Article

The Use of Acid Mine Drainage (AMD) in the Flotation of a Platinum-Group-Minerals-Bearing Merensky Ore

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Abstract: Water scarcity is compelling mining houses to not only recycle process water but to also identify alternative sources of make-up water in concentrators. South Africa has significant volumes of acid mine drainage (AMD) generated from vast mining operations. This study investigated the viability of using AMD as a replacement for potable water in the flotation of a platinum-group-minerals (PGM)-bearing Merensky ore. Rougher and cleaner flotation testwork was conducted at laboratory scale to compare the performances of potable water (baseline water), AMD treated with $Ca(OH)_2$, and AMD treated with the Veolia process. Water analysis showed that the three water types differed in pH, water hardness, conductivity, and total dissolved solids. The results showed the AMD treated with $Ca(OH)_2$ was detrimental to PGM recovery compared to potable water at depressant dosages of 50 g/t. Specifically, AMD treated with $Ca(OH)_2$ achieved a PGM rougher recovery of 67.8%, while potable water achieved a PGM rougher recovery of 88.4%. Depressant dosage optimisation and treatment of the AMD using the Veolia process were investigated as potential strategies to mitigate the detrimental effects of the AMD treated with $Ca(OH)_2$ on the flotation performance of a Merensky ore. The AMD treated with the Veolia process achieved a PGM rougher recovery of 70.8%. Thus, treatment of the AMD was beneficial, though the PGM and base metal sulphides (BMS) recoveries were still lower than those achieved in potable water. Reducing the depressant dosage to 25 g/t in AMD treated with $Ca(OH)_2$ resulted in the highest PGM, Cu, and Ni rougher recoveries of 91%, 60.2%, and 58%, respectively. The AMD treated with $Ca(OH)_2$ at lower depressant dosage outperformed the potable water in terms of PGM and BMS recoveries and concentrate grades, indicating that AMD has the potential to replace potable water as make-up water in Merensky ore processing plants. The results showed that depressant optimisation is important to achieve superior metallurgical results when using AMD treated with $Ca(OH)_2$. The use of AMD in Merensky ore processing plants not only conserves freshwater in minerals processing plants but also reduces high volumes of contaminated effluents.

Keywords: platinum-group minerals; base metals; acid mine drainage; lime precipitation; water scarcity; grade; recovery

1. Introduction

South Africa is a water-scarce country, with competing demands for water use among critical sectors such as agriculture, mining, and human consumption. In South Africa, the mining industry consumes 3% of the total water withdrawn [1]. Flotation is a water-intensive process, with water used as a process and transport medium during milling and flotation [2]. Water constitutes 80–85% of the pulp during the flotation processes [3]. According to [4], milling and flotation consume up to 6000 L/min. Water scarcity and stringent environmental regulations have compelled mining houses to not only close their water circuits but also identify alternative water sources to replace potable water as make-up water in minerals processing plants without compromising metallurgical performance.

Currently, the water used in mineral processing plants originates from various sources, e.g., freshwater, industrial wastewaters, surface waters, bore, process water, and treated sewage water [3,5,6]. South Africa has vast coal and gold mining operations which generate significant volumes of acid mine drainage (AMD). AMD is water that is formed when sulphur-bearing minerals react with water and air to form sulphuric acid and dissolved iron. The AMD process results mainly from oxidation of pyrite, as shown in Equation (1):

$$2FeS_2(s) + 7O_2(g) + 2H_2O(l) = 2Fe^{2+}(aq) + 4SO_4^{2-}(aq) + 4H^+(aq) \tag{1}$$
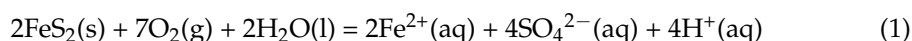
AMD poses serious safety, health, and environmental hazards. The current standard treatment for AMD is to oxidise the iron by aeration and then add lime to raise the pH. The iron and most heavy metals then precipitate out as hydroxides and carbonates [7]. The remaining AMD with a very high sulphate content is dumped in old mine dumps. AMD may be an alternative to freshwater in minerals processing; however, it is acidic due to the high concentration of H^+ ions. The pH of the AMD will need to be neutralised prior to flotation as thiol collectors, especially xanthates, are stable in alkaline media and are unstable in acidic media [8,9]. AMD also has a high concentration of SO_4^{2-} ions which are reported to negatively affect the flotation process by promoting the oxidation of sulphide minerals, the formation and precipitation of metal sulphates on minerals surfaces, as well as the replacement of the collectors with sulphate ions on minerals surfaces [10,11]. There are various strategies used to counteract the detrimental effects of process water chemistry on the flotation response of minerals. These include manipulation of the reagent regime, especially depressant type and dosage [12,13], dilution of the process water [14], and targeted treatment of the process water to reduce the concentration of detrimental ions [15,16]. Targeted treatment processes include biological processes, chemical precipitation, adsorption, and/or ion exchange [16].

Some of the key parameters used to characterise water quality are ionic strength, water hardness, and pH. The effect of water chemistry on the flotation performance of different minerals and ores is abundant in the literature. Researchers agree that increasing the ionic strength of the water system results in increased froth stability, leading to increased water recovery and mass pull [12,13,17–19]. The increased stability of the froth has been attributed to ions in the water system having a froth stabilising effect rather than changes in the hydrophobicity of the particles entering the froth phase. [12] and [13] found that Cu and Ni recoveries were not affected by increasing ionic strength of the water system in the flotation of a Merensky ore. However, an increase in ionic strength was shown to decrease Cu and Ni grades due to higher mass pulls at high ionic strength of the water system. The researchers further showed that the detrimental effect observed at higher ionic strength of the water system could be counteracted by optimising the depressant system.

Water hardness, defined as the sum of concentrations of multivalent cations in water, most commonly Ca^{2+} and Mg^{2+} cations, is also an important parameter used to characterise water quality. Water with Ca+Mg concentrations lower than 60 ppm is generally classified as soft. There is no general consensus amongst researchers on the effect of Ca^{2+} on the flotation performance of sulphide minerals. A study [18] found that 400 mg/L of Ca^{2+} is a threshold concentration beyond which the Cu grade decreased in the flotation of a Cu-Ni-PGM-containing ore. Another study [10] found that the recovery of galena increased when Ca^{2+} increased between 50 and 400 mg/L and decreased above 500 mg/L. A study [20] observed that Ca^{2+} resulted in reduced xanthate adsorption, and a reduced bubble–particle attachment probability, translating to a reduced recovery of sulphide minerals, e.g., chalcopyrite and galena. This was attributed to the passivation of the mineral surfaces as substantiated by the increase in the zeta potential of the minerals in Ca^{2+}-containing solutions. On the contrary, [21] found that cationic species (e.g., Ca^{2+} ions) enhanced the adsorption of xanthate on chalcopyrite and pentlandite through xanthate adsorption activation. This was corroborated by [22] who also concluded that Ca^{2+} ions enhanced the xanthate adsorption and subsequent floatability of copper and nickel sulphides during the flotation of Cu-Ni ore. The majority of the literature considers laboratory-based studies;

on-site understanding of the impact of water quality on flotation is anecdotal; however, recycling of on-site water within PGM operations is commonplace.

This study investigated the viability of using AMD treated with $Ca(OH)_2$ as a transport and process medium during the flotation of a PGM-bearing Merensky ore. The objective of the study was to investigate whether potable water can be replaced with AMD as make-up water in order to reduce the volume of potable water used within Merensky ore processing plants. This study further investigated the treatment of the AMD with the Veolia process and the optimisation of the chemical system as strategies to minimise any detrimental effects of the AMD.

2. Materials and Methods

2.1. Ore Chemistry and Mineralogy

A Merensky ore from the Bushveld complex in South Africa was investigated in this study. The material was crushed to 100%—1.7 mm using a cone crusher. The crushed sample was then blended and riffle-split into representative subsamples, some of which were used for mineralogical and chemical analysis. Chemical analysis was conducted on the subsamples using fire assay methods for the PGMs (Pt, Pd, and Au) assays, inductively coupled plasma-optical emission spectrometry (ICP-OES) for base metals, and combustion by LECO for total S.

Mineralogical characteristics of the ore were determined at the primary grind of 40% passing 75 μm using Quantitative Evaluation of Minerals by Scanning Electron Microscopy (QEMSCAN) (FEI, Hillsboro, Oregan, USA) and X-ray diffraction (XRD) (Bruker, Billerica, Massachusetts, United States), the mineral phases identified by the latter being used to set-up parameters for the QEMSCAN. Particle mineral maps were produced using the particle map analysis (PMA) measuring mode, from which the bulk modal proportions of the minerals present, the liberation, and the associated information of PGM-bearing minerals were derived.

2.2. Water Chemistry

A total of 3 types of water, namely potable water, AMD treated with $Ca(OH)_2$, and AMD treated with the Veolia process, were selected as the process medium in this study. Potable water was Randburg municipal water which constituted the baseline water. An amount of 2 L of potable water was collected into clean glass bottles from the tap and was immediately submitted for characterisation. Water analysis was completed within a day of collection. AMD is water that has been impacted by the mining industry and was obtained from a shaft of the Western Basin in Randfontein from the Witwatersrand mining area in South Africa. A total of 40 L of AMD was immediately refrigerated after collection, transported, and maintained at $-20\,°C$ until analysis and flotation tests. Refrigeration was necessary to preserve, as far as possible, the chemistry of the AMD. AMD treated with $Ca(OH)_2$ was further treated using the Veolia process, as shown in the flowsheet depicted in Figure 1. The Veolia process is regarded at the simplest technology to reduce high SO_4^{2-} concentrations. In Stage 1, the AMD treated with $Ca(OH)_2$ is reacted with lime at pH 12.0–12.4 to precipitate the heavy metals as metal hydroxides. The solution is then filtered to remove the metal hydroxides while the gypsum $(CaSO_4)$ is crystallised out of the solution. The saturated gypsum water from Stage 1 is reacted with $Al(OH)_3$ at pH 11.4–12.4 to further remove Ca^{2+} and SO_4^{2-} from the solution as ettringite precipitate which is dissolved in HCl in stage 4 at pH 6.5–6.8 to regenerate the $Al(OH)_3$. The overflow water from Stage 2 is then contacted with carbon dioxide to precipitate calcium carbonate at pH 7.8–8.6. The treated water was then used as one of the process and transport mediums for flotation tests.
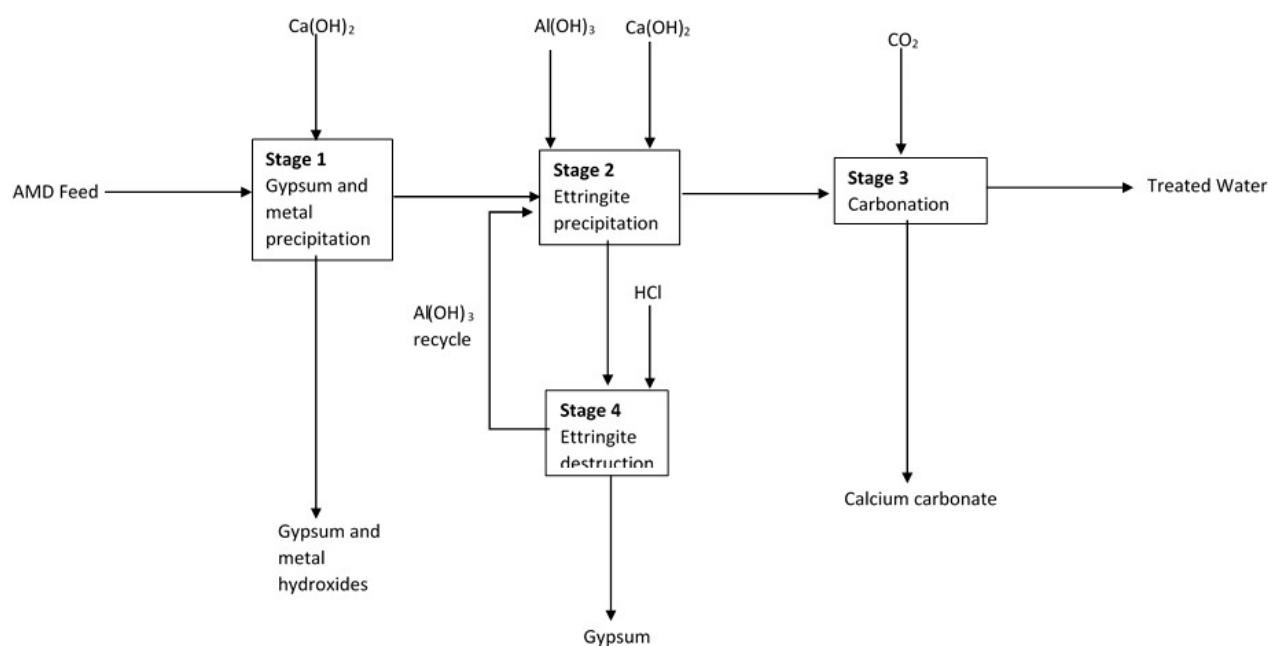
Figure 1. AMD water treatment flowsheet.

The Inductively Coupled Plasma (ICP) spectroscopy method was used to determine the concentrations of base metals in water samples. The base metals included Mg and Ca. Atomic absorption spectrometry (AAS) was used to determine the concentrations of Na and K in solutions. pH and conductivity were determined using a pH-conductivity electrode. Cl, F, NO_3, and SO_4 were characterised using ion chromatography.

2.3. Flotation Tests and Procedure

A 1 kg ore sample was milled for 34 min to attain the targeted grind of 40% passing 75 μm using high-chrome-steel media. The milled slurry was then conditioned in a 2.5 L Denver flotation cell at an impeller speed of 1500 rpm and a slurry density of 28% solids by mass. The reagents used in this study are shown Table 1

Table 1. Reagents used in this study.

Reagent	Supplier	Purity (%)
SIBX	Senmin	100
KU92	Senmin	100
Sasfroth 200	Sasol chemicals	≥85
$CuSO_4$	Sigma-Aldrich	≥99
$Ca(OH)_2$	Sigma-Aldrich	≥95

Flotation rougher and cleaner rate tests were conducted using the flowsheet and reagent conditions shown in Figure 2 and Table 2, respectively. A $CuSO_4$ activator was dosed at 20 g/t; sodium isobutyl xanthate (SIBX) was dosed at 100 g/t, and a frother, Sasfroth 200, was dosed at 50 g/t. A guar depressant, KU92, was dosed at varying dosages, as shown in Table 3. Reagents were dosed based on active content. All the flotation tests were conducted at the natural pH (~9) of the ore. All the flotation reagents were prepared at 1% strength. The flotation tests were conducted in potable water, AMD treated with $Ca(OH)_2$, and AMD treated with the Veolia process. A total of 5 timed rougher concentrates were collected after 1, 2, 4, 6, and 7 min intervals.
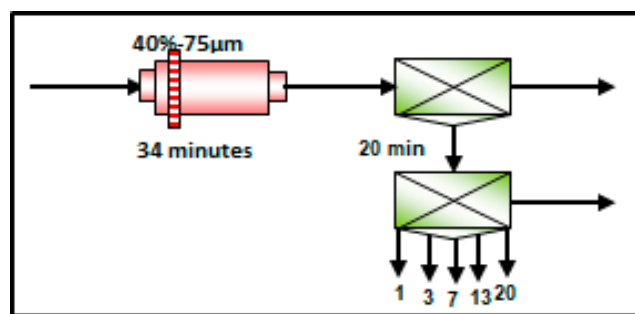
Figure 2. Flowsheet used for cleaner flotation testwork in this study. 1, 3, 7, 13, and 20 represent flotation times.

Table 2. Flotation conditions used for cleaner flotation testwork in this study.

Location	Reagents and Dosages	Cond Iime (min)	Float Time (min)
Rougher	20 g/t CuSO$_4$	3	
	100 g/t SIBX	2	
	40 g/t KU92	2	
	50 g/t Sasfroth 200	1	
	RC		20
Cleaner	10 g/t KU92	2	
	10 g/t Sasfroth 200	1	
	CC1		1
	CC2		2
	CC3		4
	CC4		6
	CC5		7

All the flotation tests conducted in this study are summarised in Table 3.

Table 3. Summary of all flotation tests conducted in this study.

Water Type	Circuit	CuSO$_4$ Dosage (g/t)	SIBX Dosage (g/t)	KU 92 Dosage (g/t)	Sasfroth 200 Dosage (g/t)
Potable water	Rougher	20	100	40	50
	Cleaner	-	-	10	10
AMD treated with Ca(OH)$_2$—HDD.	Rougher	20	100	40	50
	Cleaner	-	-	10	10
AMD treated with Ca(OH)$_2$—LDD.	Rougher	20	100	20	50
	Cleaner	-	-	5	10
AMD treated with the Veolia process—HDD	Rougher	20	100	40	50
	Cleaner	-	-	10	10
AMD treated with the Veolia process—LDD.	Rougher	20	100	20	50
	Cleaner	-	-	5	10

LDD = total low depressant dosage = 25 g/t; HDD = total high depressant dosage = 50 g/t.

For the cleaner flotation testwork, the rougher concentrate was combined and subjected to flotation in a 1 L cell. A total of 5 timed cleaner concentrates were also collected after 1, 2, 4, 6, and 7 min intervals.

All flotation tests were conducted in triplicate for reproducibility of mass pulls. Mass pulls were compared and tests which deviated by more than 5% were rejected and repeated to ensure reproducibility. Dried CC1 samples generated from each test were blended into a bulk CC1 concentrate and subsamples were removed for chemical analysis. The subsamples were assayed for 3E (i.e., Pt, Pd, and Au) using a fire assay, ICP (Cu, Ni, and Fe), and Total S analysis using a Leco sulphur analyser. The same procedure was used for RC1, RC2, RC3, RC4, RC5, CC2, CC3, CC4, CC5, and tailings samples.

3. Results and Discussion

3.1. Ore Chemistry and Mineralogical Results

The head grades of the ore presented in Table 4 show that the ore had ~4.2 g/t of PGMs (Pt, Pd, and Au), 0.11% Cu, and 0.21% Ni.

Table 4. Head grades of the Merensky ore.

PGMs	Cu	Ni	Fe	Mg	Si	Total S
(g/t)	(%)	(%)	(%)	(%)	(%)	(%)
4.2	0.11	0.21	7.7	11.1	23.7	0.40

Mineralogical analysis showed that the ore had very good liberation characteristics at the primary grind of 40% passing 75 μm, with more than 59% of the PGMs having a liberation index greater than 80%, while 35% of the PGMs occurred in particles with a liberation index of less than 20%. PGM speciation analysis showed that the ore contained 65% Pt and Pd bismuth tellurides, 28% Pt sulphides, and traces of arsenides, alloys, as well as sulfarsenides. The ore had a base metal sulphide (BMS) content of approximately 1%, with 39% pyrrhotite, 38% pentlandite, 21% chalcopyrite, and minor traces of pyrite. The major gangue minerals were enstatite and anorthite with minor contents of quartz, talc, mica, etc.

3.2. Water Characterisation Results

The chemical assays of the potable water, AMD treated with $Ca(OH)_2$, and AMD treated with the Veolia process are presented in Table 5.

Table 5. Chemical assays of potable water, AMD treated with $Ca(OH)_2$, and AMD treated with the Veolia process.

Parameter	Unit	Potable Water	AMD Treated with $Ca(OH)_2$	AMD Treated with the Veolia Process
pH		7.6	8.3	7.8
Na	ppm	11.25	102.5	49.7
K	ppm	7.11	17	10.8
Ca	ppm	6.31	667.5	1202
Mg	ppm	2.65	148.5	0.7
Cl	ppm	5.82	66.1	481.6
F	ppm	0.02	0.02	0.02
SO_4	ppm	<10	2730	109.0
Conductivity	μS/cm	163	3600	9350

The AMD was originally acidic at a pH of around 4 and was neutralised to a slightly alkaline pH of around 8 using $Ca(OH)_2$. This is because the flotation of PGMs and BMS is usually conducted at the natural pH of the PGM ore, typically at pHs of 7–8 as thiol collectors are stable in alkaline media and decompose in acidic media [8,9].

The water characterisation results in Table 5 show that the Na content was within the expected range for potable water. The AMD treated with $Ca(OH)_2$ had a water hardness (Ca^{2+} + Mg^{2+}) of 816 ppm due to mine impact as well as the pH neutralisation process, which introduces Ca^{2+} ions. The AMD treated with $Ca(OH)_2$ also had the highest concentration of SO_4^{2-} ions because of the acid mine drainage process (see Equation (1)).

Table 5 shows that treatment of the AMD using the Veolia process was able to reduce the SO_4^{2-} concentration by 90% from 2730 ppm to 109 ppm. Table 5 also shows that the AMD treated with the Veolia process had the highest concentrations of Ca^{2+} and Cl^-. The high Cl^- content was due to the HCl used in the treatment process (Figure 1). The doubling in the concentration of the Ca^{2+} ions from 668 ppm to 1202 ppm was due to the use of $Ca(OH)_2$ in the treatment process to precipitate the SO_4^{2-} (Figure 1). The increase in the concentrations of the Ca^{2+} and Cl^- explains the increase in the ionic strength of the AMD

treated with the Veolia process from 3600 µS/cm to 9350 µS/cm. Conductivity is a measure of a solution's ionic strength and is directly related to total dissolved solids and is another parameter that is used to characterise water quality. As expected, the AMD treated with $Ca(OH)_2$ had a higher conductivity than the potable water. It is clear that AMD treated with the Veolia process had the highest conductivity.

3.3. Effect of AMD Treated with Ca(OH)₂ on the Flotation Response of the Merensky Ore

The flotation performance of the Merensky ore in potable water, AMD treated with $Ca(OH)_2$, and AMD treated with the Veolia process was compared and the results are shown in Table 6 and Figure 3. The objective was to investigate the viability of replacing potable water with AMD in Merensky-ore-processing plants.

Table 6. Effect of water type and depressant dosage on the flotation response of the Merensky ore. LDD = 25 g/t; HDD = 50 g/t.

| Water Type	Circuit	Mass		Grade			Recovery (%)		
		%	PGMs (g/t)	Cu (%)	Ni (%)	PGMs (%)	Cu (%)	Ni (%)	
Potable water (HDD)	Rougher	8.4 ± 0.3	45.2	0.7	1.5	88.4	57.5	58.3
	Cleaner	5.1 ± 0.4	71.6	1.2	2.3	84.9	56.9	54.9
AMD treated with Ca(OH)₂ (HDD)	Rougher	5.5 ± 0.2	56.4	1.1	1.7	67.8	57.0	47.7
	Cleaner	3.1 ± 0.5	87.1	1.9	2.4	58.6	52.8	37.9
AMD treated with Ca(OH)₂ (LDD)	Rougher	6.5 ± 0.4	67.5	1.1	1.8	91.0	60.2	57.5
	Cleaner	4.0 ± 0.5	96.0	1.7	2.7	80.3	57.6	54.6
AMD treated with the Veolia process (HDD)	Rougher	4.8 ± 0.3	59.4	1.5	2.1	70.8	65.2	58.3
	Cleaner	2.5 ± 0.3	105.2	2.7	3.8	66.2	62.2	55.4
AMD treated with the Veolia process (LDD)	Rougher	5.4 ± 0.4	82.5	1.3	1.7	59.2	59.4	47.0
	Cleaner	3.6 ± 0.5	120.1	1.9	2.5	57.5	58.7	45.2
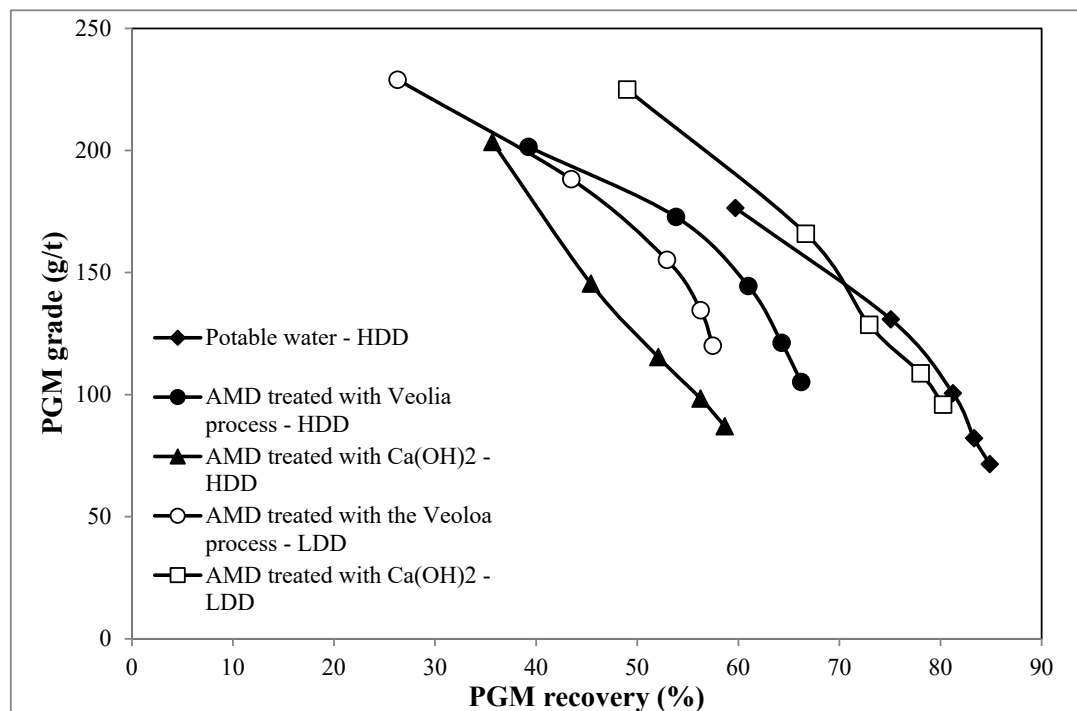
Figure 3. Effect of reducing depressant dosage on the flotation response of the Merensky ore. LDD = 25 g/t; HDD = 50 g/t.

The results in Table 6 show that potable water achieved higher rougher and cleaner mass pulls than AMD treated with $Ca(OH)_2$. It is generally reported that an increase in ionic strength increases froth stability, resulting in increased mass pull [12,13,17–19]. The AMD treated with $Ca(OH)_2$, because of its higher ionic strength, was, therefore, expected to achieve a higher mass pull than potable water. However, the opposite trend was observed in this study.

The effects of Ca^{2+} and SO_4^{2-} ions and their concentrations on the flotation of BMS are abundant in the literature [13,18–20,23–28]. However, the effects of the same ions on the flotation of PGMs are rare in literature. This is because of the assumption that the BMS can be used as a proxy to predict the flotation behaviour of the PGMs. While this may apply to Merensky ore, it is not a valid assumption for other PGM ore types. The Cl^- and the Na^+ ions have been reported to have minimal impact on the flotation performance of a Cu-Ni-PGM containing ore [18].

3.3.1. Effect of Ca^{2+} and SO_4^{2-} Ions on the Flotation Performance of PGMs

The results in Table 6 show that potable water (baseline) achieved a higher PGM rougher recovery of 88.4% than AMD treated with $Ca(OH)_2$, which achieved a lower PGM rougher recovery of 67.8% at a similar depressant dosage of 40 g/t. In terms of cleaner performance, potable water achieved 85% PGM recovery at a 72 g/t PGM grade. On the other hand, the AMD treated with $Ca(OH)_2$ achieved a 59% PGM recovery at a 87 g/t PGM grade. The results indicate that the potable water outperformed the AMD treated with $Ca(OH)_2$. The lower PGM rougher and cleaner recoveries achieved by the AMD treated with $Ca(OH)_2$, consistent with the lower mass pulls, could be attributed to the higher Ca^{2+} and SO_4^{2-} concentrations.

3.3.2. Effect of Ca^{2+} and SO_4^{2-} ions on the Flotation Performance of Ni

The results in Table 6 show that potable water achieved a Ni rougher recovery of 58%, while the AMD treated with $Ca(OH)_2$ achieved a Ni rougher recovery of 48%. Potable water also achieved a 55% Ni cleaner recovery, while the AMD treated with $Ca(OH)_2$ achieved a 38% Ni cleaner recovery. Both waters achieved a similar Ni grade of 2.3%, indicating that water type did not affect the Ni grades. It is clear that potable water outperformed AMD treated with $Ca(OH)_2$ in terms of the flotation performance of the Ni. The results obtained in this study are different from the literature [18], where Ni recoveries were not affected by the concentrations of the Ca^{2+} and SO_4^{2-} in the flotation of a Cu-Ni-PGM-containing ore. However, the Ni grade increased with the increase in the concentration of the Ca^{2+} ions up to 400 ppm. A further increase in the Ca^{2+} ions concentration to 800 ppm was found to be detrimental to the Ni grade. It was further demonstrated that the Ni grade suffered at SO_4^{2-} concentrations between 720 and 1200 mg/L [19].

3.3.3. Effect of Ca^{2+} and SO_4^{2-} Ions on the Flotation Performance of Cu

The results in Table 6 show that AMD treated with $Ca(OH)_2$ and potable water achieved similar Cu rougher recoveries of 57%. Despite similar rougher Cu recoveries, potable water achieved a higher cleaner Cu recovery than AMD treated with $Ca(OH)_2$. There is no general consensus amongst researchers on the effects of Ca^{2+} and SO_4^{2-} on the flotation performance of Cu. Some researchers [18] found that Cu recovery was not affected by the concentrations of the Ca^{2+} and SO_4^{2-} in the flotation of the Cu-Ni-PGM-containing ore. However, spiking the Ca^{2+} ions concentration to 400 mg/L resulted in higher Cu grades. A further increase in the Ca^{2+} ions to 800 ppm resulted in a decrease in the Cu grade. A concentration of 400 ppm was, therefore, established as the threshold concentration of Ca^{2+} beyond which the flotation performance of a Cu-Ni-PGM-containing ore declined. It was further established that the threshold concentration of the SO_4^{2-} was between 720 and 1200 ppm in the flotation of a Cu-Ni-PGM-containing ore [19]. Using bubble–particle attachment time, collector adsorption, and microflotation tests, the presence of Ca^{2+} in a chalcopyrite slurry, where the Ca^{2+} concentration was varied from 400 to 1207 mg/L,

was found to reduce xanthate adsorption, resulting in lower bubble–particle interaction and ultimately lower recovery of the mineral [20]. The addition of SO_4^{2-} at 63 ppm to a polymetallic copper sulphide ore resulted in decreased Cu recoveries [29]. This was accompanied by a decrease in the grade of Cu due to the activation of pyritic gangue. Cu recoveries increased when the SO_4^{2-} concentration was increased from 200 to 6000 ppm in the flotation performance of complex sulphide ores from Morocco [30]. However, this was at the expense of the metal grades. The increase in Cu recovery was attributed to the formation of slightly soluble heavy-metal sulphite salts on the minerals surfaces. The same study further established that Ca^{2+} ions had no effect of the Cu recovery.

Overall the results in Table 6 indicate that the AMD treated with $Ca(OH)_2$ was detrimental to PGM and BMS recoveries. It should be noted that the threshold concentrations of Ca^{2+} and SO_4^{2-} established by [18,19] were lower than the concentrations of the same ions in the AMD treated with $Ca(OH)_2$ reported at 667.5 ppm and 2730 ppm, respectively (Table 5). At high concentrations, the Ca^{2+} and SO_4^{2-} may negatively affect the flotation response of the Merensky ore, resulting in the observed lower mass pull and recovery of valuable minerals. SO_4^{2-} may promote the oxidation of sulphide minerals, the formation and precipitation of metal sulphate on minerals surfaces, as well as the replacement of the collectors with sulphate ions on minerals surfaces [10,11]. All the three phenomena result in reduced hydrophobicity of the valuable minerals, translating to poor metal recoveries, especially at high SO_4^{2-} concentrations associated with the AMD treated with $Ca(OH)_2$. The effect of SO_4^{2-} on flotation performance is pH- and concentration-dependent. The depressing capability of SO_4^{2-} is pronounced under alkaline pH [31]. SO_4^{2-} promoted the dissolution and oxidation of sulphide minerals, resulting in better flotation performance in acidic media and poor flotation performance in alkaline media [11]. SO_4^{2-} was shown to interact with mineral surfaces and act as a depressant, thereby negatively affecting collector adsorption [32].

3.4. Effect of AMD-Treated Veolia Process on the Flotation Performance of the Merensky Ore

The treatment of the AMD using the Veolia process was investigated as one of the strategies to mitigate the detrimental effect of the AMD on the flotation response of the Merensky ore. The objective was to reduce the concentration of the SO_4^{2-} in the AMD. The Merensky ore was floated in the AMD treated with the Veolia process, and the results are presented in Table 6 and Figure 3, which showed that the AMD treated with the Veolia process improved the PGM and BMS rougher recoveries compared to potable water. Specifically, the PGM rougher recovery was improved by 3% from 67.8% to 70.8%. The rougher Cu and Ni recoveries were improved by 8.2% and 10.6%, respectively. The same trend was observed for the cleaners in which PGM and BMS recovery increases were observed. The recovery improvements were accompanied by reduced mass pulls and improved grades of the valuable minerals. The AMD with the Veolia process achieved the highest Cu recovery and grade in both the rougher and cleaner stages than both the potable water and the AMD treated with $Ca(OH)_2$. The AMD treated with the Veolia process and potable waters achieved similar Ni rougher and cleaner recoveries, higher than those achieved by AMD treated with $Ca(OH)_2$. Overall, the results showed that the treatment of the AMD using the Veolia process was beneficial as it resulted in improved PGM and BMS recoveries, though the PGM recovery was lower than in potable water. It is clear that the doubling of the Ca^{2+} concentration from 667.5 g/L to 1202 g/L due to the treatment process did not negatively affect the flotation performance of the Merensky ore. Applying the process of elimination, the results seem to suggest that the improvement in the PGM and BMS recoveries could be attributed to the reduction in the SO_4^{2-} concentration from 2730 g/L to 109 g/L.

3.5. Effect of Depressant Dosage on the Flotation Performance of the Merensky Ore

Another strategy that was investigated to mitigate the detrimental effect of AMD treated with $Ca(OH)_2$ on the flotation response of the Merensky ore was optimisation of the

depressant dosage. Flotation tests were conducted in which the depressant dosages were halved for both the AMD treated with $Ca(OH)_2$ and AMD treated with the Veolia process. The results are shown Table 6 and Figure 3, which show that halving the depressant dosage resulted in improved rougher and cleaner mass pulls in both the AMD treated with $Ca(OH)_2$ and AMD treated with the Veolia process. The increase in mass pull was accompanied by an increase in PGM and BMS rougher and cleaner recoveries in AMD treated with $Ca(OH)_2$. PGM, Cu, and Ni rougher recoveries increased by 23%, 3%, and 10% respectively, when the depressant dosage was halved in AMD treated with $Ca(OH)_2$. PGM, Cu, and Ni cleaner recoveries also increased by 22%, 4.8%, and 17%, respectively. Figure 3 shows that the PGM grade-recovery curve shifted to the far right when the depressant dosage was halved in AMD treated with $Ca(OH)_2$. It is clear from Table 6 that the improvement in the recoveries of the PGMs and BMS was due to increased mass pull.

It is clear from the results presented in Table 6 that halving the depressant dosage in AMD treated with $Ca(OH)_2$ resulted in higher PGM and Cu rougher recoveries than potable water despite the lower rougher and cleaner mass pulls. AMD treated with $Ca(OH)_2$ at a lower depressant dosage resulted in improved PGM and BMS rougher and cleaner concentrate grades than potable water. It is interesting to note that AMD treated with $Ca(OH)_2$ at a reduced depressant dosage achieved superior BMS cleaner concentrate grades than potable water at similar overall BMS recoveries. This could be owing to the improved depressant efficiency in systems with higher ionic strengths [25]. However, AMD treated with $Ca(OH)_2$ achieved a lower PGM cleaner recovery than the potable water at reduced depressant dosages. From a process economics point of view, the use of AMD treated with $Ca(OH)_2$ at reduced depressant dosages would result in significant savings in reagent costs without compromising on metallurgical performance.

On the other hand, the increase in mass pull observed for the AMD treated with the Veolia process at reduced depressant dosage was accompanied by a decrease in PGM and BMS rougher and cleaner recoveries. Figure 3 shows that the PGM grade-recovery curve shifted to the left when the depressant dosage was halved in the AMD treated with the Veolia process. Furthermore, the reduced depressant dosage resulted in improved PGM grades and decreased BMS grades. The increased mass pull at lower depressant dosage is attributed to the fact that some of the gangue minerals could not be depressed and reported to the concentrate. At higher depressant dosage, more gangue minerals are depressed, resulting in low mass pulls and consequently higher concentrate grades.

Overall, the results show that AMD has the potential to replace potable water as make-up water in Merensky processing plants. The results demonstrated that the AMD only requires pH neutralisation using lime before use in the flotation of the Merensky ores. Further treatment of the AMD is not necessary. The results have also demonstrated that depressant optimisation is very important to achieve superior metallurgical results when using AMD treated with $Ca(OH)_2$ as a process and transport medium in the flotation of the Merensky ores. The findings made in this paper are important to industrial plants seeking to reduce the use of potable water, especially in arid areas, where the largest water demand is usually in the dry period. It must be emphasised that the reagent conditions may need to be optimised for each Merensky ore as results vary depending on mineralogy. The use of AMD will conserve freshwater in line with sustainable water management of water resources, which advocate for zero use of potable water in minerals processing operations. Furthermore, the use of AMD will reduce the volumes of AMD in old mine dumps, thereby alleviating the safety, health, and environmental impact posed by the AMD.

4. Conclusions

This study investigated the viability of using neutralised AMD as a replacement for potable water as make-up water during the flotation of a platinum-group-minerals (PGM)-bearing Merensky ore. This study further investigated the treatment of the AMD using the Veolia process and the optimisation of the chemical system as strategies to minimise any

detrimental effects of the AMD on the flotation performance of a Merensky ore. The results showed that water quality affects the flotation response of Merensky ore.

The results showed that AMD treated with $Ca(OH)_2$ was detrimental to PGM recovery compared to potable water at higher similar depressant dosages of 50 g/t. Specifically, AMD treated with $Ca(OH)_2$ achieved a PGM rougher recovery 67.8%, while potable water achieved a PGM rougher recovery of 88.4%. The treatment of the AMD using the Veolia process was able to reduce the SO_4^{2-} concentration by 90% from 2730 ppm to 109 ppm; however, the concentrations of calcium and chloride ions as well as the ionic strength of the water system were increased. The results showed that the treatment of the AMD using the Veolia process was beneficial as the AMD treated with the Veolia process achieved a PGM rougher recovery of 70.8%, though the recoveries were still lower than those achieved in potable water. Reducing the depressant dosage to 25 g/t in AMD treated with the Veolia process resulted in the lower PGM and Ni rougher recoveries of 59.4% and 47.0%, respectively, compared to potable water. Reducing the depressant dosage to 25 g/t in AMD treated with $Ca(OH)_2$ resulted in the highest PGM, Cu, and Ni rougher recoveries of 91%, 60.2%, and 58%, respectively. The AMD treated with $Ca(OH)_2$ at a 25 g/t depressant dosage outperformed the potable water in terms of PGM and BMS recoveries and concentrate grades. Overall, the results show that AMD has potential to replace potable water as make-up water in Merensky processing plants. The results have demonstrated that depressant optimisation is important to achieve superior metallurgical results when using AMD. The use of AMD will save freshwater sources and reduce high volumes of AMD in old mine dumps. The results further demonstrated that there may only be a need to neutralise the AMD before using it as make-up water in Merensky ore processing plants. Further treatment using the Veolia process may not be necessary. It should be noted, however, that studies considering water quality impacts on flotation have seen varied responses depending on ore type, and the responses noted should be taken with consideration for the mineralogy under consideration.

Author Contributions: J.T. and N.S. conceived the research idea and designed the experiments; Z.P. and N.S. conducted the experiments; J.T., Z.P. and N.S. analysed the results; J.T. interpreted the data; J.T. wrote the paper; K.C. reviewed and edited the paper. All authors have read and agreed to the published version of the manuscript.

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