Optimizing The Effluent Treatment at a Coal Mine by Process Modelling

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Abstract
The water network of a coal mine was audited and simulated by an interactive steady state model. The findings from this investigation were used to optimise the mine's water management strategy. Simulation of the interactions in the water network showed that:

1. Powder calcium carbonate can be used as an alternative to lime for neutralization of acid water at a reagent cost saving of 56 percent.
2. Gypsum crystallization in the primary neutralization and coal processing plants amount to 30% and 60% respectively.
3. During separate treatment of coal discard leachate and the less polluted streams, the capital cost for a neutralization/gypsum crystallization plant amounts to R3.0 million, compared to R10.3 million during combined treatment. Only slightly less gypsum removal is achieved during separate treatment, namely 8.9 t/d versus 9.5 t/d.
4. The OSI value can be controlled effectively at 1 by treating the feed water to the coal processing for sulphate removal. A flow of 222 m^3/h needs to be treated for removal of sulphate to 350 mg/l to obtain an OSI value of 0.98 (less than 1). The capital of a 222 m^3/h biological sulphate removal plant is estimated at R21.8 million (R4.1 million/(Ml/d)) and the running cost at R13.7 million/a (R4.10/m^3).
5. Pre-washing of the coal will result in reduced capital and running cost.

Key words: Water-network simulation, stream segregation, sulphate removal.

Background

Modelling is a useful tool to select the most suitable Water Management Strategy (van Tonder, *et al*, 2000). Navigation Plant of Landau Colliery, Witbank, South Africa, is in the process of implementing a Water Management Strategy, which includes neutralisation and treatment for sulphate removal of certain selected mine water streams. The objectives of the Water Management Strategy include:

- Providing water which is fit for coal beneficiation plant use with a limited corrosion and scaling potential.
- Mitigation of the environmental impacts associated with mine water discharges.
- Closure of mine water circuits.
- Maximum re-use and utilisation of effluent streams.

The Toe Seep (coal discard leachate) Neutralization Project has been identified as the next component of the overall Water Management Strategy to be constructed. The purpose of this investigation was to determine, through a modelling exercise, the following:

- Degree of gypsum crystallization that occurs with the **existing system** in the primary neutralization plant and in the coal processing plant.
- The effect of gypsum crystallization on the gypsum saturation index after **separate and joint treatment of Toe Seep water** and less polluted streams.
- The effect of **gypsum crystallization on the effluent from the coal processing plant** when a side-stream of the flow from the thickener to the coal processing plant is treated.

- **Additional sulphate removal required** to ensure that the water in the coal processing plant is not over-saturated with respect to gypsum.
- Amount of sulphate that could be removed through **pre-washing** of the acid coal.
- Capital and running cost associated with various treatment options.

Model description

A water flow and chemical mass balance model was developed which made provision for the following:

Stages of the water network

- Existing neutralization plant.
- New gypsum crystallization plant after existing neutralization plant.
- New Toe Seep plant which includes or excludes gypsum crystallization.
- Biological sulphate removal plant.
- Coal processing plant.
- Sludge disposal pond.
- Waste disposal area for fine coal and coal discard.

Various input parameters

- 5 flow rates (neutralization plant, discard leachate neutralization plant, sulphate removal plant, thickener underflow to discard dump and penstock return water).
- Chemical composition of 3 feed waters (feed to the neutralization plant, discard leachate and penstock).
- Chemical composition of treated water from the sulphate removal plant.
- Percentage sulphate removal through gypsum crystallization in the stages where gypsum crystallization occurs (discard dump and the coal processing plant and crystallization treatment plants).
- Alkali consumption (in the neutralization plant and in the coal processing plant).

Output parameters

- Flow rate, chemical composition and gypsum saturation level of all other streams.
- Capital and running costs.

The model is based on the following principles:

- Steady state equilibrium at each point.
- Electron neutrality. The mole equivalents of the cations (acidity, iron(II), iron(III), calcium and magnesium) is equal to that of the anions (sulphate).
- Over-saturation index (OSI) = $[SO_4]_{solution}/[SO_4]_{equilibrium}$
  where:
  $[SO_4]_{equilibrium}$ = 1500/48 + $[Mg^{2+}]$ (determined empirically)
  [ ] = concentrations in mole equivalent per litre

Results

Figure 1 shows the process flow diagram of the various treatment options listed above with the main input and output values.

The following treatment options were evaluated:

- Current situation.
- Joint treatment (neutralization and gypsum crystallization) of Toe Seep water and less polluted streams.
- Separate treatment (neutralization and gypsum crystallization) of Toe Seep water and less polluted streams.
- Gypsum crystallization of water from the coal processing plant.
- Tertiary sulphate removal.
- Pre-washing.

Appendix A shows the Input and Output values for the first Option (no treatment) as an example.

Discussion

Alkali cost

Powder calcium carbonate can be used as an alternative to lime for neutralization of acid water and offers the following benefits:

- Reduced alkali cost. The cost of powdered

$CaCO_3$ is R150/t (1 US$ = SAR 9.50, November 2002), compared to R610/t for unslaked lime. This represents an alkali saving of 56 percent (Table 1).

- No silo is required for storage. Only a sloped concrete slab or hard surface is needed.
- Reduced use of lime slaker.
- $CaCO_3$ is safe to handle. It reacts only under acidic conditions.
- No dust as the product contains 20% moisture.

Table 1. Cost comparison between $CaCO_3$ and lime for the Toe Seep Neutralization plant.

Parameter	Alkali	
	$CaCO_3$	**Unslaked lime**
Flow rate (m^3/h)	40	40
Acidity (g/l)	10	10
Acid load (t/d $CaCO_3$)	9.6	9.6
Molecular mass	100	56
Utilization efficiency (%)	80	70
Purity (%)	75	85
Consumption (t/d)	16.00	9.04
Delivered price (R/t)	150.00	610.00
Cost (R/year)	880 000	2 010 000
Saving (R/year)	1 130 000	0
Cost ratio	44	100

Gypsum crystallization under current conditions

Acid water is over-saturated with respect to gypsum after neutralization with lime in the primary neutralization plant and in the coal processing plant. This results in scaling of pipelines, screens and other equipment (e.g. cyclones and spirals). The model can be used to calculate the percentage of gypsum crystallization in the various stages. Table 2 shows that gypsum crystallization in the primary neutralization plant amounts to 30% and to 60% in the coal processing plant.

Table 2. Gypsum crystallization in the primary neutralization plant and in the coal processing plant.

Parameter	Primary neutralize. plant	Coal processing plant
Feed water (Ml/d)	4.08	4.08
Feed sulphate (mg/l SO_4)	2 400	2 224
Acid leachate from coal (t/d CaCO3)		6
Sulphate from coal (mg/l SO_4)		1 471
Sulphate from feed water and coal		3 695
Equilibrium sulphate (mg/l SO_4)	1 812	1 935
Effluent sulphate (mg/l SO_4)	2 224	2 640
Sulphate removal (%)	29.9	59.9

Separate versus Combined treatment of strong and weak acidic streams

Table 3 shows the benefit when discard leachate with an acidity of 11.5 g/l is neutralized separately from the less polluted streams with an acidity of 600 mg/l. The flow rate of the discard leachate is 40 m^3/h while that of the less polluted streams 120 m^3/h. During separate treatment the capacity of the capital construction is much lower than during combined treatment, namely R3.0 million versus R10.3 million. Only slightly less gypsum removal is achieved during separate treatment, namely 8.9 t/d versus 9.5 t/d.

Gypsum crystallization in the coal processing plant

The OSI value in the coal processing plant needs to be 1 or less to prevent gypsum scaling. This can be achieved in the following ways:

- The make-up water of the coal processing plant needs to be sufficiently under-saturated with respect to gypsum so that the OSI value is 1 or less after acid from the coal has leached into the water and is neutralized with lime or $CaCO_3$. This option will be discussed in the next section, using the biological sulphate removal process.

- Acid that leach out in the coal processing plant can instead of being neutralized with lime, be neutralized with $Mg(OH)_2$. $MgSO_4$, which is formed when $Mg(OH)_2$ is used for neutralization, has a high solubility and does not form scale as is the case with gypsum that forms during neutralization with lime or $CaCO_3$. A disadvantage of this approach is that it requires a separate stage where Mg^{2+} is precipitated with lime at pH 12, followed by gypsum crystallization. The $Mg(OH)_2$ could be recycled.
- The water in the coal processing plant can be treated for gypsum crystallization to a level near its saturation level. Table 4, however, shows that a large volume needs to be treated for gypsum crystallization to make an impact. At a high flow rate of 200 m^3/h, the OSI is still 1.25, compared to 1.37 when zero treatment is applied. The total flow of 1 250 m^3/h needs to be treated for gypsum crystallization to prevent gypsum scaling, which would not be an affordable option.

Biological treatment

From the previous section it is concluded that the most effective way to prevent gypsum scaling in the coal processing plant is to treat the feed water to below the saturation level of gypsum. The purpose of this section is to determine what volume needs to be treated and to what level sulphate needs to be removed. Table 5 shows the effect of biological treatment on the OSI value in the coal processing plant. A flow of 210 m^3/h needs to be treated for removal of sulphate to 350 mg/l to obtain an OSI value of 0.98 (less than 1) (Figure 1 and Appendix A). The capital of a 222 m^3/h biological sulphate removal plant is estimated at R21.8 million (R4.1 million/(Ml/d)) and the running cost at R4.10/m^3.

Pre-wash of ROM in coal processing plant

Leachate studies showed that when ROM coal is submerged in water, acid is washed off from the coal within a contact period of 5 min. This option will require the following modifications to the current operation at Navigation:

- Install a pre-wash system for the coal. Neutralized water could be used as wash water. A counter flow wash system will have the benefit that minimum acid remains on the coal that enters the coal washing plant.
- Neutralize the acid water resulting from the washing operation in the proposed Toe Seep Neutralization plant. Although the acid load from the ROM coal will remain the same, this change will offer the benefit that less acid needs to be neutralized in the coal processing plant and hence, scaling in the coal processing plant will be reduced. The reduction in scale will be directly related to how much acid is redirected to the Toe Seep Neutralization plant. The aim should be to transfer 80 % of the acid load currently neutralized in the coal processing plant to the Toe Seep Plant. The remaining 20 % acid could be neutralized by dosing powder $CaCO_3$-slurry at one or more places in the coal processing plant (similar to the current situation where lime is dosed).

The effect of such a change in the operation of the coal washing plant could be determined from the current model. Table 6 shows the effect when the alkali consumption in the coal processing plant is reduced from the current 6 t/d (as $CaCO_3$) to 3 and 1 t/d respectively. Implementation of such a washing operation will reduce the required capacity of a sulphate removal plant from 222 m^3/h for when 6 t/d acid is neutralized in the coal processing plant to 150 m^3/h and 105 m^3/h for 3 and 1 t/d alkali respectively. These capacities include the volume of 40 m^3/h to be discharged. If the alkali dosage is reduced from 6 to 1 t/d (as $CaCO_3$), the capital cost of the sulphate removal plant will be reduced from R25.3 million to R14.5 million and the running cost from R13.4 million/a to R8.5 million/a.

Conclusions

1. Powder calcium carbonate can be used as an alternative to lime for neutralization of acid water at a saving of 56 percent.
2. Gypsum crystallization in the primary neutralization and coal processing plants

amounts to 30% and 60% respectively.

3. During separate treatment of coal discard leachate and the less polluted streams, the capital cost for a neutralization/gypsum crystallization plant amounts to R3.0 million, compared to R10.3 million during combined treatment. Only slightly less gypsum removal is achieved during separate treatment, namely 8.9 t/d versus 9.5 t/d.
4. Gypsum crystallization from the water in the coal processing plant is an inefficient method for controlling the OSI value.
5. The OSI value can be controlled effectively at 1 by treating the feed water to the coal processing for sulphate removal. A flow of 222 m^3/h needs to be treated for removal of sulphate to 350 mg/l to obtain an OSI value of 0.98 (less than 1). The capital of a 222 m^3/h biological sulphate removal plant is estimated at R21.8 million (R4.1 million/(Ml/d)) and the running cost at R4.10/m^3.
6. Pre-washing of the coal will result in reduced capital and running cost.

Reference

van Tonder, G.J., Theron, D.J. and Maree, J.P. 2000. Cost optimisation of the water management strategy by steady-state modelling of the water network of a copper/nickel mine and processing plant, *Proceedings of the WISA 2000 Conference*, Sun City, South Africa, 28 May-1 June.

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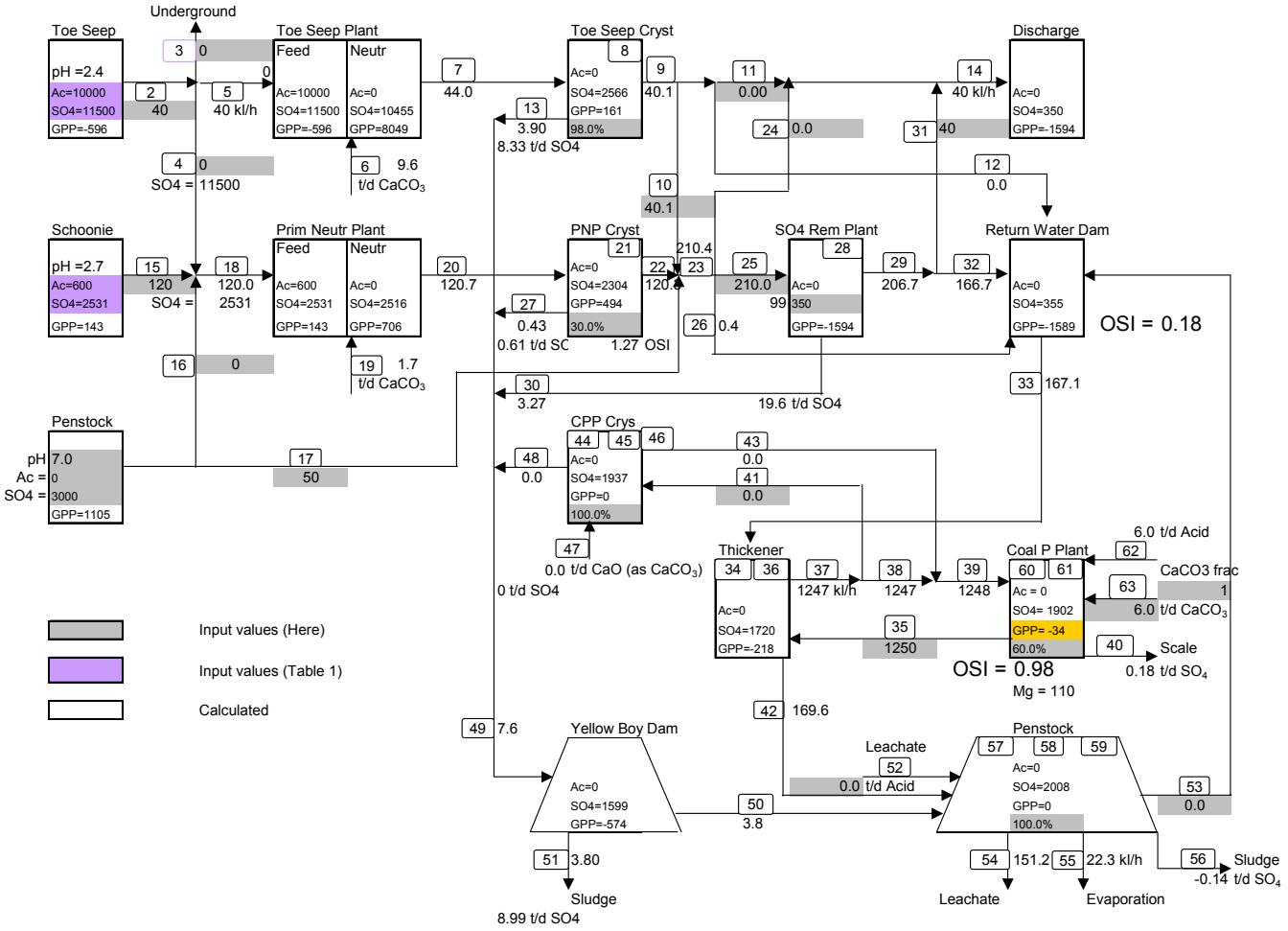
Table 3. Effect of separate and combined treatment (neutralization and gypsum crystallization) on sulphate removal.

Paramater		**Separate Option 2.1**	**Combined Option 1.3**
Flow (m^3/h)	Leachate discard	40	
	Make-up	120	
	Combined		160
SO_4 feed (mg/l)	Leachate discard	11500	
	Make-up	2531	
	Combined		4773
SO_4 treated (mg/l)		2289	2086
OSI after neutralization and crystallization		1.16	1.05
Gypsum (t/d)		8.9	10
Capital cost (R)		3 000 000	9 800 000
Running cost (R/m^3)		1.08	1.08



Option 4.3 Water flow and chemical mass balance for various effluent treatment scenarios. (Biological sulphate removal - 210 m3/h)

Figure 1. Water flow and chemical mass balance when no treatment is applied.

Table 4. Effect of the capacity of a gypsum crystallization plant on the OSI value of the coal processing plant.

Feed rate (m^3/h)	**OSI**
0	1.37
100	1.30
200	1.25

Table 5. Effect of biological treatment on the OSI value in the coal processing plant.

Parameter	**Separate neutralize. + Biological** Option 4.1	**Separate neutralize. + Biological** Option 4.2	**Separate neutralize. + Biological** Option 4.3
OSI in CPP feed	1.21	0.86	0.12
OSI in CPP	1.41	1.28	0.98
Sulphate removal (t/d SO_4)	22.4	24.4	28.8
Plant capacity (m^3/h)			
Toe Seep neutralization/crystallization	40	40	40
Sulphate removal	50	105	222
Capital cost for biological plant (R)	4 920 000	10 332 000	21 844 800
Capital cost for biological plant (R/(Ml/d))	4 100 000	4 100 000	4 100 000
Running cost for biological plant (R/m^3)	3.53	3.79	4.10

Table 6. Effect of pre-coal washing on the OSI value in the coal processing plant.

Parameter	Alkali dosage to CPP (t/d $CaCO_3$)		
	6	3	1
	Option 6.1	Option 6.2	Option 6.3
OSI:			
Feed to coal processing plant	0.16	0.58	0.86
In coal processing plant	1.00	1.00	1.00
Capacity of sulphate removal plant (m^3/h)	215.00	150.00	105.00
Capital cost (R)	25 295 529	18 899 529	14 471 529
Running cost (R/a)	13 429 951	10 515 088	8 505 088

APPENDIX A

INPUT AND OUTPUT PARAMETERS

OUTPUT:					
					Working column Option 4.3 (Biological sulphate removal - 222 m3/h)
Cryst. In PNP (%)					0.30
Cryst. in Toe Seep Neutralization/Crystallization plant (%)					0.98
Cryst. In Side-stream CPP Crystallization plant. (m3/h)					0.00
CSIRosure plant (m3/h)					222.00
Mg Rem in CPP Cr	No	Yes		0	No
Mg Rem in TSP	No		1500	1	1 500.00
	No		1100	1	1 100.00
Toe Seep (Ml/d)					0.96
Schonie (Ml/d)					0.00
OUTPUTS:					
SO4	PNP out				2 304.20
	Toe Seep Out				1 287.09
GPP:	CPP in				-1 593.33
	CPP out				-35.06
OSI	CPP in				0.12
	CPP out				0.98
Gypsum produced (t/d as SO4)					
	PNP plant				0.61
	Toe Seep Plant				9.68
	CPP Crystallization				0.00
	Pennstock				-0.15
	CPP				0.19
	Biological sulphate removal				18.42
	Total Gypsum				28.75
Treatment capacity (Ml/d)					
	PNP Cryst				2.90
	Toe Seep Cryst				1.06
	CPP Crystallization				0.00
	Sulphate removal				5.33
Capital cost (R/Ml/d)	PNP Crystallization				0.00
	Toe Seep Crystallization				4 000 000.00
	Sulphate removal				4 100 000.00
Capital cost (R)					
	PNP Cryst				0.00
	Toe Seep Cryst				4 139 529.41
	CPP Crystallization				0.00
	Sulphate removal				**21 844 800.00**
	Total				25 984 329.41
Prices					
	CaCO3 (as 100%) (R/t)				163.75
	CaO (as 100%) (R/t)				544.44
	Ethanol (R/t)				3 500.00
	Electricity (R/m3)				1.00
	Labour (R/m3)				0.50
	Maintenance (R/m3)				0.50
	Admin (R/m3)				0.10
Running cost (R/a)					
	CaCO3				1 035 672.99
	CaO				322 319.80
	Ethanol				5 252 236.80
	Electricity				3 387 668.96
	Labour				1 693 834.48
	Maintenance				1 693 834.48
	Admin				338 766.90
	Total				13 724 334.39
	Total Chemical				6 610 229.58
Value of CaCO3 produced (R/a)					753 529.66
Net Chemical cost (R/a)					5 856 699.92
Volume treated (m3/h)					382.00
Unit cost	Capital (R/(Ml/d))				**2 834 240.38**
	Running (R/m3)				**4.10**
CaCO3 usage (as 100 %) (t/d):					
	Toe Seep (t/d CaCO3)				9.60
	PNP (t/d CaCO3)				1.73
	CPP (t/d CaCO3)				6.00
	CPP Cryst. (t/d CaCO3)				0.00
	Total (t/d CaCO3)				17.33
CaO usage (as 100%) (t/d)					1.62
Ethanol usage (g EtOH/g SO4) (80 % Eff)					0.40
Ethanol usage (t/d EtOH)					4.11
CaCO3 production (as 100%) (t/d):					
	Biological plant				10.71
	Toe Seep Gypsum Cryst				1.90
Total (t/d)					12.61

INPUTS:				
Chemical composition (mg/l):				
Toe Seep	Ac			10 000.00
	H+			1 145.93
	Fe(II)			4 000.00
	Fe(III)			630.00
	Ca			376.85
	Mg			252.00
	SO4			11 500.00
	Alk			
	pH			2.80
Schoongesicht	Ac			600.00
	H+			27.29
	Fe(II)			222.00
	Fe(III)			50.00
	Ca			684.54
	Mg			79.00
	SO4			2 531.00
	Alk			
	pH			2.70
Flow rates (m3/h)	Toe Seep			40.00
	Toe Seep to Underground			0.00
	Toe Seep to PNP			0.00
	Schoongesicht			120.00
	Sconie to Toe Seep Neutr P			0.00
	CSIRosure			222.00
	CCP Crystallization			0.00
Iron(II) removal:	see blue			
Toe Seep Plant	No	Yes	1	Yes
PNP	No	Yes	1	Yes
Gypsum crystallization:				
Toe Seep	%			0.98
PNP	%			0.30
CPP	%			0.60
CPP Crys	%			1.00
Penstock	%			1.00
CSIRosure				
Effl SO4 conc (mg/l SO4)				350.00
CaCO3 concentration (%)				10.00
SS concentration (%)				25.00
SS conc. Yellow B D (%)				50.00
Acid and sulphate balance				
STAGE				ACID
				t/d CaCO3
INPUT				17.33
Inflows:				1.73
Schoongesicht				1.73
Coal:				15.60
ROM/Plant				6.00
Discard leachate				9.60
				0.00
OUTPUT				17.33
Effluents:				0.00
Underground				0.00
Seepage				0.00
Discharge				0.00
Neutralization/Crystallization:				17.33
Primary Neutralization Plant				1.73
Coal Processing Plant (CPP)				6.00
Toe Dam Neutralization Plant				9.60
CPP Crystallization				0.00
Penstock				0.00
Sulphate removal Plant				0.00
STAGE				SO4
				t/d SO4
INPUT				27.69
Inflows:				7.29
Schoongesicht				7.29
Coal:				20.40
ROM/Plant				5.76
Discard leachate				14.64
				0.00
OUTPUT				27.69
Effluents:				7.08
Underground				0.00
Seepage				6.74
Discharge				0.34
Neutralization/Crystallization:				20.61
Primary Neutralization Plant				0.61
Coal Processing Plant (CPP)				0.19
Toe Dam Neutralization Plant				9.68
CPP Crystallization				0.00
Penstock				-0.15
Sulphate removal Plant				10.28