



UNIVERSITY OF VENDA

A quality driven, financially sustainable,
comprehensive University

School of Environmental Sciences
Department of Mining and Environmental Geology

Characterization of potential acid leachate from raw coal, discard coal and slimes from Mafube Colliery: A replication to a proposed new extension, Mpumalanga Province, South Africa

By

Novhe Ntshengedzeni Obed

Student Number: 11501616

UNIVERSITY OF VENDA
LIBRARY

Thesis submitted in fulfilment of the requirements for the degree

Master of Earth Science in Environmental Geology

Supervisor: Prof J.S. Ogola
Department of Mining and Environmental Geology
University of Venda

Co-Supervisor: Dr J.P. Maree
CSIR-Natural Resources and the Environment
Pretoria

February 2013

UNIVEN LIBRARY

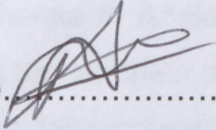
Library Item : 20132619



DECLARATION

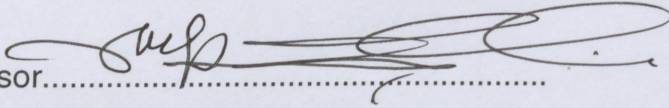
I, Novhe Ntshengedzeni Obed, hereby declare that this dissertation for the award of a Master of Environmental Geology degree at the University of Venda, hereby submitted by me, has not previously been submitted for a degree at this or any other university, and that this is my own work in design and execution and that all reference material contained therein has been acknowledged.

Signature.....



Date: 1/05/2013

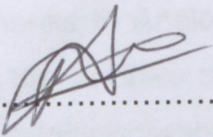
Supervisor.....



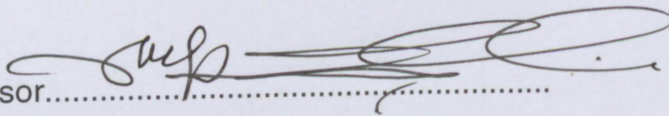
Date: 12/08/2013

DECLARATION

I, Novhe Ntshengedzeni Obed, hereby declare that this dissertation for the award of a Master of Environmental Geology degree at the University of Venda, hereby submitted by me, has not previously been submitted for a degree at this or any other university, and that this is my own work in design and execution and that all reference material contained therein has been acknowledged.

Signature.....


Date: 11/05/2013

Supervisor.....


Date: 12/08/2013

ACKNOWLEDGEMENTS

This work was supported by the THRIP funds at the Council for Scientific and Industrial Research (CSIR) to whom I express sincere thanks. Much appreciation is also expressed to the German Academic Exchange Service (DAAD) that offered me a scholarship for my master's programme. I would like to send my sincere thanks to Prof. J.S. Ogola (University of Venda) and Dr. J.P. Maree (CSIR, Natural Resources and the Environment) for their outstanding supervision and constructive comments. Special thanks to Anglo Coal personnel, Mr Peter Gunter and Mr Kevin Mclain, for arranging the samples and for their constructive comments. I would also like to thank Robert Netshitungulwana for his critical review.

ABSTRACT

Anglo Coal and Eyisizwe Coal plan to extend mining activities at the Mafube Colliery, Springboklaagte, Arnot North coal reserves. However, an integral part in every mining development project is the consideration of environmental impacts, particularly, the generation of acid mine drainage. Integrated geochemical and mineralogical study was conducted on raw coal, discard coal and slimes from the Mafube Colliery, to characterize the potential of acid leachate and also to quantify the quality of leachate from the samples. Bulk chemical and mineralogical analyses were done by means of X-ray fluorescence spectrometry and X-ray diffraction. Total sulphur and carbon content were determined by means of LECO induction furnace.

Raw coal was found to contain 0.4% of sulphide sulphur, predominantly as pyrite; 27% quartz and 73% kaolinite. Discard coal was found to contain 5% of sulphide sulphur as pyrite, and up to 80% of clay minerals such as kaolinite, as well as quartz and calcite (1%). Furthermore, raw coal contained 62% of carbon, whereas discard coal had only 29% carbon. Static tests were performed by means of acid base accounting procedures (ABA) to measure the theoretical potential of samples to generate and consume acid. Raw coal and slimes were found to be potential non-acid producers (raw coal $NNP=13.7$ kg $CaCO_3$ /ton and slimes $NNP=8.9$ kg $CaCO_3$ /ton); whereas discard coal was found to have potential to produce acid ($NNP= -12.2$ kg $CaCO_3$ /ton).

Column leaching tests were also carried out on samples using both tap water and pit water to determine the chemistry of leachate from samples over a period of time. Raw coal and slimes produced neutral leachate (raw coal $pH=6.11$ to 7.16 and slimes leachate $pH=7.12$), whereas discard coal produced acidic leachate ($pH=2.86$). Discard leachate was found to be characterized by two stages; the initial rapid acid generation stage followed by cyclic buffering due to dissolution of calcite, and possibly by less reactive kaolinite, and mica. This study has identified potential risks of acid generation from the future discard coal dump and recommendations were made to ensure that appropriate measures to prevent pollution into the environment are developed and implemented.

TABLE OF CONTENTS

DECLARATION	I
ACKNOWLEDGEMENTS.....	II
ABSTRACT	III
LIST OF FIGURES	VI
LIST OF TABLES.....	VIII
CHAPTER 1: INTRODUCTION	1
1.1. BACKGROUND.....	1
1.2. PROBLEM STATEMENT.....	3
1.3. HYPOTHESES.....	4
1.4. JUSTIFICATION	4
1.5. OBJECTIVES	4
1.6. DESCRIPTION OF THE STUDY AREA	5
1.6.1. Location	5
1.6.2. Climate.....	6
1.6.3. Hydrology.....	6
1.6.3. Topography and Drainage	6
CHAPTER 2: LITERATURE REVIEW.....	8
2.1. GEOLOGICAL SETTING.....	8
2.2. ACID MINE DRAINAGE.....	12
2.2.1. Acid Producing Minerals	16
2.2.2. Acid Consuming Minerals	17
2.3. ACID MINE DRAINAGE PREDICTION: AN OVERVIEW OF THE AVAILABLE TOOLS	19
2.4. CONTROL AND PREVENTION OF ACID MINE DRAINAGE	25
2.5. TREATMENT OF ACID MINE WATER.....	26
2.5.1. Active Treatment.....	28
2.5.2. Passive Treatment.....	28
2.6. IMPACTS OF ACID MINE DRAINAGE	31
2.6.1 Water Pollution.....	31
2.6.2. Soil Pollution	33
2.6.3. Effects on Human health.....	34
2.6.4. Economic effects.....	35

CHAPTER 3: MATERIALS AND METHODS	36
3.1. SAMPLES FOR ANALYSIS	36
3.2. BULK GEOCHEMICAL COMPOSITION ANALYSIS	38
3.3. MINERALOGICAL INVESTIGATION	38
3.4. BATCH LEACHATE TEST	38
3.5. GEOCHEMICAL STATIC AND KINETIC TESTS	39
3.5.1 Static Tests	39
3.5.2. Kinetic Leaching Test.....	40
CHAPTER 4: DATA ANALYSIS AND INTERPRETATION	44
4.1. BULK GEOCHEMICAL DATA.....	44
4.2. MINERALOGICAL DATA.....	46
4.3. BATCH LEACHATE DATA	46
4.4. GEOCHEMICAL STATIC TEST	47
4.4.1. Paste pH.....	49
4.4.2. Acid Base Accounting	50
4.5. KINETIC TESTS.....	52
4.5.1. Phase 1 Column Leaching Test.....	52
4.5.2. Phase 2 Column Leaching Test.....	59
CHAPTER 5: DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS.....	68
5.1. DISCUSSION	68
5.2. CONCLUSIONS	73
5.3. RECOMMENDATIONS.....	75
REFERENCES	77
APPENDIXES	
Figure 1. The column leaching experimental set up for phase 2.....	43
Figure 2. Mineralogical composition of the Mafube raw and discard coal.....	46
Figure 13. Pacts pH vs sulphur % for both phase 1 and phase 2 batches.....	49
Figure 14. Classification plot based on NAG pH vs NPR.....	50
Figure 15. Classification plot based on NPR vs NNP	51
Figure 16. The rate of acid generation for the Mafube raw coal and slimes samples for phase 1	54
Figure 17. The rate of acid generation rate of the Mafube discard coals for phase 1 column test	54
Figure 18. The pH profiles of the samples for phase 1 column leaching test	59
Figure 19. Sulphate generation rate of samples from phase 1 column leaching test.....	57

LIST OF FIGURES

Figure 1. Location of the proposed Mafube Colliery extension (Anglo American, 2004).....	5
Figure 2. Location of the study area in relation to its catchment, receiving water bodies and historic mines (Netshitungulwana and Yibas 2012).....	7
Figure 3. Generalised stratigraphic column for the Vryheid Formation in the Witbank Coalfield showing lithologies, coal seams and interpreted depositional environments (Cairncross et al., 1990).....	9
Figure 4. Representative Litho-stratigraphy profile for Arnot North Coal reserve area (Cairncross et al., 1990).....	11
Figure 5. Acid leachate from an old gold mine residue in the Krugersdorp, West of Johannesburg (CGS, 2012).....	14
Figure 6. Acid leachate from a coal discard dump in Carolina, Mpumalanga. (CGS, 2012).....	14
Figure 7. Acid Mine Drainage decants from an old abandoned flooded coal mine in the Witbank Coal field (CGS, 2013).....	15
Figure 8. Acid Mine Drainage flow about 15m away from the decant point with precipitates of hydroxides (CGS, 2013).....	15
Figure 9. Generic Prediction Program Flowchart (Gardguide, 2010).....	20
Figure 10. The column leachate test experimental set up for phase 1.....	41
Figure 11. The column leaching experimental set up for phase 2.....	43
Figure 12. Mineralogical composition of the Mafube raw and discard coal.....	46
Figure 13. Paste pH vs sulphur % for both phase 1 and phase 2 batches.....	49
Figure 14. Classification plot based on NAG pH vs NPR.....	50
Figure 15. Classification plot based on NPR vs NNP.....	51
Figure 16. The rate of acid generation for the Mafube raw coal and slimes samples for phase 1.....	54
Figure 17. The rate of acid generation rate of the Mafube discard coals for phase 1 column test.....	54
Figure 18. The pH profiles of the samples for phase 1 column leaching test.....	55
Figure 19. Sulphate generation rate of samples from phase 1 column leaching test.....	57

Figure 20. The rate of acid consumption of samples for phase 1 samples up to the 50th week of column leaching test..... 59

Figure 21. Rate of acid generation of samples during phase 2 column leaching test. 60

Figure 22. pH profiles of samples for phase 2 column leaching test..... 60

Figure 23. Alkalinity of samples during phase 2 column leaching test 62

Figure 24. Rate of sulphate generation of samples during phase 2 column leaching test..... 64

Figure 25. The rate of Ferrous Iron of samples during phase 2 column leaching test. 67

Table 1. Chemical composition of samples from Licking Colliery..... 37

Table 2. Chemical composition of samples from Phosf. of water..... 37

Table 3. Chemical composition of samples based on their Na₂CO₃ final pH..... 40

Table 4. Chemical composition of samples during leaching test..... 42

Table 5. The particle size distribution, their particle size and quantity..... 43

Table 6. The chemical composition of raw coal and discard coal samples..... 44

Table 7. The particle size distribution of raw coal and discard coal..... 45

Table 8. The chemical composition of the samples..... 45

Table 9. The leaching results after 60 minutes of the experiment..... 47

Table 10. The leaching results for the samples..... 47

Table 11. The acid production rate of the samples as mg CaCO₃/kg/week (phase 1)..... 53

Table 12. The sulphate generation as mg SO₄ per kg of the sample (Phase 1)..... 56

Table 13. The acid consumption as mg CaCO₃ per kg of the samples (phase 1)..... 58

Table 14. Acid production rate as mg CaCO₃ per kg of sample for phase 2 column leaching test..... 61

Table 15. Alkalinity of leachate from the samples (Phase 2 column test)..... 63

Table 16. Rate of sulphate generation as mg SO₄ per kg of the sample (phase 2 column test). 65

Table 17. Trace elements released from raw coal, discard coal, and slimes during the first week of column leaching test..... 66

Table 18. Relative mineral reactivity at pH 5 (Svardrup, 1990, and Kwong, 1993) .. 72

LIST OF TABLES

Table 1. Common Sulphides Known or Inferred to Generate Acid when Oxidized (Plumlee, 1999).....	16
Table 2. Typical NP Values and pH Buffering Ranges for Some Common Minerals (Jambor, 2003; Blowes et al., 2003)	18
Table 3. Generic Categories of Passive Treatment Systems (Gardguide, 2010).....	29
Table 4. Characteristics of passive, active and in situ methods for the treatment of acid mine drainage (Ramontja et al., 2011)	30
Table 5. Features of two batches of samples from Mafube Colliery.....	37
Table 6. Chemical composition of Anort pit water	37
Table 7. Categorization of samples based on their NAG final pH	40
Table 8. Conditions of phase 1 column leaching test.....	42
Table 9. The nature of samples, their particle size and quantity	43
Table 10. Chemical composition of raw coal and discard coal samples	44
Table 11. Trace elements composition of raw coal and discard coal	45
Table 12. Carbon and Sulphur contents of the samples	45
Table 13. The batch leachate results after 60 minutes of the experiment.....	47
Table 14. Acid base accounting results for the samples	47
Table 15 . Acid production rate of the samples as mg CaCO ₃ /kg/week (phase 1 column leaching test).....	53
Table 16. Rate of sulphate generation as mg SO ₄ per kg of the sample (Phase 1 column test)	56
Table 17. Rate of acid consumption as mg CaCO ₃ per kg of the samples (phase 1 column test).	58
Table 18. Acid production rate as mg CaCO ₃ per kg of sample for phase 2 column leaching test.....	61
Table 19. Alkalinity of leachate from the samples (Phase 2 column test).	63
Table 20. Rate of sulphate generation as mg SO ₄ per kg of the sample (phase 2 column test).	65
Table 21. Trace elements released from raw coal, discard coal, and slimes during the first week of column leaching test.	66
Table 22. Relative mineral reactivity at pH 5 (Sverdrup, 1990, and Kwong, 1993) ..	72

CHAPTER 1: INTRODUCTION

1.1. Background

An integral part in every mining development project is the consideration of environmental impacts, particularly, acid mine drainage. When sulphide-bearing geologic formation (notably with pyrite- FeS_2), such as coal, is exposed to moisture and oxygen during mining, it results in the formation of acid leachate, commonly known as acid mine drainage. The intensity and duration of acid mine drainage formation are complex functions of geology, mineralogy, hydrology, and the subsequent interaction of climatic conditions upon ore and mine waste when exposed by various mining methods (White et al., 1999). The wet and oxidative conditions experienced in mining environments are conducive to the formation of this environmental problem. In addition, the rate and degree by which acid mine drainage proceeds can be increased by the action of iron oxidizing bacteria, such as *Thiobacillus ferrooxidans* (Singer and Stumm, 1970).

Acid mine drainage is a significant and costly environmental impact of the mining industry worldwide. The legacy of mining continues to affect the natural environment, such as surface and groundwater resources, agricultural soil, fauna and flora, long after mining operations have ceased (Arnesen and Iversen, 1997). Metal leaching problems can occur over the entire range of pH conditions, but are most commonly associated with acid mine drainage (AMD). In North America, metal leaching and acid rock drainage have led to significant ecological damage, contaminated rivers, loss of aquatic life and multimillion-dollar clean-up costs for industry and government. The U.S. Forest Service (USFS) estimates that between 20,000 to 50,000 mines are currently generating acid on lands managed by that agency; with negative impacts from these mines affecting some 8,000 to 16,000 km of streams (USDA, Forest Service, 1993).

In South Africa, AMD has been/and is still receiving a lot of coverage from media, research institutions, government departments and non-government organisations (NGOs) due to its disastrous effect on the environment. The generation of

contaminated water from the old gold mines of the Witwatersrand Gold fields and abandoned coal mines in Mpumalanga still remain a major environmental concern. The environmental impacts of AMD have been reported in the gold mining areas (Scott, 1995; Hobbs et al., 1998; Naicker et al., 2003; Tutu et al., 2008) and Witbank coal mine sites (Bell et al., 2001; Hobbs et al., 2008; Mey and van Niekerk, 2009; McCarthy, 2009; Oberholster et al., 2010; McCarthy, 2011). The resulting acid leachate usually contains high concentrations of sulphates, acidity, and toxic metals such as copper, manganese, aluminium, lead, arsenic, zinc, cadmium, and cobalt that have manifold environmental consequences. Problems associated with acid mine drainage vary from pollution of surface and groundwater, disrupted growth and reproduction of aquatic plants and animals, to the corroding effects of the acid on mining equipment and infrastructure.

A prerequisite of sustainable development in mining areas must be to ensure uncontaminated streams, rivers, lakes and oceans as well as groundwater and soils, through management strategies. Development of proper acid mine drainage management strategies in coal mining areas requires fundamental understanding of physiochemical and geological properties, as well as leaching behaviour of geologic formations such as coal beds and surrounding rocks prior to actual mining.

For AMD to be managed effectively, the potential impacts and risks associated with solid mine residues need to be quantitatively predicted. Without reliable measurement of potential impacts, particularly over the long-term, there can be no meaningful plan to mitigate adverse effects, leaving limited avenues for improvement of environmental performance. Furthermore, in a legislative framework leaning towards preventative rather than remedial approaches, it is equally important that the quantification of environmental impacts and liabilities be brought into the early design stages of the project life cycle, where the choice of appropriate technology can effect a reduction in both the amounts of waste generated and the environmental hazards associated with the wastes.

Preventing impacts from AMD is the most costly and time consuming environmental issue facing the South African mining industry. It is also one of the most technically challenging. Due to poor historical practices, large remediation costs, technical

uncertainty and the potential for negative environmental impacts, AMD is a major issue of public and regulatory concern.

It is therefore crucial that potential for of acid mine water generation be known prior to actual mining activities, and once a mine is in operation environmental protection should remain the highest goal of the company, even if it means reduced mineral productivity. Adopting this common-sense ethic is the only way to ensure that the golden dreams of mining do not turn into the nightmare of polluted environment.

Today, numerous tools in the form of “static” and “kinetic” geochemical tests are widely used to quantify the risk of particular mine material to produce acid mine drainage. Static tests are short-term (measured in hours or days) and are normally done to estimate capacity of mine waste to produce and neutralize acid. Kinetic tests are long-term (usually takes months or years) and are usually done to confirm results of static tests, and more importantly, to determine the rate of reactions and quality of leachate with respect to time.

The present work focuses on the characterisation of the potential acid leachate from raw coal, discard coal and slimes in the proposed Mafube Colliery extension, a joint venture coal mining project between Anglo Coal and Eyisizwe Coal in Mpumalanga Province, by means of geochemical static and kinetic techniques, as well as mineralogical study. The leachate studies were also undertaken on various samples from different sites where the problem of acid leachate is active, for comparison purposes.

1.2. Problem Statement

Lack of knowledge on the nature and character of leachate that is likely to be produced as a result of coal mining often leads to long-term acid mine water generation that results in environmental and health impacts.

1.3. Hypotheses

- Chemical composition of leachate can be determined from raw coal, discard coal and slimes through chemical analysis.
- Leachate studies can help to determine the quantity and quality of leachate produced from coal mine water.
- Leachate studies can help to identify treatment and remedy processes that are ideal for water reuse, for example, in the coal processing plant or to meet the minimum water quality to be discharged to surface water bodies.
- Leachate study findings can be replicated in similar geological settings under similar mining methods and mineral processing.

1.4. Justification

Acid mine drainage is a widespread phenomenon affecting the quality of both underground and surface water, agricultural soil, fauna and flora in many coal mining areas in South Africa. It is therefore crucial for the mining industry to know the quality of expected leachate from coal mining before mining commences as this offers cost-effective means of reducing the environmental impacts of acid mine drainage. The present work therefore focuses on the characterisation of the potential leachate from raw coal, discard coal and slimes from the existing Mafube colliery and use of this for the intended extension project. The assumption is that the Mafube coal has the same characteristics as that at the proposed new site.

1.5. Objectives

The main objective of the study was to establish the nature and character of potential leachate from raw coal, discard coal and slimes. To achieve this, the following specific objectives were applied:

- Determination of the composition of leachate from raw coal, discard coal and slimes by means of geochemical analysis; and
- Determination of potential acid water generation and sulphate loads in leachate from raw coal, discard coal, and slimes

1.6. Description of the Study area

1.6.1. Location

The proposed Colliery is situated in the Mpumalanga Province approximately 30km east of Middelburg and 20km to the north of Arnot Power Station. The area is located within the Middelburg magisterial district and Nkangala District Municipality (Fig.1). The approximate location of Mafube colliery is: $29^{\circ} 31' 29''$ latitude and $25^{\circ} 40' 20''$ longitude. It is located at the eastern extremity of the greater Witbank Coalfield and includes the Springboklaagte, Nooitgedacht and Wildfontein resource blocks and the currently operating Mafube Mini pits. The extension area is demarcated in green colour (Fig.1).

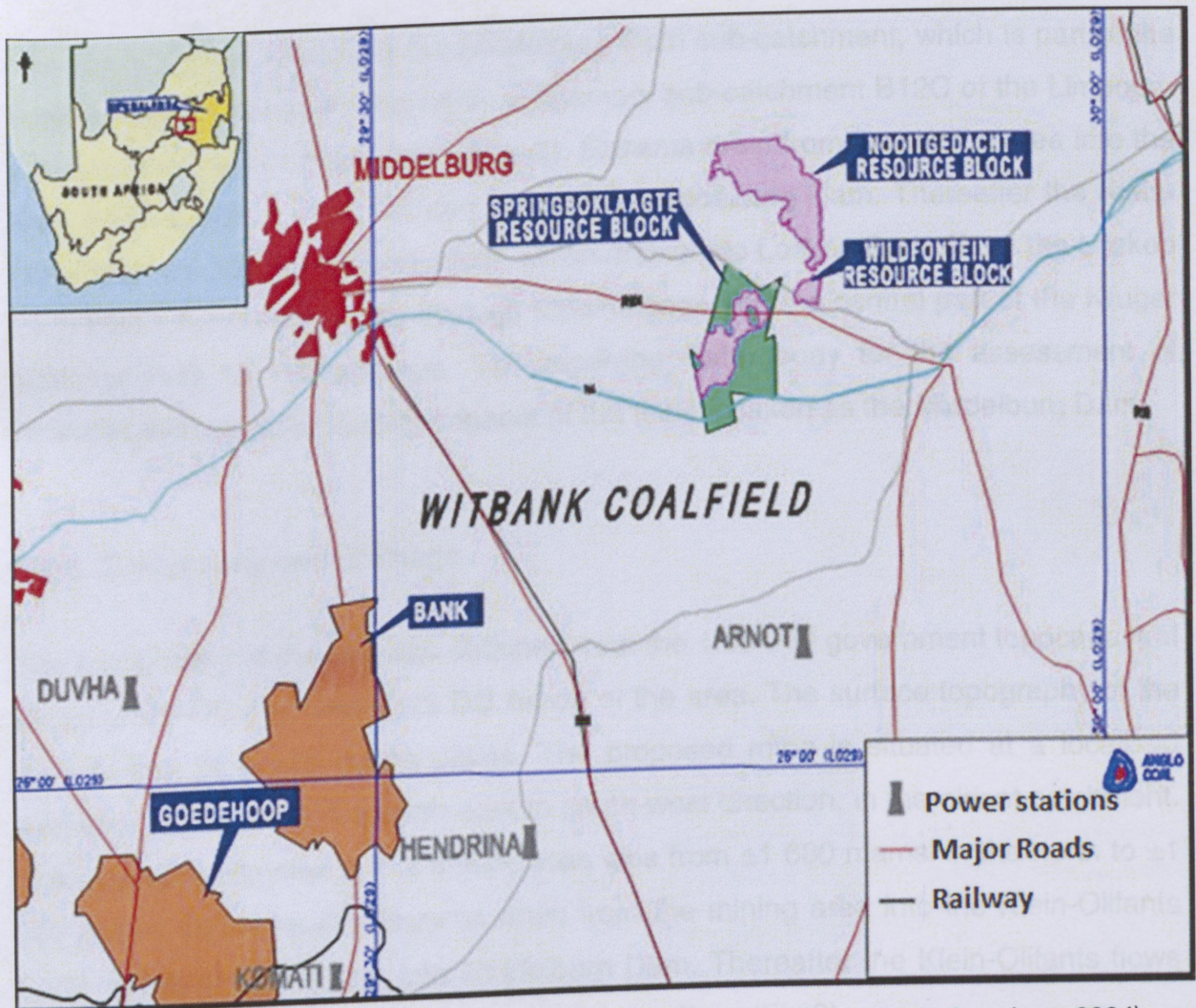


Figure 1. Location of the proposed Mafube Colliery extension (Anglo American, 2004).

1.6.2. Climate

The climate of the study area is temperate with hot wet summers (October to February) and mild dry winters (June to July). The annual rainfall, which falls mainly during summer, varies between 550 and 750 mm. The temperature ranges from 19°C to 26°C in summer and from 8°C to 26°C in winter. Average A-pan evaporation and humidity data from Bethal weather station shows that annual evaporation is 1 729 mm almost 2,7 times the annual rainfall (i.e. Precipitation deficit of 994 mm). The humidity is low during the day and increases slightly as the temperature cools at night (DALA, 2005).

1.6.3. Hydrology

The study area is located in the Middelburg Dam sub-catchment, which is part of the Loskop Dam catchment, and within quaternary sub-catchment B12C of the Limpopo-Olifants primary drainage region (Fig. 2). Streams drain from the mining area into the Klein-Olifants River, which in turn drains into Middelburg Dam. Thereafter the Klein-Olifants flows into the Olifants River, which drains into Loskop Dam. From the Loskop Dam the Olifants River flows through Mpumalanga and the central part of the Kruger National Park to Mozambique. The receiving water body for the assessment of potential surface water quality impacts of the mine is taken as the Middelburg Dam.

1.6.3. Topography and Drainage

The topography of the site was obtained from the 1:50 000 government topocadastral maps (2529 DC Pan and 2529 DD Arnot) of the area. The surface topography of the area is that of gentle rolling plains. The proposed mine is situated at a localised watershed orientated in a north-east to south-west direction, in the olifant catchment. The general inclination of the mining area dips from $\pm 1\ 680$ mamsl in the north to $\pm 1\ 660$ mamsl in the south. Streams drain from the mining area into the Klein-Olifants River, which in turn drains into Middelburg Dam. Thereafter the Klein-Olifants flows into the Olifants River, which drains into Loskop Dam (Fig.2).

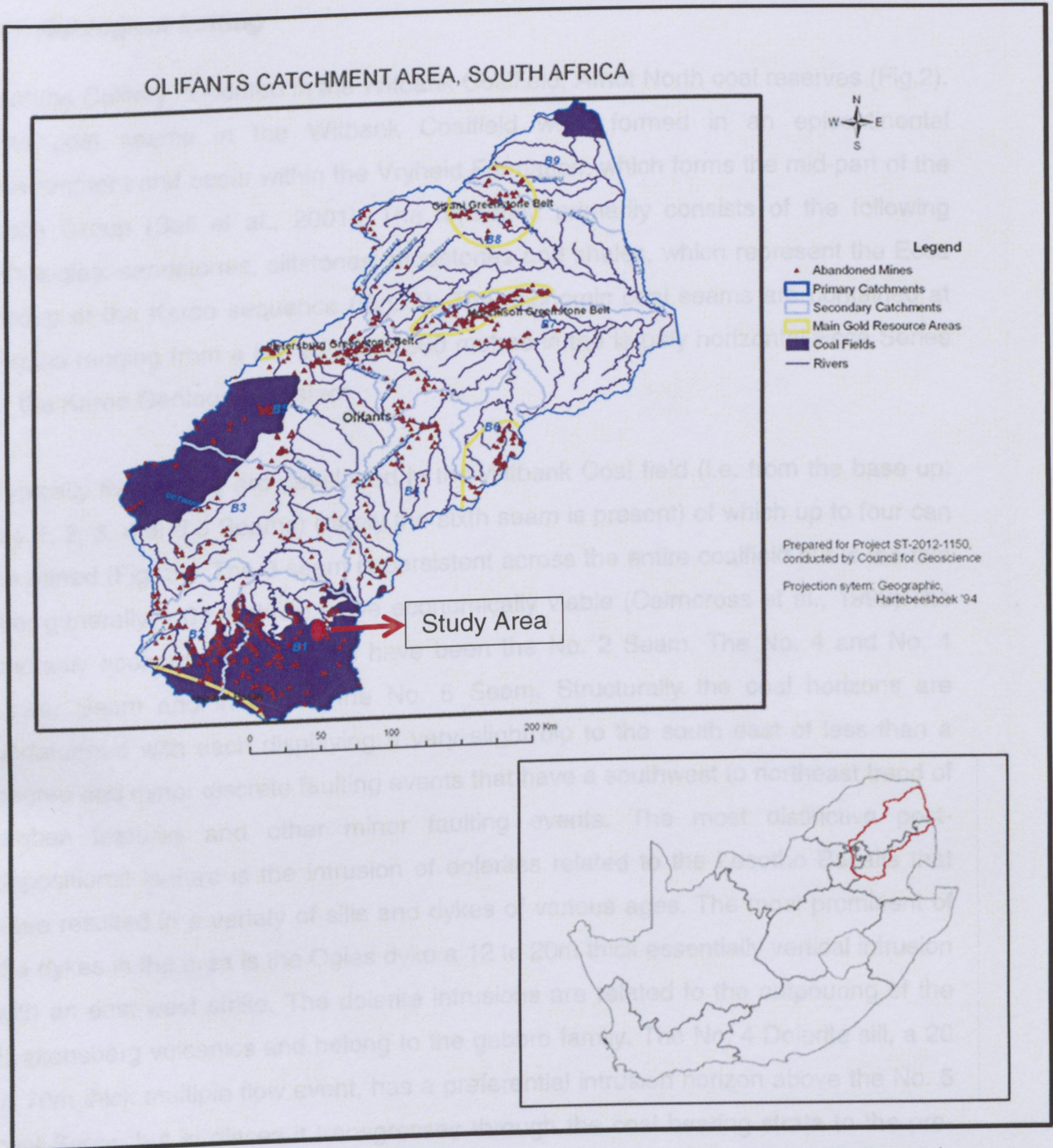


Figure 2. Location of the study area in relation to its catchment, receiving water bodies and historic mines (Netshitungulwana and Yibas 2012).

CHAPTER 2: LITERATURE REVIEW

2.1. Geological Setting

Mafube Colliery is located in the Witbank Coalfield, Arnot North coal reserves (Fig.2). The coal seams in the Witbank Coalfield were formed in an epicontinental environment and occur within the Vryheid Formation, which forms the mid-part of the Ecca Group (Bell et al., 2001). The formation primarily consists of the following lithologies: sandstones, siltstones, mudstones and shales, which represent the Ecca Group of the Karoo sequence (Fig. 3). The economic coal seams are contained at depths ranging from a few to about 300 metres in the largely horizontal Ecca Series of the Karoo Geological System.

Typically five seams are developed in the Witbank Coal field (i.e. from the base up, the 1, 2, 3, 4 and 5 Seams) (rarely the sixth seam is present) of which up to four can be mined (Fig. 3). The 3 seam is persistent across the entire coalfield but is too thin (i.e. generally < 0.5m thick) to be economically viable (Cairncross et al., 1990). The primarily economic coal Seams have been the No. 2 Seam, The No. 4 and No. 4 Lower Seam and in places the No. 5 Seam. Structurally the coal horizons are undeformed with each displaying a very slight dip to the south east of less than a degree and minor discrete faulting events that have a southwest to northeast trend of graben features and other minor faulting events. The most distinctive post-depositional feature is the intrusion of dolerites related to the Lesotho Basalts that have resulted in a variety of sills and dykes of various ages. The most prominent of the dykes in the area is the Ogies dyke a 12 to 20m thick essentially vertical intrusion with an east-west strike. The dolerite intrusions are related to the outpouring of the Drakensberg volcanics and belong to the gabbro family. The No. 4 Dolerite sill, a 20 to 70m thick multiple flow event, has a preferential intrusion horizon above the No. 5 coal Seam, but in places it transgresses through the coal bearing strata to the pre-Karoo basement and forms in other places a barrier to erosion. The large amount of exploitation in the region has resulted in the development of an efficient coal transportation infrastructure that is now resulting in previously uneconomic coal Seams such as the No. 1 and No. 2 Lower coal Seams becoming economic propositions (Exxaro, 2005).

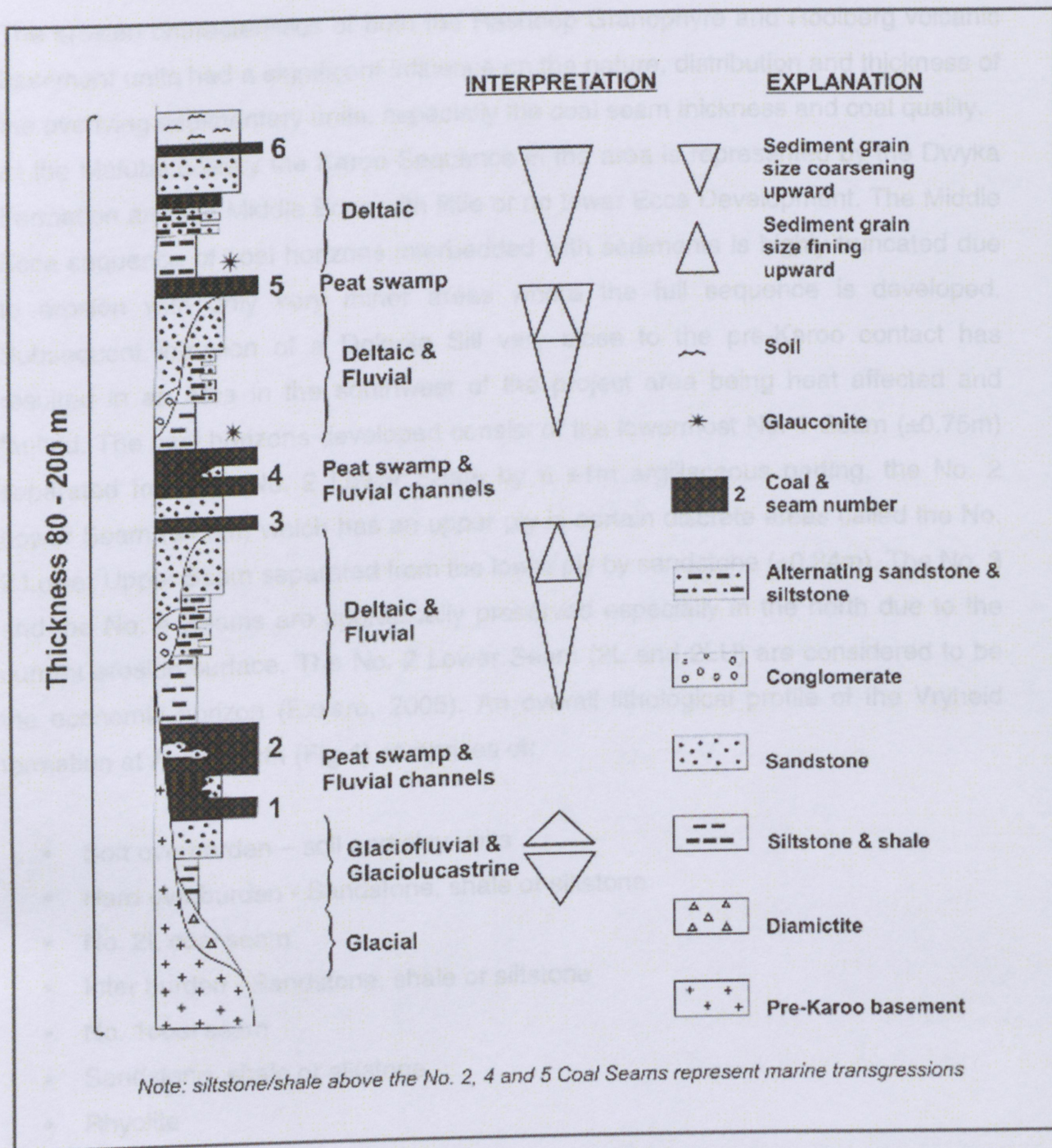


Figure 3. Generalised stratigraphic column for the Vryheid Formation in the Witbank Coalfield showing lithologies, coal seams and interpreted depositional environments (Cairncross et al., 1990).

The erosion characteristics of both the Rashedoop Granophyre and Rooiberg volcanic basement units had a significant influence on the nature, distribution and thickness of the overlying sedimentary units, especially the coal seam thickness and coal quality. At the Mafube colliery the Karoo Sequence in the area is represented by the Dwyka Formation and the Middle Ecca with little or no lower Ecca Development. The Middle Ecca sequence of coal horizons interbedded with sediments is highly truncated due to erosion with only very minor areas where the full sequence is developed. Subsequent intrusion of a Dolerite Sill very close to the pre-Karoo contact has resulted in an area in the southwest of the project area being heat affected and faulted. The coal horizons developed consist of the lowermost No. 1 Seam ($\pm 0.75\text{m}$) separated from the No. 2 Lower Seam by a $\pm 1\text{m}$ argillaceous parting, the No. 2 Lower Seam ($\pm 4.6\text{m}$) which has an upper ply in certain discrete areas called the No. 2 Lower Upper Seam separated from the lower ply by sandstone ($\pm 0.24\text{m}$). The No. 3 and the No. 4 Seams are sporadically preserved especially in the north due to the current erosion surface. The No. 2 Lower Seam (2L and 2LU) are considered to be the economic horizon (Exxaro, 2005). An overall lithological profile of the Vryheid formation at Arnot North (Fig.4) comprises of:

- Soft overburden – soil and clay units
- Hard overburden - Sandstone, shale or siltstone
- No. 2L coal seam
- Inter burden - Sandstone, shale or siltstone
- No. 1 coal seam
- Sandstone, shale or siltstone
- Rhyolite

The 1 Seam is a dull lustrous coal with scattered pyrite nodules with an average thickness of 1.3m (range: 0.79m to 2.11m)

Seam 2L has an average thickness of 2.94m. Predominately the seam comprises a hard, dull to lustrous coal with bright bands and occasional thin (~10cm) sandstone / siltstone lenses.

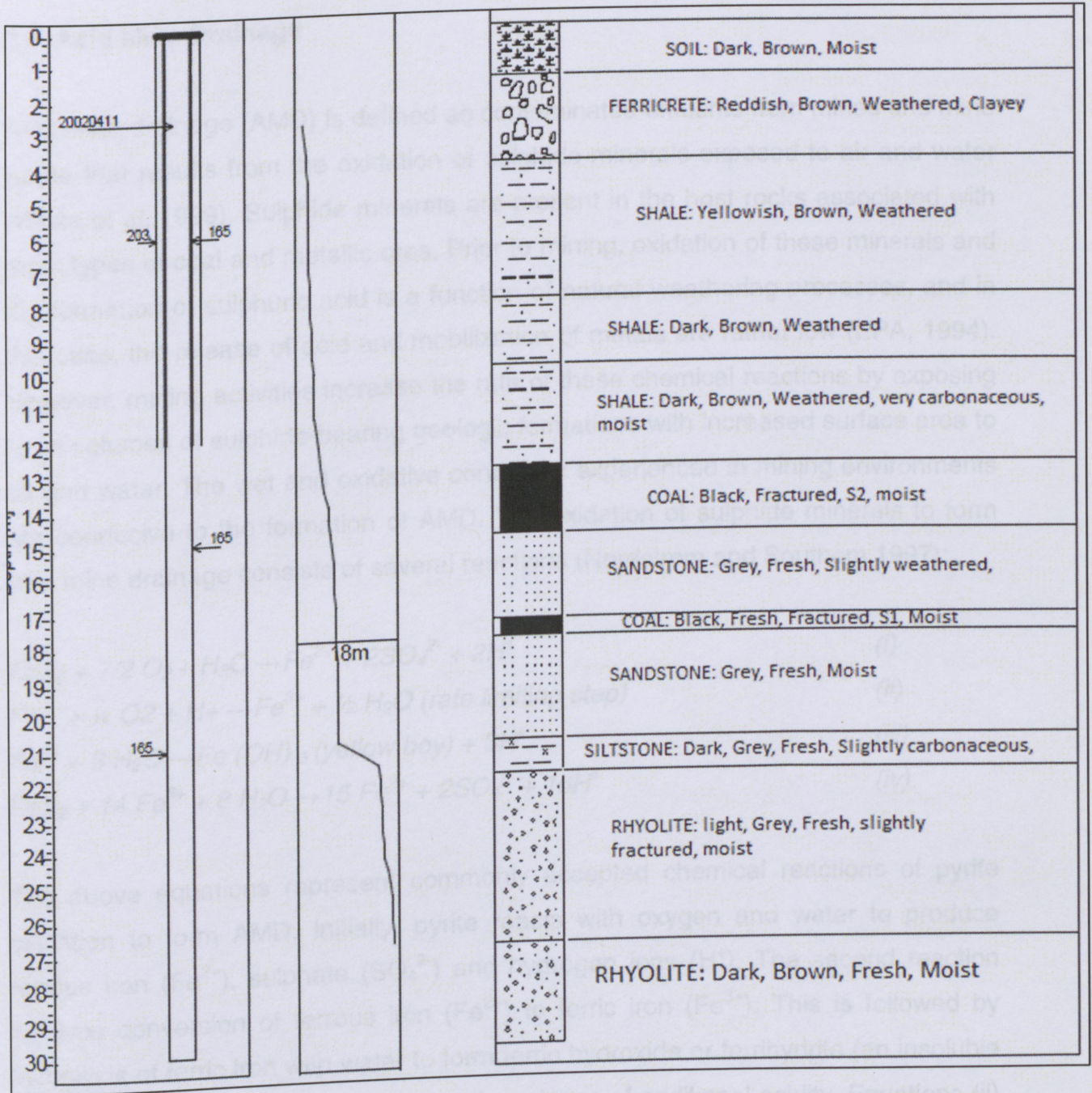
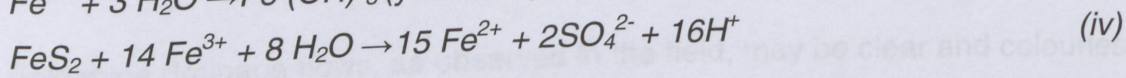
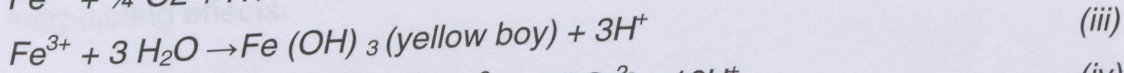
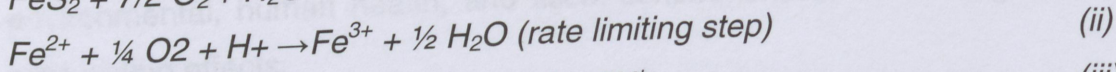
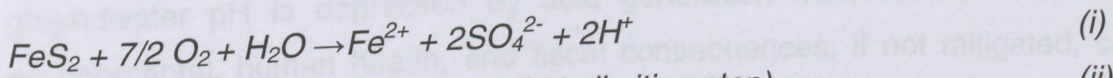


Figure 4 . Representative Litho-stratigraphy profile for Amot North Coal reserve area (Cairncross et al., 1990).

2.2. Acid Mine Drainage

Acid mine drainage (AMD) is defined as contaminated effluents from mines and mine waste that results from the oxidation of sulphide minerals exposed to air and water (White et al., 1999). Sulphide minerals are present in the host rocks associated with most types of coal and metallic ores. Prior to mining, oxidation of these minerals and the formation of sulphuric acid is a function of natural weathering processes, and in this case, the release of acid and mobilization of metals are rather low (EPA, 1994). However, mining activities increase the rate of these chemical reactions by exposing large volumes of sulphide-bearing geologic formations with increased surface area to air and water. The wet and oxidative conditions experienced in mining environments are conducive to the formation of AMD. The oxidation of sulphide minerals to form acid mine drainage consists of several reactions (Nordstrom and Southam 1997):



The above equations represent commonly accepted chemical reactions of pyrite oxidation to form AMD. Initially, pyrite reacts with oxygen and water to produce ferrous iron (Fe^{2+}), sulphate (SO_4^{2-}) and hydrogen ions (H^+). The second reaction involves conversion of ferrous iron (Fe^{2+}) to ferric iron (Fe^{3+}). This is followed by hydrolysis of ferric iron with water to form ferric hydroxide or ferrihydrite (an insoluble compound at pH greater than 3.5) and the release of additional acidity. Equations (ii) and (iii) represent the oxidation of ferrous iron to ferric iron and the consequent precipitation of ferric iron as ferric hydroxide. The two reactions account for the characteristic reddish-brown colour of sediments contaminated by acid mine drainage.

The last reaction involves the oxidation of the additional pyrite by ferric iron. The acidity is caused when the hydrogen (H^+) ions are released into water in one of the above steps. Ferrous iron can further be oxidized producing additional acidity. Iron and sulfur oxidizing bacteria, such as *Thiobacillus ferrooxidans*, are known to catalyze these reactions at low pH thereby increasing the rate of reaction by several orders of magnitude (Nordstrom and Southam, 1997). Another microbe, *Ferroplasma Acidarmanus*, has been identified in the production of acidity in mine waters (McGuire et al., 2001). This bacterium acts as a catalyst for the oxidation of sulphides and is ideally adapted to mine wastes as it can survive in water with a pH range of 1.5 to 6, but experiences optimal growth between pH 2 to 2.5 (Blowes et al., 2003).

The acid contaminated water further dissolves metals that were once part of the host rock and exacerbate the deleterious effect of low pH on terrestrial and aquatic receptors. Concentrations of common elements such as Cu, Zn, Al, Fe and Mn all dramatically increase in waters with low pH. Logarithmic increases in metal levels in waters from sulfide-rich mining environments are common where surface or groundwater pH is depressed by acid generation from sulfide minerals. These environmental, human health, and fiscal consequences, if not mitigated, can have long-lasting effects.

Acid mine drainage flows, as observed in the field, may be clear and colourless but in most cases, is distinctly yellow, amber or red, indicating high level of oxidized iron or may be greenish blue, reflecting the high concentration of sulphates. Figure 5 shows a typical acid leachate emanating from an old gold mine deposit in the Witwatersrand goldfields. The chemistry of leachate is as follows: $pH < 2$, $SO_4 > 7000$ mg/l, $Fe > 1000$ mg/l, with elevated concentration of the toxic metals such as Al, Co, U, Cu, Mn, Ni, et Zn. Figure 6 also shows a typical leachate from a coal discard dump (CGS, 2012). The leachate from the discard coal dump is also characterised by low pH, high concentration of Fe, sulphate and other toxic metals such as Al and Mn. Most of the acid generating mineral residues deposits associated with both gold and coal mining are not underlined nor designed properly, and hence they are responsible for continual degradation of both surface and groundwater resources. In most cases, such as in the Witwatersrand Goldfields and the Witbank Coalfields, contaminated

seepages from the mine residues directly discharge into the surrounding streams (CGS, 2012).



Figure 5. Acid leachate from an old gold mine residue in the Krugersdorp, West of Johannesburg (CGS, 2012).



Figure 6. Acid leachate from a coal discard dump in Carolina, Mpumalanga (CGS, 2012).

Acid mine drainage is also associated with abandoned mine sites. Figures 7 and 8 show acid mine drainage decants from an old flooded coal mine in the Witbank Coal field, near Emalahleni (CGS, 2013). The water quality is extremely poor; with high concentration of Fe, Sulphate, Al and Mn. This is one of the derelict and ownerless mine sites where the South African government has inherited the environmental liabilities.



Figure 7. Acid Mine Drainage decants from an old abandoned flooded coal mine in the Witbank Coal field (CGS, 2013).



Figure 8. Acid Mine Drainage flow about 15 m away from the decant point with precipitates of hydroxides (CGS, 2013).

2.2.1. Acid Producing Minerals

Sulphur-bearing minerals are responsible for the majority of acid in the acid mine drainage generation (Table.1). Pyrite (FeS_2) and, less commonly marcasite (FeS_2), are the principal sulphur bearing minerals in bituminous coal (Plumlee, 1999). In addition the authors indicated that pyrrhotite (FeS), arsenopyrite (FeAsS), chalcopyrite (CuFeS_2) and other sulphide minerals containing Fe, Cu, As, Sb, Bi, Se, and Mo also can produce acidic solutions upon oxidation, but these minerals are not common in coal beds. Each sulphide mineral has a different oxidation rate. For example, marcasite and framboidal pyrite will oxidise quickly, while crystalline pyrite will oxidize slowly (EPA, 1994). The rate of oxidation reaction is also a function of abundance, chemical properties (such as oxidation state) and physical characteristics (such as grain size) of acid producing mineral species (MEND, 2009).

Table 1. Common Sulphides Known or Inferred to Generate Acid when Oxidized (Plumlee, 1999)

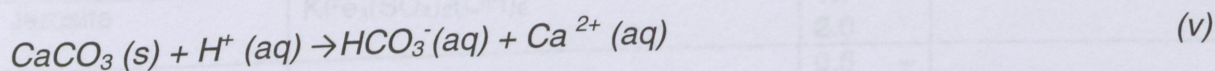
Mineral	Formula
Common sulphides known (<i>inferred</i>) to generate acid with oxygen as the oxidant:	
Pyrite, marcasite	FeS_2
Pyrrhotite	Fe_{1-x}S
Bornite	Cu_5FeS_4
Arsenopyrite	FeAsS
Enargite/famatinite	$\text{Cu}_3\text{AsS}_4/\text{Cu}_3\text{SbS}_4$
Tennantite/tetrahedrite	$(\text{Cu,Fe,Zn})_{12}\text{As}_4\text{S}_{13}/(\text{Cu,Fe,Zn})_{12}\text{Sb}_4\text{S}_{13}$
Realgar	AsS
Orpiment	As_2S_3
Stibnite	Sb_2S_3
Common sulphides that may generate acid with ferric iron as the oxidant:	
All of the above plus:	
Sphalerite	ZnS
Galena	PbS
Chalcopyrite	CuFeS_2
Covellite	CuS
Cinnabar	HgS
Millerite	NiS
Pentlandite	$(\text{Fe,Ni})_9\text{S}_8$
Greenockite	CdS

Although most of AMD from sulphide-bearing geological formations are from oxidation of sulphide minerals, the dissolution of soluble and less soluble iron sulphate minerals also contribute to the acidity of drainage (Lapakko, 2002).

Hydrated iron sulphate minerals are secondary minerals from oxidation of sulphides, and they precipitate during evaporation of acidic, iron, and sulphate-rich water within mine waste material (such as coal discard) and store acid generated by oxidation process. These hydrated iron sulphate minerals occur usually as efflorescent salts on the surfaces of weathering pyrite, and they tend to subsequently release acid upon dissolution. Common efflorescent salts that are found on the surface of weathering pyrite are: melanterite($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$); rozenite($\text{FeSO}_4 \cdot 4\text{H}_2\text{O}$); szomolnokite ($\text{FeSO}_4 \cdot \text{H}_2\text{O}$); romerite ($\text{Fe}^{2+}\text{Fe}^{3+} (\text{SO}_4)_4 \cdot 14\text{H}_2\text{O}$); and copiapite, ($\text{Fe}^{2+}\text{Fe}^{3+} (\text{SO}_4)_6 \cdot 20\text{H}_2\text{O}$) (Alper et al., 1994).

2.2.2. Acid Consuming Minerals

The common most effective acid consuming minerals are those minerals containing calcium carbonate and other carbonates. Examples of neutralizing minerals include: calcite (CaCO_3); magnesite (MgCO_3); dolomite [$(\text{CaMg}(\text{CO}_3)_2$] and ankerite[$(\text{CaFe}(\text{CO}_3)_2$]. The equation below represents dissolution reaction of calcite:



Dissolution rates are not the same for all carbonate minerals. For example, Sverdrup (1990) and Kwong (1993) have reported that the dissolution rates of magnesite and dolomite are substantially slower than that of calcite.

In addition, some silicate minerals, in particular calcium-magnesium (Ca-Mg) silicates, also contribute to buffering of acid water, but their dissolution rate is slower relative to the carbonate minerals (Jambor, 2003). These silicates are responsible for most or all dissolved K, Na, Al, Mg, and some Ca, and locally some of the Fe in the AMD solutions as indicated in equation vi, vii, and viii. These equations show how some silicate minerals contribute to buffering of acid mine water:

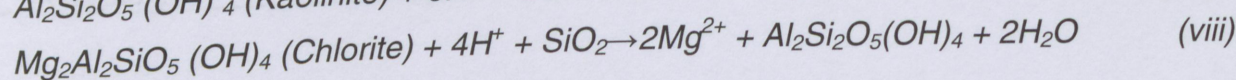
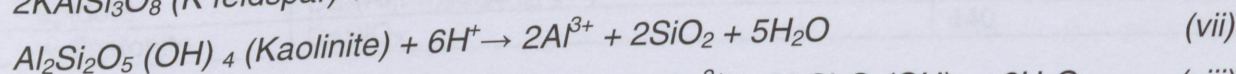
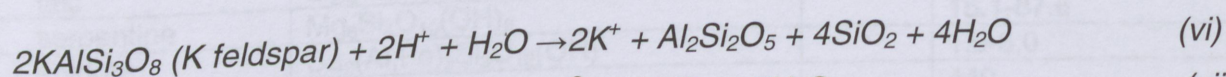


Table 2 below provides an overview of the ranges of neutralization potential and buffering pH for a number of common minerals.

Table 2. Typical NP Values and pH Buffering Ranges for Some Common Minerals (Jambor, 2003; Blowes et al., 2003)

Group	Formula	Buffer pH	Neutralization Potential Range (kg CaCO ₃ /tonne)
Carbonates			500-1,350
calcite, aragonite	CaCO ₃	5.5 – 6.9	
siderite	FeCO ₃	5.1 – 6.0	
malachite	Cu ₂ CO ₃ (OH) ₂	5.1 – 6.0	
Oxides			
gibbsite	Al(OH) ₃	3.7 – 4.3	
limonite/goethite	FeOOH	3.0 – 3.7	
ferrihydrite	Fe(OH) ₃	2.8 – 3.0	
Jarosite	KFe ₃ (SO ₄) ₂ (OH) ₆	1.7 – 2.0	
Alumino silicates		0.5 – 1.5	
Feldspar Group			
K-feldspar	(K,Na)AlSi ₃ O ₈		0.5-1.4
albite (Ab100-Ab50)	NaAlSi ₃ O ₈		0.5-2.6
anorthite (An51-An100)	CaAl ₂ Si ₂ O ₈		5.3-12.5
Pyroxene Group	(Me)(Si,Al) ₂ O ₆		0.5-9.5
Amphibole Group	(Me) ₇₋₈ ((Si,Al) ₄ O ₁₁)(OH) ₂		0.2-8.1
Mica Group			
muscovite	KA ₁₂ (AlSi ₃ O ₁₀)(OH) ₂		0.3
biotite	K(Mg,Fe) ₃ (AlSi ₃ O ₁₀)(OH) ₂		2.7-8.8
Chlorite Group	(Mg,Fe,Al) ₆ (Al,Si) ₄ O ₁₀ (OH) ₈		0.8-21.6
Clay Group	(Me)(Si,Al) ₄ O ₁₀ (OH) ₂		-2.7-29.0
Garnet Group	(Ca,Mg,Fe,Mn) ₃ (Al,Fe,Cr) ₂ (SiO ₄) ₃		1.3-6.3
Apatite Group	Ca ₅ (PO ₄) ₃ (F,Cl,OH)		2.7-11.3
Miscellaneous			
talca	Mg ₃ Si ₄ O ₁₀ (OH) ₂		1.7
serpentine	Mg ₆ Si ₄ O ₁₀ (OH) ₈		15.1-87.6
epidote	Ca ₂ (Al,Fe) ₃ Si ₃ O ₁₂ (OH)		1.0-3.0
wollastonite	CaSiO ₃		440

2.3. Acid Mine Drainage Prediction: An overview of the available tools

Prediction of drainage chemistry is a critical part of mine planning; particularly water and mine waste management (Price and Errington, 1998). The primary objective of mine and process water quality prediction is to evaluate the potential for geologic materials and mine and process wastes to generate acid and other constituents of potential environmental concern, and the potential to affect water resources. As an important corollary, the need for and nature of mitigation measures is determined through prediction.

The science of acid mine drainage prediction is still far from conclusive. As a result, it has been the subject of numerous investigations. Some general references in the subject include publications by Usher et al. (2003); Lapakko, (1993); Lawrence and Wang, (1997); and Sobek et al., (1978). Prediction of acid mine drainage is required to find out if the quality of water draining from a mine site will exceed environmental regulatory standards, and if so, what mitigation measures have to be provided at the onset. In most cases acid mine drainage prediction is based on the following:

- to determine if discrete volume of mine waste will result in acid mine generation; and
- to predict the quality of the acid mine drainage based on the rate of acid formation measured.

The following approaches have been used for predicting water quality resulting from mining activities:

- test leachability of waste materials in the laboratory;
- test leachability of waste materials under field conditions;
- geological, hydrological, chemical, and mineralogical characterization of waste materials; and
- Geochemical modelling.

Generally, the predictive program involves carrying out a number of integrated and iterative tests, analyses, and procedures to assess the future behaviour of mine wastes (Fig.9).

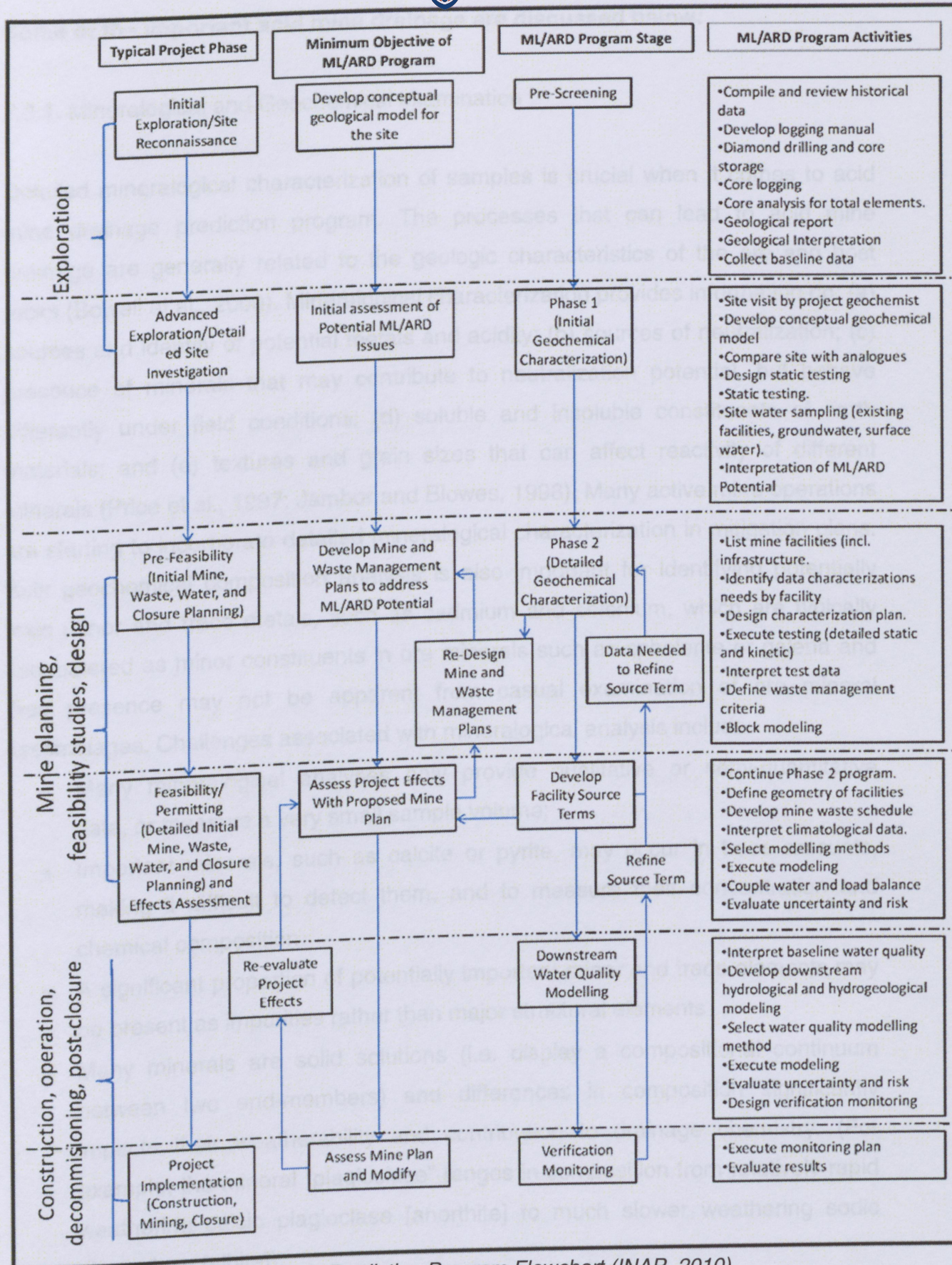


Figure 9. Generic Prediction Program Flowchart (INAP, 2010).

Some of the important acid mine drainage are discussed below:

2.3.1. Mineralogical and Geochemical examination

Detailed mineralogical characterization of samples is crucial when it comes to acid mine drainage prediction program. The processes that can lead to acid mine drainage are generally related to the geologic characteristics of the ore and host rocks (Bowell et al., 2000). Mineralogical characterization provides information on: (a) sources and identity of potential metals and acidity; (b) sources of neutralization; (c) presence of minerals that may contribute to neutralization potential, but behave differently under field conditions; (d) soluble and insoluble constituents of earth materials; and (e) textures and grain sizes that can affect reactivity of different minerals (Price et al., 1997; Jambor and Blowes, 1998). Many active mine operations are starting to incorporate detailed mineralogical characterization in mitigation plans. Bulk geochemical composition analysis is also important for identifying potentially toxic minor and trace metals, such as cadmium and selenium, which are typically sequestered as minor constituents in ore minerals such as sphalerite or galena and their presence may not be apparent from casual examination of ore mineral assemblages. Challenges associated with mineralogical analysis include:

- Many mineralogical analyses only provide qualitative or semi-quantitative data, or measure a very small sample volume;
- Important minerals, such as calcite or pyrite, may occur in trace amounts, making it difficult to detect them, and to measure their concentration and chemical composition
- A significant proportion of potentially important minor and trace elements may be present as impurities rather than major structural elements
- Many minerals are solid solutions (i.e. display a compositional continuum between two end-members) and differences in composition significantly impacts their weatherability and contribution to drainage chemistry. (For example, the mineral “plagioclase” ranges in composition from relatively rapid weathering calcic plagioclase [anorthite] to much slower weathering sodic plagioclase [albite]).

The most common mineralogical analyses that are used during mine drainage prediction program are the following:

- visual description;
- petrographic analysis;
- X-ray Diffraction (XRD);
- scanning Electron Microscopy with Energy Dispersive Spectrophotometer (SEM/EDS);
- Electron microprobe;
- laser ablation and other microbeam techniques;
- image analysis; and
- Calculated mineralogy from solid phase elemental data.

2.3.2. Static and Kinetic Geochemical Tests

Static Tests

Static tests predict drainage quality by comparing sample maximum acid production potential (AP) with its maximum neutralization potential (NP) (EPA, 1994). Acid potential of a sample is defined as the measure of acid producing minerals or species such as pyrite, whereas neutralization potential of a sample is the measure of carbonate minerals such as calcite (CaCO_3) available to buffer the acid that is produced. In the laboratory these are done by means of acid base accounting (ABA) techniques first developed in 1974 by the University of Virginia, and later modified by Sobek et al., (1978). Further modifications were also done by other researchers, such as: Ferguson and Robertson, (1994), Lapakko (1993), Usher et al., (2003). Rules and guidelines of acid base accounting procedures have been developed by mine regulatory and permitting agencies.

ABA is a screening procedure whereby the acid-neutralizing potential (assets) and acid-generating potential (liabilities) of rock samples are determined, and the difference, net neutralizing potential (equity), is calculated. The net neutralizing potential (NNP), and/or the ratio of neutralizing potential to acid-generation potential, is compared with a predetermined value, or set of values, to divide samples into categories that either require, or do not require, further determinative acid potential

generation test work. The NNP is the difference between NP and AP i.e. $NNP = NP - AP$. The neutralization potential ratio (NPR) is the ratio of NP to AP: $NPR = NP/AP$. The NNP is used to categorise the tested material into acid-producing or non-acid producing material.

Kinetic Test

Neutralization potential (NP) refers to amount of acid consuming species available in a sample. Generally, NP is determined by acid digestion procedure followed by titration with a base. Literature on neutralization potential determination procedures may be reviewed on Sobek et al., (1978), Lapakko, (1994), Lawrence and Wang, (1997), and Mills, (1997). Despite individual procedural differences, these methods all involve the:

- reaction of a sample with a mineral acid of measured quantity;
- determination of the base equivalency of the acid consumed; and
- conversion of measured quantities to a neutralizing potential in g/kg or kg/tonne or tonne/1000 tonne calcium carbonate ($CaCO_3$).

Acid potential (AP) refers to the amount of acid generating materials available in a sample. Generally, acid potential of a sample is determined by two different methods, namely, sulphur assay method, and peroxide method. In sulphur assay method there is a factor of 31.25 that is typically used to convert weight percentage of total sulphur or sulphide sulphur to standard units of AP ($Kg CaCO_3/ton$ of material) (Lapakko, 1994). This method is based on the assumption that all sulphide sulphur is present as pyrite and that all pyrite oxides according to a stoichiometry, result in two protons per mole of pyrite. Therefore, when no organic material containing sulphur is present in samples, potential for acid generation is attributed to the potential oxidation of sulphide minerals to sulphate (sulphuric acid). But if other forms of sulphur are present, the method tends to overestimate the AP.

Sulphide minerals include the common iron minerals pyrite (FeS_2) and pyrrhotite ($Fe_{1-X}S$), and metallic sulphides such as chalcopyrite ($CuFeS_2$), sphalerite (ZnS), galena (PbS). The sulphide sulphur content is taken to react stoichiometrically with oxygen and water to form sulphuric acid which has equivalence in calcium carbonate, and hence acid generation potential in $kg CaCO_3/tonne$ or $tonne CaCO_3/1000 tonne$

is calculated (Mills, 1997). The peroxide method, however involves the use of peroxide (strong oxidizing agent) to oxidize available sulphides in a sample, and the mixture is then titrated with a base to determine the AP.

Kinetic Test

Kinetic tests are distinguished from static tests in that they attempt to mimic natural oxidation of the field setting (EPA, 1994). Generally, kinetic leaching test involves simulation of mine drainage production from samples of strata to be affected by mining, followed by chemical analyses of effluent quality produced from the simulated conditions. Unlike the static tests, kinetic geochemical tests are undertaken over a long period of time (for months or years) and are quite expensive. They provide information on the rate of sulphide mineral oxidation; acid production; water quality with respect to time. Kinetic testing involves leaching of representative samples and monitoring water quality over a period of months or years under laboratory or field conditions. Common kinetic geochemical methods which are used for acid mine drainage characterization include: humidity cells, lysimeters, Soxhlet extraction, column test, shake-flask tests, biological test, field test pads, mine wall washing, and examination of site drainage

Humidity cells are commonly used laboratory kinetic tests and as a result an American Society for Testing and Materials (ASTM) method has been adopted for humidity cells. They are normally conducted in a plastic container with ports for air input and air output. The humidity cells as conducted by Sobek (1978), leaches 200 g crushed sample in an enclosed container. Conditions to accelerate the natural acceleration rates of material are induced so that diagnostic weathering products can be produced, collected, and quantified. Therefore, these kinetic tests do not exactly mimic actual field weathering rate, thus, it is difficult to extrapolate results from humidity cells to actual field conditions. The test is run for ten weeks, and then follows a seven day cycle of dry and humid air respectively. For instance, during the seven-day period, dry air is passed through the sample for the first three days and humidified air for the next three days. On the seventh day the sample is rinsed with 200 ml of distilled water. The leachate is then analysed for various parameters such as pH, acidity, alkalinity, conductivity, sulphates, and metals of interest.

Column test: This test involves stacking of sample/material in a cylinder or similar device (EPA, 1994). Wetting and drying cycles are created by adding water and then allowing the column to dry. The water added is collected and analysed for pH, acidity, alkalinity, conductivity, and selected dissolved metals. Unlike the humidity cell, no oxygen is forced into the column. Column test equipment, like humidity cells, is a relatively simple apparatus compared to a Soxhlet extraction device. It is easily modified to test control options, such as the addition of limestone, the influence of bacteria, and water saturation (Water Resources Control Board 1990). Results from research indicate that column tests of well sorted tailings material greater than 0.5 cm in diameter accurately represents field test conditions (Bradham and Caruccio, 1990). Tests of waste rock material were not reported. Some of the disadvantages of column type tests are that the long time required, the associated high costs, and as mentioned above, the potential for channelling

Soxhlet Extraction Tests: This test simulates geochemical weathering using a Soxhlet extraction apparatus to recirculate solution through the sample. The sample is placed in a thimble in the unit and solution is circulated from a reservoir. Two procedures are used—one is the standard test described by Singleton and Lavkulich, (1978); the other is the modified test described by Sobek et al., (1978). In the standard test the sample is leached using a 70°C solution of acetic acid or distilled water over a period of six weeks (duration of the procedure may vary). The modified test uses only distilled water at 25°C. Research by Coastech, (1989) determined that use of acetic acid yielded unrealistic results. Soxhlet extraction test conditions are more extreme than other kinetic tests. However, it is a shorter test and may be useful in simulating long weathering trends in a relatively short test time. Drawbacks include the complex equipment required and the more complex nature of the test in general.

2.4. Control and Prevention of Acid Mine Drainage

Many laws and regulations have been passed to help treat and control the problem of acid drainage. For instance, the EPA has helped establish new U.S.A. effluent limits including reduced drainage acidity in which the pH must fall between 6 and 9, and the average iron content must not exceed 3 mg/L.

The most cost-effective and rational approach is to control acid mine drainage from its source, for example, by controlling oxidation of iron sulphide minerals. Traditional control of acid mine drainage involved the use of surfactants such as sodium dodecyl sulphate (SDS). These surfarcant have not been widely used because research shows that they temporally prevent AMD, and over time they bind to surface and subject to degradation (Mudder and Olson, 2004). Source control has also been attempted by application of solutions to coat reactive sulphides with silica, phosphate, ferric hydroxide, or manganese. Generally, these approaches have not been adopted because of several reasons, including efficiency, stability, and cost.

In addition, water management techniques for controlling AMD include water diversion, soil covers and plastic liners, dewatering, inundation, underground mine sealing, barriers, grout curtains and walls, and underground mine filling by injection of surfactants that binds acid-generation of materials.

2.5. Treatment of Acid Mine Water

Preventing the formation or the migration of AMD from its source is generally considered to be the preferable option (Barrie and Hallberg, 2004). However, in cases where AMD already exists it is necessary to collect, treat, and discharge mine water. The objectives of mine drainage treatment are varied and may include one or more of the following (INAP, 2010):

- Recovery and reuse of mine water within the mining operations for processing of ores and minerals, conveyance of materials, and operational use (e.g., dust suppression, mine cooling, and irrigation of rehabilitated land).
- Protection of human health in situations where people may come in contact with the impacted mine water through indirect or direct use of mine water drainage.
- Environmental protection, specifically related to mining water impacts on surface water and groundwater resources. Mine drainage may act as the transport medium for a range of pollutants, which may impact on-site and off-site water resources. Water treatment would remove the pollutants contained in mine drainage to prevent or mitigate environmental impacts.

Some of the treatment options are active and passive treatment:

- Useful and potentially saleable products may be recovered from mine drainage. It is unlikely that by-products recovery would be a sole driver to the installation of a water treatment facility. However, when commodity prices are high, the recovery of saleable products will improve the financial viability of mine drainage treatment projects.
- Regulatory requirements may stipulate a mine water discharge quality or associated discharge pollutant loads. Any discharge of mine drainage to a public stream or aquifer must be approved by the relevant regulatory authorities. Discharge quality standards may not be set for many developing mining countries, but internationally acceptable environmental quality standards may still apply as stipulated by project financiers and company corporate policies.
- Mine water is a valuable resource and much of the world is facing water stress. The beneficial use of mine water to satisfy the needs of a variety of mining and non-mining water users can be a key driver supporting the installation of mine drainage treatment facilities. There is an increasing number of mine drainage treatment projects aimed at supplying treated mine water to neighbouring communities and industries around mines.
- Sustainability of mining will require the mitigation, management, and control of mining impacts on the environment. In many cases, the mining impacts on water resources are long term and persist in the post-closure situation. Mine drainage treatment may be a component of overall mine water management to support a mining operation over the mine's entire life and enhances post-closure and sustainable use of the mine property long after the ore deposit is depleted.

Some of the treatment options are active and passive treatment:

2.5.1. Active Treatment

Active treatment, as normally applied to acid mine drainage, involves chemical neutralization of the acidity followed by precipitation of iron and other suspended solids. Several solutions have been proposed to reduce acid mine drainage. Some of the buffering agents that have been found effective include hydrated lime, sodium hydroxide, detergents, and several carbonate compounds. When dumped into the streams, they raise the pH, thus, neutralizing the effects of acid in the water. Limestone has been found to be cost-effective neutralising agent in the treatment of acid mine drainage (Maree et al., 2004). To date several limestone neutralization plants to treat acid mine drainage more satisfactory in most South African coal mines (Neutralization plants in Landau Navigation, Optimum and Grootvlei coal mines) have been developed. Several methods that are used to neutralise acid water in South Africa include:

- Chemical treatments with lime or limestone, and with barium salts for sulphate removal;
- Gypsum crystallization ion exchange process (GYP-CIX) for Sulphate removal;
- Membrane technology for sulphate removal that includes slurry precipitation and recycles reverse osmosis (SPARRO) process, and electrical dialysis reversal (EDR); and
- Biological sulphate removal by means of bioreactors, such as the Rhodes Bio SURE process.

2.5.2. Passive Treatment

Passive treatment is defined as a water treatment system that utilises naturally available energy sources such as topographical gradient, microbial metabolic energy, photosynthesis and chemical energy and requires regular but infrequent maintenance to operate successfully over its design life (Pulles and Heath, 2004).

There are number of passive treatment system that, ranging from limestone drains to constructed or artificial wetlands that are currently in use worldwide. Table 3 shows generic categories of passive treatment systems.

Table 3. Generic Categories of Passive Treatment Systems (Gardguide, 2010)

Passive Treatment Technology	Application Niche in Mine Drainage
Aerobic wetlands	Net alkaline drainage
Anoxic limestone drains (ALD)	Net acidic, low Al ³⁺ , low Fe ³⁺ , low dissolved oxygen drainage
Anaerobic wetlands	Net acidic water with high metal content
Reducing and alkalinity producing systems (RAPS)	Net acidic water with high metal content
Open limestone drains (OLD)	Net acidic water with high metal content, low to moderate SO ₄ .

The history of passive treatment systems is dated back in the past 30 years, when a group of researchers at Wright State University and West Virginia University identified potential of natural wetlands to attenuate mine pollution (Huntsman et al., 1978; Wieder and Lang, 1982). These field observations prompted the U.S. Bureau of Mines to examine whether wetlands might be constructed for the intentional treatment of coal mine drainage. It was thought that small seeps present at many abandoned mine sites could be passively treated in this manner. Research efforts were initiated by the U.S. Bureau of Mines, in cooperation with Wright State University (Kleinmann et al., 1983).

Artificially wetlands are constructed with the aim to remediate and treat AMD from coal and metals mines. Artificial wetlands to treat zinc-rich mine drainage have been reported at United Keno Hills mines in Canada. The zinc concentrations were reduced as the water flowed through the wetland, from an initial concentration of 25 mg/L to approximately 5 mg/L (Microbial Technologies, 1997). This is a removal rate of 80%, which is reasonably good. Passive treatment technologies offer many advantages over the conventional active treatment technologies. The comparison between these technologies is summarized in table 3.

Table 4. Characteristics of passive, active and in situ methods for the treatment of acid mine drainage (Ramontija et al., 2011)

Characteristic	Active Treatment	Passive Treatment	In Situ Treatment
Operational involvement	Active and on-going plant operations and maintenance systems and personnel.	Constant operations not required, but regular maintenance essential.	Active and on-going operational personnel required, but permanent presence on site not required.
Operational inputs and materials	Requires chemicals, operations staff, maintenance staff, electrical power, continuous and/or regular monitoring.	Self-sustaining processes, periodic maintenance, intermittent monitoring. May require replacement or supplement of materials at low frequency.	Requires chemicals, operations staff, intermittent field maintenance, electrical power and low frequency monitoring.
Supply of power	Electrical and mechanical energy sources.	Natural energy sources of gravity flow, solar energy and bio-chemical energy.	Electrical and mechanical energy sources.
Management and supervision requirements.	On-going management engagement, constant facility supervision.	Low level management engagement and low frequency intermittent supervision.	High frequency supervision, but no permanent site presence required.
Range of application (flow rates and constituents)	Application to all flow rates, especially high flow rates and any constituent of interest.	Mainly applied to low flow rates and acidity, metals, and sulphate removal.	Large spectrum of volume and flow applications, mainly to deal with acidity and metals removal.
Treated water quality	Treatment process can be purpose built to deal with spectrum of treated water requirements.	Treated water quality poorer and more variable than other options.	Treated water quality lower and more variable than active treatment process.
Waste sludge and brine production.	Waste sludge and brine are produced, depending on level of treatment, requiring disposal.	No brine production, but longer term liability to deal with accumulated pollutants in wetland sludge.	Sludge and waste production accumulated <i>in situ</i> which may pose a long term environmental liability.
Capital investment cost	High capital investment and periodic capital replacement required.	Moderate capital investment with periodic reinvestment to replace depleted wetlands media.	Low capital investment typically to deal with a short term problem.
Operating and maintenance cost	High operating and maintenance cost, with some potential for cost recovery by sale of product water, metals and by-products.	Low operating cost.	Moderate operating costs, but chemical usage may be high due to process inefficiency.

2.6. Impacts of Acid Mine Drainage

Acid leachate has been a detrimental by-product of coal and other sulphide ore mining for many years. At present, AMD continues to pose a potential problem in some areas, despite improved prediction and prevention techniques. Acid leachate usually contains high concentrations of sulphates, acidity, and toxic metals that have manifold environmental consequences. Problems associated with acid mine drainage vary from pollution of drinking water, disrupted growth and reproduction of aquatic plants and animals, to the corroding effects on mining equipment and infrastructure.

2.6.1 Water Pollution

Degradation of groundwater and surface water resources is the major environmental problem associated with acid mine drainage. The pH of the water is lowered due to the introduction of acid, resulting from sulphide mineral oxidation. Heavy metal ions can also be released into the water due to chemical reaction on other sulphide minerals.

Ground and surface water pollution is one of the major problems associated with acid leachate in South Africa. Department of Water Affairs (DWA) (2009) found that the increase in average total dissolved solids (TDS) content of water in the Vaal Barrage has accelerated since 1965, due to adjacent mining activities. A total of dissolved solids content of 550 mg/L has been measured in the late seventies as opposed to an average of 100 mg/L in the early sixties. Acid mine drainage arising from gold mining activities is said to be contributing significantly to the quality of groundwater and surface water emanating from Witwatersrand's watershed (Naicker et al., 2003). It is noted that the polluted groundwater is discharging into streams in the area and contributes up to 20% of stream discharge, causing a lowering of pH of the stream water. Much of the metal load is precipitated in the stream: Fe and Mn precipitate because of oxidation, whereas other heavy metals are being removed by co-precipitation.

Mey et al., (2009) estimated that seepage from the old Middaburg Steam coal mines

A study conducted by Naicker et al., (2003) in the West Rand and Central Rand goldfields also indicated that acidified water seeping from the mine residues contributes an average of about 20% of stream flow. In addition, a study conducted by Tutu et al., (2008) also revealed the deterioration of surface and groundwater quality in the immediate vicinity of mine residues. AMD resulting from the abandoned underground mines was first noticed in 2002 August in the West Rand, west of Johannesburg. As an emergency solution the polluted mine water is currently being pumped and neutralised with lime to precipitate toxic metals such as iron (Fe), manganese (Mn) and sulphate before being discharged into a nearby streams. This active treatment option is considered to be very much expensive and has limited efficiencies in removing other contaminants such as sulphates. No management measures are currently implemented in respect of polluted mine water contained in the old pits and seepages from the mine residues, and hence this is posing continuous substantial impacts on the environment

In addition, Bell et al., (2001) also reported marked deterioration of groundwater quality and eradication of aquatic fauna and flora associated with AMD from coal mining in the Witbank coalfield area. The Olifants river catchment is known to be one of South Africa's most degraded rivers because of impacts from coal mines, abandoned mines, agriculture, industry and sewage pollution. Coal mining in this catchment started in the 1890s and by 2004 an estimated 50 000 m³ of mine water was discharged into the Olifants River daily, as well as 64 000 m³/day from closed and abandoned mines (Maree et al., 2004; Hobbs et al., 2008)

Oberholster et al., (2010) and Maree et al., (2004) reported that Loskop Dam has sulphate concentrations that exceed target drinking water standards around its inflow areas. The Loskop Dam provides water to the second-largest irrigation scheme in South Africa, irrigating about 16 000 hectares of crops that include sunflowers, soya, wheat, vegetables, tobacco, peanuts, cotton and citrus fruit (Loskop Irrigation Board, 2011). McCarthy (2009) also reported high concentration of sulphate in the Witbank dam.

Mey et al., (2009) estimated that seepage from the old Middleburg Steam coal mines into the Blesbokspruit is at a rate between 20 000 and 120 000 m³ per month, depending on rainfall and season. This has resulted into the degradation of the water quality. Similarly, AMD seepage from the burning mine flows into the Brugspruit tributary, which divides the abandoned mining area from rapidly expanding urban settlements.

The effect of AMD on the aquatic environment can be disastrous due to high acidity. The acid leachate both acidifies the local watercourses and so destroys or limits the growth of the river ecology due to its low pH. In reality the vast majority of natural life can only live and survive at, or near, pH 7 (neutral). If the pH falls below the tolerance range, death will occur due to respiratory failure (Kimmel, 1983). Low pH causes a disturbance of the balance of sodium and chloride ions in the blood of aquatic animals. At low pH, hydrogen ions may be taken into cells and sodium ions expelled (Morris et al., 1989).

Impacts of acid mine drainage to aquatic life also arises due to metals contained. For instance, in most coal mines, iron is the metal of concern due to its physical properties than its toxic effects. Iron may be found in two forms, ferrous and ferric. Small concentrations of iron in water are capable of producing large volumes of precipitates, which cover the surfaces of the land and streams close to the drainage. These precipitates tend to have negative impacts on the aquatic ecology, for instance, the precipitates coat the gills of vertebrate life forms (such as fish) and cause fatalities. In addition, the precipitates also tend to block sunlight and, thus delay the process of photosynthesis.

2.6.2. Soil Pollution

Another consequence of AMD is soil pollution. Soils also lose their ability to support plant growth when they become polluted by means of acid mine drainage. For instance, seepage of acid mine water in the soil increased heavy metals levels which are highly toxic, not only to plants, but also to the micro-organisms living in the soil. In addition this can render the soil barren for many years.

2.6.3. Effects on Human health

Mine polluted water contains high levels of sulphates and dissolved heavy metals (such as manganese, aluminium, iron, nickel, zinc, cobalt, copper, radium, and uranium) that have detrimental effects on human health. In areas where surface and groundwater have been contaminated by mine drainage, treatment of water supplies becomes more difficult, more time consuming, and more expensive. Listed below are constituents, which are typically elevated in mine drainage or in groundwater recharged by mine drainage and their properties which can render a municipal or domestic water supply unusable without treatment, unpalatable, or aesthetically offensive (Dairy Reference Manual, 1995).

Iron - The taste threshold of iron in water has been given as 0.1 and 0.2 mg/L of iron from ferrous sulfate and ferrous chloride respectively. It has been reported that ferrous iron imparts a taste at 0.1 mg/L and ferric iron at 0.2 mg/L. Staining of plumbing fixtures occurs at 0.3 mg/L. Certain animals are sensitive to minor changes in iron concentration. Cows will not drink enough water (taste threshold 0.3 mg/L) if it is high in iron, and consequently, milk production is affected

pH - The hydrogen ion concentration can affect the taste of water. At a low pH water tastes sour. The bactericidal effect of chlorine is weakened as pH increases and it is advantageous to keep the pH close to 7. Water with a pH below 7.0 is corrosive to plumbing and can result in constituents such as copper, zinc, cadmium, and lead being dissolved in drinking water.

Sulphate - High sulphate levels in water may have laxative effects and cause taste and odour problems.

Total Dissolved Solids (TDS) - Physiological effects related to TDS include laxative effects, effects on the cardiovascular system, and toxemia associated with pregnancy.

CHAPTER 3: MATERIALS AND METHODS

Manganese - Elevated manganese causes several specific problems when encountered in drinking water, such as unpleasant tastes, deposits on food, laundry staining, reduction in water main capacity, and discoloration of porcelain fixtures. Staining may occur at concentrations above 0.5 mg/L.

2.6.4. Economic effects

The effects of AMD are also costly to the government and/or mining industry: In 1989, Robert Kleinman, a researcher at the U.S. Bureau of Mines, stated that the US industry spends in excess of \$1 million per day treating acidic mine water. In 1995, it was estimated that AMD in the US had polluted 180 000 acres of reservoirs and lakes as well as 12 000 miles of streams and rivers (Kleinman, 1989). The calculated cost for the rehabilitation of these waterways was estimated at \$32 billion and \$72 billion, respectively (Speart, 1995). Other reported cases relating to economic effects of AMD include:

- Acidic drainage has been identified as the largest environmental liability facing the Canadian mining industry and is estimated at \$2 to \$5 billion dollars (MEND, 2001)
- The ARD liability associated with existing Canadian tailings and waste rock is estimated to be between \$2 billion and \$5 billion (Feasby and Tremblay, 1995).
- It has been estimated that the cost of managing AMD at operating mines in Australia amounts to US \$60 million per year (Harries, 1997)
- In South Africa, the Department of Mineral Resources (DMR) has estimated about R30 billion required to rehabilitate the 5 906 mines derelict and ownerless mines. However, this estimate does not include long-term treatment of AMD and the construction and operating cost of treatment plants.

CHAPTER 3: MATERIALS AND METHODS

3.1. Samples for Analysis

Three types of representative samples of raw coal, discard coal and slimes were used for this investigation. The samples were collected from the study area by Anglo Coal and brought to the Council for Scientific and Industrial Research, Natural Resource and the Environment (CSIR-NRE) Laboratory for geochemical tests and analysis. The features of two batches of samples that were collected from Mafube Colliery are presented in Table 5.

The first batch was firstly sieved into different particle sizes before analysis, and the main aim was to determine the influence of particle size on acid generation. Coarse fractions of the samples were further pulverized to prepare them for static tests (acid base accounting tests and paste pH).

The second batch samples were brought to the CSIR-NRE laboratory together with the pit water samples. The water samples were analysed for pH, acidity, alkalinity, ferrous iron, sulphate, calcium, and magnesium (Table 6). In addition, another raw coal and discard coal set of samples were collected from the Kroomdraai Colliery for comparison purposes, because previous researchers (Maree, 2004) categorise them as acid producing samples.

A number of intergraded geochemical and mineralogical tests, analyses and procedures were undertaken on representative samples to assess their behaviour such as acid generating and acid consumption. Bulk geochemical composition and mineralogical investigations were also done on raw coal and discard coal samples in order to understand their environmental signatures. Both static and kinetic geochemical tests were done on samples. The static tests undertaken included paste pH, acid potential and neutralization potential, whereas kinetic test was done by means of column leaching test.

3.2. Bulk Geochemical Composition Analysis

Table 5. Features of two batches of samples from Mafube Colliery.

First batch samples after sieving		Features	
Sample		Particle size (mm)	Mass (g)
Raw 1		< 1.2	959.4
Raw 2		< 4.8	1412.8
Raw 3		> 4.8	672.9
Slimes		As received	2413.3
Discard 1		< 1.2	535.6
Discard 2		< 4.8	1107.1
Discard 3		> 4.8	895.2
Second batch samples, as received		Features	
Sample		Particle size (mm)	Mass (kg)
Raw coal		mixed (fines & coarse)	19.7
Raw coal		>27.5	27.6
Raw coal		>27.5	20.0
Discard coal		mixed (fines & coarse)	42
Slimes		>0.5	33.8

Table 6. Chemical composition of Anort pit water

pH	7.86
Acidity (as CaCO ₃ mg/l)	
Alkalinity (as CaCO ₃ mg/l)	215.6
Fe (II) (as mg/ l)	2.2
Sulphate (mg/l)	4400
Calcium (mg/l)	413
Magnesium	622

3.2. Bulk Geochemical Composition Analysis

In this study, geochemical composition of samples was determined using X-ray fluorescence spectrometry (XRF) technique at the Council for Geoscience. Both major and minor metals were analysed in the form of oxides (SiO_2 , Al_2O_3 , Fe_2O_3 , MnO , TiO_2 , MgO , CaO , Na_2O , K_2O , P_2O_5 , and Cr_2O_3).

Trace elements (Rb, Sr, Zr, Nb, Co, Ni, Cu, Zn, V, Cr, Ba, Pb, Ga, La, Ce, Sc, Th, As, Mo, Sn, U) were also analysed. In addition, sulphur and carbon content of raw and discard samples were also determined using LECO induction furnace method at the Council for Geoscience.

3.3. Mineralogical Investigation

Mineralogical identification of samples was done using X-ray diffraction technique at the Council for Geoscience (CGS). Samples were scanned from 2 to 65° 2 θ $\text{Cu}_{\text{K}\alpha}$ radiation at a speed of 0.02° 2 and generator settings of 40 kV and 35mA. Phase concentrations were determined as semi-quantitative estimates, using relative peak heights/areas proportions.

3.4. Batch Leachate Test

This is a short-term chemical leaching test, which was done on the samples to determine their immediate quality of leachate with respect to time. Batch chemical test was done at CSIR laboratory for a period of 60 minutes. The raw coal, slimes and discard coal samples were mixed with one litre of distilled water in 1000 ml beakers; the mixture was stirred for 60 minutes. Samples were taken at regular intervals of 5, 15, 30, and 60 minutes, and filtered using whatman number 1 filter paper. Sulphate, acidity, alkalinity, and pH determinations were carried out manually according to procedures described in Standard Methods (APHA, 1989), and iron (II). For the elapsed time of 60 minutes, samples were additionally analysed for calcium, magnesium, iron, and aluminium.

3.5. Geochemical Static and Kinetic Tests

The batch chemical leachate study was followed by geochemical leachate tests. Both static and kinetic geochemical methods were used, because in reality it is highly unlikely that any one test can produce reliable results. Static tests that were done on samples included: paste pH, acid and base potential tests. Kinetic test was also done by means of column leaching testwork.

the pH of the mixture was recorded, prior to titration, and this provides qualitative indication of the potential for acid generation for a sample, but serves as a rough guideline not as stand-alone criterion in categorizing the samples. The samples were then categorized as non-acid generating, low risk, and high risk (Table 7).

3.5.1 Static Tests

a) Paste pH

This is a measure of the sample's immediate acidity or alkalinity and reflects current geochemical conditions. This was done by means of a procedure developed by Usher et al., (2003), which involves mixing dry sample with deionised water and measuring the pH of the mixture after 12 hours. Samples with paste pH of 4.0 or less were classed as acid/toxic, because solubility and mobility of many trace elements and metals in water are strongly dependent on pH. For example, at pH 4.0 or lower, elements such as aluminium, copper, zinc, and lead can be released into groundwater or surface water.

b) Neutralization Potential Analysis

Acid neutralization capacity is determined by titration-based procedures as described by Sobek et al., (1978), Lapakko (1994) and Miller et al., (1995). In this study the neutralization potential of the samples was carried out by means of modified Sobek Method, which involves adding a known quantity and quality of strong acid to a 2g dry pulverized sample in a conical flask. The mixture was then heated on a hot plate at 80 to 100 °C for two hours, and then cooled at room temperature for one hour. The cooled mixture was back titrated manually with NaOH to pH 4.3, and then two drops of hydrogen peroxide (30% H₂O₂ stabilised) was added to oxidize the remaining Fe (II). The titration was then continued to the pH of 7, and the NaOH titration volume was recorded. The formula of calculating neutralization potential used is as follows:

done in two phases: the first phase was done for 48 weeks using a 2-litre cylinder,

NP (kg CaCO₃ / ton) = [N x Vol (mL) of acid used) – (N x Vol (mL) NaOH x 50) / [weight of sample (g)].

c) Acid Potential Determination

This was done by means of hydrogen peroxide method, which involves reacting a sample with strong oxidant such as hydrogen peroxide (H₂O₂). The sample (2 grams) was mixed with hydrogen peroxide (125mL), and the mixture left in a fume cupboard until effervescence stops. After cooling, the pH of the mixture was recorded, prior to titration, and this provides qualitative indication of the potential for acid generation for a sample, but serves as a rough guideline not as stand-alone criterion in categorizing the samples. The samples were then categorized as non-acid generating, low risk, and high risk (Table 7).

Table 7. Categorization of samples based on their NAG final pH

Acid generation potential	Final pH
Non-acid generating	>5.5
Low risk	3.5 – 5.5
High risk	<3.5

3.5.2. Kinetic Leaching Test

Kinetic leaching test was undertaken by means of column leaching test that is regarded as kinetic experiments in that they provide information regarding the rate of mineral reactivity, acid generation rate and duration, metal dissolution, and other geochemical reactions including secondary mineral formation. The main aim was to monitor water (leachate) quality with time by cyclic (weekly) sampling.

In this study kinetic tests were performed to attempt mimic oxidation reaction under field conditions and also define rates of reaction. Generally, column leaching test was chosen over humidity cell test in that it simulates actual field conditions. For instance, the columns were opened to atmosphere so that there would be no oxygen barrier, but there was no forced oxygenation as with humidity cells. Column leaching test was done in two phases: the first phase was done for 48 weeks using a 2-litre cylinder,

whereas second phase of column leaching test was done for 19 weeks and big columns of about 80 cm height and 18 cm diameter were used.

Experimental Setup

Two phases of column leaching tests were carried out during this study:

a) Phase 1 column leaching test: During this phase five columns with diameter of 8.8 cm and height of 36 cm were conducted as indicated in Table 8. Figure 10 below shows experimental set up of phase 1 column leaching test that was done on the first batch samples and it lasted for 48 weeks. Tap water was used in the experiment.



Figure 10. The column leachate test experimental set up for phase 1.

Table 8. Conditions of phase 1 column leaching test

Column Number	Sample	Particle size (mm)	Mass (g)	H ₂ O (mL)
1	Raw coal	>1.2	605.87	400
2	Raw coal	<4.75	604.07	400
3	Slimes	As received	601.06	400
4	Discard coal	>1.2	300.55	200
5	Discard coal	<4.75	603.1	400

b) Phase 2 column leaching test: This was done on second batch samples by means of large PVC column of 80 cm height and 18 cm diameter (Fig. 11) as indicated in Table 9. In column 6, 9, and 11, pit water from Anort Colliery was used instead of tap water, and the main aim was to determine the impact of Mafube pit water on the chemical composition of the leachate. In addition, two additional columns were conducted on raw coal and coal discards from Kroomdraai for comparison purposes because the Kroomdraai coal is known to be acidic. Unlike in phase 1, the test was conducted for 19 weeks.

c) The samples were stacked in columns and water allowed to percolate through it. The wetting and drying cycles were created within a period of seven days. The samples were immersed in water for three days, and then allowed to drain for four days. No forced oxygen was pumped, but rather the columns were left open in assumption that oxygen is freely available in air.

d) The following parameters were determined:

- Acidity and alkalinity, determined manually by means of standard titration methods;
- Iron (II), determined manually by of standard method;
- Sulphate, determined by means of spectrometry meter; and
- Aluminium, calcium, and magnesium, determined by means of atomic absorption spectrometry at CSIR-NRE laboratory.



Figure 11. The column leaching experimental set up for phase 2.

Table 9. The nature of samples, their particle size and quantity

Columns	Sample name	Particle size (mm)	Mass (kg)	Water type	Volume (ml)
6	Mafube Raw	>27.5	10	Pit water	5000
7	Mafube Raw	>27.5	10	Tap water	5000
8	Mafube Raw	>27.5	10	Tap water	5000
9	Mafube discard	>27.5	10	Pit water	5000
10	Mafube discard	>27.5	10	Tap water	5000
11	Mafube slimes	-0.5	10	Pit water	5000
12	Kroomdrai raw	>27.5	10	Tap water	5000
13	Kroom discard	>27.5	10	Tap water	5000

CHAPTER 4: DATA ANALYSIS AND INTERPRETATION

4.1. Bulk Geochemical Data

Chemical data of raw coal and discard coal analysed by XRF spectrometry technique are also presented in Table 10. Major and minor elements are presented in the form of oxides. SiO_2 and Al_2O_3 are predominate oxides in raw coal. In addition, other oxides occurring within coal, but in lesser quantities are TiO_2 , Fe_2O_3 , K_2O , Na_2O , MgO , MnO , and Cr_2O_3 . In discard coal, loss on ignition (L.O.I), SiO_2 , Al_2O_3 , and Fe_2O_3 occur as major oxides, whereas TiO_2 , CaO , Na_2O , K_2O , P_2O_5 and MnO_2 are relatively low. In addition, the distribution of trace elements was determined and is presented in Table 11. Discard coal contains significant amounts of As, Cr, Pb, Ni, and Ce which are potential toxic metals, whereas raw coal is enriched in Sr, Ba, Co and Zn.

Carbon and sulphur contents as determined by leco furnace analysis are presented in Table 12. Mafube raw coal and slimes contains highest concentration of carbon (ranging from 55 to 62%) and lowest concentration of sulphur (ranging from 0.3 to 0.6%), whereas Mafube discard samples and Kroomdraai samples are comprised of highest concentration of sulphur and lowest concentration of carbon.

Table 10. Chemical composition of raw coal and discard coal samples

Chemical constituent	Raw coal wt%	Discard coal wt%
SiO_2	10.49	38.14
TiO_2	0.32	0.94
Al_2O_3	5.14	11.9
$\text{Fe}_2\text{O}_3(\text{t})$	0.22	6.8
MnO	0.022	0.04
MgO	0.05	0.16
CaO	0.14	0.59
Na_2O	0.07	0.28
K_2O	0.08	0.21
P_2O_5	0.18	0.04
Cr_2O_3	0.01	0.013
L.O.I.	81.88	39.66
TOTAL	98.61	98.78
H_2O^-	5.39	4.49

Table 11. Trace elements composition of raw coal and discard coal

Chemical constituents	Raw coal (as ppm)	Discard coal (as ppm)
As	<4	12
Ba	563	245
Br	4.7	101
Ce	56	103
Co	18	12
Cr	42	74
Ga	15	24
Ge	3.4	<1
La	29	51
Mo	<2	3.3
Nb	4	16
Nd	23	37
Ni	24	26
Pb	9	23
Rb	5	13
Sc	6.9	13
Se	<1	2.1
Sr	441	64
Th	4.2	16
U	4.4	3.1
V	40	61
Yb	<2	3.7
Zn	3.80%	1.20%
Zr	85	179

Table 12. Carbon and Sulphur contents of the samples

Samples	Carbon (%)	Sulphur (%)
Raw coal 1	62,4	0,3
Discard coal 1	29	0,6
Slimes 1	59,8	0,4
Raw coal 2	61,8	0,3
Discard coal 2	20,1	3,7
Slimes 2	55,2	0,6
Kroondraai Raw coal	27	1,3
Kroondraai Discard coal	25,7	1,4

4.2. Mineralogical Data

The XRD analysis of raw coal and discard coal indicated high content of quartz and kaolinite (Fig. 12). Kaolinite ($\text{Al}_2\text{Si}_2\text{O}_5(\text{OH})_4$) is clearly the most abundant mineral in raw coal, whereas quartz (SiO_2) is dominant in discard coal. On the other hand, the Mafube discard coal also contains of pyrite (FeS_2), siderite (FeCO_3), mica [$\text{KAl}_2(\text{Si}_3\text{Al})\text{O}_{10}(\text{OH}, \text{F})_2$], and calcite (CaCO_3).

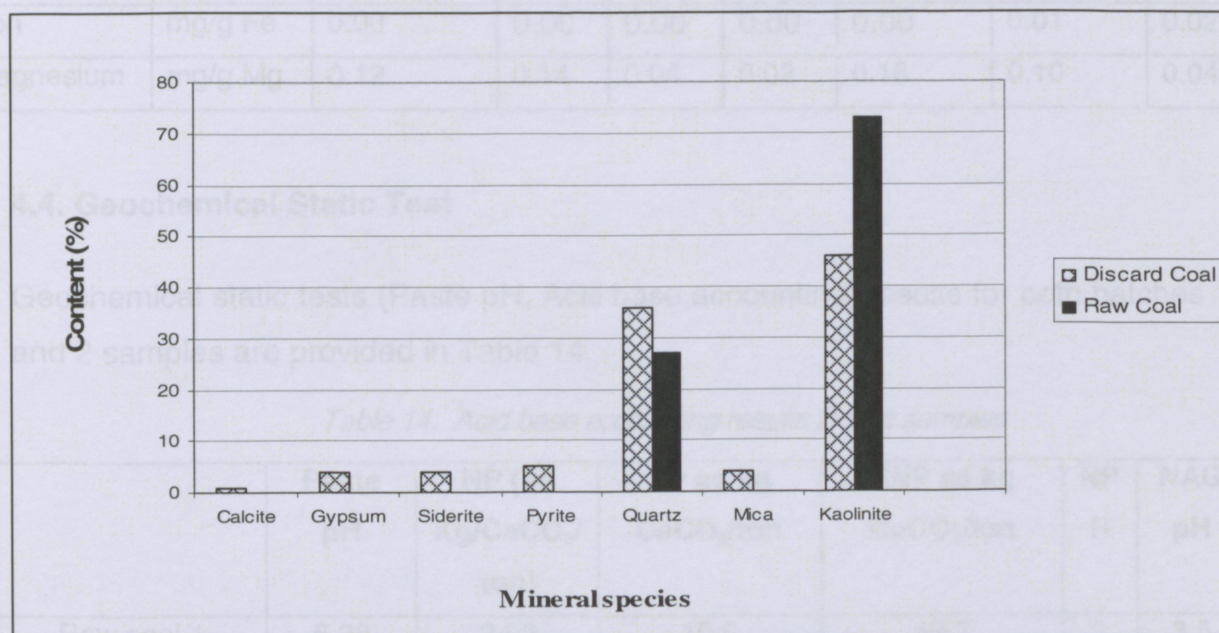


Figure 12. Mineralogical composition of the Mafube raw and discard coal.

4.3. Batch Leachate Data

Chemical leaching gives an indication of the amount of directly leachable acid and other chemical constituents over a given period of time. The results for chemical batch analysis are presented in Table 13. The leachate from raw coal and slimes samples is nearly neutral, as their pH ranges from 6.61 to 7.03, whereas for the discard samples the pH ranges from 5 to 6.24 after 60 min of experiment. In addition, leachate from all samples is impoverished in Al and Fe, but contains small amounts of SO_4 , Mg and Ca.

Table 13. The batch leachate results after 60 minutes of the experiment

Beaker		1	2	3	4	5	6	7
Sample		Slimes	Raw 1	Raw 2	Raw 3	Discard 1	Discard 2	Discar3
Particle size (mm)		as received	- 1.2	- 4.75	+ 4.75	- 1.2	- 4.75	+ 4.75
Results for chemical leachate studies								
PH		6.88	7.03	6.61	6.77	6.24	5.00	5.23
Sulphate	mg/g SO ₄	3.01	3.99	3.00	2.98	4.00	1.99	1.00
Iron (II)	mg/g Fe	<0.54	<0.54	<0.54	<0.54	<0.54	<0.54	<0.54
Acidity	mg/g	1.00	0.50	1.60	0.50	4.00	1.59	1.00
Calcium	mg/g Ca	0.72	0.64	0.16	0.06	0.58	0.26	0.16
Iron	mg/g Fe	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Magnesium	mg/g Mg	0.12	0.14	0.04	0.02	0.16	0.10	0.04

4.4. Geochemical Static Test

Geochemical static tests (Paste pH, Acid base accounting) results for both batches 1 and 2 samples are provided in Table 14.

Table 14. Acid base accounting results for the samples

	Paste pH	NP (as Kg/CaCO ₃ /ton)	AP as kg CaCO ₃ /ton	NNP as kg CaCO ₃ /ton	NP R	NAG pH
Raw coal 1	6.28	24.3	10.6	13.7	2	3.5
Discard coal 1	3.83	15.5	17.9	-2.4	1	2.31
Slimes 1	7.5	21.4	12.5	8.9	2	2.82
Raw coal 2	6.24	23.3	10.9	12.4	2	3.74
Discard coal 2	3.05	-4.6	115.6	-120.2	0	1.66
Slimes 2	3.51	5.9	18.7	-12.8	0	1.86
Kroomdraai Raw coal	2.18	-15.7	40.6	-56.3	0	2.14
Kroomdraai Discard coal	2.32	-26.1	45.3	-71.4	-1	1.62

The criteria used to classify the acid producing potential of the samples analysed are those used by Usher *et al.*, (2003). The criteria used to classify the samples in terms

of acid generation potential should not be used in isolation, but should be used in combination to categorise material from non-acid generating to acid-generating with a “slight grey area in between” Usher et al., (2003).

The following criteria have been used:

- Paste pH – which is a measure of sample’s immediate acidity or alkalinity
- Net Acid-Generating Test (Nag) pH (Table 7).

Acid generation potential	Final pH
Non-acid generating	>55
Low risk	3.5 – 5.5
High risk	<3.5

- Net Neutralization Potential (NNP): (NP-AP)

NNP < 0	Sample has the potential to generate acid
NNP > 0	Sample has the potential to neutralise acid produced
-20 > NNP < 20	If the sample has an NNP value within this range, its acid producing potential remains inconclusive and other criteria should also be considered in order to determine its acid generation status

- Neutralizing Potential Ratio (NPR)

Price et al. (1997) provide the following screening criteria based on the NPR generated during static ABA analysis:

Potential for AMD	Initial NPR screening Criteria	Comments
Likely	<1	Likely AMD generating
Possibly	1 to 2	Possibly AMD generating if NP is insufficiently reactive or is depleted at a faster rate than sulphides
Low	2 to 4	Not potentially AMD generating unless significant preferential exposures of sulphides along fracture planes or extremely reactive sulphides in combination with insufficiently reactive NP
None	>4	No further AMD testing required unless materials are to be used as a source of alkalinity

Figure 13. Paste pH vs sulphur % for both phase 1 and phase 2 batches

4.4.1. Paste pH

Results for paste pH are presented in Table 14. In both batches, paste pH of leachate from Mafube raw coal is greater than 6, whereas in the discard coal and Kroomdraai sample it is less than 4. This indicates that immediate oxidation of pyrite is likely to occur in the Mafube discard and Kroomdraai samples. A low pH may be an indicative of sulphides that have reacted to produce acid or oxidation, whereas a high paste pH could be an indicative of a high concentration of alkaline minerals in the sample or might be generated in alkaline rock with sulphide that has not yet reacted. Figure 13 shows a scatter plot for paste pH vs sulphur content. Paste pH increases with decreasing concentration of sulphur percentage and vice versa. Based on this, Mafube raw coal and slimes are less likely to generate significant acid, whereas the discard coal samples and Kroomdraai samples have a high potential to generate acid.

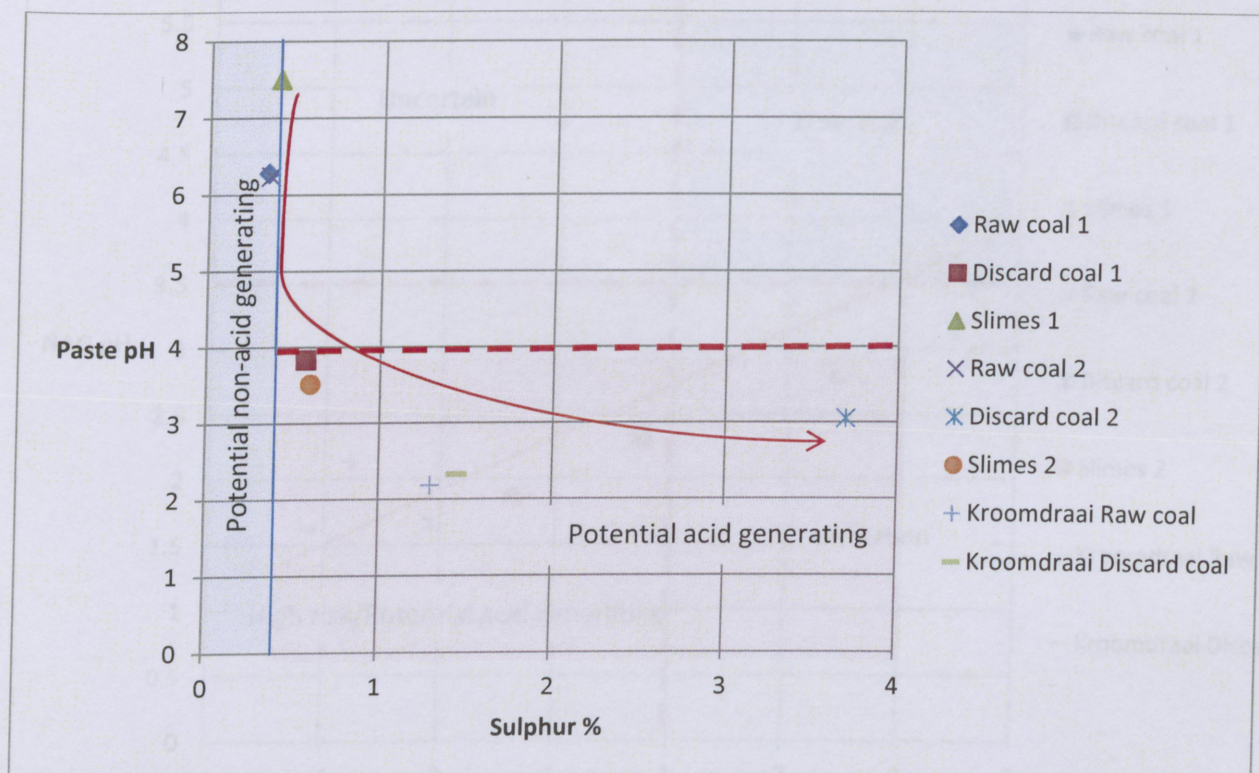


Figure 13. Paste pH vs sulphur % for both phase 1 and phase 2 batches.

Figure 14. Comparison of pH based on NAD pH vs NPR.

4.4.2. Acid Base Accounting

NAG pH vs NPR

Figure 14 is a plot of NPR (an ABA parameter) and NAG pH and identifies four quadrants. Samples with NPR greater than 1 and NAG pH greater than 3.5 plot in the low risk quadrant and samples with NPR less than 1 and NAG pH less than 3.5 plot in the potentially acid forming quadrant. Samples with conflicting ABA and NAG results plot in the “uncertain” quadrants. Mafube discard coal are classified as high risk/potentially acid generating together with the Kroomdraai samples, whereas mafube raw coal are classified as low risk acid generating.

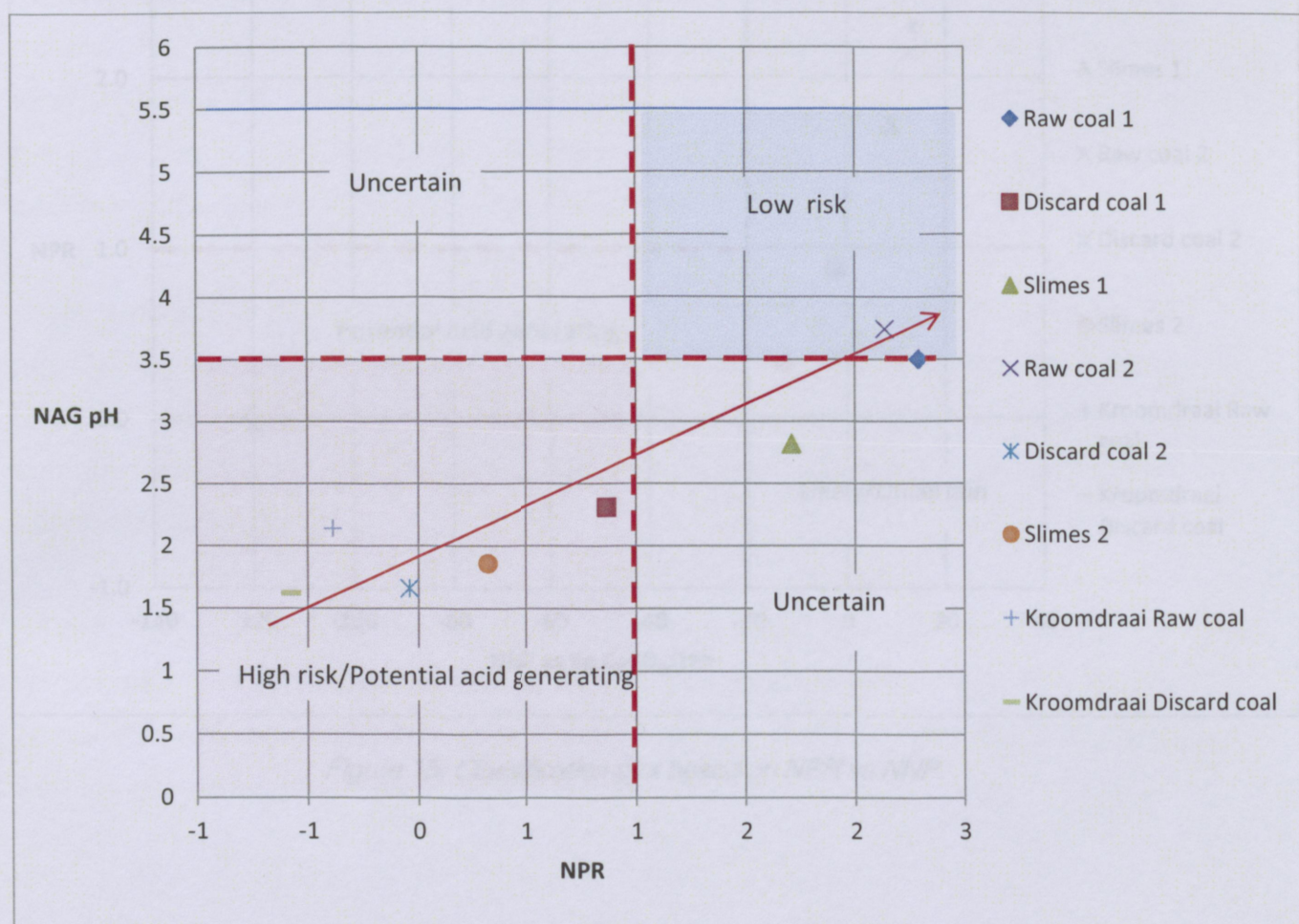


Figure 14. Classification plot based on NAG pH vs NPR.

4.5. Kinetic Tests

NPR vs NNP

Results of column leaching tests for some of the samples are presented in the figures 16 to 18. Based on the NPR vs NNP, it is uncertain if the Mafube raw coal and slime 1 will generate acid, but the possibility to generate acid exist if NP is insufficiently reactive or is depleted at a faster rate than sulphides. Mafube discard coal1 and slimes 2 are likely to generate acid but uncertainty exists based on their NNP. Mafube discard coal 2 and Kroomdraai samples have a potential to generate acid (Fig.15).

a) Rate of Acid Generation

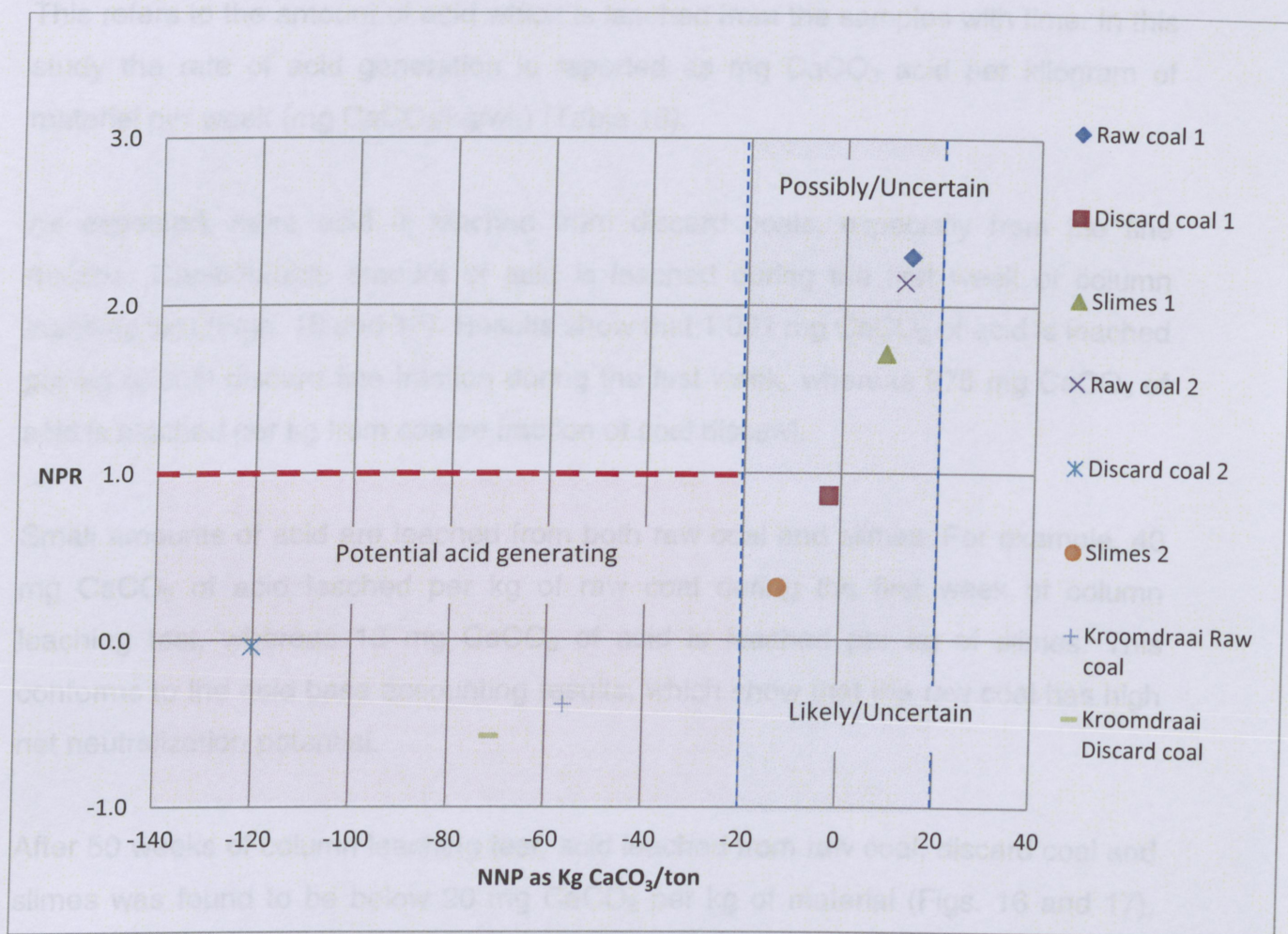


Figure 15. Classification plot based on NPR vs NNP.

4.5. Kinetic Tests

Results of column leaching tests, for both phases, are presented in the figures 16 to 25. All parameters are plotted against time (weeks).

4.5.1. Phase 1 Column Leaching Test

a) Rate of Acid Generation

This refers to the amount of acid which is leached from the samples with time. In this study the rate of acid generation is reported as mg CaCO₃ acid per kilogram of material per week (mg CaCO₃/kg/wk) (Table 16).

As expected, more acid is leached from discard coals, especially from the fine fraction. Considerable amount of acid is leached during the first week of column leaching test (Figs. 16 and 17). Results show that 1,091 mg CaCO₃ of acid is leached per kg of coal discard fine fraction during the first week, whereas 975 mg CaCO₃ of acid is leached per kg from coarse fraction of coal discard.

Small amounts of acid are leached from both raw coal and slimes. For example, 40 mg CaCO₃ of acid leached per kg of raw coal during the first week of column leaching test, whereas 18 mg CaCO₃ of acid is leached per kg of slimes. This conforms to the acid base accounting results, which show that the raw coal has high net neutralization potential.

After 50 weeks of column leaching test, acid leached from raw coal, discard coal and slimes was found to be below 20 mg CaCO₃ per kg of material (Figs. 16 and 17). Generally, acid generation rate of samples decreases with time, and this is the case with the pH values (Fig. 18).

Table 15 . Acid production rate of the samples as mg CaCO₃/kg/week (phase 1 column leaching test).

Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75	Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75
17-Jan-	1	15.68	39.69	39.92	1091.33	974.96	18-Jul	27	10.56	11.25	12.97	13.31	12.93
24-Jan	2	9.24	11.58	13.31	598.90	383.02	25-Jul	28	10.56	11.25	12.97	13.31	12.93
31-Jan	3	9.90	12.20	11.31	244.55	328.30	01-Aug	29	10.56	11.25	12.97	13.31	12.93
07-Feb	4	11.14	11.99	12.89	133.09	288.51	08-Aug	30	10.56	11.25	12.97	13.31	12.93
14-Feb	5	8.91	7.94	11.31	9.15	11.81	15-Aug	31	10.56	11.25	12.97	13.31	12.93
21-Feb	6	9.90	7.61	10.64	8.32	13.26	22-Aug	32	10.56	11.25	12.97	13.31	12.93
28-Feb	7	9.90	12.40	14.97	9.15	14.92	29-Aug	33	10.56	11.25	12.97	13.31	12.93
07-Mar	9	10.23	10.58	15.38	9.98	15.13	05-Sep	34	10.56	11.25	12.97	13.31	12.93
14-Mar	10	10.56	13.23	11.97	9.98	14.92	12-Sep	35	10.56	11.25	12.97	13.31	12.93
21-Mar	11	10.56	10.58	14.97	10.81	14.92	19-Jan	36	10.56	11.25	12.97	13.31	12.93
28-Mar	12	13.20	13.23	15.18	11.23	15.13	09-Jan	37	10.56	11.25	12.97	13.31	12.93
04-Apr	13	13.20	13.23	15.18	11.65	14.92	26-Sep	38	10.56	11.25	12.97	13.31	12.93
11-Apr	14	13.20	13.23	15.38	12.89	14.92	03-Oct	39	10.56	11.25	12.97	13.31	12.93
18-Apr	15	13.20	14.06	15.38	13.72	15.34	10-Oct	40	10.56	11.25	12.97	13.31	12.93
25-Apr	18	13.20	14.06	15.59	14.97	15.54	17-Oct	41	10.56	11.25	12.97	13.31	12.93
02-May	19	13.20	14.06	16.22	16.64	16.17	24-Oct	42	10.56	11.25	12.97	13.31	12.93
09-May	20	10.56	11.25	12.97	13.31	12.93	31-Oct	43	10.56	11.25	12.97	13.31	12.93
16-May	21	10.56	11.25	12.97	13.31	12.93	07-Nov	44	10.56	11.25	12.97	13.31	12.93
23-May	22	10.56	11.25	12.97	13.31	12.93	14-Nov	45	10.56	11.25	12.97	13.31	12.93
30-May	23	10.56	11.25	12.97	13.31	12.93	21-Nov	46	10.56	11.25	12.97	13.31	12.93
06-Jun	24	10.56	11.25	12.97	13.31	12.93	28-Nov	47	10.56	11.25	12.97	13.31	12.93
13-Jun	25	10.56	11.25	12.97	13.31	12.93	23-Jan	54	10.56	11.25	12.97	13.31	12.93
20-Jun	26	10.56	11.25	12.97	13.31	12.93							

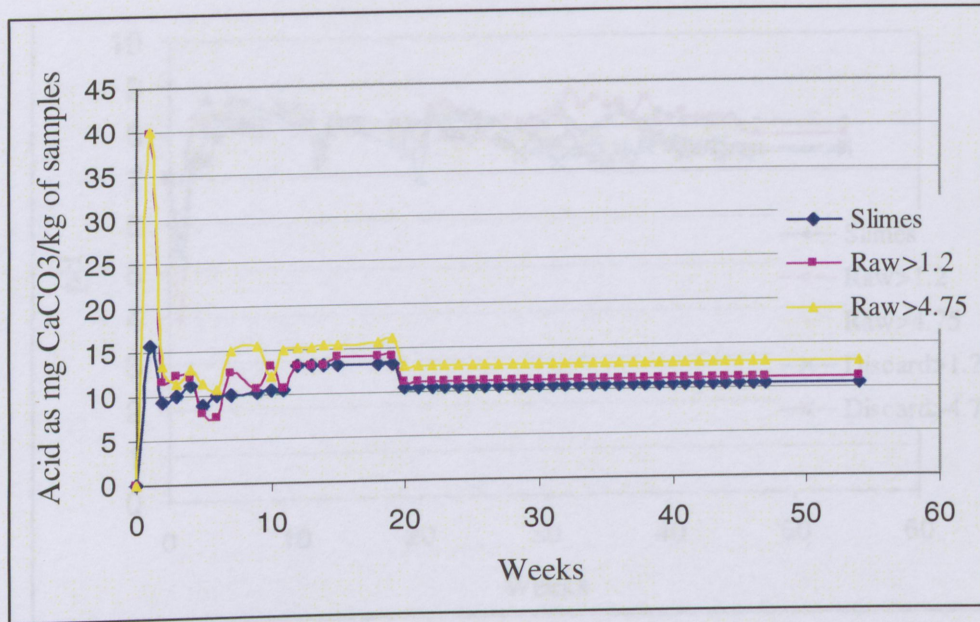


Figure 16. The rate of acid generation for the Mafube raw coal and slimes samples for phase 1.

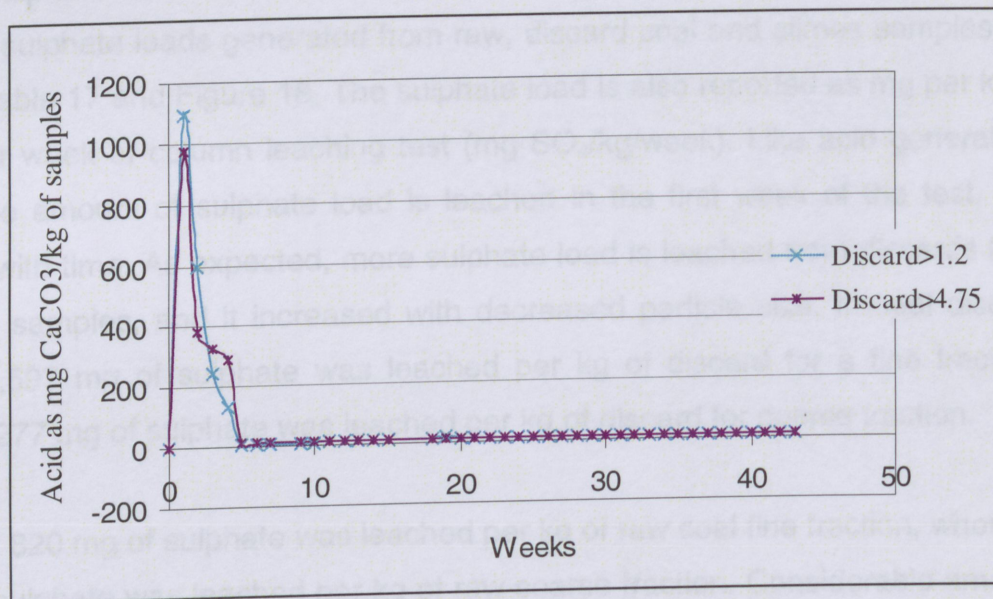


Figure 17. The rate of acid generation rate of the Mafube discard coals for phase 1 column test

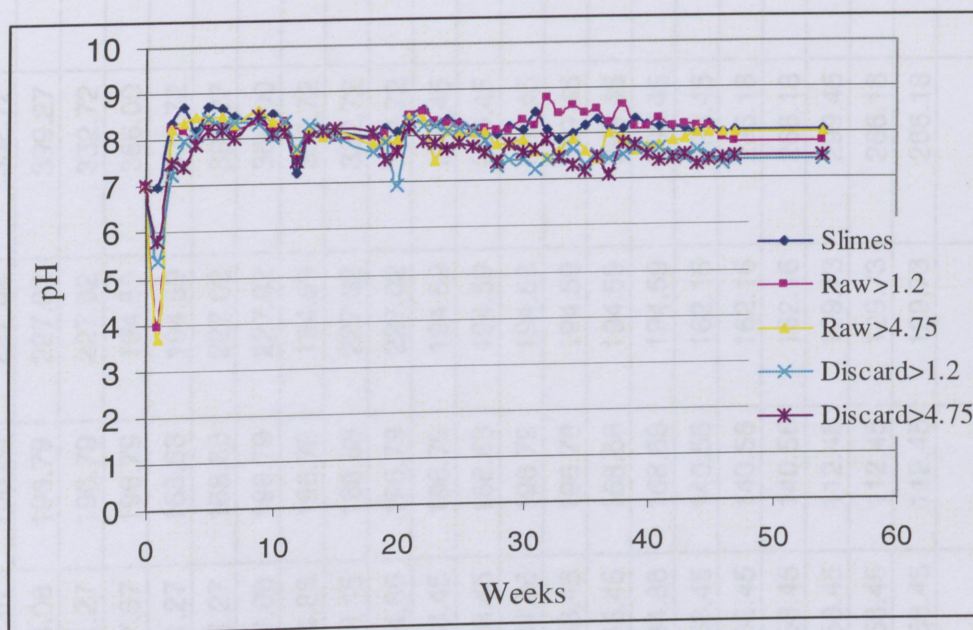


Figure 18. The pH profiles of the samples for phase 1 column leaching test.

b) Rate of Sulphate Generation

Results for sulphate loads generated from raw, discard coal and slimes samples are plotted in Table 17 and Figure 18. The sulphate load is also reported as mg per kg of material per week of column leaching test ($\text{mg SO}_4/\text{kg}/\text{week}$). Like acid generation, considerable amount of sulphate load is leached in the first week of the test, and decreases with time. As expected, more sulphate load is leached from discards than in raw coal samples, and it increased with decreased particle size. In coal discard samples, 1,597 mg of sulphate was leached per kg of discard for a fine fraction, whereas 1,277 mg of sulphate was leached per kg of discard for coarse fraction.

In raw coal, 820 mg of sulphate was leached per kg of raw coal fine fraction, whereas 718 mg of sulphate was leached per kg of raw coarse fraction. Considerable amount of sulphate was also leached in the slimes; 1,348 mg of sulphate per kg of slimes in the first week of the test. The leachate from raw coal and slimes during the first week of column leaching test was enriched in SO_4 , indicating earlier acid mine drainage generation.

Table 16. Rate of sulphate generation as mg SO₄ per kg of the sample (Phase 1 column test)

Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75	Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75
17-Jan	1	1348.47	820.23	718.49	532.36	1276.74	18-Jul	27	237.67	168.68	227.02	332.72	291.00
24-Jan	2	854.97	787.16	399.16	598.90	355.66	25-Jul	28	264.08	196.79	227.02	399.27	323.33
31-Jan	3	693.22	609.80	197.92	296.96	328.30	01-Aug	29	211.27	196.79	227.02	332.72	323.33
07-Feb	4	401.08	311.72	154.68	299.45	240.42	08-Aug	30	237.67	196.79	194.59	366.00	291.00
14-Feb	5	89.13	79.38	113.10	183.00	118.14	15-Aug	31	211.27	168.68	194.59	332.72	291.00
21-Feb	6	123.79	133.12	133.05	183.00	291.83	22-Aug	32	211.27	168.68	227.02	399.27	258.66
28-Feb	7	74.27	198.44	119.75	256.20	149.23	29-Aug	33	184.86	196.79	227.02	366.00	291.00
07-Mar	9	102.33	79.38	123.07	519.05	211.82	05-Sep	34	184.86	196.79	194.59	332.72	258.66
21-Mar	10	79.22	370.43	119.75	439.19	268.61	12-Sep	35	158.45	168.68	227.02	332.72	258.66
28-Mar	11	105.63	264.59	89.81	432.54	208.92	19-Jan	36	184.86	196.79	227.02	332.72	258.66
04-Apr	12	105.63	317.51	121.41	426.72	181.56	09-Jan	37	158.45	196.79	194.59	299.45	226.33
11-Apr	13	132.04	211.67	182.12	419.23	238.77	26-Sep	38	158.45	168.68	194.59	299.45	226.33
18-Apr	14	158.45	211.67	215.38	412.58	298.46	03-Oct	39	184.86	196.79	194.59	299.45	226.33
25-Apr	15	237.67	253.01	307.69	439.19	460.12	10-Oct	40	158.45	196.79	194.59	299.45	194.00
02-May	18	211.27	449.80	498.95	748.63	715.06	17-Oct	41	158.45	168.68	194.59	299.45	226.33
23-May	19	264.08	140.56	194.59	632.17	517.33	24-Oct	42	184.86	168.68	194.59	299.45	226.33
30-May	20	237.67	224.90	194.59	532.36	484.99	31-Oct	43	158.45	140.56	162.16	299.45	226.33
06-Jun	21	264.08	224.90	227.02	499.09	452.66	07-Nov	44	158.45	140.56	162.16	266.18	226.33
13-Jun	22	264.08	253.01	259.46	465.81	452.66	14-Nov	45	158.45	140.56	162.16	266.18	226.33
20-Jun	23	290.49	281.13	389.18	499.09	420.33	21-Nov	46	158.45	112.45	129.73	299.45	226.33
27-Jun	24	369.72	337.35	518.91	532.36	388.00	28-Nov	47	158.45	112.45	129.73	266.18	226.33
04-Jul	25	343.31	281.13	454.05	465.81	388.00	23-Jan	54	158.45	112.45	129.73	266.18	226.33
11-Jul	26	316.90	253.01	324.32	432.54	420.33							

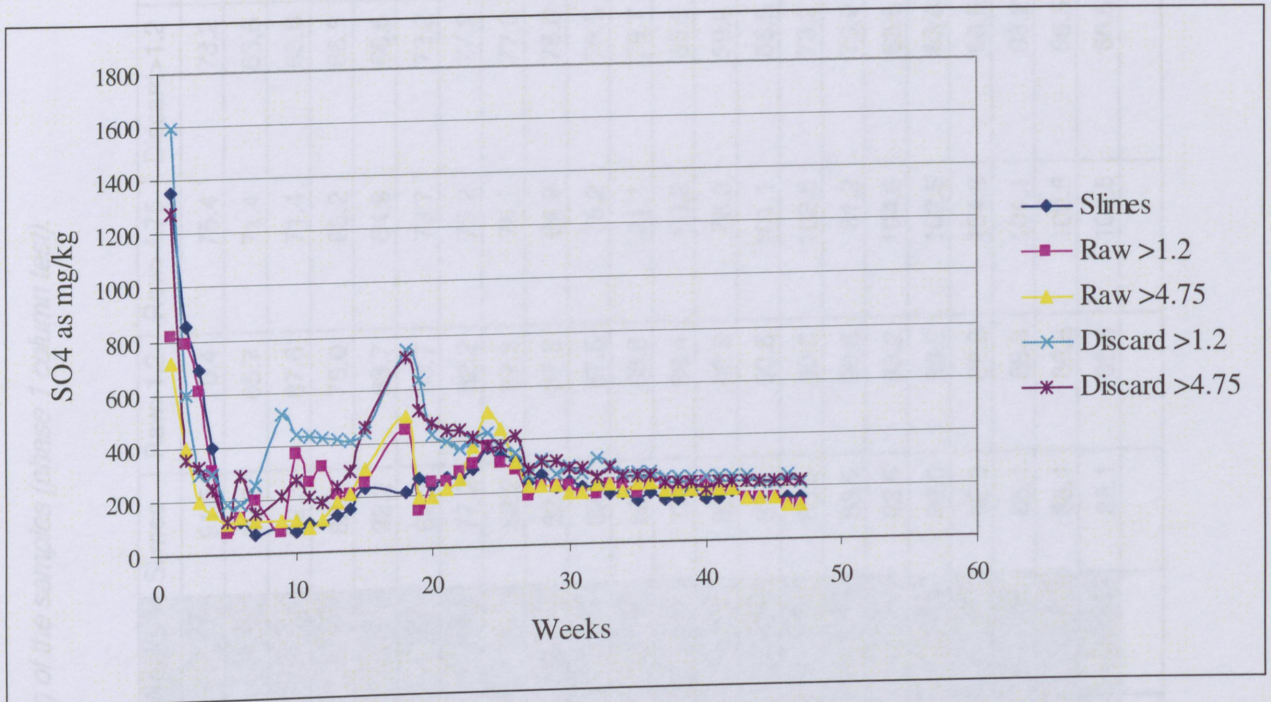


Figure 19. Sulphate generation rate of samples from phase 1 column leaching test.

c) Rate of Acid Consumptions

This refers to load of alkalinity leached as a function of time, and is reported as mg CaCO_3 per kg of material. The results are presented in table 18 and Figure 20. Little amount of alkali was leached from the samples in the first week of column leaching test, just 8 mg of alkali was leached per kg of fine fraction discard (>1.2), whereas 19 mg of alkali is leached per kg of coarse fraction discard (>4.75) in the first week. For raw coal samples, 14 mg of alkali was leached per kg of fine fraction raw (>1.2), whereas 12 mg was leached per kg of coarse fraction raw (>4.75). For slimes, 22 mg of alkali was leached per kg of material during the first week of column leaching test. The load of alkali leached also increased with time. Gradual increase occurred in raw and slimes samples. However, the profiles were also characterized by cyclic fluctuations.

Table 17. Rate of acid consumption as mg CaCO₃ per kg of the samples (phase 1 column test).

Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75	Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75
17-Jan	1	21.6	14.4	12.1	7.9	18.6	18-Jul	27	91.5	70.4	75.4	73.2	64.7
24-Jan	2	83.2	81.9	72.2	39.5	36.3	25-Jul	28	82.2	65.7	71.4	63.6	58.5
31-Jan	3	93.5	92.7	89.3	40.5	43.3	01-Aug	29	82.3	87.6	71.4	63.6	51.7
07-Feb	4	71.8	79.2	89.3	51.6	52.9	08-Aug	30	82.3	76.0	83.2	66.5	51.7
14-Feb	5	57.0	55.2	57.7	33.1	38.6	15-Aug	31	82.2	83.7	64.9	66.5	49.4
21-Feb	6	129.3	79.3	94.3	52.6	77.7	22-Aug	32	82.2	83.7	73.7	73.2	58.2
28-Feb	7	130.9	111.1	129.3	78.6	88.6	29-Aug	33	77.2	82.2	75.2	77.2	54.3
14-Mar	9	118.7	94.2	133.7	78.9	125.4	05-Sep	34	82.2	87.3	75.2	77.3	58.2
21-Mar	10	116.2	76.2	94.1	56.5	69.5	12-Sep	35	82.3	87.5	64.9	78.0	60.8
28-Mar	11	77.3	87.7	81.0	67.1	69.7	19-Jan	36	82.3	87.5	75.2	78.5	62.1
04-Apr	12	82.0	77.4	70.4	63.4	70.3	09-Jan	37	82.3	88.8	101.1	79.7	61.5
11-Apr	13	82.3	82.3	70.9	65.8	65.7	26-Sep	38	77.2	88.4	83.2	66.5	61.5
18-Apr	14	83.5	83.6	78.8	59.9	69.4	03-Oct	39	82.3	88.8	76.0	59.9	61.5
25-Apr	15	85.1	87.3	78.9	60.4	71.7	10-Oct	40	82.3	90.6	101.1	66.5	61.5
16-May	18	91.5	87.5	78.1	57.3	96.5	17-Oct	41	83.5	90.6	102.5	73.2	64.7
23-May	19	91.5	120.1	73.7	78.5	49.4	24-Oct	42	83.5	90.6	81.2	79.9	76.3
30-May	20	77.2	87.3	91.6	77.3	75.0	31-Oct	43	83.5	93.2	104.6	63.6	74.5
06-Jun	21	82.0	90.6	104.6	73.2	71.1	07-Nov	44	82.0	90.6	102.5	63.6	76.3
13-Jun	22	95.1	101.2	112.3	77.2	73.5	14-Nov	45	82.0	88.8	104.6	66.5	66.0
20-Jun	23	87.6	88.8	100.9	75.6	75.1	21-Nov	46	85.1	88.3	101.1	63.2	64.7
27-Jun	24	95.1	67.5	64.9	66.5	51.7	28-Nov	47	85.1	88.8	102.5	66.5	66.5
04-Jul	25	105.6	67.5	64.9	66.5	51.7	23-Jan	54	85.1	88.8	102.5	66.5	66.5
11-Jul	26	95.1	65.7	76.0	99.0	80.2							

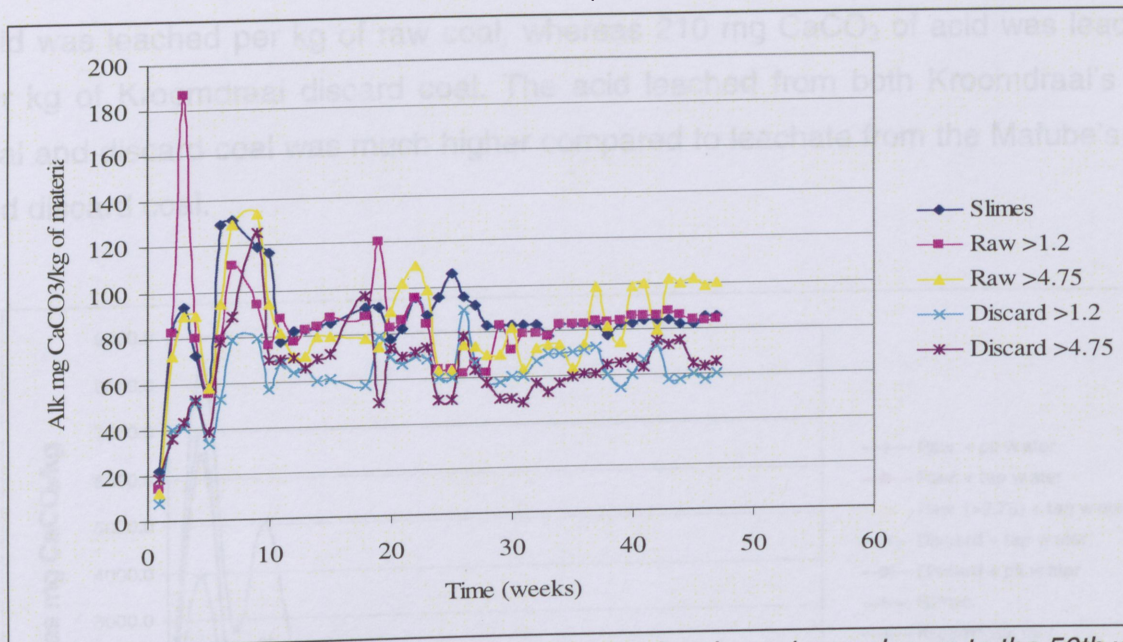


Figure 20. The rate of acid consumption of samples for phase 1 samples up to the 50th week of column leaching test.

4.5.2. Phase 2 Column Leaching Test

a) Rate of Acid Production

The rate of acid generation for second batch samples is presented in Table 19 and Figure 21. Like in phase 1, considerable amount of acid was leached from coal discard than in raw coal. In discard coal, 6,435 to 7,000 mg CaCO₃ of acid was leached per kg of discard coal in the first week of the column leaching test, whereas only 1,125 to 1,500 mg CaCO₃ acid was leached per kg of raw coal. Acid generation rate of the Mafube coal decreases with time. For example, after nineteen weeks of leaching test, 70 mg CaCO₃ acid was leached per kg of discard coal, whereas 8 mg CaCO₃ of acid was leached per kg of raw coal. In addition, this conforms to the pH values, which, decreased with time (Fig. 22). This suggests that acid producing minerals that were available in the samples were more reactive than the available neutralizing minerals.

Comparison which has been made with samples from Kroomdraai indicates that considerable amount of acid was leached from Kroomdraai samples, especially discard coal. In discard coal, 8,437 mg CaCO₃ of acid was leached per kg of material, whereas 3,937 mg CaCO₃ of acid was leached per kg of raw coal in the first week of column leaching test. Acid generation rate of Kroomdraai samples also decreased with time. After nineteen weeks of column leaching test 70 mg CaCO₃ of

acid was leached per kg of raw coal, whereas 210 mg CaCO_3 of acid was leached per kg of Kroomdraai discard coal. The acid leached from both Kroomdraai's raw coal and discard coal was much higher compared to leachate from the Mafube's raw and discard coal.

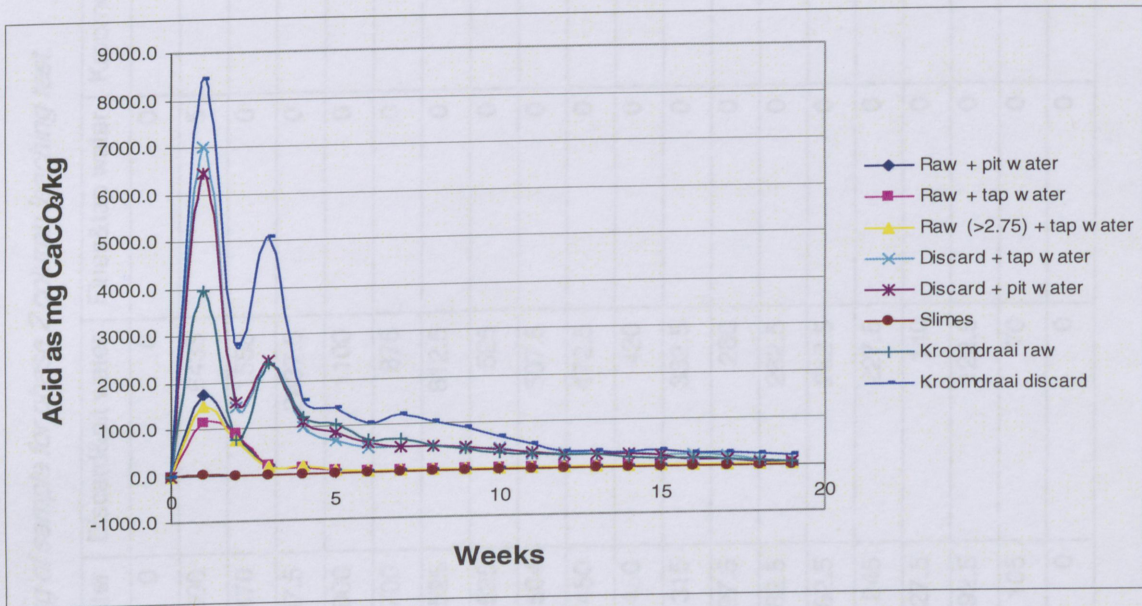


Figure 21. Rate of acid generation of samples during phase 2 column leaching test.

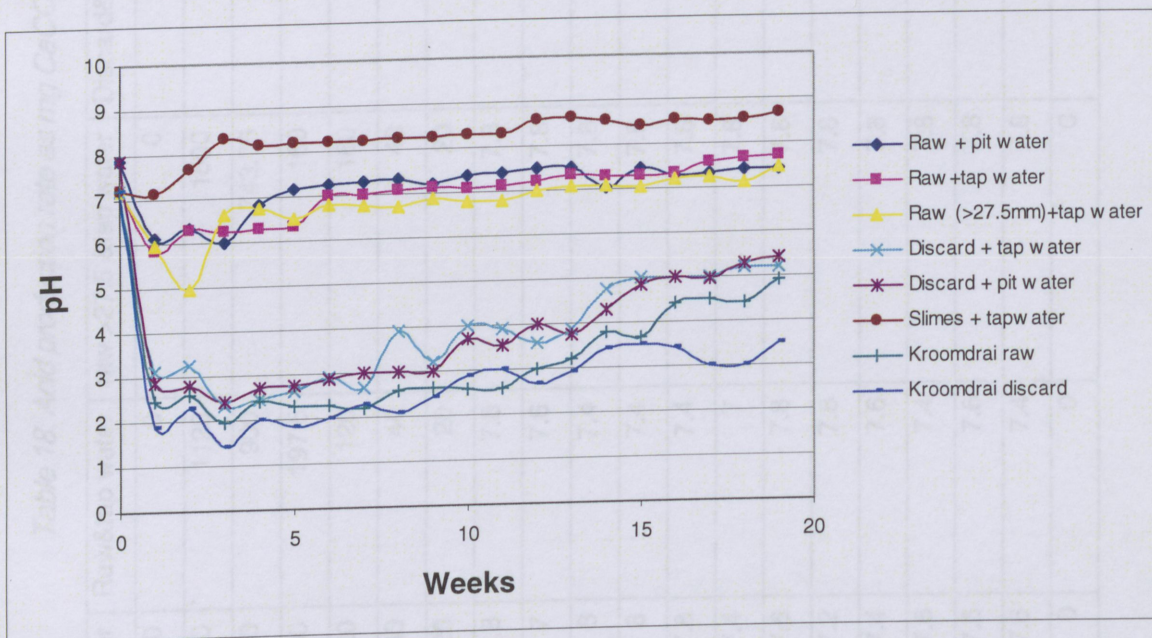


Figure 22. pH profiles of samples for phase 2 column leaching test.

Table 18. Acid production rate as mg CaCO₃ per kg of sample for phase 2 column leaching test.

Date	Weeks	raw&pit water	Raw&tap water	raw >27.5 &tap water	Discard&tap water	Discard&pit water	Fines&tap water	Kroomdrai raw coal	Kroomdrai discard
17-Jan-06	0	0	0	0	0	0	0	0	0
23-Jan-06	1	1750	1125	1500	7000	6435	5	3937.5	8437.5
29-Jan-06	2	840	900	743.75	1470	1558	0	750	2800
04-Feb-06	3	200	197.5	160	2437.5	2437.5	0	2362.5	5075
11-Feb-06	4	120	120	160	1000	1100	0	1225	1575
16-Feb-06	5	40	40	40	700	875	0	1050	1400
22-Feb-06	6	20	20	20	525	612.5	0	700	1050
28-Feb-06	7	7.8	7.8	7.8	525	525	0	700	1225
06-Mar-06	8	7	7.6	7.8	504	507.5	0	525	1050
12-Mar-06	9	8	7.4	7.8	450	472.5	0	437.5	1050
18-Mar-06	10	8	7.4	7.8	450	420	0	350	700
24-Mar-06	11	7.8	7.4	7.8	315	332.5	0	315	525
30-Mar-06	12	7.4	7	7.8	297.5	280	0	280	350
06-Apr-06	13	7.6	7.8	7.8	262.5	262.5	0	262.5	332.5
13-Apr-06	14	7.2	7.8	7.8	262.5	262.5	0	210	315
17-Apr-06	15	7.4	7.6	7.8	245	227.5	0	175	332.5
23-Apr-06	16	7.6	7.4	7.8	227.5	140	0	157.5	280
29-Apr-06	17	7.6	7.6	7.8	192.5	122.5	0	122.5	262.5
05-May-06	18	7.6	7.4	7.8	105	70	0	105	245
11-May-06	19	0	0	0	0	0	0	0	0

b) Rate of Acid Consumption

Results for alkalinity of leachate from Mafube raw coal and slimes samples are presented in Figure 23 and Table 17. The alkalinity slightly decreased in the first week of leaching due to slight release of acid from raw coal, and then increased with time suggesting depletion of sulphide oxidation. This also suggest that the raw and slimes samples contain insignificant amount of sulphide minerals. The highest values of alkalinity were obtained from the leachate from slimes, and in a column where pit water was used for leaching purposes. This indicate that pit water has a high buffering capacity than tap water, and this conforms to the measured values of alkalinity of both tap and pit water. For example, Anort pit water had alkalinity value of 215 CaCO₃ mg/l, whereas tap water was found to contain 184 CaCO₃ alkalinity as mg/l. The alkalinity of leachate from the Mafube discard was not measured, since the pH was below 4.5.

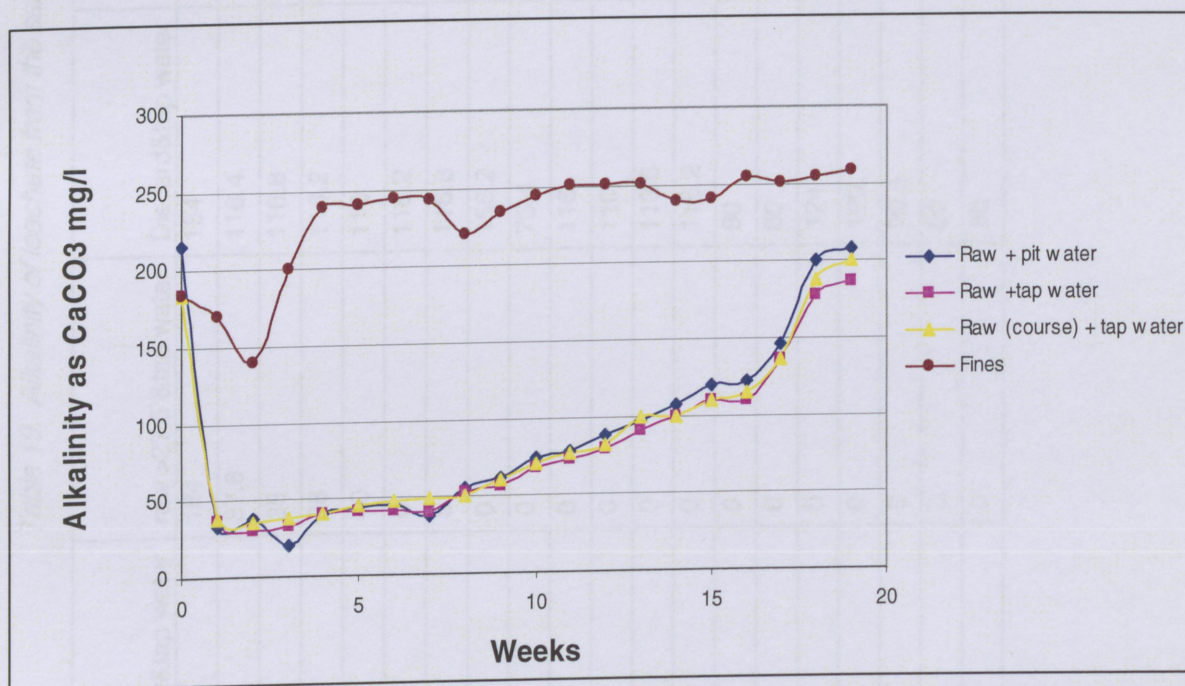


Figure 23. Alkalinity of samples during phase 2 column leaching test

Table 19. Alkalinity of leachate from the samples (Phase 2 column test).

Date	Weeks	raw&pit water	Raw&tap water	raw >27.5 & tap water	Discard&tap water	Discard&pit water	Fines&tap water	Kroomdrai raw coal	Kroomdrai discard
17-Jan-06	0	215.6	184	184	184	215.6	184	184	184
23-Jan-06	1	32.7	36	37.6	116.4	166.8	170.4	184	184
29-Jan-06	2	38	30	35	116.8	166	140	184	184
04-Feb-06	3	20	33	38	116.2	167.2	140	184	184
10-Feb-06	4	40	40	40	110	179.6	140	184	184
16-Feb-06	5	0	0	0	116.2	167.2	188	184	184
22-Feb-06	6	0	0	0	116.8	166	188	184	184
28-Feb-06	7	0	0	0	155.2	89.2	200	184	184
06-Mar-06	8	0	0	0	76.4	246.8	200	184	184
12-Mar-06	9	0	0	0	116	167.6	200	184	184
18-Mar-06	10	0	0	0	110	179.6	220	184	184
24-Mar-06	11	0	0	0	113.6	172.4	200	184	184
30-Mar-06	12	0	0	0	116.2	167.2	232	184	184
05-Apr-06	13	0	0	0	80	239.6	232	184	184
11-Apr-06	14	0	0	0	80	239.6	240	184	184
17-Apr-06	15	0	0	0	124	151.6	240	184	184
23-Apr-06	16	0	0	0	100	199.6	255	184	184
29-Apr-06	17	0	0	0	90.4	218.8	251	184	184
05-May-06	18	0	0	0	80	239.6	261.2	184	184
11-May-06	19	0	0	0	80	239.6	264.4	184	184

c) Rate of Sulphate Generation

The rate of sulphate generation is presented as mg sulphate per kg of material in Figure 24 and Table 21. Considerable amount of sulphate load was leached in the first week of column leaching test from discard samples, particularly from columns where pit water was used for leaching. For example, 3,315 mg of SO_4 was leached per kg of Mafube discard coal when pit water used for leaching, whereas 1,440 mg SO_4 was leached per kg of discard when tap water used. However, the rate of sulphate generation decreases with time and it was determined that only 105 mg SO_4 was leached per kg of discard after 19 weeks of leaching. It was found that 1,700 mg SO_4 was leached per kg of Mafube raw coal when pit water used for leaching purpose in the first week, whereas only 175 mg SO_4 was leached per raw coal when tap water used. The sulphate loads from the samples decreased with time, and only 74 mg was leached per kg after 19 weeks of column leaching test. Considerable amount of sulphate loads are leached from Kroomdraai samples, particularly discard sample, but also decreased with time. For example from Kroomdraai samples; 7,175 mg of SO_4 was leached per kg of raw coal in the first week, whereas 12,750 mg SO_4 was leached per kg of discard coal (Fig.24).

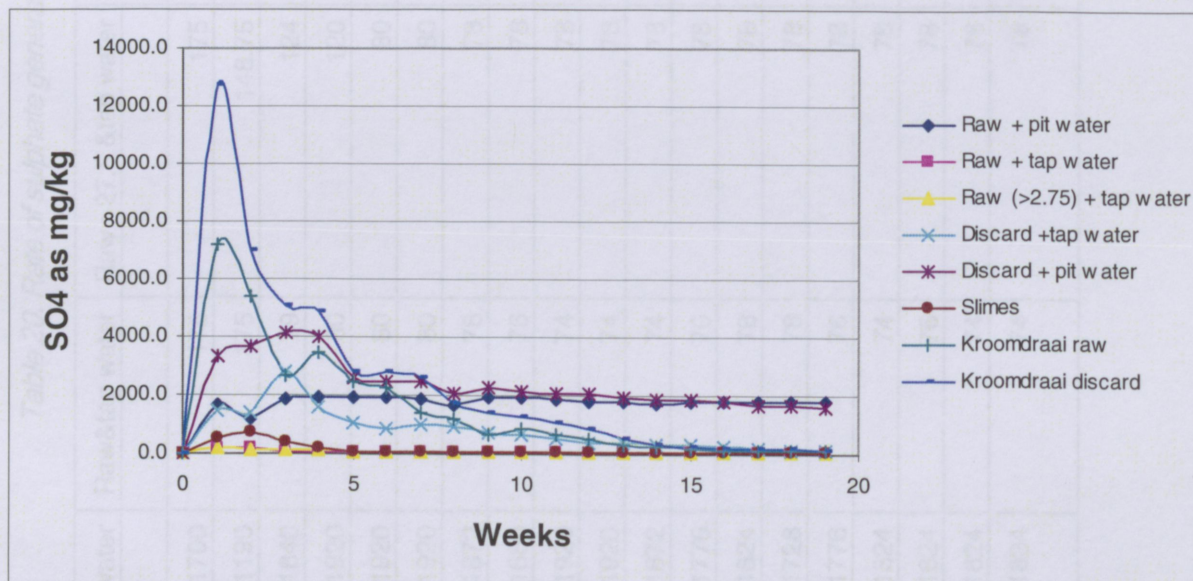


Figure 24. Rate of sulphate generation of samples during phase 2 column leaching test.

Table 20. Rate of sulphate generation as mg SO4 per kg of the sample (phase 2 column test).

Date	Weeks	Raw&pit water	Raw&tap water	Raw >27.5 & tap water	Discard&tap water	Discard&pit water	Fines&tap water	Kroombrai raw coal	Kroombrai discard
17-Jan-06	0								
23-Jan-06	1	1700	175	175	1440	3315	525	7175	12750
29-Jan-06	2	1190	175	148.75	1428	3690	735	5400	7000
04-Feb-06	3	1840	79	124	2812.5	4125	425	2700	5075
10-Feb-06	4	1920	80	120	1600	4000	200	3500	4900
16-Feb-06	5	1920	80	80	1050	2625	60	2450	2800
22-Feb-06	6	1920	80	80	875	2450	60	2275	2800
28-Feb-06	7	1872	78	78	980	2450	60	1400	2625
06-Mar-06	8	1680	76	78	936	2100	60	1225	1750
12-Mar-06	9	1920	74	78	720	2275	60	700	1400
18-Mar-06	10	1920	74	78	648	2135	60	875	1400
24-Mar-06	11	1872	74	78	560	2100	60	700	1050
30-Mar-06	12	1776	70	78	420	2065	60	525	892.5
05-Apr-06	13	1824	78	78	367.5	1925	60	350	542.5
11-Apr-06	14	1728	78	78	350	1890	60	280	332.5
17-Apr-06	15	1776	76	78	350	1890	60	210	280
23-Apr-06	16	1824	74	78	280	1820	60	140	227.5
29-Apr-06	17	1824	76	78	210	1680	60	122.5	227.5
05-May-06	18	1824	74	78	157.5	1680	60	122.5	175
11-May-06	19	1824	74	78	105	1610	60	105	157.5

d) Metal Release

The amount of trace elements that were released during the first week of the test was determined and is presented in Table 21. Leachate from raw coal was impoverished in aluminium (Al), iron (Fe) and manganese (Mn), but enriched in calcium (Ca) and magnesium (Mg). However, leachate from coal discard samples was quite rich in Al, Fe, and Mn, as well as Ca and Mg.

In comparison, the Kroomdraai samples (raw coal and discards) were extremely rich in Al; Fe and Mn than the Mafube discard coal. The leachate from the Kroomdraai discard had aluminium of about 507 mg/l, whereas leachate from Mafube discard coal contained between 2.6 - 5.4 mg/l of aluminium. Iron content ranged from 1570 to 6080 mg/l in leachate from Kroomdraai samples, whereas Mafube discard coal contained about 175-159 mg/l of iron.

Table 21. Trace elements released from raw coal, discard coal, and slimes during the first week of column leaching test.

Trace elements released from the samples								
Column No		Column 6	Column 8	Column 9	Column 10	Column 11	Column 12	Column 13
	Pit water	Raw+ pit water	Raw+ tap water	Discard +tap water	Discard + pit water	Fines	Kromdraai raw coal	Kromdraai discard coal
Al(mg/l)	<0.07	<0.07	<0.07	2.6	5.4	<0.07	473	507
Ca (mg/l)	413	1250	322	692	1060	643	586	425
Fe (mg/l)	0.09	0.16	0.08	175	159	0.11	1570	6080
Mg (mg/l)	622	755	54	201	837	132	176	109
Mn (mg/l)	<0.04	6.0	4.0	35	36	9.3	43	13

e) Rate of Ferrous Iron released

Ferrous iron was also found to be highest in leachate from discard coal at the initial stages of column leaching test, but decreased with time (Fig. 25). Leachate from raw coal was found to contain 11.17 mg/l of ferrous iron during the 1st initial week, whereas leachate from discard coal contained 949 mg/l.

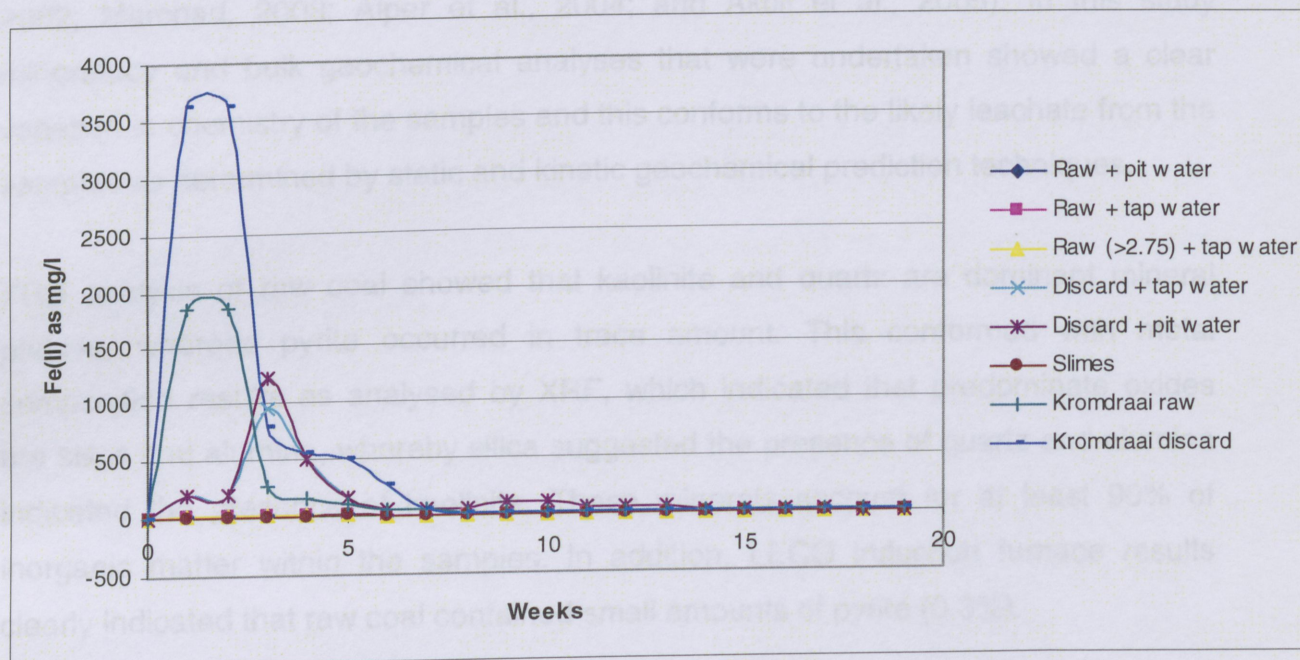


Figure 25. The rate of Ferrous Iron of samples during phase 2 column leaching test.

CHAPTER 5: DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1. Discussion

Given exposure to air and water, mineralogy of geologic materials (raw coal, slimes and discard coal) remain a key factor to determine the quality of likely leachate, and this has been confirmed by various authors (Sobek et al., 1978; Genaudrialine, 1997; Lapakko et al., 1999; Ferguson et al, 1994; Bowel et al., 2000; Hammaritron et al., 2002; Marchad, 2003; Alper et al., 2004; and Akcil et al., 2005). In this study mineralogy and bulk geochemical analyses that were undertaken showed a clear variation in chemistry of the samples and this conforms to the likely leachate from the samples as determined by static and kinetic geochemical prediction techniques.

XRD analysis of raw coal showed that kaolinite and quartz are dominant mineral phases, whereas pyrite occurred in trace amount. This conformed with metal composition results as analysed by XRF, which indicated that predominate oxides are silica and alumina, whereby silica suggested the presence of quartz and alumina indicated the presence of kaolinite. These minerals account for at least 90% of inorganic matter within the samples. In addition, LECO induction furnace results clearly indicated that raw coal contained small amounts of pyrite (0.3%).

Kaolinite and quartz are non-acid producing minerals. Previous researchers showed the capacity of kaolinite to neutralize acid, especially at very low pH. For instance, Jambor (2003) indicated that kaolinite has a potential to neutralize acid produced by oxidation of sulphide minerals available in a sample, but to a much lesser extent compared to carbonate minerals such as calcite. In contract, Sverdrup (1990) and Kwong (1993) studied the extent of dissolution in terms of weathering of different buffer minerals at different pH values. The authors found that kaolinite had a slow weathering rate and a relative reactivity of 0.02 at a pH of 5, whereas calcite was found to have highest relative reactivity of 0.1 at the same pH level. Minerals such as quartz on the other hand had no potential of acid neutralization, and this is mainly due to its physical property (hardness), and the authors also indicated that it has a relative reactivity of 0.004, which is twice slower than the relative reactivity of kaolinite.

It is clear that raw coal is composed mainly of non-acid producing minerals, notably kaolinite and quartz, but impoverished in sulphide minerals. However, kaolinite is only dominant buffer mineral, but the available trace amount of sulphide minerals in the sample is not significant enough to produce much acid leachate. This was also evidenced from the results obtained from geochemical static and kinetic tests. Static test results indicated that neutralization potential in raw coal exceeds acid potential (i.e. $NNP = 2$), which implies that the available mineral species are significant enough to produce neutral leachate. Therefore, high static neutralization capacity in raw coal and slimes could be mainly attributed to kaolinite. Furthermore, static paste pH, which is a measure of immediate acidity or alkalinity, also suggested the presence of buffer minerals. For example, the paste pH of leachate from raw coal and slimes was found to be greater than 4 in both batches of samples, and this implies that the samples are non-acid producing.

Kinetic leaching tests that were done on the first batch of raw coal samples (i.e. Phase 1 test) showed that a small amount of acid was leached during the initial week, but this was quickly neutralized, possibly due to available kaolinite to produce neutral leachate. The pH was found to remain at neutral for the period of 48 weeks, and what was interesting was that once the pH reached 7 there was no gradual increase of pH. The possible reason for this was that kaolinite has low neutralization potential at high pH level. The same also applied to phase 2 column leaching tests, whereby the sample leached out more acid in the initial weeks and immediately neutralized with increased time.

What seemed clear was that the acid leachate formed during the early stages of leaching test interacted with the non-acid producing mineral, notably kaolinite available in the raw and slimes samples to produce neutralization and also to promote the removal of Fe, Al, and Mn. In addition, SO_4 loads from the sample gradually decreased with time. For example, after 48 weeks of column leaching test, 126 mg of sulphate was leached per kg of raw coal, whereas 213 to 221 mg of sulphate was leached per kg of discard coal. The little loads of sulphate leached after 48 weeks in both raw coal and slimes suggested weak sulphide oxidation, due to lack of sulphide minerals in the samples.

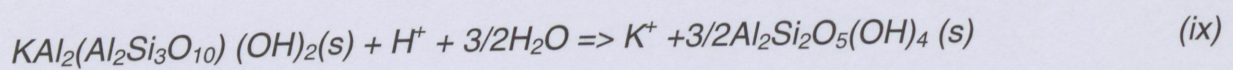
reactivity are different. The order of neutralization capacity is calcite>mica>kaolinite. Mineralogy of discard coal comprised mainly of kaolinite and quartz. Other minerals identified by means of x-ray diffraction technique were pyrite (FeS_2), siderite (FeCO_3), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), and calcite (CaCO_3). Pyrite which is a major acid producing mineral was found to be considerably high and this conforms well to the Leco furnace sulphur content of 4.1 %.

The presence of siderite and gypsum suggested weathering of primary minerals that were available in the sample. For example, siderite is known to be a secondary mineral from chemical weathering of sulphide minerals such as pyrite. Although siderite (FeCO_3) is a carbonate, there is controversy concerning its contribution to acid mine drainage neutralization. For instance, *Bowell et al., (2000)* indicated that siderite had a limited neutralization capacity and the probable reason is that ferrous iron in this mineral is an additional source of acidity due to strong hydrolysis of ferrous iron in solution.

On the other hand, gypsum is a secondary sulphate mineral resulting from the oxidation of sulphide minerals. The presence of these secondary minerals suggested that the samples had undergone pre-oxidation prior to analysis.

Calcite was found to occur in very small quantities in the Mafube discards coal. This is an important buffer mineral for acid mine drainage. Like other carbonates, calcite decomposed through a series of chemical reactions which resulted in the neutralisation of the acid water thereby raising the pH, and then precipitating the iron contained in the water.

Another mineral identified in the samples was mica that is known to have the capacity to neutralize acid. The reaction below shows how mica (muscovite) dissolves to neutralize acid produced in a sample.



Generally, acid producing mineral available in discard coal is pyrite, whereas calcite, kaolinite, and mica are possible acid consuming minerals, but their rate and extent of

reactivity are different. The order of neutralization capacity is calcite>mica>kaolinite. The extent of neutralization is largely dependent on the pH.

Although pyrite (5%) and carbonate (1%) only compromised a small percentage of the sample, these respective acid-forming and acid-neutralizing minerals, are highly reactive and are responsible for the quality of potential leachate.

However, at lower pH other minerals such as kaolinite, siderite, and mica do contribute to neutralization of acid but to a much lesser extent, that decreases with time. This was seen in the column leaching test results, which showed that leachate from discard generally occurred in two phases; the initial rapid acid leachate, followed by cyclic buffering due to dissolution of calcite and less reactive silicate minerals, notably kaolinite and siderite. The rapid acid leachate formation might be attributed to high reactive acid forming minerals, both pyrite and its oxidation products (hydrated sulphates). For instance, Cravotta and Mary (1999) indicated that rock with a high percentage of pyrite will produce acidity faster than rock with a low percentage of pyrite, and this was also seen in this study.

The comparison that has been made between Mafube's and Kroomdraai's samples showed that the Kroomdraai's samples leached out much acid and sulphate loads, as well as toxic metals. This is a clear indication that the extent of acid mine drainage in the Kroomdraai discard dumps can possibly be quite high as compared to the potential of discard coal from Mafube Colliery. The Kroomdraai raw coal will obviously leach out acid in the coal processing plant, and the water quality could eventually deteriorate as water is recycled throughout the water network. However, the Mafube Colliery raw coal could possibly be non-problematic in the coal processing plant because quite a small amount of acid could be leached out in the initial stages but would be quickly neutralized by the available buffer minerals in the sample.

Table 22. Relative mineral reactivity at pH 5 (Sverdrup, 1990, and Kwong, 1993)

MINERAL GROUP	TYPICAL MINERALS	RELATIVE REACTIVITY AT pH 5-
Dissolving	Calcite, aragonite, dolomite magnesite, brucite	1.0
Fast weathering	Anorthite, nepheline, olivine. garnet, jadeite, leucite, spodumene, diopside, wollastonite	0.6
Intermediate weathering	Epidote, zoisite, enstatite, hypersthene, augite, hedenbergite, hornblende, glaucophane, tremolite, actinolite, gntophyllite, serpentine, chrysotile, talc, chlorite, biotite	0.4
Slow weathering	Albite, oligoclase, labradorite, montmorillonite, vermiculite, gibbsite, kaolinite	0.02
Very slow weathering	K-feldspars, muscovite	0.01
Inert	Quartz, rutile, zircon	0.004

5.2. Conclusions

The following conclusions have been drawn from this study:

- The Mafube raw coal and slimes have potential to produce neutral leachate as confirmed by the following: Mineralogy and geochemical composition, static and kinetic geochemical tests. X-ray diffraction analysis indicated that the samples were mainly composed of silicates (99.7%) and impoverished in sulphides (0.3%). Static test by means of acid base accounting showed that acid neutralization capacity of the samples exceeded acid potential, and their net neutralization potential was high (NPR =2). This was confirmed by paste pH analysis which showed that raw coal and slimes had paste pH greater than 4. In addition, kinetic leaching test done by means of columns continuous experiment indicated that leachate from the samples remained neutral after 48 weeks of operation.
- Leaching test on raw coal and slimes using Anort pit water indicated that there was no effect on the acidity or the alkalinity, except on the sulphate content of the leachate. Therefore, utilization of Anort pit water in the coal processing plant will not be problematic as far as acidity of water is concerned, it could only impact on the sulphate saturation level.
- Discard coal on the other hand was found to be a potential producer of acid upon leaching. X-ray diffraction analysis indicated that discard coal contained about 5% of pyrite (acid producing mineral), and about 1% of calcite (buffer mineral). The rest of minerals consisted of silicates, which are less reactive and have no significant neutralization capacity. Static tests also showed that acid potential of discard coal exceeds neutralization capacity (NPR = 0), and paste pH was below 3. In addition, kinetic test showed that discard coal produced acidic leachate upon leaching.
- Generally, raw coal was found to contain 0.4% of sulphide sulphur, predominantly as pyrite; 27% quartz and 73% kaolinite. Discard coal was found to contain 5% of sulphide sulphur as pyrite, and up to 80% of clay minerals such as kaolinite and silicate minerals such as quartz, as well as 1% of carbonate mineral as calcite.

Furthermore, raw coal contained 62% of carbon content, whereas discard coal contained only 29% carbon.

- Comparison of leachate from Mafube's samples, particularly from discard coal, with those from Kroomdraai showed that samples from Kroomdraai produced higher acid leachate (i.e. 8.4 of acid as g CaCO_3 per kg of sample is produced from Kroomdraai discard coal, whereas 6.7 of acid as g CaCO_3 per kg of sample is produced from Mafube raw coal in the initial stages of leaching test).
- Based on column leachate results, leachate from discard coal generally occurred in two phases: the initial rapid acid leachate phase over a period of 1 to 7 days, followed by cyclic buffering due to dissolution of calcite and less reactive silicate minerals, notably kaolinite and siderite.
- Considerable amount of acid was leached from discard coal. Column leaching test showed that approximately 6.7 to 6.4g CaCO_3 of acid leached per kg of discard coal at the initial stages, whereas approximately 0.07 g CaCO_3 acid leached per kg of discard coal after nineteen weeks of periodic leaching. Generally, discard coal leaches out acid upon leaching even at the initial stages of mining.
- More sulphate load was leached from discard coal. Approximately 1.4 g of sulphate was leached per kg of discard coal in the first week. The amount of sulphate leached from discard coal decreased with time. Relatively small amounts of acid were leached from the samples after nineteen weeks of column leaching test.
- The overall conclusion from this study is that raw coal and slimes will not produce significant leachate, whereas discard coal produces acidic and sulphate rich leachate, especially at the initial stages of mining followed by cyclic buffering due to available calcite, kaolinite and mica.

5.3. Recommendations

• *Future studies*

• *Discard Dump Design*

The study showed that discard coal will produce significant acid leachate. Therefore, the main challenge of the company is to ensure that long-term, environmentally acceptable approaches are put in place to meet the stringent regulatory requirements and public concerns, and to reduce possible environmental contamination that may result from the discard dumps. Consequently, there is a need to carry out further work on the design of discard dumps to ensure minimal acid water generation.

• *Water treatment scenario*

Due to the fact that the scale of mining will be extensive, acidification of discard water is probably unavoidable. The mine should provide a plan for neutralization of mine water. The recommended approach is limestone neutralisation, which is a cost-effective neutralization method of acid leachate from discard dumps. The approach offers the following advantages.

- a) acid is neutralised with the cheapest alkali aid; removal is achieved within 20 minutes in a fluidised bed reactor where crushed limestone with a particle size smaller than 4mm is used;
- b) sulphate is removed from concentrations as high as 200g/l (as SO_4) to less than 2g/l;
- c) metals are precipitated as metal hydroxides. If the acid water is rich in iron (II), it is oxidised biologically prior to the neutralisation stage. Iron (II) - concentrations of 3g/l (as Fe) are completely oxidised within two hours reaction time; and
- d) besides cost savings, the benefits of this process are that the pH is controlled naturally at neutral or near neutral values; a small reactor with contact time of only 15 minutes is needed, high - density sludge is produced; by-product recovery is possible, for example, CO_2 gas and gypsum; the limestone is safe to handle; and water with a propensity to form gypsum scale is stabilised.

REFERENCES

- *Future studies*

Generally, the study has managed to cover some important aspects concerning characterization of likely leachate from Mafube raw coal, discard coal and slimes. Considering the fact that mineralogy is the key factor to control the quality of leachate, further detailed mineralogical study by means of transmitted and reflected light microscope, scanning electron microscopy (SEM) and electron probe microanalysis (EPMA) is recommended. SEM and EPMA are particularly useful in the determination of the chemical composition of sulphide oxidation products such as rims, inclusions, and amorphous (non-crystalline) species.

Prasad, V.V.S.R., 2007. *Environmental impact assessment of coal seam gas (CSG) production in the Surat Basin, Queensland, Australia*. Ph.D. thesis, University of Queensland, Australia. pp. 107-108.

Shaw, D.J. and Hetherington, S.W., 2002. *Acid mine drainage: assessment, control and remediation*. 2nd ed. London: Elsevier, 2002. 25 p. 43.

Shaw, D.J., Davis, S.P., and Hetherington, S.W., 2003. *Environmental impacts associated with an abandoned coal mine: a case study from the United Kingdom*. *International Journal of Coal Geology*, pp. 149-153.

Shaw, D.J., Payne, C.J., Jones, L.J. and Walker, G.R., 2008. *The geochemistry of acid mine drainage*. In: Holland, H.D. and Turekian, K.K. (eds.) *Treatise on Geochemistry*. Elsevier, New York, vol. 9, pp. 149-204.

Shaw, D.J., Rose, S.B., and Parschley, J.V., 2000. *Geochemical indicators of metal leaching and acid generation: Geologic controls and regional assessment*. *Geology and Ore Deposits: The Great Basin and Beyond Proceedings*, vol. 2, pp. 6-20.

Bradford, W.S. and F.T. Carlisle, 1930. *A Comparative Study of Tailings Analysis using Neoprene Accounting, Cells, Columns and Soxhlets*. *Proceedings of the 1930 Mining and Reclamation Conference and Exhibition*, Charleston, W.V., April 23-25, 1930. pp.12-25.

Calmerode, B., Hill, R.J. & Yule, J.P., 1990. *Geochemistry and sedimentology of the coal seams from the Pompano Wilbank Coalfield, South Africa: a means of identification*. *International Journal of Coal Geology*, vol. 10, pp. 309-325.

CQS, 2012. *Council for Geoscience, Fieldwork site characterization in Witwatersrand Goldfields and Ermelo Coal Fields*.

CQS, 2013. *Council for Geoscience, Site visit to derelict and unregulated mines*.

Crescador Research Inc., 1999. *Investigation of Prediction techniques for Acid Mine Drainage*. MEND Project 1.16.1a. Canada Center for Mineral and Energy Technology, Energy, Mines, and Resources Canada. p. 61.

Cravotta, C.A., and Mary, K.T., 1999. *Limestone drains to increase pH and remove dissolved metals from acidic mine drainage*. *Applied Geochemistry*, pp. 581-606.

REFERENCES

- Anglo American (pty) Ltd., 2004. [<http://www.angloamerican.co.za/our-operations/thermal-coal.aspx>; accessed 17 January 2012).
- Akcil, A., and Koldas, S., 2005. Acid mine drainage (AMD): Causes, treatment and case studies. *Journal of Cleaner Prediction*, www.sciencedirect.com.
- Alper, C.N., Blowes, D. W., Nordstrom, D. K., Jambor, J.L., 1994. Secondary minerals and acid mine water chemistry. *Handbook on Environmental Geochemistry of sulphides mine wastes*, Waterloo, Ontario. Mineralogical Association of Canada, pp. 247-270.
- APHA., 1989. Standard method for the examination of water and waste. American Public Health Association, 17 Edit. Washington, DC, pp. 44-90.
- Arnesen, R.T. and Iversen, E.R., 1997. The Lokken Project - flooding a sulphide ore mine. *Proceedings of 4th International Conference on Acid Rock Drainage*, Vancouver, BC, vol 3: pp. 1093-1107.
- Barrie, D.J. and Hallberg, K.B., 2004. Acid mine drainage remediation options: a review. *School of Biological Sciences, University of Wales, Bangor LL57 2UW, UK*, p. 43.
- Bell, F.G., Bullock, S.E.T., Halbich, T.F.J., Lindsay, P., 2001. Environmental impacts associated with an abandoned mine in the Witbank Coal field, South Africa. *International Journal of Coal Geology*, pp. 11-25.
- Blowes D.W.; Ptacek, C.J., Jambor, L.J. and Weisener, C.G., 2003. The Geochemistry of Acid Mine Drainage. In: Holland, H.D. and Turekian, K.K. (Eds.), *Treatise on Geochemistry*. Elsevier, New York, vol 9: pp. 149-204.
- Bowell, R.J., Rees, S.B., and Parsshley, J.V., 2000. Geochemical predictions of metal leaching and acid generation: Geologic controls and baseline assessment. *Geology and Ore Deposits: The Great Basin and Beyond Proceedings*, vol 2: pp. 8-20.
- Bradham, W.S., and F.T. Caruccio, 1990. A Comparative Study of Tailings Analysis using Acid/Base Accounting, Cells, Columns and Soxhlet. *Proceeding of the 1990 Mining and Reclamation Conference and Exhibition*, Charleston, WV, April 23-26, 1990. pp.19-25.
- Cairncross, B., Hart, R.J. & Willis, J.P., 1990. Geochemistry and sedimentology of the coal seams from the Permian Witbank Coalfield, South Africa; a means of identification. *International Journal of Coal Geology*, vol 16: pp. 309-325.
- CGS., 2012. Council for Geoscience. *Fieldwork/Site characterization in Witwatersrand Goldfields and Ermelo Coal Fields*.
- CGS., 2013. Council for Geoscience. *Site visit to derelict and ownerless mines*.
- Coastech Research Inc., 1989. Investigation of Prediction techniques for Acid Mine Drainage. MEND Project 1.16.1a. *Canada Center for Mineral and Energy Technology, Energy, Mines, and Resources Canada*. p. 61.
- Cravotta, C.A., and Mary K.T., 1999. Limestone drains to increase pH and remove dissolved metals from acidic mine drainage. *Applied Geochemistry*, pp. 581-606.

CSS., 2002. Center for Streamside Studies. "Environmental impacts of hardrock mining in Eastern Washington." College of Forest Resources and Ocean and Fishery Sciences, University of Washington, Seattle, WA.

DALA., 2005. Department of Agriculture and Land Administration. Integrated Resource Information Report.

Dairy Reference Manual., 1995. Third Edition. Authored by faculty of the College of Agricultural Sciences, Pennsylvania State University, in cooperation with the Northeast Regional Agricultural Engineering Service, p. 293.

DWAF., 2009. Department of Water Affairs and Forestry, South Africa, September 2009. integrated water quality management plan for the vaal river system: task 8: water quality management strategy for the vaal river system, report no. p rsa c000/00/2305/7.

EPA., 1994. (USA)., Acid Mine Drainage, Technical report of acid mine drainage prediction. Office of Solid Waste, Washington. pp. 8-28.

Exxaro., 2005. An independent competent person's report on mining assets of Exxaro Resources Ltd. http://www.exxaro.com/pdf/icpr/a/mining_assets/intro.htm

Feasby, G. and Tremblay, G., 1995. New technologies to reduce environmental liability from acid generating mine wastes. Proceedings, Sudbury '95 Mining and the Environment, vol 2: pp. 643-647.

Ferguson, K.D. and Robertson, J.D., 1994. Assessing the risk of ARD. International land reclamation and mine drainage conference, vol 4: pp. 2-11.

Harries, J, 1997. Acid mine drainage in Australia: Its extent and potential future liability Supervising Scientist Report 125, Supervising Scientist, Canberra.

Hobbs, P., Oelofse, S., Rascher, J., 2008. Management of Environmental Impacts from Coal Mining in the Upper Olifants River Catchment as a Function of Age and Scale, *Water Resources Development*, 24, vol 3: pp.417-431.

Huntsman, B.E., J.B. Solch, and M.D. Porter., 1978. Utilization of a Sphagnum species dominated bog for coal acid mine drainage abatement. Abstracts, 91st Annual Meeting Geologic Society America, Ottawa, Ontario, Canada.

INAP (2010). The International Network for Acid Prevention. Global Acid Rock Drainage Guide. [www.gardguide.com; accessed 10 June 2012].

Jambor, J.L., and Blowes, D.W., 1998. Theory and application of mineralogy in environmental studies of sulfide-bearing mine wastes, in Cabri, L.J. and Vaughan, D.L., eds., Modern approaches to ore and environmental mineralogy, Mineralogical Association of Canada Short Course Series, vol 27: pp. 367-401.

Jambor, J.L., 2003. Mine-Waste Mineralogy and Mineralogical Perspectives of Acid-Base Accounting. In: J.L. Jambor, D.W. Blowes and A.I.M. Ritchie (Eds.), Environmental Aspects of Mine Wastes, Short Course Series, Mineralogical Association of Canada, vol 31: pp.117-146.

Kimmel, W.G., 1983. The impact of acid mine drainage on the stream ecosystem. In: Pennsylvania Coal: Resources, Technology and Utilization, (S. K. Majumdar and W. W. Miller, eds.), The Pa. Acad. Sci. Publ, pp. 424-437.

Kleinmann, R. L. P., Tiernan, T. O., Solch, J. G., and Harris, R. L.: 1983, 'A Low-cost, Low Maintenance Treatment System for Acid Mine Drainage Using Sphagnum Moss and Limestone', in S. B. Carpenter and R. W. DeVore (ed.), National Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation, University of Kentucky, Lexington

Kwong, Y.T.J.1993, Prediction and Prevention of Acid Rock Drainage from a Geological and Mineralogical Perspective, MEND Report 1.32.1, Ottawa, ON (NHRI Contribution CS-92054).

Lapakko, K. 1994. Evaluation of neutralization potential determinations for metal mine waste and a proposed alternative. IN: International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, USA, April 24-29,. U.S. Bureau of Mines Special Publication SP 06A-94, vo1, pp.129-137.

Lapakko, K.A.,1993. Predictive Testing for Mine Waste Drainage Quality. In Mine operation and Closure Short Course. Sponsored by EPA and others. Helena, MT. pp.23-58.

Lapakko, K.A., 2002. Metal mine drainage rock and waste characterization tools: An overview. www.macky.unr.edu/adti.

Lawrence, R.W. and Wang, Y., 1997. Determination of neutralization potential in the prediction of acid mine drainage. In: Proceedings of the Fourth International Conference on Acid Rock Drainage. Vol.1, May 31 – June 6, Vancouver, BC. pp. 449-464.

Loskop Irrigation Board., 2011.[http://www.loskopbesproeiingsraad.co.za/index.php?page=loskopdam-waterskema&hl=en_US; accessed 5 January 2013].

McCarthy, T.S. and Pretorius, K., 2009. Coal mining on the Highveld and its implications for future water quality in the Vaal system. IMWA Mine Water Forum, 19 – 23 September 2009, Pretoria.

McCarthy, T.S., 2011. The impact of acid mine drainage in South Africa.South African Journal of Science, 107(5/6): pp.1 – 7.

McGuire, M. M., K.J. Edwards, J.F. Banfield, and Hamers R.J., 2001."Kinetics, surface chemistry, and structural evolution of microbially mediated sulfide dissolution."GeochimicaetCosmochimicaActa 65(8): pp.1243-1258.

Marchad, E.A., 2003. Minerals and mine drainage. Literature review. www.sciencedirect.com.

Maree, J. P., Hlabela, P., Nengovhela, A. J., Geldenhuys, A. J., Mbhele, N.,Nevhulaudzi, T. and Waanders, F. B., 2004. Treatment of mine water for sulphateand metal removal using barium sulphide, Mine Water and the Environment,23 (4): pp.195–203.

Maree, J.P (2004).Personal communication. The Acid generating potential of Kroomdraai Discard spoil

MEND, 2001. "List of Potential Information Requirements in Metal Leaching/ Acid Rock Drainage Assessment and Mitigation Work". Mining Environment Neutral Drainage Program. W. A. Price, CANMET, Canada Centre for Mineral and Energy Technology.

MEND, 2009. Prediction manual for Drainage Chemistry from Sulphidic Geological Material. Report.1.20.1.

Mey, W.S. and van Niekerk, A.M., 2009. Evolution of mine water management in the Highveld coalfields. International Mine Water Conference, 19 – 23 October 2009, Pretoria, South Africa.

Microbial Technologies, 1997. Design of wetlands systems to treat mine drainage at United Keno Hills mines. [http://technology.infomine.com/enviromine/wetlands/cw_cases.htm, accessed 12 March 2012].

Miller, S.D., Jeffery, J.J., and Murray, G.S.C., 1995. Identification and management of acid generating mine wastes--procedures and practices in Southeast Asia and the Pacific Regions, in J.W. Gadsby, J.A. Malick, and S.J. Day, eds., Acid mine drainage designing for closure: Vancouver, BiTech Publishers Ltd. p. 1-11.

Mills, C., 1997. An Assessment of the Results of Acid Base Accounting (ABA) and Mineralogical Testwork on Eight Samples from the Proposed Minto, Yukon Territory, Minesite, report to The Selkirk First Nation, Pelly Crossing, Yukon.p. 30.

Morris, R., E.W. Taylor, D.J.A. Brown and J.A. Brown.,1989. Acid toxicity and aquatic animals. Society for Experimental Biology Seminar Series, v. 34, Cambridge University Press, p. 282 .

Mudder, T. and G. Olson., 2004. Chemical control of acid rock drainage. Mining Environ. Management, May issue: pp. 8-13.

Naicker, K., Cukrowska, E., and McCarthy, T.S., 2003. Acid mine drainage arising from gold mining activity in Johannesburg, South Africa. Wits Dept of Chemistry Env pollution. Vol 122, issue 1. pp 22-31.

Netshitungulwana R and Yibas B (2012) Investigations of the stream sediments geochemistry for the metal pollution sources of the Olifants River Catchment, Technical Report, Council for Geoscience, unpublished report, pp. 87.

Nordstrom, D. K., and G. Southam., 1997."Geomicrobiology- interactions between microbes and minerals." Mineral Soc. Am 35: pp.261-390.

Oberholster, P.J., Myburgh, J.G., Ashton, P.J. and A.-M. Botha., 2010. Responses of phytoplankton upon exposure to a mixture of acid mine drainage and high levels of nutrient pollution in Lake Loskop, South Africa, Ecotoxicology and Environmental Safety, 73: pp. 326-335

Plumlee, G.S., 1999. The Environmental Geology of Mineral Deposits. In: G.S. Plumlee and M.J. Logsdon (Eds.), The Environmental Geochemistry of Mineral Deposits, Part A: Processes, Techniques and Health Issues, Reviews in Economic Geology Vol. 6A, Society of Economic Geologists, Inc., pp.71-116.

Price, W.A. and Errington, J., 1998. Guidelines for Metal Leaching and Acid Rock Drainage an Minesites in British Columbia. British Columbia Ministry of Energy and Mines, Victoria, British Columbia.

Price, W.A. and Errington, J.C., 1995. ARD guidelines for minesites in British Columbia. B.C. Ministry of Energy, Mines and Petroleum Resources. p. 29.

Price, W.A., Errington, J., and Koyanagi, V., 1997. Guidelines for the prediction of acid rock drainage and metal leaching for mines in British Columbia: part I. pp.20-32.

Pulles W, Coetser L, Heath R, Muhlbauer R., 2004. Development of high-rate passive sulphate reduction technology for mine waters. In: Proceedings of IMWA Conference, September 19-23, UK. pp. 253-265.

Ramontja T, Coetzee H, Hobbs PJ, Burgess J E, Thomas A, Keet M, Yibas B, van Tonder D, Netili F, Rust UA, Wade P, Maree., 2011. Mine Water Management in the Witwatersrand Gold Fields With Special Emphasis on Acid Mine Drainage Inter-Ministerial-Committee on Acid Mine Drainage, Pretoria

Scott R., 1995. Flooding of Central and Grand Rand Gold Mines: an investigation into controls over the inflow rate, water quality and the predicted impacts of flooded mines. Water Research Commission Report, 486/1/95, South Africa, pp 238.

Singer, P.C., and Stumm, W., 1970. Acid Mine Drainage: the rate determining step. Science 167. pp.1121-1123.

Singleton, G.A. and L.M. Lavkulich., 1978. Adaption of the Soxhlet Extractor for Pedologic Studies. Soil Science Society of America Journal, Vol. 42, pp. 984-986.

Sobek, A.A., Schuller, W.A., Freeman, J.R. and Smith, R.M., 1978. Field and laboratory methods Applicable to overburdens and mine soil, WVU, EPA report No. 600/02-78-054, pp. 47-50.

Speart, J., 1995. "A Lust for Gold," Mother Jones (Jan-Feb 1995) p.60. In: US Bureau of Mines, Acid Mine Drainage: Mining and Water Pollution (2000). Miningwatch Canada website. Website Address <http://www.Miningwatch./index.php>.

Sverdrup, H.U., 1990. The Kinetics of Base Cation Release due to Chemical Weathering, Lund University Press, Lund, p 246.

Tutu H, McCarthy TS, Cukrowska E., 2008. The chemical characteristics of acid mine drainage with particular reference to sources, distribution and remediation: The Witwatersrand Basin, South Africa as a case study. Applied Geochemistry 23: pp. 3666-3684.

USDA, 1993. "Acid Mine Drainage form Impact of Hard Rock Mining on the National Forests: A Management Challenge." USDA Forest Service, Program Aid 1505: 12.

U.S. Environmental Protection Agency, Office of Solid Waste Special Waste Branch., 1994. Technical document Acid Mine Drainage Prediction. EPA 530-R-94-036 NTIS PB94-201829

Usher, B.H., Cruywagen, L.M., Necker, E., and Hodgson, F.D.I., 2003. On-site and laboratory investigation of spoil in open cast collieries and the development of acid-base accounting procedures, WRC Report No. 1055/1/03, pp.627-638.

Water Resources Control Board, State of California.,1990. Report to the Legislature on Acid-Generation Potential Tests, 90-18CWP, December 1990. Written by Richard Humphreys, Division of Clean Water Programs.

White , W.W., Lapakko, K.A., and Cox, R.L., 1999. Static test methods most commonly used to predict acid mine drainage: practical guidelines for use and interpretation. Society of Economic Geology., vol.7, pp.325-338.

Wieder, R. K., and Lang G. E.: 1982, 'Modification of Acid Mine Drainage in a Freshwater Wetland', in B. R. McDonald (ed.),Proceedings of the Symposium on Freshwater Wetlands of the Unglaciated Appalachian Region, West Virginia University, Morgantown.

Sample ID#	4070	4074	4071	4036	4039	4037	4032
Sample particle size (mm)	44	41.2	41.2	41.2	41.2	41.2	41.2
Total H ₂ O (ml)	1000	1000	1000	1000	1000	1000	1000
Time (min)	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0
15	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0
30	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0
Time (min)	Iron (II) (mg/l as Fe)						
0	27.3	27.3	27.3	27.3	27.3	27.3	27.3
5	27.3	27.3	27.3	27.3	27.3	27.3	27.3
10	27.3	27.3	27.3	27.3	27.3	27.3	27.3
15	27.3	27.3	27.3	27.3	27.3	27.3	27.3
20	27.3	27.3	27.3	27.3	27.3	27.3	27.3
30	27.3	27.3	27.3	27.3	27.3	27.3	27.3
60	27.3	27.3	27.3	27.3	27.3	27.3	27.3
Time (min)	Acidity (mg/l as CaCO ₃)						
0	0	0	0	0	0	0	0
5	25	25	25	25	25	25	25
10	25	25	25	25	25	25	25
15	25	25	25	25	25	25	25
20	50	50	50	50	50	50	50
30	50	50	50	50	50	50	50
60	50	50	50	50	50	50	50
Time (min)	Total Iron (mg/l as Fe)						
0	<0.03	<0.03	<0.03	0.03	0.03	0.03	0.03
Time (min)	Cadmium (mg/l as Cd)						
0	0	0	0	0	0	0	0
50	0	0	0	0	0	0	0
Time (min)	Magnesium (mg/l as Mg)						
0	6	7	2	3	8	5	2
Time (min)	Aluminum (mg/l as Al)						
0	<0.07	<0.07	<0.07	0.24	<0.07	<0.07	<0.07

APPENDIXES

Appendix A: Batch leachate experiment

EXP No 1: Batch studies							
Beaker	1	2	3	4	5	6	7
Sample	Slimes	Raw 1	Raw 2	Raw 3	Discard 1	Discard 2	Discard 3
Sample (g/l)	49.79	50.15	50.01	50.38	50.02	50.37	50.12
Sample particle size (mm)	As received	< 1.2	< 4.75	> 4.75	< 1.2	< 4.75	> 4.75
Dist H ₂ O (ml)	1000	1000	1000	1000	1000	1000	1000
Time(min)	pH						
0	5.63	5.63	5.63	5.63	5.63	5.63	5.63
5	—	5.65	4.72	4.52	5.43	4.55	4.42
15	6.73	6.61	4.6	6.29	5.8	5.06	5.38
30	6.28	6.34	5.67	4.09	5.81	4.84	5.12
60	6.88	7.03	6.61	6.77	6.24	5	5.23
Time(min)	Sulphate (mg/l as SO ₄)						
0	0	0	0	0	0	0	0
5	50	50	50	0	0	0	100
30	50	50	50	0	50	0	150
15	150	150	150	150	100	100	50
60	150	200	150	150	200	100	50
Time(min)	Iron (II) (mg/l as Fe)						
0	27.9	27.9	27.9	27.9	27.9	27.9	27.9
5	27.9	27.9	27.9	27.9	27.9	27.9	27.9
15	27.9	27.9	27.9	27.9	27.9	27.9	27.9
30	27.9	27.9	27.9	27.9	27.9	27.9	27.9
60	27.9	27.9	27.9	27.9	27.9	27.9	27.9
Time(min)	Acidity (mg/l as CaCO ₃)						
0	0	0	0	0	0	0	0
5	25	25	25	100	200	150	100
15	25	25	80	25	200	80	25
30	50	50	50	80	200	100	80
60	50	25	80	25	200	80	50
Time(min)	Total Iron (mg/l as Fe)						
60	<0.03	<0.03	<0.03	0.03	<0.03	0.44	0.8
Time(min)	Calcium (mg/l as Ca)						
60	36	32	8	3	29	13	8
Time(min)	Magnesium (mg/l as Mg)						
60	6	7	2	<1	8	5	2
Time(min)	Aluminium (mg/l as Al)						
60	<0.07	<0.07	<0.07	0.24	<0.07	<0.07	<0.07

Appendix B: Acid Base Accounting Test

ABA for batch 1 samples

Neutralization potential (modified Sobek method)

SAMPLE	Mass (g)	size (mm)	HCL (ml)	HCl (N)	NaOH (ml)	NaOH (N)	Const	Acid consumed (ml)	NP (as kg CaCO ₃ /ton)
Slimes	2.5		40.0	0.1	30.2	0.1		8.6	21.4
Raw 1	2.5	-1.2	40.0	0.1	29.1	0.1		9.7	24.3
Discard 1	2.5	-1.2	40.0	0.1	32.5	0.1		6.2	15.5
Blank	0.0		40.0	0.1	38.5	0.1	1.0	0.0	0.0

Calculations

- constant (c) = ml in blank/ml base in blank
- ml acid consumed = (ml acid added) – (ml base added x constant)
- Neutralization potential
 NP (metric tons CaCO₃/1000 tons of material = ml acid consumed x (25.0) x Normality of acid

Acid potential using EPA Sobek method

Sample	Mass (g)	Particle size (mm)	H ₂ O ₂ (ml)	Initial pH	Final pH	NaOH (N)	Tit vol (ml)	NAG (kg H ₂ SO ₄ /ton)
Slimes	2.5		125	3.69	2.82	0.1	5.3	10.388
Raw 1	2.5	-1.2	125	3.1	2.6	0.1	6.2	12.152
Discard 1	2.5	-1.2	125	2.64	2.31	0.1	9.8	19.208

Calculations

$$\text{Net acid generation (NAG)} = 49 \times V \times M/W$$

Where V is the titrated volume of base used, M is the molarity of base used, and W is the weight of sample used.

Normality of acid

Acid potential using IGS method

Sample	Mass (g)	Particle size (mm)	H ₂ O ₂ (ml)	Final pH	NaOH (N)	Titrvol (ml)	NAG as kg H ₂ SO ₄ /ton	SO ₄	AP
Slimes ⁴			120	2	0.1	8	9.8	400	12.5
Raw 1	4	>0.3	120	3.5	0.1	9.8	12.005	340	10.625
Discard 1	4	>0.3	120	2.21	0.1	15	18.375	550	17.1875

Calculations

Acid potential AP: SO₄ (mg/l)/weight (g) x ml (H₂O₂) = kg SO₄/t of sample

Acid open (AP CaCO₃ kg/t) = SO₄ kg/t x 50

Net acid generation (NAG) = 49*V*M/V

ABA for batch 2 samples

Neutralization potential

SAMPLE	Mass (g)	HCL (ml)	HCl (N)	NaOH (ml)	NaOH (N)	Const	Acid consumed (ml)	NP (as kg CaCO ₃ /ton)
1. Raw coal	2.2	40.0	0.1	29.5	0.1		9.3	23.3
2. Discard coal	2.0	40.0	0.1	40.3	0.1		-1.9	-4.7
3. Slimes	2.0	40.0	0.1	36.2	0.1		2.4	5.9
4. Kroomdrai raw coal	2.0	40.0	0.1	44.5	0.1		-6.3	-15.7
5. Kroomdrai discard coal	2.0	40.0	0.1	48.5	0.1		-10.4	-26.1
Blank	0.0	40.0	0.1	38.5	0.1	1.0	0.0	0.0

Calculations

1. constant (c) = ml in blank/ml base in blank

2. ml acid consumed = (ml acid added) - (ml base added x constant)

3. Neutralization potential

NP (metric tons CaCO₃/1000 tons of material) = ml acid consumed x (25.0) x

Normality of acid

Acid potential using IGS method

Sample	Mass (g)	Particle size (mm)	H ₂ O ₂ (ml)	Final pH	NaOH (N)	SO ₄	AP
1. Raw coal	4	-0.63	120	3.74	0.1	350	10.9375
2. Discard coal	4	-0.63	120	1.66	0.1	3700	115.625
3. Slimes	4	-0.5	120	1.86	0.1	600	18.75
4. Kroomdrai raw coal	4	-0.63	120	2.14	0.1	1300	40.625
5. Kroomdrai discard coal	4	-0.63	120	1.62	0.1	1450	45.3125

Calculations

1. Acid potential AP: $SO_4 \text{ (mg/l) / weight (g) } \times \text{ ml (H}_2\text{O}_2) = \text{kg SO}_4\text{/t of sample}$
2. Acid open (AP CaCO₃ kg/t) = $SO_4 \text{ kg/t } \times 50$
3. Net acid generation (NAG) = $49 \times V \times M/V$

UNIVEN LIBRARY
Library Item : 20132619



Appendix C: Column Leaching Test

Phase 1 column leaching test

Leachate (ml)		1		2		3		4		5	
Date	Columns Weeks	Slimes	Raw>1.2	Raw>1.2	Raw>4.75	Raw>4.75	Discard>1.2	Discard>1.2	Discard>4.75	Discard>4.75	
01-Jan	1	190	320	320	320	280	40	280	27	320	
24-Jan	2	280	280	320	320	330	180	330	28	320	
01-Jan	3	300	295	340	340	330	105	330	29	320	
07-Feb	4	270	290	310	310	290	100	290	30	320	
04-Feb	5	270	240	340	340	285	110	285	31	320	
21-Feb	6	300	230	320	320	320	100	320	32	320	
28-Feb	7	300	300	360	360	360	110	360	33	320	
04-Mar	9	310	320	370	370	365	120	365	34	320	
01-Mar	10	320	320	360	360	360	120	360	35	320	
28-Mar	11	320	320	360	360	360	130	360	36	320	
04-Apr	12	320	320	365	365	365	135	365	37	320	
11-Apr	13	320	320	365	365	360	140	360	38	320	
18-Apr	14	320	320	370	370	360	155	360	39	320	
25-Apr	15	320	340	370	370	370	165	370	40	320	
16-May	18	320	340	375	375	375	180	375	41	320	
23-May	19	320	340	390	390	390	200	390	42	320	
30-May	20	320	340	390	390	390	200	390	43	320	
06-Jun	21	320	340	390	390	390	200	390	44	320	
13-Jun	22	320	340	390	390	390	200	390	45	320	
20-Jun	23	320	340	390	390	390	200	390	46	320	
27-Jun	24	320	340	390	390	390	200	390	47	320	
04-Jul	25	320	340	390	390	390	200	390	48	320	
11-Jul	26	320	340	390	390	390	200	390			

Acidity as mg CaCO₃/L

Date	Weeks	Slimes	Raw>1. 2	Raw>4.7 5	Discard>1. 2	Discard>4. 75	Date	Weeks	Slimes	Raw>1. 2	Raw>4.7 5	Discard>1. 2	Discard>4. 75
17-Jan-	1	50	75	75	8200	2100	18-Jul	27	20	20	20	20	20
24-Jan	2	20	25	25	1000	700	25-Jul	28	20	20	20	20	20
31-Jan	3	20	25	20	700	600	01-Aug	29	20	20	20	20	20
07-Feb	4	25	25	25	400	600	08-Aug	30	20	20	20	20	20
14-Feb	5	20	20	20	25	25	15-Aug	31	20	20	20	20	20
21-Feb	6	20	20	20	25	25	22-Aug	32	20	20	20	20	20
28-Feb	7	20	25	25	25	25	29-Aug	33	20	20	20	20	20
14-Mar	9	20	20	25	25	25	05-Sep	34	20	20	20	20	20
21-Mar	10	20	25	20	25	25	12-Sep	35	20	20	20	20	20
28-Mar	11	20	20	25	25	25	19-Jan	36	20	20	20	20	20
04-Apr	12	25	25	25	25	25	09-Jan	37	20	20	20	20	20
11-Apr	13	25	25	25	25	25	26-Sep	38	20	20	20	20	20
18-Apr	14	25	25	25	25	25	03-Oct	39	20	20	20	20	20
25-Apr	15	25	25	25	25	25	10-Oct	40	20	20	20	20	20
16-May	18	25	25	25	25	25	17-Oct	41	20	20	20	20	20
23-May	19	25	25	25	25	25	24-Oct	42	20	20	20	20	20
30-May	20	20	20	20	20	20	31-Oct	43	20	20	20	20	20
06-Jun	21	20	20	20	20	20	07-Nov	44	20	20	20	20	20
13-Jun	22	20	20	20	20	20	14-Nov	45	20	20	20	20	20
20-Jun	23	20	20	20	20	20	21-Nov	46	20	20	20	20	20
27-Jun	24	20	20	20	20	20	28-Nov	47	20	20	20	20	20
04-Jul	25	20	20	20	20	20	23-Jan	54	20	20	20	20	20
11-Jul	26	20	20	20	20	20							

Fe (II) as mg/l

Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75	Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75
17-Jan-05	1	27.925	55.85	55.85	111.7	83.775	18-Jul	27	5.585	5.585	5.585	5.585	5.585
24-Jan	2	13.962	13.962	13.962	83.775	55.85	25-Jul	28	5.585	5.585	5.585	5.585	5.585
31-Jan	3	11.17	13.962	13.962	83.775	55.85	25-Jul	28	5.585	2.234	2.234	2.234	2.234
7-Feb	4	13.62	13.962	13.962	83.775	55.85	01-Aug	29	2.234	2.234	2.234	2.234	2.234
14-Feb	5	11.17	13.962	11.17	11.17	27.925	08-Aug	30	2.234	2.234	2.234	2.234	2.234
21-Feb	6	11.17	13.962	11.17	13.962	13.962	15-Aug	31	2.234	2.234	2.234	2.234	2.234
28-Feb	7	11.17	13.962	13.962	11.17	13.962	22-Aug	32	2.234	2.234	2.234	2.234	2.234
4-Mar	9	11.17	11.17	13.962	11.17	13.962	29-Aug	33	2.234	2.234	2.234	2.234	2.234
11-Mar	10	11.17	13.62	13.962	11.17	11.17	05-Sep	34	2.234	2.234	2.234	2.234	2.234
18-Mar	11	11.17	11.17	13.962	13.962	11.17	12-Sep	35	2.234	2.234	2.234	2.234	2.234
4-Apr	12	13.62	13.62	13.962	11.17	13.962	19-Jan	36	2.234	2.234	2.234	2.234	2.234
11-Apr	13	13.62	13.62	13.962	13.962	13.962	09-Jan	37	2.234	2.234	2.234	2.234	2.234
18-Apr	14	13.62	13.62	13.962	13.962	13.962	26-Sep	38	2.234	2.234	2.234	2.234	2.234
25-Apr	15	13.62	13.62	13.962	13.962	13.962	03-Oct	39	2.234	2.234	2.234	2.234	2.234
2-May	18	13.62	13.62	13.962	13.962	13.962	10-Oct	40	2.234	2.234	2.234	2.234	2.234
23-May	19	13.62	13.62	13.962	13.962	13.962	17-Oct	41	2.234	2.234	2.234	2.234	2.234
30-May	20	5.585	5.585	5.585	5.585	5.585	24-Oct	42	2.234	2.234	2.234	2.234	2.234
06-Jun	21	5.585	5.585	5.585	5.585	5.585	31-Oct	43	2.234	2.234	2.234	2.234	2.234
13-Jun	22	5.585	5.585	5.585	5.585	5.585	07-Nov	44	2.234	2.234	2.234	2.234	2.234
20-Jun	23	5.585	5.585	5.585	5.585	5.585	14-Nov	45	2.234	2.234	2.234	2.234	2.234
27-Jun	24	5.585	5.585	5.585	5.585	5.585	21-Nov	46	2.234	2.234	2.234	2.234	2.234
04-Jul	25	5.585	5.585	5.585	5.585	5.585	28-Nov	47	2.234	2.234	2.234	2.234	2.234

11-Jul	26	5.585	5.585	5.585	5.585	5.585	23-Jan	54	2.234	2.234	2.234	2.234
--------	----	-------	-------	-------	-------	-------	--------	----	-------	-------	-------	-------

Alkalinity as mg CaCO₃/L

Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75	Date	Weeks	Slimes	Raw>1.2	Raw>4.75	Discard>1.2	Discard>4.75
17-Jan	1	68.8	27.2	22.8	59.6	40	18-Jul	27	173.2	125.2	116.2	110	100
24-Jan	2	180	176.8	135.6	66	66.4	25-Jul	28	155.6	116.8	110	95.6	90.4
31-Jan	3	188.8	190	158	116	79.2	01-Aug	29	155.8	155.8	110	95.6	80
07-Feb	4	161.2	165.2	173.2	155.2	110	08-Aug	30	155.8	135.2	128.2	100	80
14-Feb	5	128	139.2	102	90.4	81.6	15-Aug	31	155.6	148.8	100	100	76.4
21-Feb	6	261.2	208.4	177.2	158	146.4	22-Aug	32	155.6	148.8	113.6	110	90
28-Feb	7	264.4	224	216	214.8	148.4	29-Aug	33	146.2	146.2	116	116	84
06-Mar	9	232	178	217.2	197.6	207.2	05-Sep	34	155.6	155.2	116	116.2	90
13-Mar	10	220	144	157.2	141.6	116.4	12-Sep	35	155.8	155.6	100	117.2	94
20-Mar	11	146.4	165.8	135.2	155.2	116.8	19-Jan	36	155.8	155.6	116	118	90
27-Mar	12	155.2	146.2	116	141.2	116.2	09-Jan	37	155.8	158	155.8	119.8	90
03-Apr	13	155.8	155.6	116.8	141.2	110	26-Sep	38	146.2	157.2	128.2	100	112
10-Apr	14	158	158	128	116.2	116.2	03-Oct	39	155.8	158	117.2	90	102.8
17-Apr	15	161.2	155.2	128.2	110	116.8	10-Oct	40	155.8	161.2	155.8	100	106
24-Apr	18	173.2	155.6	125.2	95.6	155.2	17-Oct	41	158	161.2	158	110	100
01-May	19	173.2	213.6	113.6	118	76.4	24-Oct	42	158	161.2	125.2	120	118
08-May	20	146.2	155.2	141.2	116.2	116	31-Oct	43	158	165.8	161.2	95.6	115.2
15-May	21	155.2	161.2	161.2	110	110	07-Nov	44	155.2	161.2	158	95.6	118
22-May	22	180	180	173.2	116	113.6	14-Nov	45	155.2	158	161.2	100	102
29-May	23	165.8	158	155.6	113.6	116.2	21-Nov	46	161.2	157.1	155.8	95	100
05-Jun	24	180	120	100	100	80	28-Nov	47	161.2	158	158	100	102.8
12-Jun	25	200	120	100	100	80	23-Jan	54	161.2	158	158	100	102.8
19-Jun	26	180	116.8	117.2	148.8	124							



Sulphate as mg/l

Date	Week s	Slime s	Raw>1. 2	Raw>4.7 5	Discard>1. 2	Discard>4.7 5	Date	Week s	Slime s	Raw>1. 2	Raw>4.7 5	Discard>1. 2	Discard>4.7 5
17-Jan	1	4300	1550	1350	4000	2750	18-Jul	27	450	300	350	500	450
24-Jan	2	1850	1700	750	1000	650	25-Jul	28	500	350	350	600	500
31-Jan	3	1400	1250	350	850	600	01-Aug	29	400	350	350	500	500
07-Feb	4	900	650	300	900	500	08-Aug	30	450	350	300	550	450
14-Feb	5	200	200	200	500	250	15-Aug	31	400	300	300	500	450
21-Feb	6	250	350	250	550	550	22-Aug	32	400	300	350	600	400
28-Feb	7	150	400	200	700	250	29-Aug	33	350	350	350	550	450
14-Mar	9	200	150	200	1300	350	05-Sep	34	350	350	300	500	400
21-Mar	10	150	700	200	1100	450	12-Sep	35	300	300	350	500	400
28-Mar	11	200	500	150	1000	350	19-Jan	36	350	350	350	500	400
04-Apr	12	200	600	200	950	300	09-Jan	37	300	350	300	450	350
11-Apr	13	250	400	300	900	400	26-Sep	38	300	300	300	450	350
18-Apr	14	300	400	350	800	500	03-Oct	39	350	350	300	450	350
25-Apr	15	450	450	500	800	750	10-Oct	40	300	350	300	450	300
16-May	18	400	800	800	1250	1150	17-Oct	41	300	300	300	450	350
23-May	19	500	250	300	950	800	24-Oct	42	350	300	300	450	350
30-May	20	450	400	300	800	750	31-Oct	43	300	250	250	450	350

06-Jun	21	500	400	350	750	700	07-Nov	44	300	250	250	400	350
13-Jun	22	500	450	400	700	700	14-Nov	45	300	250	250	400	350
20-Jun	23	550	500	600	750	650	21-Nov	46	300	200	200	450	350
27-Jun	24	700	600	800	800	600	28-Nov	47	300	200	200	400	350
04-Jul	25	650	500	700	700	600	23-Jan	54	300	200	200	400	350
11-Jul	26	600	450	500	650	650							

Phase 2 column test: Volume of leachate from the samples (phase 2 column leaching test)

Date	Weeks	raw&pit water	Raw&tap water	Raw&tap water	raw >27.5 & tap water	Discard&tap water	Discard&pit water	Fines&tap water	Kroondrai coal	Kroondrai raw water	Kroondrai discard
17-Jan-06	0										
23-Jan-06	1	5	5	5	5	4	3.9	2.5	3.5		3.75
29-Jan-06	2	3.5	5		4.25	4.2	4.1	3.5	3		3.5
04-Feb-06	3	4	3.95		4	3.75	3.75	2.5	2.25		3.5
10-Feb-06	4	4	4		4	4	4	2.5	3.5		3.5
16-Feb-06	5	4	4		4	3.5	3.5	3	3.5		3.5
22-Feb-06	6	4	4		4	3.5	3.5	3	3.5		3.5
28-Feb-06	7	3.9	3.9		3.9	3.5	3.5	3	3.5		3.5
06-Mar-06	8	3.5	3.8		3.9	3.6	3.5	3	3.5		3.5
12-Mar-06	9	4	3.7		3.9	3.6	3.5	3	3.5		3.5

18-Mar-06	10	4	3.7	3.9	3.6	3.5	3	3.5	3.5
Date	Weeks	raw&pit water	Raw&tap water	raw >27.5 & tap water	Discard&tap water	Discard&pit water	Fines&tap water	Kroomdrai coal	Kroomdrai discard

24-Mar-06	11	3.9	3.7	3.9	3.5	3.5	3	3.5	3.5
30-Mar-06	12	3.7	3.5	3.9	3.5	3.5	3	3.5	3.5
05-Apr-06	13	3.8	3.9	3.9	3.5	3.5	3	3.5	3.5
11-Apr-06	14	3.6	3.9	3.9	3.5	3.5	3	3.5	3.5
17-Apr-06	15	3.7	3.8	3.9	3.5	3.5	3	3.5	3.5
23-Apr-06	16	3.8	3.7	3.9	3.5	3.5	3	3.5	3.5
29-Apr-06	17	3.8	3.8	3.9	3.5	3.5	3	3.5	3.5
05-May-06	18	3.8	3.7	3.9	3.5	3.5	3	3.5	3.5
11-May-06	19	3.8	3.7	3.9	3.5	3.5	3	3.5	3.5

Acidity as CaCO₃ mg/l (phase 2 column test)

Ferrous iron as Fe(II) mg/l (phase 2 column test)

Date	Weeks	raw&pit water	Raw&tap water	raw >27.5 & tap water	Discard&tap water	Discard&pit water	Fines&tap water	Kroombrai coal	Kroombrai raw	Kroombrai discard
17-Jan-06	0	2.234	2.234	2.234	2.234	2.234	2.234	2.234		2.234
23-Jan-06	1	11.17	11.17	11.17	195.475	195.475	5.585	1843.05		3630.25
29-Jan-06	2	11.17	11.17	11.17	195.475	195.475	5.585	1843.05		3630.25
04-Feb-06	3	27.925	27.925	27.925	949.45	1228.7	5.585	279.25		781.9
10-Feb-06	4	27.925	27.925	27.925	502.65	502.65	2.234	167.55		558.5
16-Feb-06	5	11.17	11.17	11.17	167.55	167.55	11.17	111.7		502.65
22-Feb-06	6	1.117	1.117	1.117	55.85	55.85	0	55.85		279.25
28-Feb-06	7	1.117	1.117	1.117	55.85	55.85	0	55.85		55.85
06-Mar-06	8	1.117	1.117	1.117	55.85	55.85	0	27.925		27.925
12-Mar-06	9	1.117	1.117	1.117	111.7	111.7	0	27.925		27.925
18-Mar-06	10	1.117	1.117	1.117	111.7	111.7	0	27.925		27.925
24-Mar-06	11	1.117	1.117	1.117	55.85	55.85	0	27.925		27.925
30-Mar-06	12	1.117	1.117	1.117	55.85	55.85	0	27.925		27.925
05-Apr-06	13	1.117	1.117	1.117	55.85	55.85	0	27.925		27.925
11-Apr-06	14	1.117	1.117	1.117	27.925	27.925	0	27.925		27.925

17-Apr-06	1.117	1.117	1.117	1.117	27.925	0	27.925	27.925	27.925
23-Apr-06	1.117	1.117	1.117	1.117	27.925	0	27.925	27.925	27.925
29-Apr-06	1.117	1.117	1.117	1.117	27.925	0	27.925	27.925	27.925
05-May-06	1.117	1.117	1.117	1.117	5.585	0	5.585	27.925	27.925
11-May-06	1.117	1.117	1.117	1.117	5.585	0	5.585	27.925	27.925

SO₄ as mg/l (phase 2 column test)

Date	Weeks	raw&pit water	Raw&tap water	raw >27.5 & tap water	Discard&tap water	Discard&pit water	Fines&tap water	Kroomdrai coal	Kroomdrai raw	Kroomdrai discard
17-Jan-06	0	4400	200	200	200	4400	200	200		200
23-Jan-06	1	3400	350	350	3600	8500	2100	20500		34000
29-Jan-06	2	3400	350	350	3400	9000	2100	18000		20000
04-Feb-06	3	4600	200	310	7500	11000	1700	12000		14500
10-Feb-06	4	4800	200	300	4000	10000	800	10000		14000
16-Feb-06	5	4800	200	200	3000	7500	200	7000		8000
22-Feb-06	6	4800	200	200	2500	7000	200	6500		8000
28-Feb-06	7	4800	200	200	2800	7000	200	4000		7500

06-Mar-06	8	4800	200	200	200	2600	6000	200	3500	5000
12-Mar-06	9	4800	200	200	2000	6500	200	2000	4000	
18-Mar-06	10	4800	200	200	1800	6100	200	2500	3550	
24-Mar-06	11	4800	200	200	1600	6000	200	2000	3000	
30-Mar-06	12	4800	200	200	1200	5900	200	1500	2550	
05-Apr-06	13	4800	200	200	1050	5500	200	1000	1550	
11-Apr-06	14	4800	200	200	1000	5400	200	800	950	
17-Apr-06	15	4800	200	200	1000	5400	200	600	800	
23-Apr-06	16	4800	200	200	800	5200	200	400	650	
29-Apr-06	17	4800	200	200	600	4800	200	350	650	
05-May-06	18	4800	200	200	450	4800	200	350	500	
11-May-06	19	4800	200	200	300	4600	200	300	450	

4. Rate of acid production, sulphate generation and acid consumption calculations

- Acid production rate (as mg CaCO_4 /kg/week) = Acidity of leachate (mg/l) * Leachate volume (l) / Mass of sample (kg).
- Sulphate generation rate as mg SO_4 /kg/week = Sulphate (mg/l) * Leachate volume (l) / Mass of sample (kg)
- Acid consumption rate as mg CaCO_3 /kg/week = Alkalinity (mg/l) * Leachate volume (l) / Mass of sample (kg)