Realistic simulation of acid mine drainage generation in the gold mines of the Witwatersrand, South Africa

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Abstract Acid mine drainage generated in Witwatersrand mines has been identified as an environmental challenge. Following the cessation of underground mining, interconnected mine voids have been allowed to flood, posing a threat to the environment when acidified water discharges into the shallow aquifers and surface streams. The voids include an upper aerated zone overlying a saturated zone. Sulphides exist in both environments, contributing to the total contaminant load. A kinetic experiment was undertaken to simulate these conditions and assess the relative contributions to the generation of AMD. Results confirm that AMD generation is retarded in a completely flooded environment.

Keywords Acid Mine Drainage, Witwatersrand, gold mines voids, pyrite, oxidation

Introduction

Gold mining in the Witwatersrand area started in 1886 and continued to date, with majority of the mines ceasing underground operations in the 1970s. During almost this entire period gold was mined in three main, different, areas namely: the Eastern Basin (Springs-Nigel area), the Central Basin (Johannesburg area) and the Western Basin (Krugersdorp-Randfontein area), while additional quantities were mined in later years. In all three basins mining was mainly undertaken underground via vertical and steep inclined shafts. As a consequence of these mining activities a significant amount of waste tailings and underground mine voids were produced. The cessation of mining and abandonment of mines resulted in mine voids being flooded, with the first discharge to surface occurring in 2002 in the Western Basin. A similar situation could occur in the Eastern and Central basins (Ramontja *et al.* 2011), unless adequate steps are taken to prevent this.

The geochemical interaction of the underground water with sulphide (mainly pyrite) bearing rock and waste tailings dumps in the presence of oxygen generates acidic mine water which has a significantly high metals and salt load. The oxidation of iron pyrite (FeS_2) and the release of acidity into waters flooding underground mining voids has been described elsewhere (Singer and Stumm 1970, Tutu *et al.* 2008).

Rationale

Since the underground mine voids in the Witwatersrand gold mining basins are rapidly flooding with water, there are concerns regarding the fate of the mine water that is being generated. Two opinions regarding the management of this problem have been expressed:

1. The mine water should be pumped out and be treated for discharge purposes in which case the walls of the mine voids with pyritic rock will be further exposed to oxygen.
2. The mine voids should be allowed to flood with water which will be devoid the oxygen and oxidation of the pyritic rock will be limited.

This experiment therefore aims to simulate these two scenarios and to understand which of the two options above generate bet-

ter quality mine water. It was decided to carry out column leach experiments simulating the two conditions and results are presented in this paper.

Materials and methods

A two column experiment was set up in a way to resemble saturated and unsaturated underground mine void conditions. Approximately 8 kg of a pyrite bearing rock was acquired from one of the Witwatersrand Western Basin mines and stored in a sealed plastic container to protect the material from oxidation. The sample was crushed to a particle size of 100 % <4 mm and split into equivalent portions using a ten way rotating splitter. Portions of the materials were analysed for mineralogy, metals and total sulphur content. These results are illustrated on Table 1, 2 and 3.

Two columns made of Perspex and of identical dimensions 50 mm internal diameter ($i.d$) and a height (h) of 480 mm, C_A and C_B were packed with 1272 g and 1278 g of the split material respectively. Each column was inoculated with 500 mL of AMD sample acquired from a shaft which was discharging AMD to the surface. The AMD was inoculated into the columns to introduce iron oxidizing bacteria (*Thiobacillus ferrooxidans* and *Leptospirillum ferrooxidans*) to the sample in order to achieve optimum oxidation conditions. The columns were left to incubate for a period of 192 hours.

Deionised water was used as a leachant and delivered into the columns using a peristaltic pump as the driver at a speed of 3 revolutions per minute (rpm) through 0.51 mm i.d polyvinylchloride pump tubing. One column

(C_A) was run in an upward flow configuration, allowing the packed pyritic ore sample to be completely covered in leachant simulating the saturated zones in the underground mine environment. The second column (C_B) was run from top to bottom with an air inlet allowing oxygen to ingress the column. The column was not allowed to flood, resembling the unsaturated zones in the upper part of the underground mine environment. The first leachate was collected over a period of seven days and mainly comprised the AMD that was inoculated. The two columns were continuously leached for 22 weeks at a rate of around 0.45 L/week with leachate collection and analysis performed every seven days. The leachates were syringe filtered using 0.45 μm hydrophilic filter discs. The leachates were then analysed for pH, electrical conductivity (EC), dissolved metals and anions. The leachate solutions were acidified with three to five drops of 3M Nitric acid (HNO_3) prior to dissolved metals analysis.

Results and discussion

The mineral composition results illustrated in Table 1 indicate that the predominant component is quartz with a 80 % weight fraction, followed by pyrophyllite at 12 % and pyrite at 9 %. Mineral composition and the total sulphur results of 4.32 wt. % is a good indication that the material is a good source of sulphide for AMD studies.

X-Ray Fluorescence (XRF) results presented on Tables 2 and 3 confirms that the material contains predominantly quartz and has a potential to release significantly high con-

Mineral	Composition (weight %)	Mineral	Composition (weight %)
Quartz	74	Jarosite	1
Pyrophyllite	12	Plagioclase	1
Pyrite	9	Mica	1
Kaolinite/Chlorite	2		

Table 1 X-Ray Diffraction (XRD) mineralogical determination on the pyrite bearing ore sample was performed and the results are listed below expressed in weight %.

Element	Concentration (ppm)	Element	Concentration (ppm)	Element	Concentration (ppm)
As	107	La	129	Pb	58
Ba	68	Mo	6.3	Rb	5
Bi	4.1	Nb	12	Sc	8
Ce	228	Nd	73	Se	4.4
Co	91	Ni	80	Sm	10
Cr	509	V	29	Sr	57
Cu	45	Y	12	Ta	3.2
Ga	6.5	Zn	35	Th	34
Hf	18	Zr	664	U	83

Table 2 XRF trace elements determination on the pyrite bearing sample was performed and the results are listed below expressed in weight ppm.

Element	Concentration (weight %)	Element	Concentration (weight %)
SiO_2	80.01	CaO	<0.01
Fe_2O_3	8.87	Na_2O	<0.01
Al_2O_3	4.89	MnO	0.002
TiO_2	0.41	MgO	<0.01
K_2O	0.11	P_2O_5	0.05
Cr_2O_3	0.073		

Table 3 XRF major element determination on pyrite bearing rock

centrations of metals such as As, U, Ni, Co, Al, Zn, Cr and Zr into the water through leaching.

The weekly SO_4^{2-} loads, cumulative loads and the leachate pHs for the two columns are graphically illustrated on Fig. 1. Metal and sulphate concentrations, pH, EC and volume results of the leachate analyses from the column leach experiments, for a period of 22 weeks, are provided in Table 4.

Results for the two columns for week 0 showed high values for EC, metal and sulphate concentrations and pH values lower than 3 followed by sharp decreases and increase respectively. This is due to the AMD aliquot that was inoculated into the columns.

From weeks 4 to 22 the EC, metals and sulphate concentrations for column C_A showed a steady decrease and increasing pH. This is indicative that pyrite oxidation and associated acid generation is inhibited. Column C_B results showed steady increases in EC, metal and sulphate concentrations and a decrease in pH from weeks 4 to 18. From week 19, column B re-

sults showed a sharp increase in EC, metals and sulphate concentrations and sharp decreases in pH with values well below 2.5. The results for column C_B showed that there is acid generation from pyrite oxidation and release of metals into the water.

Conclusion

The purpose of this study was to assess the quality of the mine water produced in the saturated and the unsaturated areas in the underground mine voids in Witwatersrand gold mining area and whether the water should be pumped out or be left to continue flooding to displace oxygen and thereby limit acid generation through oxidation of the pyritic rock. The study revealed that the oxidation of pyrite in the flooded (saturated) zones is severely retarded with pH values above 4.5 and reduced salt loads, however in aerated (unsaturated) zones, pyrite is oxidised and produces a leachate with pH values of below 2.5 and high EC, salt and metal loads. This information can
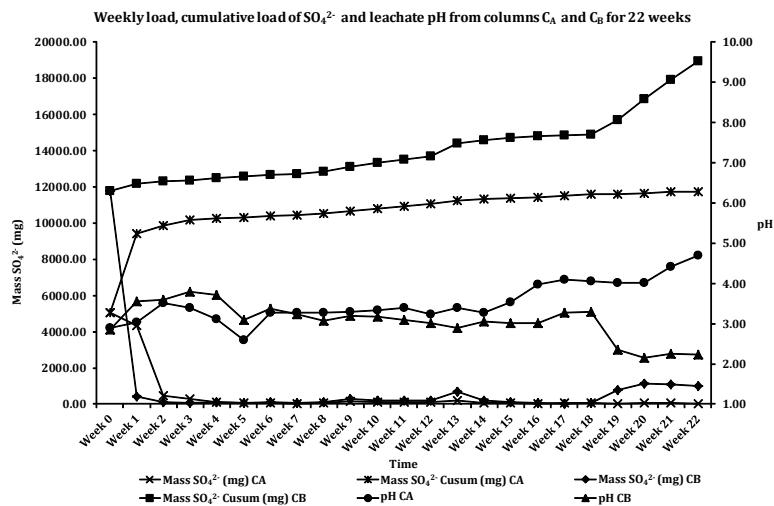
Weekly load, cumulative load of SO_4^{2-} and leachate pH from columns C_A and C_B for 22 weeks

Figure 1 *A graphical illustration of weekly load and cumulative load of SO_4^{2-} and leachate pH for column C_A and C_B for 22 weeks.*

Week	Column	0	1	2	3	4	5	6	7	8	9	10	11
Al (mg)	C_A	136.5	147.7	11.7	3.1	0.999	0.601	0.214	0.170	0.000	0.337	0.223	0.191
	C_B	316.0	4.27	1.77	0.278	0.116	0.115	0.236	0.388	0.000	2.987	1.191	0.644
Co (mg)	C_A	2.40	2.34	0.214	0.077	0.022	0.011	0.006	0.007	0.006	0.007	0.005	0.005
	C_B	5.28	0.215	0.026	0.010	0.010	0.010	0.013	0.013	0.010	0.057	0.016	0.009
Cu (mg)	C_A	2.57	0.868	0.077	0.034	0.000	0.000	0.003	0.000	0.000	0.000	0.000	0.000
	C_B	6.83	0.936	0.212	0.017	0.003	0.000	0.002	0.000	0.000	0.086	0.012	0.000
Fe (mg)	C_A	733.3	834.1	88.43	28.56	6.40	2.61	0.700	1.000	0.760	1.44	0.650	0.440
	C_B	1699	46.40	22.52	9.87	11.96	9.35	5.81	6.49	2.92	17.57	6.08	2.51
Mn (mg)	C_A	18.36	19.53	1.51	0.550	0.158	0.066	0.029	0.027	0.020	0.028	0.018	0.016
	C_B	39.17	0.887	0.180	0.074	0.074	0.064	0.060	0.063	0.046	0.099	0.037	0.023
Ni (mg)	C_A	4.09	4.82	0.488	0.198	0.066	0.035	0.022	0.025	0.000	0.027	0.000	0.000
	C_B	10.33	0.695	0.176	0.054	0.044	0.040	0.045	0.048	0.039	0.215	0.060	0.038
SO4^{2-} (mg)	C_A	5047	4346	483.5	273.8	101.8	66.70	75.37	36.46	86.90	151.4	125.5	123.2
	C_B	11758	428.7	103.3	81.19	126.6	65.87	88.96	62.65	112.0	293.9	210.5	182.6
Zn (mg)	C_A	0.756	1.05	0.369	0.274	0.188	0.215	0.229	0.192	0.000	0.324	0.237	0.188
	C_B	1.60	0.000	0.527	0.000	0.153	0.172	0.237	0.177	0.000	0.433	0.212	0.158
pH	C_A	2.90	3.04	3.52	3.39	3.11	2.59	3.28	3.28	3.27	3.29	3.33	3.39
	C_B	2.85	3.56	3.60	3.79	3.72	3.09	3.38	3.24	3.08	3.19	3.17	3.09
EC (µS/cm)	C_A	10120	4280	1316	705	571	476	349	335	315	316	278	276
	C_B	8690	347	273	225	230	241	310	350	403	484	408	382
Vol (mL)	C_A	240	740	400	480	420	450	400	460	400	530	450	420
	C_B	660	1640	800	430	460	465	400	410	400	520	450	420

Week	Column	12	13	14	15	16	17	18	19	20	21	22	Σ
Al (mg)	C_A	0.187	0.194	0.188	0.227	0.041	0.000	0.027	0.022	0.030	0.090	0.049	302.8
	C_B	0.683	14.60	0.847	0.701	0.322	0.110	0.120	10.119	3.374	2.948	1.067	362.93
Co (mg)	C_A	0.005	0.006	0.004	0.004	0.003	0.004	0.004	0.004	0.004	0.004	0.005	5.15
	C_B	0.016	0.278	0.027	0.032	0.013	0.007	0.006	0.650	0.810	0.759	0.592	8.86
Cu (mg)	C_A	0.016	0.049	0.025	0.030	0.000	0.000	0.000	0.000	0.000	0.000	0.000	3.67
	C_B	0.033	1.62	0.131	0.186	0.014	0.000	0.000	4.932	1.50	0.749	0.492	17.76
Fe (mg)	C_A	0.400	5.12	2.14	6.16	4.96	5.10	4.81	3.66	2.02	4.81	5.20	1742.7
	C_B	3.53	83.12	12.71	15.51	3.15	1.08	2.50	147.8	224.0	193.2	161.7	2690
Mn (mg)	C_A	0.014	0.022	0.021	0.019	0.014	0.013	0.010	0.010	0.010	0.010	0.010	40.47
	C_B	0.031	0.197	0.035	0.027	0.016	0.012	0.012	0.227	0.045	0.033	0.021	42,43
Ni (mg)	C_A	0.000	0.027	0.023	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	9.82
	C_B	0.054	1.14	0.083	0.095	0.046	0.027	0.000	1.88	1.39	1.13	0.852	18.47
SO4^{2-} (mg)	C_A	129.7	178.0	83.91	76.46	31.88	76.27	77.38	27.47	44.08	68.93	16.82	11729
	C_B	181.4	700.3	185.9	122.6	84.44	39.96	67.18	785.7	1152	1100	1015	18949
Zn (mg)	C_A	0.200	0.250	0.262	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	4.73
	C_B	0.272	0.773	0.221	0.000	0.000	0.000	0.000	0.472	0.349	0.245	0.184	6.19
pH	C_A	3.24	3.39	3.28	3.53	3.97	4.09	4.05	4.01	4.01	4.42	4.69	
	C_B	3.02	2.89	3.05	3.02	3.00	3.27	3.30	2.36	2.15	2.26	2.24	
EC (µS/cm)	C_A	255	327	297	148	130.6	122.1	122.3	129.1	124.4	100.1	82.7	
	C_B	384	1410	517	472	466	336	282	2066	3480	3630	3210	
Vol (mL)	C_A	420	420	440	450	420	430	450	380	430	450	480	
	C_B	420	420	430	410	410	440	500	430	460	430	450	

Table 4 *Weekly leachates volumes, pH, EC and volume corrected mass loads of constituents for columns C_A and C_B for a period of 22 weeks.*

be used to assist decision making regarding the flooding of the Witwatersrand mines, however a decision cannot be made solely based on the results of these reactions. There are other factors that must be taken in to consideration when deciding to flood or pump the water in the Witwatersrand mine voids. Factors as reported by Ramontja *et al.* (2011) such as:

Flooding risks

- pollution of shallow groundwater resources required for agricultural use
- impact on the underground infrastructure due to their proximity to urban areas
- seismic activity
- the rate of seepage
- potential subsidence

Decant of AMD to the environment risks

- impact on ecological systems
- localised flooding of low lying areas
- impact on major river systems
- estimated water volume

Other factors such as the interaction of generated AMD with dolomitic rock strata and water that has being in contact with dolomitic rock strata prior to interacting with the sulphide rock must also be taken into consideration.

Acknowledgements

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