing minerals, and is thus valuable information for site-specific predictions of drainage chemistry.

The mineralogical composition of the tailings samples is given in Table 4-1. Copies of the analytical reports are presented in Appendix A.

The samples are dominated by silicate minerals, particularly quartz, pyrophyllite, muscovite and kaolinite. Quartz is the primary constituent ranging between 33.1 to 93.1% by weight. The difference in the samples mineralogy is suspected to be due to the tailings being sourced from different ores and have been deposited on the Millsite TSF over many years.

The non-silicate minerals are dominated by hematite and jarosite, which are oxidised Fe minerals. Pyrite was only detected in Sample 6, at a concentration of 0.6% by weight meaning that pyrite is not significant in the tailings. Although no calcite minerals have been detected in any of the samples, pyrophyllite, muscovite, jarosite, and kaolinite are hydroxides and have the potential to buffer acidity.

Based on the mineralogy alone, the TSF is acid neutralising although pockets of potential acid generation (e.g. in the area where Sample 6 was collected) cannot be excluded. However, this needs to be supported by the ABA analysis that will be discussed in the subsequent sections.

The mineralogy of the Dump 20 is also included in Table 4-1. At 1.4%, the pyrite content is the higher than that of Millsite where the maximum recorded is 0.6%. At the same time there are more silicate hydroxides (mainly Chloritoid and Chlorite) in Dump 20 which could assist in buffering any acid generation. More comparisons on the ABA and leachate quality between the two TSFs is discussed below.

Table 4-1: Weight % of the Mineralogy

Mineral	Approximate Formula	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8	Dump 20 composite
Quartz	SiO ₂	83.24	93.09	82.94	77.47	33.14	81.71	70.81	84.99	90.59
Pyrophyllite	Al(Si ₂ O ₅)(OH)	10.68	5.04	10.92	9.21	4.78	11.66	16.7	9.89	2.83
Hematite	Fe ₂ O ₃				3.69	59.56				
Muscovite	KAl ₂ ((OH) ₂ AlSi ₃ O ₁₀)	3.48	1.86	3.38	4.52	1.22	3.79	6.48	1.87	2.04
Jarosite	KFe ₃ (SO ₄) ₂ (OH) ₆	2.6		2.75	2.94	1.3	2.21	2.78	1.69	
Bassanite	CaSO ₄ •0.5H ₂ O				2.18			1.57	1.57	
Kaolinite	Al ₄ (OH) ₈ (Si ₄ O ₁₀)							1.66		
Pyrite	FeS ₂						0.63			1.41
Chloritoid	(Fe,Mg,Mn) ₂ Al ₄ Si ₂ O ₁₀ (OH) ₄									2.42
Chlorite	(Mg,Fe,A1) ₆ (Si,A1) ₄ O ₁₀ (OH) ₈									0.71

4.2 Acid-Base Accounting

ABA is the most widely used static test to predict acid-mine drainage potential. The ABA results are summarised in Table 4-2 below and laboratory certificates are available in Appendix A.

The test consisted of six measurements:

- The paste pH;
- The amount of acidity a sample can produce (acid potential or AP);
- The inherent neutralization potential (NP) of the same sample;
- Sulphur speciation;
- The net neutralisation potential (NNP) which is NP-AP; and
- The neutralisation potential ration (NPR) which is NP/AP.

Table 4-2: Summary of the ABA Results

Sample ID	Paste pH	AP (kgCaC O ₃ /t)	NP (kgCaC O ₃ /t)	NNP (kgCaC O ₃ /t)	NPR	Total S%	Sulphate S %	Sulphide S%
Sample1	3.1	9.68	0.1	-9.68	0.01	0.31	0.1	0.21
Sample2	3.3	8.12	0.24	-8.12	0.030	0.26	0.21	0.05
Sample3	1.9	34.3	0.1	-34.3	0.003	1.1	0.82	0.28
Sample4	2.6	27.5	0.1	-27.5	0.004	0.88	0.84	0.04
Sample5	6.9	0.31	9.45	9.45	30.48	<0.01	<0.01	0.01
Sample6	1.7	22.8	0.1	-22.8	0.004	0.73	0.11	0.62
Sample7	2.1	21.8	0.1	-21.8	0.005	0.7	0.44	0.26
Sample8	2	18.7	0.1	-18.7	0.005	0.6	0.33	0.27
Dump 20 Composite	10.1	87.53	1.96	-85.57	0.02	2.8	0.01	2.78
Dump 20 Slime	8.4	22	9.4	-12.6	0.4	1	0.88	0.71
Dump 20 Sand	8.4	21	9.1	-11.9	0.4	0.91	0.71	0.67

4.2.1 Paste pH

The paste pH is used to provide a preliminary estimation on the acid generation potential of a rock sample. The sample is placed in a plastic beaker and 10 mL of distilled water (pH 5.33) is added to make a paste. The paste is stirred with a wooden spoon to wet the powder. This way, a quick measure of the relative acid-generating (pH<4) or acid-neutralizing (pH>7) potential of the waste material can be evaluated (Sobek et al. (1978)).

The paste pH of the samples was found to be acidic ranging between 1.7 and 3.3 (with the exception of Sample 5 at a pH of 6.9). Although this indicates the potential for the residue to generate acid, paste pH alone is not a conclusive methodology for ABA classification. The sulphide content, acid generating and acid neutralisation materials of the tailings need to be quantified for a more comprehensive ABA evaluation.

The paste pH of Dump 20 was found to be alkaline with an average of 9.0; indicating that without oxidising the residue is still alkaline.

4.2.2 Sulphur Speciation

The objective of sulphur analysis is to identify and measure the concentration of different sulphur species present in the sample. Sulphide minerals are the primary sources of acidity and leaching of trace metals, and their measurement is a critical requirement for acid drainage chemistry prediction.

A set of rules, which has been derived based on several of the factors calculated in ABA, was reported by Soregaroli and Lawrence (1998). It has been shown that for sustainable long-term acid generation, at least 0.3% Sulphide-S is needed. Values below this can yield acidity but this is likely to be only of short-term significance.

The sulphur species analysed for the tailings samples included total sulphur-S, sulphate-S and sulphide-S. The highest Sulphide-S was detected in Sample 6 at 0.62%. The rest of the samples have approximately 0.25% which is slightly less than the 0.3% benchmark required to generate acid sustainably. As discussed above, pyrite was only detected in Sample 6. The 0.25% sulphide-S should therefore be present in other Fe containing minerals.

Sulphur species and mineralogical assessment were also conducted by Mintek (2013) on 8 different samples from the Millsite TSF. The sulphide-S and pyrite were found at higher concentrations than those conducted during this study. The sulphide concentration ranged between 0.3 and 0.7%, with the average being 0.6%. This is a clear indication that there is sufficient sulphide to generate acid. The pyrite content was also found to range between 0.7 and 1.7 and is likely to be the source of the sulphides. Although the depth of sampling is not available, the samples tested by Mintek are expected to have been collected from a greater depth where it is less oxidised and hence higher pyrite and sulphide content.

The sulphide content of the Dump 20 was on average 1.4% and is more than that of Millsite. It could generate acid more sustainably than Millsite if not buffered by the alkaline minerals present. This is also in line with the mineralogical content since more pyrite was detected in Dump 20.

4.2.3 Net Neutralisation Potential (NNP)

The difference between the neutralisation potential (NP) and the acid potential (AP) is defined as the net neutralization potential (NNP); i.e. $NNP = NP - AP$.

A positive NNP would indicate that there is more neutralising material than acid forming material in any given sample, i.e.:

- If NNP is less than 0 then the sample has the potential to generate acid;
- If NNP is more than 20 then the sample will probably be alkaline; and
- If the NNP is between 0 and 20, the acid or alkaline properties are not certain and it falls in a category which could go either way. Further investigation would be needed to confirm the properties of the sample and there may be a time delay in either effect being apparent.

The NP, AP and NNP of the samples is given in Table 4-2 and shows that the samples are all acid producing. Although some neutralisation potential is detected in some samples, their overall acid generation potential is more than the neutralisation potential.

The average NP is 1.3 CaCO₃/tonne, while the average AP is 17.9 CaCO₃/tonne. This means that the average NNP is -16.7 CaCO₃/tonne, indicating that the samples are potentially acid generating.

Sample 5 is unique whereby the NNP is 9.5 CaCO₃/tonne. This together with its relatively high paste pH (6.9) and low sulphide content (0.01%), the sample is different from the rest and not potentially acid-generating. The high haematite levels indicate that it may be calcine material.

The average NNP of the Dump 20 was -36.7 CaCO₃/tonne and this is more acid generating than Millsite.

4.2.4 Neutralisation Potential Ratio

Similar to the NNP, the Neutralisation Potential Ratio (NPR) is used to identify and separate potentially acidic generating from not potentially acidic generating materials. The NPR is calculated by dividing the NP by the AP.

The potential for acid generation was evaluated by using the screening criterion set by Price (1997) as shown in Table 4-3. The NPR of the tailings samples (excluding Sample 5) was quantified between 0.0 and 0.03, the average being 0.01, which confirms that the TSF is likely to be acid generating (Figure 4-1). The geochemistry of Sample 5 is excluded from the rest of the samples as its NPR is 30.5 and falls in the non-acid generating category. This sample is an exception and overall Millsite TSF can be classified as potentially acid generating.

The NPR of Dump 20 is also included in Figure 4-1. The three samples from this TSF are marked with red and all fall on the potentially acid-generating zone and have similar geochemical ABA values to that of the Millsite TSF.

Table 4-3: Criteria for Interpreting ABA Results

Potential for ARD	Criterion	Comments
Likely	$NPR < 1$	Potentially acid generating, unless sulphide minerals are non-reactive
Possible	$1 < NPR < 2$	Possibly acid generating if NP is insufficiently reactive or is depleted at a rate faster than sulphides
Low	$2 < NPR < 4$	Not potentially acid generating unless significant preferential exposure of sulphide
None	$NPR > 4$	Non-acid generating

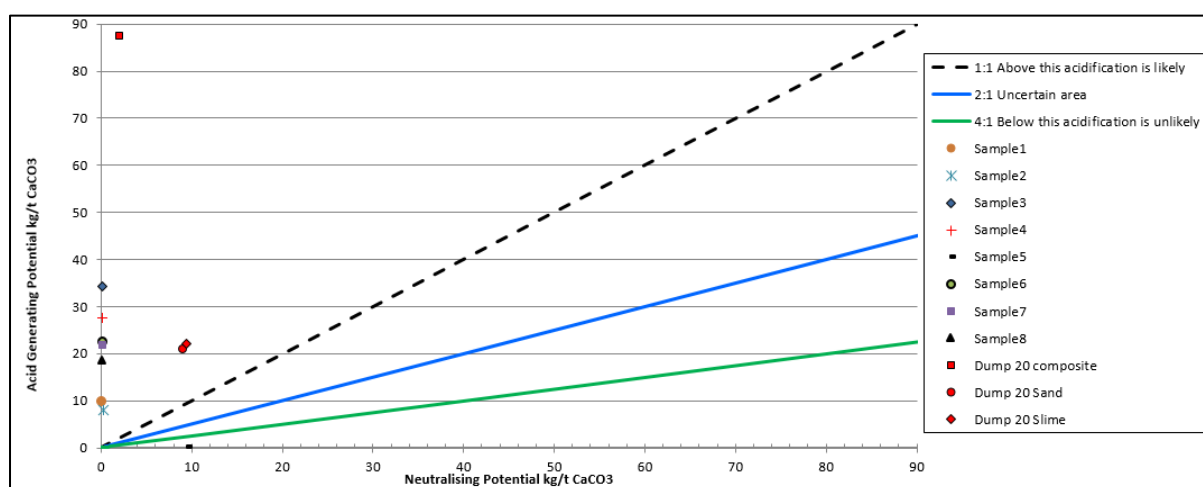


Figure 4-1: Comparison of the Neutralisation Potential and Acid Potential of the Sample

Another method for classifying non-potentially acid-generating material from the potentially acid-generating materials is based on the ratio of neutralisation potential ratio (NPR) versus sulphide-sulphur (Soregaroli and Lawrence, 1998). Should the NPR be less than 1 and the sulphide-S content greater than 0.3%, the sample is considered to be potentially acid generating.

As can be seen in Figure 4-2, half of the samples (including Dump 20) are acid generating due to their sulphide content being more than 0.3% and NPR values being less than 1. The remaining half fall in the non-acid generating zone due to their sulphide content being less than 0.3%, although their NPR values are still less than 1.

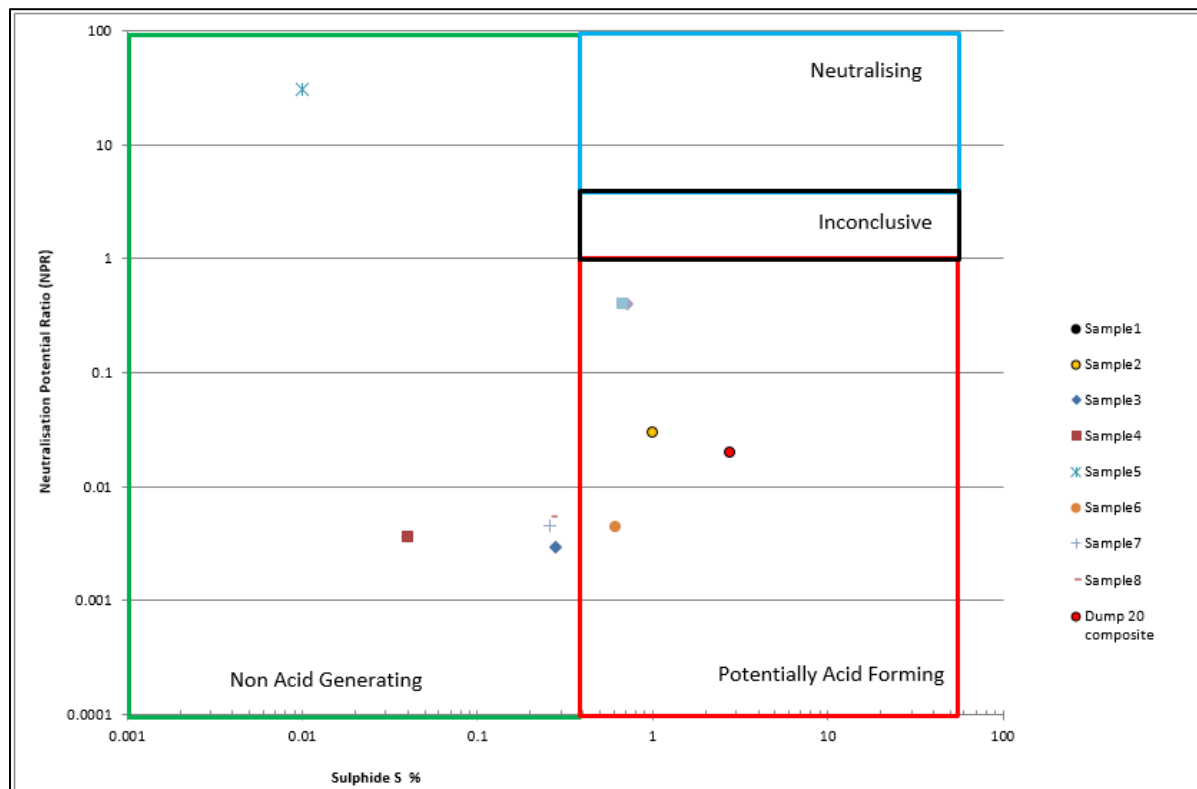


Figure 4-2: Sulphide-S vs NPR

4.2.5 Net Acid Generation (NAG)

The net acid generating (NAG) test is associated with ABA to classify the acid generating potential of a sample. It is conducted by reacting the sample with hydrogen peroxide to assess the components released by fast mineral dissolution and oxidation reactions, especially sulphide oxidation and carbonate dissolution. Both acid generation and acid neutralization reactions occur simultaneously and the net result represents a direct measure of the amount of acid generated.

As stated by the Global Acid Drainage Guide (GARD, 2017) a pH after reaction (NAG pH) of less than 4.5 indicates that the sample is net acid generating. This subdivision is slightly arbitrary and can serve as a rough guideline but not as stand-alone criteria in categorising the sample.

Miller (1998) provided a predictive criteria for NAG testing as shown in Table 4-4 and the laboratory results are provided in Table 4-5.

Table 4-4: Predictive Criteria for NAG Testing

NAG Prediction	Final NAG pH	NAG as H ₂ SO ₄ (kg/t)
High capacity of acid generation	< 4.5	> 5
Low capacity of acid generation	< 4.5	0-5

NAG Prediction	Final NAG pH	NAG as H₂SO₄ (kg/t)
Potentially non net acid generating and potentially net acid neutralizing	4.5	0
Uncertain	Any disagreement between the above NAG predictions and the ABA prediction	

Table 4-5: NAG Test Results

Sample ID	NAG pH	NAG as H₂SO₄ (kg/t)
Sample1	4.7	1.0
Sample2	4.9	1.0
Sample3	2.6	9.89
Sample4	4.6	1.0
Sample5	7.1	<1
Sample6	2.1	9.17
Sample7	3.3	0.8
Sample8	2.9	1.8
Dump 20 Composite	2.2	29.01
Dump 20 Slime	2.9	NA
Dump 20 Sand	2.8	NA

Figure 4-3 is a plot of NPR and NAG pH and identifies four quadrants.

- Samples with NPR greater than 1 and NAG pH greater than 4.5 plot in the non-acid forming quadrant. Only Sample 5 falls in this zone;
- Samples with NPR less than 1 and NAG pH less than 4.5 plot in the potentially acid forming quadrant. Sample 5 falls in this quadrant;
- Samples with conflicting ABA and NAG results plot in the uncertain quadrants. In Figure 4-3, only Sample 2 plot in the uncertain quadrant and follow up testing can be targeted on this sample to confirm the classification; and
- The remaining 7 Millsite and 3 Dump 20 samples fall in the potentially acid forming category.

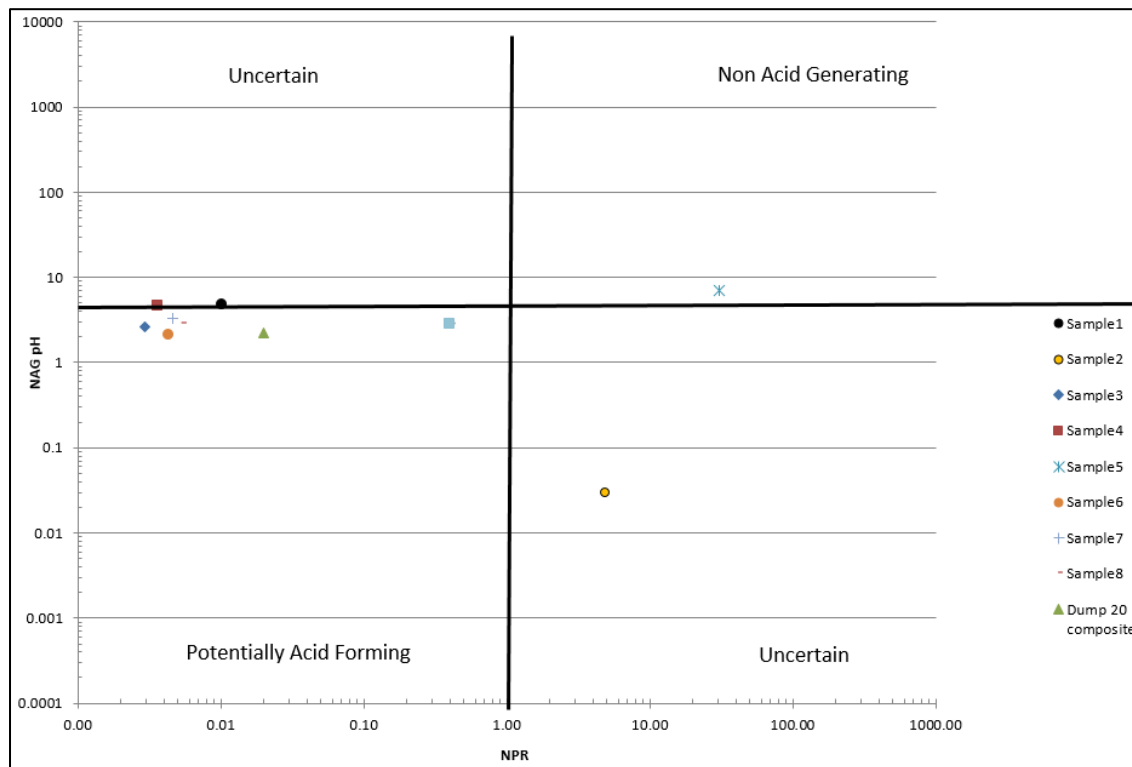


Figure 4-3: NNP vs NAG pH

4.3 Multi-Element Composition

The objective of the multi-element analysis is to provide a measure of the solid-phase levels of various mineral-forming cations that may be of environmental concern. Combined with the metal leachate test, these levels allow the calculation of metal depletion times and can be used as a screening tool to detect constituents which occur in anomalously high concentrations and may, under unfavourable geochemical conditions, be of concern as a constituent in AMD.

In this study, determination of which elements occur in high concentrations is made by comparing the multi-element analytical results with the average range of concentrations of these elements in the continental crust as shown in Table 4-6. The average range of metal concentrations in the crust is obtained from Price (1997).

A number of elements (the most being in Sample 5) are found at higher concentrations in the samples than they are usually encountered in the crustal rocks (highlighted in orange in Table 4-6), out of which arsenic can be considered as the main elements that should be looked at from an environmental perspective. This is to be expected from a mineralised and enriched sample.

Noteworthy is the scarcity of uranium in the tailings. This is because uranium had been previously extracted and its concentration in the tailings is below the detection limit.

The Dump 20 samples were not exposed to aqua regia digestion in 2012 and their multi element analysis is not included in Table 4-6.

Table 4-6: Result of the Multi-Element Composition Analysis

Element (mg/Kg)	Average value in continental crust (ppm)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
Ag	0.075	<0.400	<0.400	<0.400	<0.400	<0.400	<0.400	<0.400	<0.400
Ti	5,650	227	199	193	200	210	199	184	147
Al	82,300	28,815	17,500	31,310	24,110	16,870	50,095	48,030	13,290
Fe	56,300	20,515	18,370	23,930	39,310	430,800	16,965	12,110	11,270
Mn	950	193	183	187	185	454	136	70	177
Mg	23,300	1,251	1,399	1,104	971	1,767	1,135	698	551
Ca	41,500	1,427	2,760	1,102	7,254	6,993	1,711	4,649	3,623
Na	23,550	712	306	586	599	318	628	1,215	241
K	20,850	2,431	951	2,363	4,573	1,306	2,808	3,531	1,280
As	1.8	269	51	45	350	1,363	62	98	56
Co	25	5	3	41	37	703	11	12	26
Cr	102	188	130	186	138	140	156	179	97
Cu	60	37	14	67	36	773	12	51	28
Ni	84	26	20	122	72	928	22	38	65
Sb	0.2	<1.000	<1.000	<1.000	<1.000	<1.000	<1.000	<1.000	<1.000

Element (mg/Kg)	Average value in continental crust (ppm)	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5	Sample 6	Sample 7	Sample 8
Be	2.8	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200
Bi	0.0085	<0.500	<0.500	<0.500	<0.500	<0.500	<0.500	<0.500	<0.500
Cd	0.15	2	1	1	3	10	1	1	1
Pb	14	43	27	42	273	275	38	41	48
Mo	1.2	<0.100	<0.100	<0.100	<0.100	<0.100	<0.100	<0.100	<0.100
Se	0.05	16	10	12	32	363	<3.000	<3.000	<3.000
Sr	370	32	16	25	33	9	28	44	22
Tl	0.85	<0.900	<0.900	<0.900	<0.900	<0.900	<0.900	<0.900	<0.900
Th	9.6	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200	<0.200
Sn	2.3	<2.000	<2.000	13	<2.000	11	<2.000	<2.000	<2.000
U	2.7	<0.400	<0.400	<0.400	<0.400	<0.400	<0.400	<0.400	<0.400
V	120	38	27	33	24	44	31	28	17
Zn	70	51	77	110	138	515	32	67	73
Zr	165	95	78	90	88	44	82	81	64
Ba	425	55	28	52	130	31	56	62	30

4.4 Leachate Test

Distilled water and SPLP leachate tests assist in characterising the mobile elements that could be released from the tailings under neutral and acidic pH conditions. The distilled water leachate results are given in Table 4-7 and the SPLP are given in Table 4-8. Both results have been compared with the mine's WUL for groundwater quality.

4.4.1 Distilled Water Leachate

The pH of the leachate is acidic and is below the WUL limit of 6.0, with the exception of Sample 5 where it is 8.2. This is in line with the paste pH results whereby all samples were acidic (except for Sample 5).

The elements that exceed the WUL include:

- Ca in all samples, except in Sample 3;
- EC in samples 3, 5, and 8;
- Fe in samples 3, 4, 6, 7 and 8;
- Mn in samples 1, 3, 4, 7 and 8;
- Although As is found at higher concentrations in the solid phase (as observed using the multi-element analysis), it is inert in neutral solvent and its solubility is below the detection limit of 0.02 mg/L; and
- The concentration of U is below the detection limit of 0.004, which is way below the WUL limit of 0.07 mg/L.

4.4.2 SPLP Leachate

The pH of the SPLP leachate is similar to that of the distilled water. All of the samples leached at a pH that is below the WUL limit, except for Sample 5 where it is 7.3. This is a further confirmation that Sample 5 has more neutralisation potential that was also confirmed using the ABA analysis and can buffer acid generated at least in the short-term. The rest of the samples are likely to generate acid with no or limited buffering capacity.

More metals leached under acidic condition (SPLP) than when the solution is neutral (reagent water). The metals that exceed the WUL include:

- Ca and Fe in all samples;
- Mn in all but Samples 2, 5 and 6;
- There is no arsenic limit provided in the WUL. However, it is expected to leach to some extent if acidic environment prevails. This is particularly true for Sample 5 where the As concentration is 2.6 mg/L; and
- As was the case with the distilled water leach result, the concentration of U is below the detection limit of 0.004.

Table 4-7: Distilled Water Leachate Test Results

Variables	WUL limits	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5	SAMPLE 6	SAMPLE 7	SAMPLE 8	Dump 20 composite	Dump 20 Slime	Dump 20 Sands
pH	6.0-8.5	4.1	4.9	2.7	3.9	8.2	3	3.2	3	10	9.1	9
EC (mS/m)	150	38.2	58.6	174	113	148.4	71.9	88	153.5	NA	20	33
Ca (mg/L)	32.01	48	138	25	307	386	44	133	223	195	30	52
Mg (mg/L)	21.73	6.5	0.7	48	1.7	22	1.1	3.7	25	0.315	2.9	4.2
Na (mg/L)	12.21	3	2.8	2.7	2.9	4.9	3	3	3.2	21	1.6	1.4
Alkalinity (CaCO ₃ mg/L)	100	-	4	-	-	30	-	-	-		20	15
Cl (mg/L)	10.23	0.8	0.7	1.4	0.8	1.5	0.7	0.7	1.6	101	1.1	0.46
SO ₄ (mg/L)	600	156	225	726	525	713	161	276	621	360	70	139
Nitrate (mg/L)	0.74	<0.1	0.3	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.2	<0.1	<0.1
F (mg/L)	0.09	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	<0.2	0.21	0.25
Al (mg/l)	NA	6.3	0.1	83	1.6	0.07	1.7	7.7	14.6	3.3	0.42	0.5
As (mg/l)	NA	<0.020	<0.020	<0.020	<0.020	2.9	<0.020	<0.020	<0.020	<0.01	0.01	<0.01
Cr (mg/l)	NA	<0.003	<0.003	0.61	0.003	<0.003	0.008	0.04	0.16	0.11	0.008	0.004
Cu (mg/l)	NA	0.21	0.01	2	0.05	0.008	0.05	0.2	0.35	<0.01	<0.02	<0.02
Fe (mg/L)	0.2	0.04	0.04	28	0.25	0.11	6.7	0.83	1.3	0.047	<0.05	<0.05
Hg (mg/L)	NA	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.0001	<0.0001
Mn (mg/L)	0.1	0.31	0.03	2.4	1.5	0.002	0.04	0.46	13.1	<0.01	<0.01	<0.01
Ni (mg/l)	NA	0.14	0.01	4.6	0.12	<0.003	0.08	0.5	5	<0.01	<0.005	<0.005

Variables	WUL limits	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5	SAMPLE 6	SAMPLE 7	SAMPLE 8	Dump 20 composite	Dump 20 Slime	Dump 20 Sands
Pb (mg/l)	NA	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.010	<0.01	<0.01	<0.01
U (mg/L)	0.07	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.01	0.02	0.02
Zn (mg/l)	NA	0.12	0.05	3.7	0.31	0.005	0.21	0.69	4.8	<0.01	0.03	<0.01

Table 4-8: SPLP Leachate Test Results

Variables	WUL limits	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5	SAMPLE6	SAMPLE 7	SAMPLE 8	Dump 20 composite	Dump 20 Slime	Dump 20 Sands
pH	6.0 - 8.5	4.1	4.7	2.7	3.8	7.3	2.7	3.1	3.2	6.7	5.7	5.8
EC (mS/m)	150.0	45.3	64.8	194	132.0	49.3	125.0	115.0	128.0	NA	89.0	85.0
Ca (mg/L)	32.0	53	142	51	346	92	80	190	210	278	210	160
Mg (mg/L)	21.7	10.6	0.8	70	2.1	10.6	2.5	5.4	16.6	27	18	16
Na (mg/L)	12.2	3.0	3.6	3.1	3.1	4.0	3.2	3.1	3.2	21	6.5	9.9
Alkalinity (CaCO3 mg/L)	100.0	-	1.0	-	-	22.0	-	-	-		400	450
Cl (mg/L)	10.2	0.5	0.2	0.9	0.3	1.3	0.4	0.2	0.6	86	<0.05	0.6
SO4 (mg/L)	600.0	180.0	240.0	814	622	163.0	273.0	475.0	567.0	330.0	164.0	73.0
Nitrate (mg/L)	0.7	0.1	<0.1	<0.1	0.2	0.4	0.2	0.1	<0.1	0.2	<0.1	<0.1
F (mg/L)	0.1	0.1	<0.1	<0.1	<0.1	0.1	<0.1	<0.1	<0.1	<0.2	0.1	0.1
Al (mg/l)	NA	10.8	0.5	118.0	2.2	0.1	4.6	12.0	16.8	0.1	0.2	0.0

Variables	WUL limits	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5	SAMPLE6	SAMPLE 7	SAMPLE 8	Dump 20 composite	Dump 20 Slime	Dump 20 Sands
As (mg/l)	NA	0.1	0.1	<0.02	0.1	2.6	0.0	0.1	0.1	0.0	0.0	0.0
Cr (mg/l)	NA	<0.003	<0.003	0.8	<0.003	<0.003	<0.003	<0.003	<0.003	0.1	0.0	<0.002
Cu (mg/l)	NA	0.2	<0.002	2.3	0.0	<0.002	0.1	1.4	0.6	<0.01	1.9	0.1
Fe (mg/L)	0.2	0.58	0.32	44	0.95	1.4	37	1.4	1.1	0.2	1.3	<0.05
Hg (mg/L)	NA	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.01	<0.0001	<0.0001
Mn (mg/L)	0.1	0.45	<0.001	3	1.6	<0.001	0.0	0.54	10.4	1.57	1.3	2.1
Ni (mg/l)	NA	0.2	0.0	5.5	0.2	0.0	0.3	0.6	4.2	0.7	0.4	0.4
Pb (mg/l)	NA	<0.010	0.0	0.0	0.0	0.0	<0.010	<0.010	0.0	<0.01	0.0	<0.01
U (mg/L)	0.1	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	0.194	0.1	0.1
Zn (mg/l)	NA	0.2	0.1	4.6	0.4	0.0	0.7	1.0	4.0	0.2	3.3	0.2

5 Conclusions and Recommendations

The following conclusions and recommendations are made based on the source-term study:

- The Millsite TSF mineralogy is dominated by silica, constituting 33.1 to 93.1% by weight. The difference in the samples mineralogy is suspected to be due to the tailings being sourced from different ores and have been deposited on the TSF over the years. One sample with low silica could be a calcine sample or otherwise is very high in iron. Pyrite was only detected in one of the 8 samples, at a concentration of 0.6% by weight meaning that pyrite is not an issue. Although no calcite minerals have been detected in any of the samples, pyrophyllite, muscovite, jarosite, and kaolinite are hydroxides and have the potential to buffer acidity.
- The paste pH of the samples was found to be acidic ranging between 1.7 and 3.3 (with the exception of Sample 5 at a pH of 6.9). Although this indicates the potential for the residue to generate acid, paste pH alone is not a conclusive methodology for ABA classification. The sulphide content, acid generating and acid neutralisation materials of the tailings need to be quantified for a more comprehensive ABA evaluation.
- The sulphur species analysed for the tailings samples included total sulphur-S, sulphate-S and sulphide-S. The highest Sulphide-S was detected in Sample 6 at 0.62%. The rest of the samples have approximately 0.25% which is slightly less than the 0.3% benchmark required to generate acid sustainably. As discussed above, pyrite was only detected in Sample 6. The 0.25% sulphide-S should therefore be present in other Fe containing minerals.
- Sulphur species were also analysed by Mintek (2013) on 8 different samples from the Millsite TSF. The sulphide-S was found at higher concentrations than those conducted during this study. The concentration ranged between 0.3 and 0.7%, with the average of 0.6%. This is a clear indication that there is sufficient sulphide to generate acid.
- The average neutralisation potential is 1.3 kg CaCO₃/tonne, while the average acid potential is 17.9 kg CaCO₃/tonne. This means that the average NNP is -16.7 kg CaCO₃/tonne, indicating that the samples are potentially acid generating.
 - Sample 5 is unique whereby the net neutralisation potential is 9.5 kg CaCO₃/tonne. This together with its relatively high paste pH (6.9) and low sulphide content (0.01%), the sample is different from the rest and not potentially acid-generating.
- The neutralisation potential ratio (NPR) of the tailings samples (excluding Sample 5) was quantified at 0.01, which confirms that the TSF is likely to be acid generating. The geochemistry of Sample 5 is excluded from the rest of the samples as its NPR is 30.5 and falls in the non-acid generating category. This sample is an exception and overall Millsite TSF can be classified as potentially acid generating.

- A solid-phase total concentration analysis shows that a number of elements (the most being in Sample 5) are found at higher concentrations in the samples than they are usually encountered in the crustal rocks, out of which arsenic can be considered as the main elements that should be looked at from an environmental perspective. However this is to be expected from a mineralised and enriched sample.
 - Noteworthy is the scarcity of uranium in the tailings. This is because uranium had been previously extracted and its concentration in the tailings is below the detection limit.

The pH of the mine void is generally acidic but is expected to be neutral in the vicinity of the pits where the reclaimed tailings (which is high in pH of around 10-11) is being deposited. The samples were leached under neutral (distilled water) and acidic (SPLP) solutions in order to reflect the mine void groundwater under a range of pH conditions.

- The distilled water leach test shows that under neutral pH the following elements can be released at concentrations in excess of the WUL limits :
 - Ca in all samples, except in Sample 3;
 - EC in samples 3, 5, and 8;
 - Fe in samples 3, 4, 6, 7 and 8;
 - Mn in samples 1, 3, 4, 7 and 8;
 - Although As is found at higher concentrations in the solid phase (as observed using the multi-element analysis), it is inert in neutral solvent and its solubility is below the detection limit of 0.02 mg/L; and
 - The concentration of U is below the detection limit of 0.004, which is way below the WUL limit of 0.07 mg/L.
- The SPLP leach test shows that under acidic pH the following metals can be released at concentrations in excess of the WUL limits :
 - Ca and Fe in all samples;
 - Mn in all but Samples 2, 5 and 6;
 - There is no arsenic limit provided in the WUL. However, it is expected to leach to some extent if acidic environment prevails. This is particularly true for Sample 5 where the As concentration is 2.6 mg/L; and
 - As was the case with the distilled water leach result, the concentration of U is below the detection limit of 0.004.
- The geochemical results of the Millsite TSF have been compared to previous work conducted on Dump 20 to evaluate if the Millsite is more of an environmental concern than Dump 20. The result shows that the two tailings have similar acid generation potential. The metals expected to leach under neutral or acidic conditions are also generally similar.

6 Reference

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Appendix A: Laboratory Certificate