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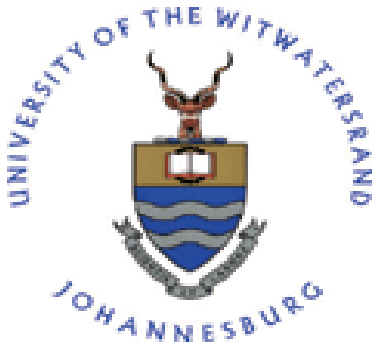
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PASSIVE TREATMENT OF ACID MINE DRAINAGE THROUGH PERMEABLE CONCRETE AND ORGANIC FILTRATION

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ABSTRACT

The aim of this research was to reduce heavy metal and sulfate content of acid mine drainage (AMD) through the methods of passive filtration by combining permeable concrete and organic materials. This was to achieve a low cost, yet effective temporary treatment method for rural/poor communities who are affected by AMD. The acids are filtered through layers of alternating pervious concrete and biological composting layers. The concrete layers target removal of heavy metals such as iron, manganese, potassium, and magnesium, etc. through precipitation as well as reduce sulfate content to a small degree along with total dissolved solids. The concrete layers also aid in raising the pH of the AMD to more acceptable levels. The biological layers achieve sulfate remediation through the metabolism of sulfate-reducing- bacteria (SRB). This process however required time and the organic layers were thus thicker and less permeable than the concrete layers in order to allow seepage to take place at a reduced rate. A wide variation of composting layers were tested, including cow manure, chicken manure, sawdust, straw, zoo manure, and leaf compost to find an optimum mix of materials which allows for the greatest sulfate reduction through sulfate reducing bacteria in the shortest possible time. Short as well as Long-term testing of rigs was undertaken to establish effectiveness, limitations and lifespan of the filtration systems. AMD from a mine in the Mpumalanga coal fields with exceptionally high sulfate content was used to test effectiveness of the organic materials over a short period of time. With long term testing conducted with a synthetic AMD, due to limited supply from the mine. The short term testing yielded removal of sulfates in the order of 56% when using kraal manure as the biological reagent mixed with sawdust for added organic carbon. The mix percentages by volume were 80%Sawdust to 20%manure and this setup was able to achieve the 56% removal of sulfates within 14 days. The filter also successfully raised the pH to 8 while removing a significant portion of heavy metals. The long term tests showed complete (100%) remediation of sulfates after a period of approximately sixty days. The tests are continuing to determine their finite lifespan and limitations. The results show promise for using the technology as a low cost, temporary measure to protect locally impacted groundwater, especially for isolated and/or rural communities while a permanent long term solution is sought.

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ETHICAL STATEMENT

The research did not involve any form of animal or human testing as defined in A.4 of the Senate Standing Orders on Higher degrees and therefore does not require ethical clearance. All tests were conducted with the utmost care and regard for health and safety with appropriate PPE equipment used at all times during construction, setup, clean up and dismantle of filter, sampling and testing, and especially when handling any form of AMD.

DECLARATION

I declare this research report to be my own original unaided work. It is being submitted as part of the requirements for the degree of Masters of Engineering at the University of Witwatersrand, Johannesburg within the faculty of Engineering and the Built Environment. This research report has not been submitted before, for any degree or examination at this or any other University. I am aware that plagiarism is a violation of both the General Rules for Student Conduct and the Plagiarism Policy of the University of the Witwatersrand.



STEVEN ZAAL

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CHAPTER 1

INTRODUCTION

CHAPTER 1 INTRODUCTION

1.1 PURPOSE OF THE STUDY

The aim of this research was to remove heavy metal and sulfates of acid mine drainage (AMD) through the methods of passive filtration combining permeable reactive concrete and organic treatment.

The driving motivation and purpose of the research was to create a low-cost, easily constructed system that would effectively remediate AMD in the short- to medium-term to address the need for a low-cost, effective, "emergency treatment technique". The filters would be simple and easily made by local communities and made out of materials that would be readily available to them. These filters would need to be able to protect their livelihoods, water sources, and farming lands in the short term whilst a more robust and long term treatment method was sought and implemented.

The concrete layers of the filter would aid in raising the pH of the AMD while the bio reactive layers would remove sulfates through the mechanism of dissimilatory sulfate reduction.

1.2 AN OVERVIEW OF ACID MINE DRAINAGE

Acid Mine Drainage (AMD) is the name given to outflows of water that contain high levels of acidity and heavy metals due to the reaction and oxidation of geological layers which consist of sulfide containing minerals, especially pyrite(FeS_2) (Akcil et al. 2006). The amount and rate at which AMD is generated is a function of the rock mineralogy and degree of exposure/presence of oxygen and water. This creates a highly acidic, sulfate-rich mixture with a characteristically low pH and often a high content of heavy metals in soluble form (Akcil et al. 2006, Durand et al. 2010).

This acid generating phenomenon is also a naturally occurring process resulting from the weathering and erosion of sulfide bearing minerals in exposed rocks on hills and valleys or through ground water seepage. This however creates AMD at a slow rate due to the relatively small exposed surface area. In the case of ground water seepage, the lack of excess oxygen, reduces the rate of AMD generation and surrounding alkaline rocks are able to neutralise the AMD, or water bodies dilute it sufficiently before it has a chance to significantly impact the environment (Durand et al. 2010)

Mining activities however; such as deep pit excavation, strip mining, crushing and dumping of rock for minerals, quarrying, mine waste rock, tailings that are exposed to the elements and tunnelling result in large volumes of rock being exposed to weathering, which can potentially create acid mine drainage if they contain pyrite or other sulfurous chemicals. This AMD has adverse effects on the environment, its biodiversity, as well as causing long-term damage to waterways, aquifers and ultimately our drinking water (Coetzee et al. 2010).

AMD can also cause damage to structures such as culverts and bridge abutments exposed to waterways that have a high concentration of AMD as the high acidity and sulfate levels have an accelerated corrosion effect on steel reinforcing (Gurdeep 2006).

More importantly, AMD poses a health risk to human settlements, especially those of the mining communities often living in low cost, slum/squatter camp type environments adjacent to or nearby mine dumps/tailings. Some of the heavy metals contained in AMD are extremely toxic if there is a pathway between the source and a receptor – some are even carcinogenic (USEPA Region 9 PRG, 2004)

1.3 EXTENT OF THE PROBLEM IN SOUTH AFRICA

AMD is an extensive problem, primarily with coal and gold mining, as marcasite and pyrite, or fool's gold as it is often known, are common in the mine wastes and surrounding geology. The AMD issue in Johannesburg is, in part, a result of closed mines no longer executing draw down pumping, which consequentially leads to the ground water table rising back up to its natural level. This is resulting in large amounts of AMD welling up inside the mine voids left from deep excavations, and uncontrolled decant is now the greatest risk in some areas, although with the installation of new pumps this risk has significantly receded in the Witwatersrand Basins. To give a perspective, the potential volume of AMD produced by the Witwatersrand Goldfields could amount to as much as 350Ml/day which is approximately 10% of the daily supply of potable water by Rand Water according to Hobbs et al (2009).

According to a report issued to the inter-ministerial committee on acid mine drainage produced by a team of experts under the coordination of the council of Geoscience (2010) there have been reports of high risk and uncontrolled levels of AMD at the following locations: Witwatersrand Gold Fields (currently being mitigated), Mpumalanga and KwaZulu-Natal Coal Fields and the O'Kiep Copper District.

One of the largest concerns of AMD in the Western Basing, according to Durand (2010) was the accelerated karstification of dolomite (which is soluble in acid) resulting in large sinkholes and soil subsidence coupled with the consequential contamination of aquifers and decanting into waterways which ultimately pollutes and impacts all types of biodiversity including; with time; our drinking water. This same threat is faced by the cradle of humankind and is a significant concern, as the structural stability of the surrounding areas could be destabilised. This could threaten the heritage site and the artefacts contained within its soil as the dolomitic aquifers carry increasing amounts of highly acidic AMD into the area (Durand et al. 2010). To date, these threats have not been realised; however they are not fully mitigated.

According to a case study done by Hochmann et. al (2010) on coal mining in South Africa, an account of the mining community living at Maguqa Township near an open cast coal mine in the Brugspruit valley was given.

This study described acid mine drainage carrying toxic heavy metals including carcinogenic substances such as benzene and toluene flowing into the Brugspruit stream and from there into the Olifants river system. The children of the township play soccer on the flat white surfaces of sulfate precipitates left by the AMD, oblivious to the potential health risks it may pose to them. This account reiterates the need for a rapid, temporary solution, which has the potential to reduce the risk to such impacted communities whilst a long term solution is sought at various locations.

1.4 PROBLEM STATEMENT AND RESEARCH MOTIVATION

It is clear that AMD is a significant problem in South Africa and that property, infrastructure, and people are increasingly exposed to the risks and issues associated with AMD each year. Thus the need for a low cost, yet effective short term method of treating AMD is sorely needed, especially for rural communities who may not have the resources or finances to deal with ever increasing AMD issue.

The aim of this research was therefore to develop a method to passively treat AMD that would achieve significant sulfate removal within a relatively short period of time (6-8 weeks), without the high operational and initial outlay costs of currently available treatment methods. It was envisaged that the results could be translated to local communities which would be able to install a number of these low cost filters using their local resources and labour to achieve a short term, quick-fix solution to allow a respite to the issue while a more robust, long term solution could be considered and implemented.

1.5 STRUCTURE OF THIS RESEARCH REPORT

This research report includes the following Sections:

1. An introduction to the problem
2. A survey of available literature to place the research in context.
3. A description of the materials and methods used to conduct the research.
4. A discussion of the results.
5. Concluding remarks and further study.

The work was also accepted for presentation at the 2015 ICARD IMWA conference held in Santiago, Chile in April of 2015. The paper presented at the conference was fully peer reviewed and a copy of this paper is presented in Appendix A.

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2 LITERATURE REVIEW

This chapter discusses the processes involved in the creation of AMD along with various factors which influence its production rate. It discusses the current most commonly used treatment techniques along with their respective pros, cons and limitations. It also addresses a new technique used to counteract and mitigate AMD generation in the form of permeable concrete. The chapter is then concluded with the research objectives based on the findings of the literature study.

2.1 THE AMD GENERATION PROCESS

The formation of Acid mine drainage (AMD) is a complex process, but there are four chemical reactions that are accepted as the most common/prominent as they represent the degradation process of pyrite into AMD. These are listed below [Shabalala (2013), Younger et al. (2002), Sheridan et al. (2012)]:

$$2FeS_2(s) + 7O_2\ (aq) + 2H_2O \rightarrow Fe^{2+} + 4SO_4{}^{2-} + 4H^+ \qquad \textit{Equation 1}$$

$$2Fe^{2+} + \frac{1}{2}O_2 + 2H^+ \rightarrow 2Fe^{3+} + H_2O \qquad \textit{Equation 2}$$

$$2Fe^{3+} + 6H_2O \rightarrow 2Fe(OH)_3(s) + 6H^+ \qquad \textit{Equation 3}$$

$$14Fe^{3+} + FeS_2(s) + 8H_2O \rightarrow 2SO_4{}^{2-} + 15Fe^{2+} + 16H^+ \qquad \textit{Equation 4}$$

The first step in the formation of AMD is the creation of ferrous iron caused by the exposure of pyrite (FeS_2) to oxygen and water as can be seen in Equation 1.

This ferrous iron is further oxidised into ferric iron which is a reaction that is catalysed by acidophilic bacteria activity. This is pH dependant, starting slowly at a low pH (~3) and accelerating as the pH increases towards 5. This reaction is shown in Equation 2 and it is noted that this reaction consumes some acidity through the consumption of H^+ ions, thus forcing the reaction to accelerate and oxidise faster as the solution gets less acidic by raising the pH slightly (Chimuka et al. 2009).

The benefits of this reduction in acidity is however overshadowed by the subsequent reaction where the ferric iron can either react to create ochre (which is the brownish red substance often seen in rivers and streams affected by AMD where it precipitates out) or the ferric iron can react with further pyrite to create more ferrous iron and acidity as shown in Equation 3.

Ferrous iron can also be created as shown in Equation 4 which creates a feedback loop that perpetuate Equations 2 and 3 until there is no dissolved oxygen present and will thereafter run until completion creating high volumes of SO_4^{2-} and more importantly greatly increased acidity through the formation of H^+ ions. In essence this is a self-driving process running from Equation 4 --> 2 --> 3 --> 4 creating large amounts of H^+ ions until depletion of reactants (Sheridan et al. 2013).

This resultant acidity causes the leaching of many previously stable heavy metals. Some of the metals typically found in AMD that originated from the Witwatersrand super group are manganese, aluminium, iron, nickel, zinc, cobalt, lead, radium, thorium and uranium [Durand et al. (2010), Akcil & Koldas (2006)]. It is these metal compounds and large sulfate contents that pose a great health risk when they decant into rivers and ground water sources in large volumes.

2.2 FACTORS WHICH AFFECT PRODUCTION RATE OF AMD

There are a number of factors which impact significantly on the rate and ability of AMD to be produced according to Akcil & Koldas (2006) and Younger et al (2002) which are presented here. Most remedial solutions to AMD prevention work using one or more of these factors:

- **Acidity**, or the pH of the solution. This plays a major role on the rate of AMD production, as certain ferrooxidan bacteria (such as Acidithiobacillus) thrive at a low pH which act to accelerate the oxidation of pyrite as described in the equations presented in the preceding section.
- **Temperature** is a further factor which affects the production rate, as higher temperature results in higher oxygen ingress through convection, and also is favourable to the bacteria, as they require warmer temperatures to proliferate and become increasingly less active as temperatures drop.
- **Oxygen** and **Water content** are important factors which play a significant role in the reaction process as water ingress and saturation levels are the main driving force of the oxidation as can be seen in Equations 1 & 3, without which the reaction would be able to progress.
- **Permeability,** which links to the oxygen and water content mentioned above. The rate at which oxygen and water reach the reactive zone directly impact the rate at which AMD can be generated. The lower the permeability of the reaction zone the lower the AMD generation rate.

2.3 CURRENT TREATMENT TECHNIQUES

Treatment of AMD is technologically complex, costly and requires a large amount of capital and infrastructure to be implemented and maintained (Hobbs et al. 2009). There are a number of effective treatment techniques, all of which can be broadly characterised as either active or passive.

Active treatments are those treatments which involve ongoing and continual input and often involve some form of electrical and mechanical infrastructure to be implemented such as batch treatment plants that are highly sophisticated and engineered. These plants requires a large degree of maintenance and materials and thus require significant capital to setup and have high running costs [Shabalala (2013) , Skousen et al. (2000)].

Passive treatment techniques are those which can operate with little ongoing maintenance or input over the long term, and often require longer periods of time/processing in order to reach the same level of effectiveness as an active system. These passive systems generally require little or no mechanical or chemical inputs (Jennings & Blicker 2008). Passive systems typically have higher initial costs to set up but have far lower ongoing operational costs. They may represent long-term cost saving and are most often used when full time supervision or chemical/industrial infrastructure are not always viable or needed (Shabalala 2013).

When looked at from the perspective of cost per litre treated, passive methods are more often than not favoured but may have limitations when compared to active methods such as a finite lifespan, and limitations with available space or time required to achieve complete treatment [Durand et al. (2010), Akcil & Koldas (2006)].

Treatment solutions can often be a combination of techniques and include both passive and active treatment such as a high density sludge treatment plant followed by an oxidation pond. This literature review discusses mainly passive treatment techniques, as these are most relevant to the research and solution proposed. [Taylor et al. (2005), Fripp & Ziemkiewicz (2000)].

2.4 MOST COMMONLY AND WIDELY USED PASSIVE TECHNOLOGIES

Wetland treatment is one of the simplest and easiest ways of treating acid mine drainage. This technique involves the construction of a large planted pond system which the AMD is directed through and chemical reactions are allowed to take place at a slow pace as the water progresses through the system. The net effect being that the water leaving the system is of a higher or better quality then when it entered. This treatment method is largely time dependent meaning that it can only treat AMD if the effluent stays in the ponding system for a specific period of time (the longer the better). Wetlands can be sub-divided into two types, aerobic and anaerobic wetlands [Zipper et al. (2011), Skousen et al. (2000)**].** These are discussed separately here.

2.4.1 AEROBIC CONSTRUCTED WETLANDS

Aerobic wetlands are best suited to treating AMD sources that are more alkali or mildly acidic (Zipper & Skousen 2011). This system achieves treatment through allowing oxygen into the AMD, driving the oxidation process and thereby forcing metals such as Fe, Al and Mn to precipitate out. The reaction process lowers the pH through the release of H^+ ions. However the alkalinity buffers the system and allows the oxidation process to continue. These wetlands require shallow waters, 10cm-30cm deep which translates to a large surface area requirement, in order to treat greater volumes of AMD. The areas are planted with aquatic plants such as Cattails (*Typha*). They are often constructed with a membrane or clay lining to prevent contact with the natural environment [Zipper et al. (2011), Taylor et al. (2005)].

Research by Hellier et al. (1994) describing 73 instances of wetland usage to treat AMD has shown that the use of aerobic wetlands yielded favourable results and represents a long term cost saving when the effluent in question is of low acid content. However, for highly acidic seepages other means of treatment such as permeable reactive barrios or lime drains need to be sought which was confirmed by Brodie (1991). The results indicated the effectiveness of aerobic wetlands at lower pH levels and highlighted the need for low flow rates and low turbidity to allow heavy metal settlement. It was also shown that the use of aquatic plants had a positive effect on the treatment ability of the system.

More recent work of Sheridan et al. (2012) showed that utilizing charcoal and slag based constructed wetlands along with aquatic plants can remediate acid mine drainage to a level where 75% of sulfates where removed along with almost all soluble iron over a period of 60 hours.

2.4.2 ANAEROBIC CONSTRUCTED WETLANDS

This system is a modification of an aerobic wetland and incorporates a bed of limestone with a thick layer of organic rich medium to promote bacterial growth. This system creates anaerobic conditions when the AMD permeates through the thick organic layer. Anaerobic constructed wetlands are thus described as a sub-surface treatment method as they require sub surface flow of the AMD (Skoussen et al. 2000). This treatment method is shown in Equations 5.

$$Fe^{2+} + SO_4^{2-} + CH_2O \rightarrow FeS + HCO_3^- \qquad \textit{Equation 5}$$

The non-biological creation of alkalinity is shown in Equation 6.

$$CaCo_3 + H^+ \rightarrow Ca^{2+} + HCO_3^- \qquad \textit{Equation 6}$$

Due to the combined processes outlined in the preceding equations, this treatment method can treat highly acidic AMD because it produces large quantities of alkalinity. This system however requires a large surface area and extended residence time within the ponds for effective treatment with low/slow flow rates [Skousen et al. (2000), Zipper et al. (2011)]. A further issue this treatment method is often faced with, is that armouring of the limestone can occur if the AMD does not pass through sufficient organic material prior to passing through the limestone. Under incorrect conditions, iron precipitates are able to coat the limestone and thus prevent further reaction (this is known as armouring)

Experiments conducted by Sexstone et al. (1993) involving anaerobic wetlands resulted in pH increases to almost neutral levels upon exiting the wetland (pH of 6.5) which was largely attributed to the limestone. The tests were run for a period of four years over which it was observed the systems became less and less effective with metal retention and pH increase due to the system having a finite capacity. This highlights the need for larger areas as smaller setups are less effective and have a shorter lifespan.

According to Ziemkiewicz et al. (2003) these systems can be used to treat 3.5g of acidity/m^2/day but this value will depend on the respective volumes of limestone, flow rate of AMD, as well as the surface area of wetland. Wieder (1992) documented that the performance of wetlands is different depending on the season and age of the wetland. This was attributed to factors such as bacteria activity, loading of the wetland and ability of the aquatic plants to absorb precipitated heavy metals.

From this discussion it is clear that anaerobic wetlands are an effective method of treating both heavy metals and sulfates in AMD but require anaerobic conditions and large surface areas to be effective.

2.4.3 ANOXIC LIMESTONE DRAINS (ALD)

An ALD is a trench that is filled with crushed limestone and covered, which AMD is allowed to flow through for treatment. The acid in the water dissolves the limestone as it passes through the drain which then raises the pH. This method is thus used to treat highly acidic waters. The cell is covered with compacted soil or clay to create anoxic conditions so as to prevent the armouring of the limestone aggregates through iron hydroxides due to Fe^{2+} not precipitating as $Fe(OH)_2$ at a PH less than 6 [Zipper et al. (2011), Skousen (1998)].

As AMD typically contain varying amounts of Fe^{3+} and Al^{3+} in solution which can precipitate as Al and Fe hydroxides, inevitable clogging of the ALD is a major obstacle as well as the possibility of preferential flow paths forming. This means the systems have a finite lifespan for the treatment after which they would need to be replaced or replenished however represent a lower cost solution compared to other techniques.

2.4.4 PERMEABLE REACTIVE BARRIERS (PRBS)

Permeable reactive barriers are created for the protection of subsurface water bodies. They are normally created by the excavation of a trench into which a permeable and reactive substrate is installed which the groundwater can pass through and whilst passing through they remediate the water. They have been successfully used for the remediation of many contaminants, including petroleum (Esperanza et. al (2015)), Caesium (De Pourcq et. al (2015)), Copper and Zinc (Abbas et. al (2015)), volatile organic carbon (VOC) (Mahmoodlu et. al (2015)), nitrogenous compounds (Huang et. al (2015)), mercury (Robles et. al (2015)), landfill leachate (Dan Zhou et. al (2014)) and others (Obiri-Nyarko et. al). For AMD, the successful use of PRBs has been described by Shabalala (2013). The remediation of AMD is achieved in the majority of cases through the use of large quantities of Iron metal and silica sand, with some instances using organic matter to treat nitrate and sulfate depending on the content of the AMD that is being targeted [Powell et al. 1998, Blowes et. al (2000)].

The use of permeable reactive barriers amended with an organic substrate to remove sulfate has also been investigated and applications have been found to be favourable due to the following barrier properties which are controllable (Ludwig et al. 2002):

- Controlled temperatures which do not fluctuate heavily due to being underground;
- Constant, measurable and controlled effluent inflow;
- Controllable residence time through a fixed permeability; and
- Low oxygen influx due to being sub surface.

According to work done by Blowes et al. (2000) the use of solid organic matter such as wood chips, sawdust, compost and leaves have positive effects on sulfate reduction in AMD due to the proliferation of sulfate reducing bacteria which reduce sulfate to sulfide. This in turn leads to the formation of insoluble metal sulfides which is the primary removal mechanism.

One of the most important considerations of using a PRB for treatment is the fact that sulfides have low solubility in anaerobic conditions and thus if oxidation occurred, metals could be released by the barrier (Blowes et al. 2000). This could be detrimental to ecosystems in the downstream flow path and this is a recognised limitation of this technology.

A further disadvantage of the Installation of a PRB, is that it can require a large amount of earthworks and labour for installation (especially when the plume to be treated is at great depth). PRB often require an impermeable structure in order to channel the AMD into the barrier such as a secant pile or continuous slurry walls which carry a significant cost (Powell et. Al 1998).

Examples of full scale remediation given by Powell (1998) include:

- the installation of a sheet pile wall, funnelling AMD into four reactive gates (pea gravel PRB) at a government facility in Lakewood Colorado in 1996;
- the installation of a slurry funnel and reactive gate in Belfast, Northern Ireland in 1995;
- the installation of a continuous 15ft slurry wall at a mine site in Ontario Sudbury also in 1995.

All of these projects demonstrate a large constructive effort to install the techniques, however were able to achieve AMD remediation.

One of the limiting factors according to Taylor et al. (2005) is the finite amount of reactive substrate available and the need for the AMD to have low oxygen content upon entering the system to prevent clogging. The organic substrate is consumed in the treatment process which creates void spaces that are then filled with the metal precipitates - compaction and the filling of these void spaces can lead to reduced porosity and effectiveness of the system.

2.4.5 BIOREACTORS AND (SRB) SULFATE REDUCING BACTERIA

For biologically mediated sulfate remediation, the system will require sulfate reducing bacteria (SRB). The bacteria consume organic forms of carbon (CH_20) under anaerobic conditions to produce $HCO3^-$ which increases alkalinity and pH. This creates an environment where low solubility metals will precipitate out as shown in Equation 7 and 8. In this equation, *Me* represents a dissolved metal in solution such as *Cd, Co, Cu, Fe, Ni, Pb and Ni* [Shabalala (2013) , Ludwig et al. (2002), Younger et al. (2002)]:

$$SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2HCO_3^- \qquad \textit{Equation 7}$$

$$H_2S + Me^{2+} \rightarrow MeS_{(s)} + 2H^+ \qquad \textit{Equation 8}$$

The process is highly dependent on the availability of nutrient for the bacteria, particularly in the form of organic carbon (Sheridan et.al 2013).

Therefore it is necessary for effective long term sustainability, that there is a surplus of organic carbon and controlled temperature environment. Temperature also plays a role with the bacterial activity where they become increasingly more active at higher temperatures and less so at lower temperatures [Akcil & Koldas (2006), Younger et al. (2002)]

Whilst sulfur reduction utilising bacteria has been researched extensively over the past two decades, the use of SRB treatment on a large widespread scale has not as of yet been implemented and has been the subject of sustained research and interest (Rose et al. 1996). It remains thought of as one of the pivotal components of a sustainable passive treatment methodology.

Research done by Golder associates and the University of Cape Town (Hille et al. 2012) has produced a report on passive treatment of AMD through oxidation of sulphides utilising bacteria. Their report highlights the following advantages of utilising SRB bodies to microbiologically convert sulfide into elemental sulphur:

- There is inherently low energy consumption by the system
- There is no requirement for catalysts or oxidants other than air
- No chemical sludge is created in the process that would need to be disposed of
- There is a possibility of reuse of the resulting sulfur created
- There is low sulphate or thiosulfate discharge from the system
- There is little biological sludge produced which can be managed.
- Microbial processes operate at ambient temperatures and atmospheric pressures

Their research gives an example of a system where microbes have been used to remediate AMD through integrated managed passive (IMPI) treatment system, where sulphide oxidation is facilitated by a floating sulphur biofilm (FSB) in a linear flow channel reactor (LFCR). It has been piloted at the Middleburg mine, and laboratory scale testing done at the Golder Associates Research Laboratories (GARL) and University of Cape Town (Hille et al. 2012).

The results indicate that the use of the biofilm achieved near to complete sulphide removal, however the recovery of elemental sulfur was low. Numerous bio reactive configurations were tested prior to the above solution such as membrane and tank reactors.

Some of the disadvantages of SRB usage is the reliance of the reactor on availability of active carbon sources which if not renewed limits the systems lifespan, the growth rate of the SRB population and their inherent population at initiation (some systems require the cultivation of a bacteria population at their setup which increases the start-up costs) [Younger et. al].

Another example of an engineered solution to AMD treatment utilising SRB is the Water research commission's patented Rhodes BioSURE process which utilises a Falling Sludge Bed Reactor (FSBR), an Anaerobic Baffle Reactor (ABR), an Up-flow Anaerobic Sludge Blanket Reactor (UASBR), and High Rate Algal Ponds (HRAP) in a complex setup with mechanical pumping in the form of a treatment plant.at the No 3 shaft at the Grootvlei Gold Mine in South Africa (Rose 2013).

The above pilot tests give an indication of the wide spread research, complexity and application of biological remediation and its importance in sustainable AMD remediation.

2.4.6 USE OF CONCRETE IN AMD TREATMENT

Concrete can be described as man-made rock: we are able to mould and manipulate it to create vast structures by changing its make-up and composition to suit our needs. Concrete usually consists of three basic materials, water, aggregates (usually a mix of fine and larger crushed rock particles in a controlled ratio), and Portland cement. Cement is manufactured from a lime and calcium based product such as lime, chalk or shells (klinker is used for Portland cement) and consists mainly of Calcium Silicate (Ca_3SiO_5), Calcium Aluminoferrite (Ca_4AlFeO_7), and Calcium Aluminate ($Ca_3Al_2O_4$). The cement acts as the bonding agent to hold aggregates together and is activated when water is added through a process known as hydration. Hydration is the process whereby the calcium silicates react with water to form calcium silicate hydrate, calcium hydroxide and heat (it is the release of the calcium hydroxides that raise the pH of cement to around 12). The crystalline structures created bind the aggregates together and the reaction speed (or curing time) is controlled by temperature and availability of water molecules to drive the reaction. The manipulation of the above process through the addition of pozzolanic materials (such as fly ash, blast furnace slag), various additives and aggregates has been the area of vast study and experimentation to create concretes that react and behave differently to suit a wide spread of applications. Some examples are sulfate resistant concretes (CEM-V), rapid hardening concretes, self-compacting concretes and many more.

Thus for this research, it was proposed that the design and use of a pre-determined concrete mix created to be permeable so as to allow effluent to pass through it at a controlled rate coupled with lime based cement and a thick anaerobic organic layer be tested. This solution however should consist of readily available materials so as to be viable for the targeted use of rural communities.

The use of concrete in the treatment of AMD has not been extensively tested. There has been some experimental work done by Ekolu (2013) with generic concrete, where it was shown that removal of iron in the order of 95-99% was achieved through a single pass through concrete cubes along with high effectiveness in the removal of other metals and approximately 30% sulfate removal.

2.5 RESEARCH OBJECTIVES

The background presented here indicates that there is significant potential for the use of PRBs combined with Concrete and Biological treatment to remediate AMD plumes, especially as a temporary measure as most of the drawbacks are long term problems.

However, the technology has not been used much for the above mentioned application, and this resulted in the formation of the following research objectives:

1. To determine if porous concrete could be used as the basis of the PRB;
2. To assess at least seven different types of organic substrates' ability to remediate sulfate on an artificial AMD;
3. To determine the appropriate mix of organic substrate/substrata to be used in conjunction with the concrete barrier;
4. To determine the short to medium-term performance of an optimised set of conditions.
5. To determine the rate of sulfate removal after the system has reached equilibrium; and
6. To determine if the technology could be applied as a low-cost solution for the in-situ remediation of AMD.

It was anticipated that it would be possible to achieve removal of sulfates (minimum 50% after a two week period and complete sulfate removal after an eight week period) through a low cost filtration process using only materials such as manure, leaf compost, sawdust etc. combined with permeable concrete barriers. The materials were chosen so as to be readily available to most small mining/rural communities whilst still being inexpensive and compatible with the permeable concrete.

The filtration device would attempt to encompass as many of the positive attributes of larger more costly AMD treatment processes and methods whilst remaining as simple and easy to create as possible.

CHAPTER 3

RESEARCH METHODOLOGY

CHAPTER 3 RESEARCH METHODOLOGY

This chapter outlines the research statement and methodology/ testing procedures that will be followed including construction setup and sampling methods. It also addresses the various kinds of organic mediums that are to be used in the experiment along with the batching information for the permeable concrete.

3.1 RESEARCH STATEMENT

This research explicitly seeks to assess the potential use of permeable reactive concrete barriers, combined with an organic substrate to remediate AMD contaminated groundwater while remaining cost effective, at least as a short-term solution.

There are six research objectives which were considered for this research as listed in section 2.5 and the following methodology was formulated to achieve those objectives:

3.2 RESEARCH METHODOLOGY

3.2.1 DETERMINING THE OPTIMUM ORGANIC SUBSTRATE

The organic substrate should satisfy the following criteria to be successful in the PRB:

- The organic material would need to be free of any fertilizers or sulfate generating minerals and materials, and should not contain any harmful chemicals or substances that could create or pose a risk to the environment, property or people;
- The organic substrate would need to be readily available (and in suitable quantities) to the rural communities and be easily transportable;
- The substrate should be inexpensive or have the ability to be “self-made” at the locations that are adversely affected by AMD; and
- The organic material must have inherent SRB population and the ability to sustain and proliferate this population. Culturing of bacteria would not be considered practical for rural communities and would add to the cost and complexity of the filtration system.

Based on these criteria, seven organic substrates were considered for further testing. The seven substrates were as follows: chicken manure, sawdust, straw, zoo manure, leaf compost, wood chips, and cow manure.

3.2.2 OBTAINING AMD FOR THE EXPERIMENTS

AMD was sourced from one of the coal mines in Mpumalanga for the testing of the organic substrates and was chosen as it had extremely high sulfate content. This would give a realistic representation of how the selected organic medium and permeable concrete would perform when exposed to a real world example of AMD.

Unfortunately a limited supply of the Mpumalanga coal mine AMD was given for this research topic and as such an artificial AMD had to be created for the long term testing procedures.

Since heavy metals were expected to be removed by the concrete in a real PRB, the artificial AMD was rich in sulfate only. It was prepared by adding 97% sulfuric acid to deionised water to a concertation of 8000ppm of sulfate. Following this, the pH was raised to 3.1 through the addition of 50% sodium hydroxide (analytically pure reagent from Merck). This allowed the creation of a high sulfate, AMD without any heavy metals (or other metals except sodium which remains soluble throughout the experiment.

The Sodium was not expected to have any effect on the results. Iron was excluded from the laboratory trials since it was decided that in a natural system, iron would not be present in the organic layers since it would have precipitated in the porous concrete layers.

3.2.3 PERMEABLE CONCRETE BATCHING

Concrete cubes and cylinders were batched using no-fines concrete and 9.5mm dolerite aggregates. Dolerite aggregates were used instead of limestone due to their hardness and resistance to acidity which is expected to increase the lifespan of the concrete in AMD remediation. Based on initial research conducted by Ekolu (2013), the cement created sufficient alkalinity that AMD passing through it was no longer acidic and also was free of dissolved iron. Typical ranges for pervious concrete mix design proportions are given in Table 1:

Table 1 : Pervious concrete mix design

Material	Typical range of Values
Portland Cement	267 - 388 kg/m^3
Coarse Aggregate	1190-1480kg/m^3
Fine Aggregate	0-297kg/m^3
Water/Cement Ratio	0.27-0.36

For this study, the water to cement ratio for batching was 0.3 with a Portland cement content of 325kg/m^3 thus requiring 88 litres of water and 1500kg/m^3 of coarse aggregate (9.5mm dolerite). Fines were omitted from the mix design so as to create sufficient void space between the coarse aggregate. This would allow increased reactive surface area and permeability. The design was chosen to allow maximum permeability and hence flow of the AMD through the cube whilst still maintaining concrete workability and strength.

3.2.4 EXPERIMENTAL CONSIDERATIONS

The experimental procedures were conducted in two phases each of which are discussed fully in the next two Sections of this thesis. The first phase of testing (PHASE 1) focused on finding the substrate which could achieve the objectives listed in Section 2.5 from the seven biological media. An initial test was run to determine if the systems showed any remediation after two weeks. Following this, tests were run for a period of 3 weeks (21 days) as after this period it would be clear if the setups were achieving their objectives.

The second phase (PHASE 2) of testing was focused on medium to long-term performance of the filtration system, over a 3-6 month period utilising the most suitable biological medium as determined in the phase one testing. For Phase 2, three experiments were conducted.

Two replicates were set up with each having the same mixtures of organic substrate and identical concrete cubes. The third rig contained only concrete cubes. This provided a control and also indicated the effect of the concrete on the remedial capacity of the PRB.

3.2.5 PHASE 1 FINDING THE CORRECT SUBSTRATE

The experimental rigs were constructed from Perspex sheets and were glued together and sealed to form rectangles with internal dimensions of 105mm in order to accommodate a standard 100x100x100mm concrete cube. The rig had a length of 500mm in order to allow for sufficient space between the two concrete cubes for a composting layer of 200mm.

The rigs were placed vertically to allow the AMD to percolate through the filter under gravitational force. The base plate and midpoint of the filter were constructed with a 5mm hole drilled into them which was fitted with a nozzle and tap system to allow samples to be taken during filtration in order to sample as fluid passes through the rig as can be seen in Figure 2.

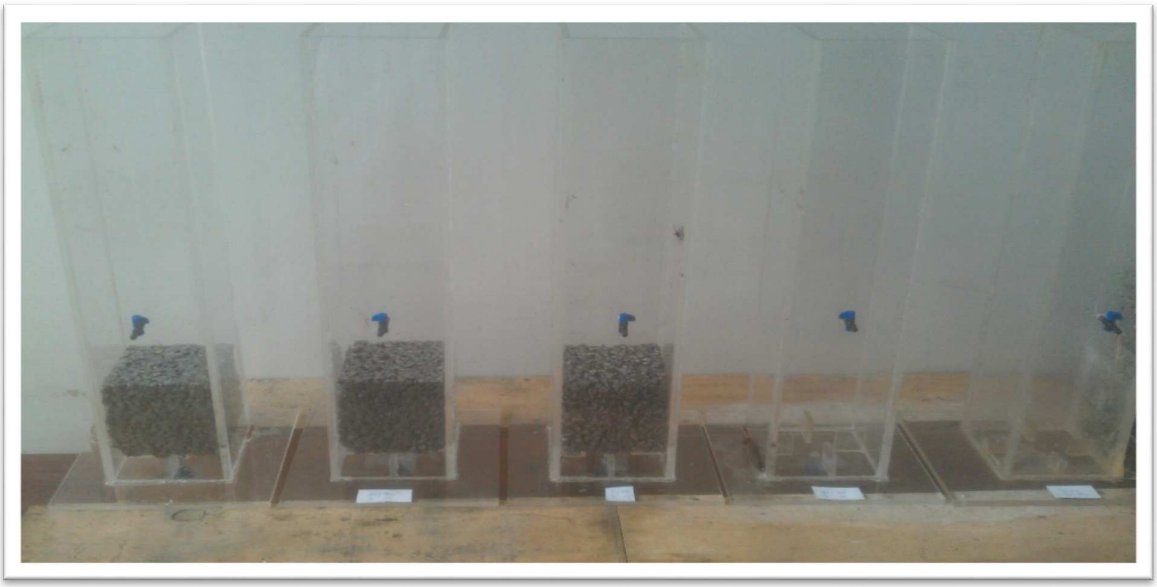


Figure 1: Short term Perspex testing rigs post construction

Cubes for the Phase 1 testing were cast in 100mm cubes in a standard sized concrete mould and layers no thicker than 30mm were placed and compacted a minimum of 25 times with a hand help tamper before adding further layers of concrete - repeating the process until the mould was full. The cylindrical shaped test setups needed a custom mould of 110mm and were created out of PVC piping with the same compaction process followed during casting.

Once the cubes and cylinders had been cast they were covered immediately with plastic wrapping to prevent any moisture loss for 24 hours. Thereafter they were submerged and allow to cure for 28days before commencement of AMD testing.

For Phase 1, the initial organic layers were prepared from various substrates in different ratios. The layers tested consisted of leaf compost, wood chips, sawdust, cow manure, chicken manure, garden compost, soil and zoo manure, elephant dung and straw.

These are shown in Table 2 (Phase 1). Those experiments with organic substrates that were less effective were terminated and the favourable ones continued. These substrates and mixing ratios are also shown in Table 2 (Phase 2).

Table 2: Substrates and Mixing ratios used in the experiment

Phase 1	
Substances	**Mixing Ratios**
Cow Manure : Sawdust	100 : 0
Cow Manure : Sawdust	80 : 20
Cow Manure : Sawdust	20 : 80
Cow Manure : Sawdust	0 : 100
Chicken Manure : Sawdust	100 : 0
Chicken Manure : Sawdust	80 : 20
Zoo Manure : Straw	100 : 0
Zoo Manure : Straw	20 : 80
Leaf Compost : Wood Chips	100 : 0
Leaf Compost : Wood Chips	20 : 80
Elephant Dung : Straw	80 : 20
Cow Manure : Sawdust	50 : 50
Concrete Cubes only	-
Phase 2	
Kraal Manure : Sawdust	20 : 80
Concrete Cubes only	-

Once the AMD had been added to the top of the rig, it was sealed to prevent any evaporation during the experiment and to induce anaerobic conditions. The experiments were run over a period of 2-3 weeks with samples taken at 3, 7, 10, 14 and finally at 21 days.

Following from the Phase 1 screening, Phase 2 experiments were conducted using a flowing feed of AMD. For these experiments, a drip system was used to pass AMD continuously through the filter and outlet concentrations were monitored with time.



Figure 2: Short term test rigs in operation. F.l.t.r Sawdust : Cow manure: 50:50; 80:20; 0:100; 20:80

3.2.6 PHASE 2 "ACTIVE" FILTER CONSTRUCTION

Long term experiments were conducted similarly, but the test rigs were constructed from 110mm cylindrical PVC piping which is more robust than Perspex. The concrete was cast directly into cylindrical moulds made from the PVC piping and where vibrated to achieve adequate compaction and permeability. The long term rigs had sample ports at the discharge. The rigs are shown in Figure 3.



Figure 3 : Long term test rigs post construction. F.l.t.r : Manure : Sawdust 80:20; 80:20; Permeable concrete only

Filters will be installed below ground level directly in the plume of an AMD outflow in practice, and as such will have no direct sunlight interference and thus Perspex was not used for these setups. Sunlight seemed to promote some algal growth in some of the short term tests cylinders and so was avoided in the long term setups.

Figure 4 gives an indication of the three long term setups in operation, with the outflows of each cylinder feeding into a lined waste bin.

The figure also shows how the kraal manure discolours the AMD when passing through the cylinders as opposed to the far right setup which contains only permeable concrete cubes.



Figure 4: Long term rigs in operation with lined waste bin. F.l.t.r : Manure : Sawdust 80:20; 80:20; Permeable concrete only

3.3 SAMPLING AND ANALYTICAL TECHNIQUES

During Phase 1, samples were taken from the top, centre and bottom of the rigs. During Phase 2, samples were only taken from the discharge out let only. Samples were collected using pipettes in aliquots of 50 mL. The samples were immediately cooled and then frozen within 2 hours to inhibit any addition DSR activity. The samples were stored in a deep freeze at -18℃ until sufficient samples had been collected. Samples were then thawed followed by immediate analysis in the laboratory.

The samples were tested for sulfate concentration using two methods. For Phase 1, the sulfate was assessed using barium chloride as per the test methodology stipulated in the sulfate testing method IS: 3025 (Part 24) - Reaffirmed 2003 and ASTM D516 methods.

For this method, prepared sulfate solutions of know concentration are reacted with a small quantity of $BaCl_2$. The Ba forms an insoluble $BaSO_4$ precipitate which can be measured using spectrophotometric tests. The data for the calibration curves is shown in Table 3.

Table 3: Calibration curve data for sulfate analysis

Sulfate content (ppm)	Absorption
0	0.056
10	0.161
20	0.239
30	0.316
40	0.351

For Phase 2, the samples were assayed in the School of Chemical and Metallurgical Engineering Biochemical Engineering laboratory. This laboratory uses a Merck Pharo 300 Spectroquant and Merck Spectroquant test kits and hence sulfate was analysed differently for this experiment. The method for sulfate analysis is explicitly described by Merck Millipore, Spectroquant reagent test kit: Cat No. 100617, order no. 1.00617.0001 HS code 3822 00 00.

CHAPTER 4

RESULTS AND DISCUSSION

CHAPTER 4 RESULTS AND DISCUSSION

This chapter present the findings and results from the experiments and also includes a discussion of the results. The results are presented chronologically, i.e. from the initial organic screening to the long-term experiments. A list of all experiments undertaken is given in Table 2. The research was conducted through the observational method whereby the results from the testing dictated the way forward and testing evolved as more data became available.

4.1 AMD USED FOR TESTING

Three different AMD's were used during the research. One donated from an anonymous coal mine in Mpumalanga (TDDB), one from the Witwatersrand gold mines (WZ), and an artificial AMD created for the phase two long term testing.

The TDDB had the following properties as determined from sample analysis conducted by Water Lab South Africa and confirmed by the authors through laboratory testing at the University of Witwatersrand:

- Sulfate content 1st batch : 7400 mg/l
- Sulfate content 2nd batch : 8200-8400 mg/l
- pH : 3.1
- Total dissolved solids : 12.56 mS/mm

Only a small drum of AMD from the Witwatersrand mining belt (WZ) was available for testing. It was found to contain a far lower sulfate content (in the order of 3300 ppm) and a PH of 2.3 as well as high quantities of heavy metals. This was used to quantify the ability of the permeable concrete to remove heavy metals

The artificial AMD created for phase two testing was made with 8000 ppm of sulfate and a pH of 3 as discussed in chapter 3.

4.2 PHASE ONE EXPERIMENTS

As described, this experiment was conducted in Perspex cylinder pilot rigs which contained an organic substrate consisting of leaves, soil, compost, and wood chips along with two concrete cubes on either end. The initial screening experiment ran for a period of fourteen days and the remediation of sulfates was found to be in the order of 27%. It was therefore concluded that the system could affect some remediation and the experiment was continued.

This screening experiment is shown in Figure 5.



Figure 5: Pilot test rig exhibiting large degree of evaporation. Sawdust 50% and manure 50%

After the pilot test was completed, two additional Perspex cylinders were constructed and the testing of different substrates began.

4.2.1 MANURE AND ORGANIC MATERIALS TESTING

Zoo manure was placed in one reactor, pure sawdust and wood shavings in a second reactor and kraal manure in a third reactor. Each of the reactors had a permeable concrete cube placed at their top and bottom. The three reactors were filled with 3 litres of TDDB AMD and sealed at the top to prevent evaporation. Sulfate testing was conducted after a period of 14 days to determine their effectiveness at sulfate remediation

Table 4 gives an indication of the concentration, pH, and overall sulfate removal of the three materials:

Table 4: Pilot stage biological medium testing results

Reactor substrate	Initial sulfate concentration (ppm)	Final sulfate concentration (ppm)	Initial pH	Final pH	Percentage change in sulfate
Kraal Manure	7400	3432	3.1	6.3	-53.49%
Sawdust and Wood chips	7400	3597	3.1	8.4	-51.25%
Zoo Manure	7400	5172	3.1	7.3	-30.11%

The results show greater sulfate removal by the kraal manure and the sawdust than that of the zoo manure. For this reason, experiments were conducted blending sawdust in different ratios with kraal manure as well as zoo manure.

4.2.2 Batch testing of Kraal Manure

Table 5 outlines the mix ratios and the resulting removal efficiencies. A test cylinder was also run containing only concrete cubes as a control to understand the contribution to sulfate removal by the concrete blocks alone. And acid only control was also employed (i.e. acid with no SRB and no concrete). The tests were once again done over a period of 21 days with samples taken from the top, middle and bottom of the cylinders and the data presented in Table 5 indicative of the average of the three values.

Table 5 : Batch testing results for Kraal manure after 21 days (feed concentration of 7400ppm)

Mixture (%Sawdust / %Manure)	*Resulting ppm*	*Percentage change in sulfate content*
50/50	4440	-39.85%
100/0	3600	-51.25%
0/100	3432	-53.49%
80/20	3201	-56.62%
20/80	4188	-43.25%
Concrete cubes only	6176	-24.83%
TDDB AMD	7400	00.00 %

These results show that the permeable concrete was responsible for 25% of the sulfate removal which correlates well with the work conducted by Ekolu et al (2013). The most favourable mix ratio was the 80% sawdust to 20% manure mix which yielded a sulfate reduction of 57% over the test period. The 50/50 split yielded only around 40% sulfate removal which was less than the pure sawdust mix. This was unexpected and the cause is unknown.

The reason for the performance differences between the mixes is possibly a result of a number of different mechanisms: adsorption to the sawdust, growth of the SRB, utilisation of the organic feed by the SRB etc.

Based on these results the 80/20 mix would be specified as the optimum design criterion. However, pure manure and pure sawdust also have high removal efficiencies and thus they could also be used on their own.

One of the observations during the testing was that the concrete cubes had significant build up and scaling on them. This is attributed to the pH driven precipitation of metal oxides from the AMD as it passed through the concrete cubes. This in time could cause clogging of the filter and is a known limitation of this technology (indeed it is a common cause of failure in many lime based treatments where complete encrustation can occur and render the system redundant (Cravotta et al. 2002, Sasowsky et al. 2000). Scaling, however, only occurred where the concrete cubes were exposed to oxygen and anaerobic conditions were not maintained and thus it is not believed to be a significant drawback. The photographs in Figure 6 show the precipitation on the concrete surface.



*Figure 6 : Precipitate build up on permeable concrete cubes. *The cube on the left experienced exposure to the atmosphere when AMD levels dropped lower than the cubes surface while the cubes on the right remained submerged and show significantly less precipitate. The precipitate is indicated by the brown discoloration*

4.2.3 Batch testing of Zoo Manure

Following the strong performance of the kraal manure with the addition of sawdust; and the similarity in expected SRB population between the zoo and kraal manure due to the nature of their origin; it was hypothesized that the zoo manure could have better performance when mixed with sawdust.

Therefore a second confirmation test was executed in order to check the zoo manures behaviour when combined with sawdust. The same 80%/20% split by volume was used.

The results are summarized in Table 6. Similar to the leaf mulch the addition of sawdust in fact was counterproductive to sulfate reduction with the zoo manure and this negative effect is attributed to a smaller population of active SRB and the inability of the population to proliferate to significant levels within the organic medium in the time frame tested.

Table 6: Summary of test results for Zoo Manure mixed with 80% Sawdust after 21 days (feed concentration of 8400ppm)

Mixture (%Sawdust / %Manure)	*Resulting ppm*	*Percentage change in sulfate content*
0/100	3908	-53.34%
80/20	6800	-18.80%
Concrete cubes only	6176	-26.27%
TDDB AMD	8400	0.00

4.2.4 Batch testing of chicken manure

Chicken compost was sourced from a chicken hatchery in Pretoria and was expected to be a good substrate as it is often mixed with soil, straw and grass resulting from the cleaning of the chicken pens. It is normally taken from the pens, left in the sun for a number of days before packaging and it is then sold as compost. The ratios for testing are shown in together with the results in Table 7.

Table 7 : Batch testing results for chicken manure after 10 days (feed concentration of 8400ppm)

Mixture (%Sawdust / %Manure)	*Resulting ppm*	*Percentage change in sulfate content*
0/100	9298	+11.00%
80/20	8533	+1.87%
TDDB AMD	8400	0.00

Following the first 10 days of chicken manure testing the experiment was stopped as sulfate levels were increasing. The increase in sulfate content is attributed to this compost having fertilisers added to it as it is a commercial product. As a test to confirm if the chicken manure could still be a viable option the addition of 10% (by mass) of powdered lime was added to the mixtures in order to neutralize the fertilizers and a second test was run for a period of 14 days.

Table 8 : Batch testing results for chicken manure with lime (feed concentration of 8200ppm)

Mixture (%Sawdust / %Manure / %Lime)	*Resulting ppm*	*Percentage change in sulfate content*
7 days results		
70/20/10	5895	-29.64%
80/10/10	6507	-22.33%
10 day results		
70/20/10	6536	-21.98%
80/10/10	7150	-14.65%
14 day results		
70/20/10	7762	-7.34%
80/10/10	7780	-7.13%

Surprisingly there was little difference between the two cylinders ability to treat the AMD and this is attributed to the added lime creating a high pH environment where precipitation is limited to soluble ions at a pH of 9-12 as well as creating an environment that is not conducive to SRB population proliferation. The overall trend was unfavourable with the sulfate content slowly creeping up again with the initial reduction attributed to absorption within the permeable concrete and sawdust. It was thus concluded that the chicken manure was not a suitable organic medium for the process based on this data. However, if it is possible to source chicken manure and cage sweepings without any added fertiliser, it may be possible that this could be used however for large scale treatment it may be problematic to source in large quantities in rural communities.

4.2.5 Batch testing of Leaf compost (leaf mulch)

The leaf mulch used for this experiment was obtained from the Johannesburg Zoo. It would have contained some small quantity of animal manure as this is caught up with it when it is raked. The mulch used for testing had been left to compost for approximately 4 months before sampling for testing. The ratios of mulch to sawdust and the remedial effects are shown in Table 9.

Table 9 : Batch testing results for leaf compost (feed concentration of 8200ppm)

Mixture (%Sawdust / % Leaf Compost)	*Resulting ppm*	*Percentage change in sulfate content*
7 day results		
80/20	5930	-27.8%
0/100	5980	-27.23%
14 day results		
80/20	7436	-9.5%
0/100	6684	-18.66%
21 day results		
80/20	7185	-12.56%
0/100	5851	-28.79%

These results show a repaid decline in sulfate followed by a rebound. The decline is attributed to the concrete removing sulfate followed by the initial stages of DSR.

The experiment with leaf mulch only showed higher sulfate removal than the experiment with a mixture of mulch and sawdust – this is attributed to the degradation of the cellulosic structure during composting which makes it available to the SRB. This effect confirms the findings of Magowo et al (2015).

The leaf mulch experiment demonstrated a reduction in sulfate of approximately 29% after a period of 21 days. This is not as effective as the manure substrates at sulfate reduction and the leaf mulch is not considered the best option for long term testing. An observation however found during testing was the concentration of sulfate at the top and bottom of the cylinder was consistently higher than in the middle. This is a clear indication of the microbial activity occurring within the organic medium while the permeable concrete is acting as a reactive filter by retaining the sulfates.

4.2.6 Batch testing of concrete control

In order to determine what proportion of the sulfate removal could be attributed to the concrete cubes alone, a control experiment was conducted. A cylinder was filled with 4 permeable concrete cubes without any organic substrate and the cylinder was then filled with AMD and sealed. The results in Table 10 indicate the same initial rapid removal of sulfates but with a significantly higher sulfate rebound. The final sulfate concentration was found to be approximately 25% after 14 days. The reason for the behaviour is not well understood and could be the subject of future investigation.

Table 10 : Control test of permeable concrete only (feed concentration of 8200ppm)

Concrete cubes only	*Resulting ppm*	*Percentage change in sulfate content*
7 day	2879	-64.96%
14 day	6189	-24.67%
21 day	6176	-24.83%

Following on from this trial, an experiment with continuous AMD flowing through the concrete cubes was conducted. The effluent leaving the cylinder was tested at regular intervals over a two week period.

The results of the experiment are summarized in Table 11. Similarly, the outlet of the reactors have approximately 75% to 80% of the starting sulfate concertation over a 14 day lifespan. This indicates that the concrete will contribute a maximum of 25% of the remediation within a new PRB. This is highly advantageous as it allows the PRB to treat AMD whilst the SRB are establishing and growing.

Table 11: Summary of results for continuous flow (feed of 8200 ppm)

Permeable concrete cube with AMD cycled through it	Absorption	Concentration	Dilution	Resulting PPM	Percentage change in sulfate
3rd day	0.2384	25.43	250	6358	-22.5%
4th day	0.2279	23.736	250	5934	-27.6%
5th day	0.2333	24.596	250	6149	-25.0%
6th day	0.2451	26.541	250	6635	-19.1%
7th day	0.2447	26.34	250	6585	-19.7%
14th day	0.2468	25.27	250	6318	-23.0%

The pH of samples was checked during testing and it was found that the concrete cubes were effective at raising the pH of the AMD from 3 to an average of 7.68 across all experiments. The reactor containing only permeable concrete cubes and no organic substrate had a pH of 11 after a 21 day period indicative of the exceptional increase in pH the lime based cement has.

4.3 SUMMARY OF PHASE ONE RESULTS

The results of Phase 1 are graphically summarised in Figure 7. The results presented are an average of the three samples taken from the top, middle and bottom of each of the filters.

The short term data indicates that a mixture of kraal manure with sawdust in the proportions 80% sawdust to: 20% manure had the most significant remedial effect. The manure sourced from the Johannesburg zoo also had a significant effect on sulfate removal but is hard to come by and in short supply especially in rural areas. There is also concern for its long term effectiveness due to the limited carbon based cellulose which would be the food source in order for the SRB population to thrive over an extended period of time. The Chicken manure and mixture of zoo leaf compost with sawdust had the least effect.

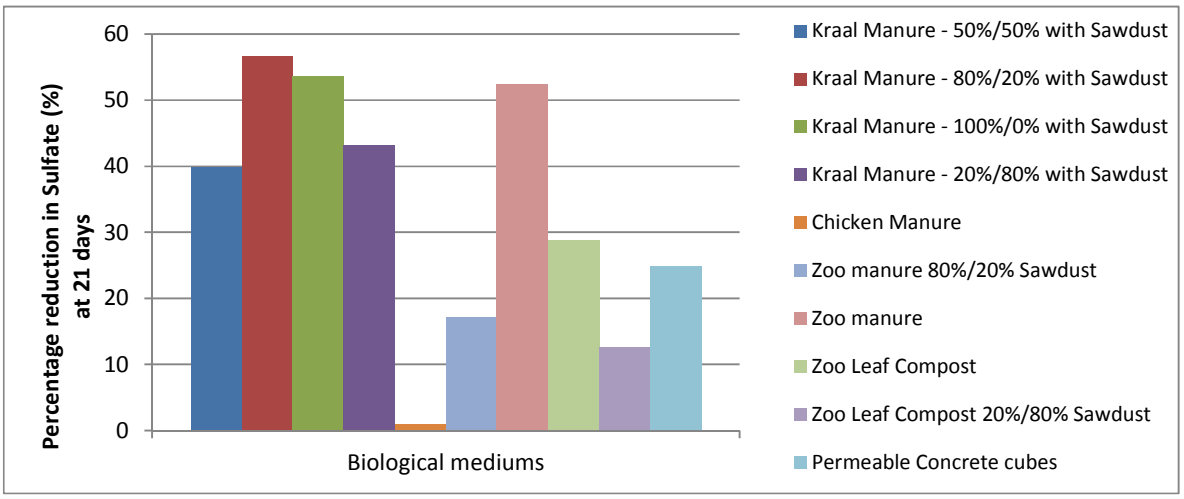


Figure 7 : Sulfate removal after 21 days for different substrates

A summary of the effect of reaction time on the removal of sulfate for 5 selected feed stocks is presented in Figure 8. Similarly to the data shown in Figure 7, kraal and zoo manure were the fastest removers of sulfate with chicken manure having almost no effect after 7 days. The sharp initial drop in sulfate concentration at the start of all the experiments (shown as the difference between AMD and the series) is attributed to the absorption of sulfates into the permeable concrete cubes and organic materials. This effect, however, is short-lived as the filter quickly becomes saturated and sulfate concentrations rise before DSR begins.

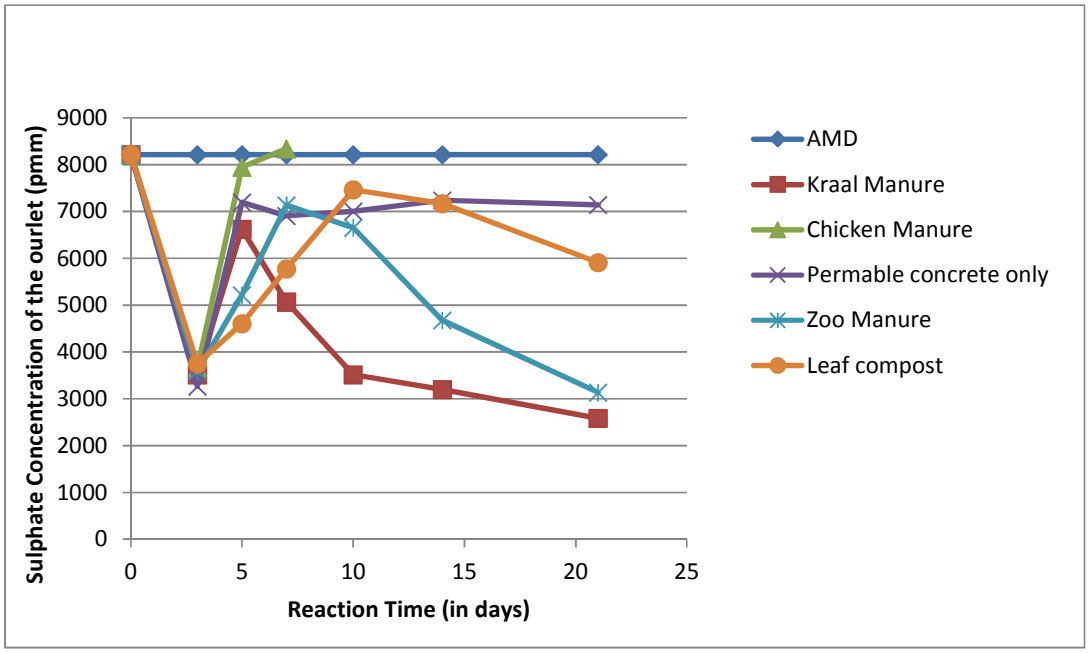


Figure 8: Effect of reaction time on sulfate removal for all feed stocks

The kraal manure was shown to be the most effective of the different substrates selected for testing for sulfate removal. This is highly desirable as kraal manure is found across Africa and is therefore a readily available feedstock for the implementation of PRBs, especially in rural/isolated locations.

4.4 PHASE TWO TESTING

Three long term reactors were created in order to determine if the filters would be able to reduce the sulfate concentrations in the passing AMD to zero; and if so after what period of time. This data would allow the designer to anticipate the lifespan of the PRBs as well as the frequency of replacing the organic substrate.

Two identical rigs were created with 80% sawdust and 20% manure and they were closed with permeable reactive concrete blocks at the top and bottom. A third rig was setup with only concrete cubes at the top and bottom as a control and also to assess the long-term clogging of the concrete.

Artificial AMD was created for this experiment as a large volume was needed in order to permanently pass AMD through all three filters for the entire duration of the testing which was a period of 6 months. The rigs were gravity fed at maximum flow. This equated to approximately 15mL/hour (which equates to a flux of 1.91 litre/m^2/hour). Each cylinder was filled with AMD with the bottom value closed in order to ensure no air was present in the system and that anaerobic conditions were achieved and thereafter the valves opened. The three test setups were fed through a drip system from a single 50 litre drum which contained the artificial AMD and throughout the testing was continuously topped up in order to maintain the drip rate.

The results of the long term experiments are presented in Figure 9**.** Rig A and Rig B are the duplicates.

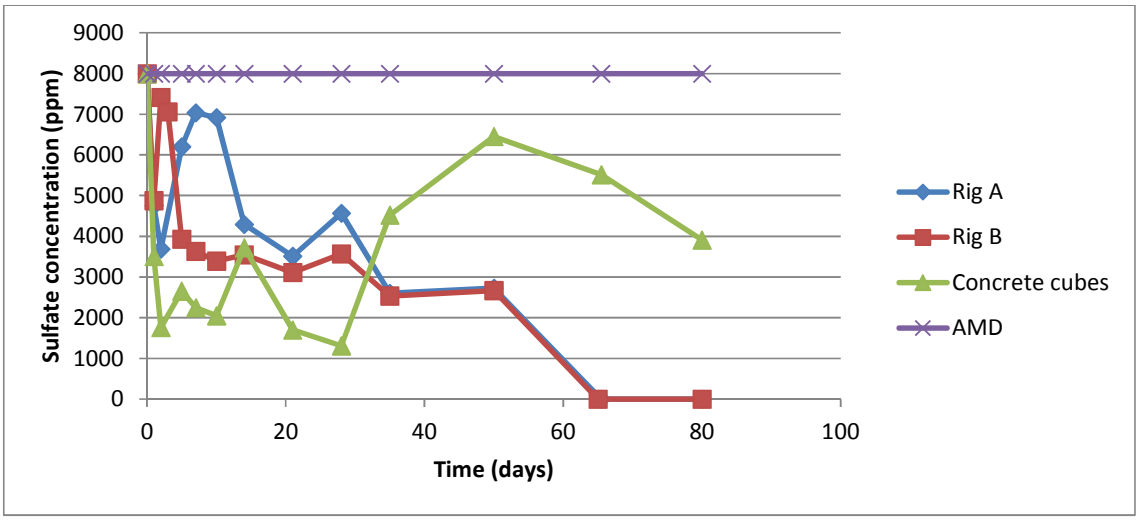


Figure 9 : Sulfate reduction over 80 days for manure and sawdust based PRBs.

The results show the same initial drop in sulfate at the start of the testing as a result of the concrete reacting with the AMD followed by rebound. However, with increasing time there was an increase in the sulfate concentration of the AMD leaving the concrete cubes. Conversely, with increasing time the duplicates showed a decrease in the sulfate concentration such that by 65 days there was no sulfate left. This would imply that the system would be fully functional by 65 days.

Both Rig A and Rig B show a slight decrease in effective reductions at the 28 day mark and this is thought to be the repercussion of a cold front that was experienced in the week leading up to the 28 day sample and this could have had a negative impact on the SRB activities due to the reduced temperature in the cylinders.

4.5 DISCUSSION OF THE RESULTS

From the phase one results of the research, it is concluded that kraal manure was the most effective and readily available of the organic feed stocks, and when coupled with permeable concrete as well as sawdust/wood chips is able to remediate sulfates in a relatively short time frame (favourable results in 2-3 weeks) while raising the pH to neutral (6.5-7.2).

Similar results were shown by the long term testing with the research showing the PRBs achieving 100% sulfate remediation after 65 days and maintaining this level for a period of at least 80 days with no signs of performance drop off. The system is expected to have a finite lifespan influenced by two factors: the fixed amount of organic carbon within the rig (which when depleted will prevent further SRB activity), and the permeable concrete will inevitably become blocked. The timeframe for these two events have not been determined in this study, however the filters have managed to effect remediation for a period of at least 3 months which is sufficient evidence of the potential for a short term remedial solution to rural communities.

CHAPTER 5

CONCLUSIONS AND FURTHER STUDY

CHAPTER 5 CONCLUSIONS

Referring back to the research objectives set out for this research report, the following findings are most relevant:

1. *To determine if porous concrete could be used as the basis of the PRB;*

The filter was able to successfully raise the pH to 8 while removing a significant portion of heavy metals indicative that porous concrete is a viable and in fact good basis for the PRB as it not only increases alkalinity and removes heavy metals, but additionally provides support and robustness to the reactor and allows freedom of shape and construction as concrete is fluid and malleable allowing freedom of construction.

2. *To assess at least seven different types of organic substrates' ability to remediate sulfate on an artificial AMD;*

The short term testing results yielded removal of sulfates in the order of 56% when using kraal manure as the biological reagent mixed with sawdust for added organic carbon.

3. *To determine the appropriate mix of organic substrate/substrata to be used in conjunction with the concrete barrier;*

The mix percentages by volume were found to be 80% Sawdust to 20% manure and this setup was able to achieve 56% removal of sulfates within 14 days.

4. *To determine the short to medium-term performance of an optimised set of conditions.*

The long term tests showed complete (100%) remediation of sulfates after a period of approximately sixty days.

5. *To determine the rate of sulfate removal after the system has reached equilibrium;*

The Flux of the system was calculated at 1.91 litre/m^2/hour thus showing that the small laboratory scale tests were able to achieve complete sulfate remediation after a period of approximately 60 days at the above mentioned flow rate.

6. *To determine if the technology could be applied as a low-cost solution for the in-situ remediation of AMD :*

The system was demonstrated to be a practicable real-world solution for the temporary amelioration of AMD where it was able to remove all sulfate content from an AMD source. The outer concrete walls would trap (through the processes of precipitation) many metals, especially the divalent or trivalent ones (which include most heavy metals) and the inner organic substrate would effectively remove much of the sulfate. Thus, the AMD passing through the system would be of significantly better quality than if left untreated and the technology offers promise towards temporarily shielding sensitive receptors from an uncontrolled plume of AMD.

The costs of the materials needed to construct these filters is significantly lower than other current passive solutions, and thus the filter system shows great promise as a low cost temporary solution to communities such as those like Maguqa township and others in Johannesburg where AMD might present a risk. The technology could also be used to protect shallow abstraction wells if they are located near a shallow aquifer which has been impacted by AMD.

Permanent long term solutions in South Africa, more often than not require enormous capital outlay and infrastructure from government or mining bodies that may take a number of years to be implemented. The hope is that the proposed filter system would be able to offer some short term relief to heavily affected receptors, especially in poor and/or rural communities.

5.1 LIMITATIONS

Some of the limitations of the research are that it was conducted in laboratory small scale systems only and does not as of yet quantify the effects of scaling or external environmental impacts such as fluctuating weather and temperature conditions and it was noted that during a particularly cold period the performance of the system was adversely impacted.

A second limitation is the timeframe over which the experiment were run. Due to the short time frame for experimentation the results only give an indication of the time to become effective at remediation, and thus the timeframe over which it would remain effective is still unknown.

5.2 FURTHER STUDY

While the filters show significant promise as a short term solution due to their ability to completely remove sulfate and their cost effectiveness along with ease of construction. The finite lifespan of the system needs to be determined in further studies. This would allow a cost benefit analysis to be done to further determine the filters viability to communities.

A second concern, which has not been addressed in this research report, is the impact on the environment or level of water contamination that the kraal manure could possibly have if implemented on a large scale.

Due to the large volumes of kraal manure needed for pilot or full scale installations, along with the resulting heavy discoloration of passing fluids, there may be some harmful contagions or E.coli that are released into the plume. This would need to be investigated and quantified in further studies to ensure the filters safety for use in rural communities.

CHAPTER 6

REFERENCES

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CHAPTER 7

APPENDICES

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Appendix A: Peer reviewed conference paper.

A summary of the work was accepted for Oral presentation at the 2015 ICARD IMWA held in Santiago, Chile on 21 April 2015. The paper was double – blind peer reviewed and was published in the proceedings under ISBN 978-956-9393-27-3. The paper can be accessed online at: https://www.imwa.info/imwa-meetings/proceedings/293-proceedings-2015.html.

A copy of this paper is presented below

Permeable concrete with bio-reactive layers to target heavy metals and sulfates in Acid Mine Drainage

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ABSTRACT

The aim of this research is to reduce heavy metal and sulfate content of acid mine drainage (AMD) through the methods of passive filtration by combining permeable concrete and organic materials to achieve a low cost, yet effective temporary treatment method for rural/poor communities who are affected by AMD. The acids are filtered through layers of alternating pervious concrete and biological composting layers. The concrete layers target removal of heavy metals such as iron, manganese, potassium, magnesium, etc. through precipitation as well as reduce sulfate content to a small degree along with total dissolved solids. The concrete layers aid in raising the pH of the AMD to more acceptable levels. The biological layers achieve sulfate reduction through the metabolism of sulfate-reducing- bacteria (SRB) - this process however will require time and the organic layer thus will be thicker and less permeable than the concrete layers in order to allow seepage to take place at a reduced rate. A wide variation of composting layers were tested including cow manure, chicken manure, sawdust, straw, zoo manure, leaf compost, grass cuttings and river mud to find an optimum mix of materials which allows for the greatest sulfate reduction through SRB's. Long-term testing and effectiveness of the rigs will be undertaken to establish limitations and lifespan of the filtration system. AMD from the Witwatersrand gold fields and Mpumalanga coal fields with exceptionally high sulfate content were used to test effectiveness of the organic materials over a short period of time with long term testing being conducted with a synthetic AMD due to limited supply of the reagent. The short term testing yielded reductions of sulfates in the region of 56% when using kraal manure as the biological reagent mixed with sawdust for added organic carbon. The filter also successfully raised the pH to 8 while removing a significant portion of heavy metals. The results show promise for using the technology as a low cost, temporary measure to protect locally impacted groundwater, especially for isolated and/or rural communities.

Keywords: AMD, SRB, permeable concrete, remediation

INTRODUCTION

Acid Mine Drainage (AMD) is the name given to outflows of water that contain high levels of acidity and heavy metals due to the reaction and oxidation of geological layers which consist of sulfide containing minerals, especially pyrite(FeS_2). The amount and rate at which AMD is generated is a function of the rock mineralogy and degree of exposure/presence of oxygen and water. The sulfides in the rock oxidise when in contact with these substances to create a highly acidic, sulfate rich mixture with characteristically low pH and often a high content of heavy metals in soluble form.

This acid generating phenomenon is a naturally occurring process resulting from the weathering and erosion of sulfide carrying minerals in exposed rocks weathering on hills and valleys or through ground water seepage. This however creates AMD at a slow rate due to the relatively small exposed surface area; and in the case of ground water seepage the lack of excess oxygen; therefore allowing the surrounding alkaline rocks to neutralise the AMD, and water bodies to dilute it sufficiently before it has a chance to significantly impact the environment (Durand, Meeuvis, & Fourie, 2010).

Mining activities however; such as deep pit excavation, crushing, quarrying, mine waste rock pilling, tailings and tunnelling; result in massive volumes of rock being exposed, which when weathered creates excessive amounts of acid mine drainage. This AMD has greatly adverse effects on the environment, its biodiversity, as well as long-term damage to waterways, aquifers and ultimately our drinking water (Coetzee et. al, 2010). AMD can also cause damage to structures such as culverts and bridge abutments exposed to waterways that have a high concentration of AMD as the high acidity and sulfate levels have an accelerated corrosion effect on steel reinforcing (Gurdeep, 2006). More importantly, AMD carries a health risk to human settlements, especially those of the mining communities often living in low cost, slum/squatter camp type environments adjacent or nearby mine dumps/tailings. Some of the Heavy metals contained in AMD can be extremely harmful if consumed in elevated consecrations and in some cases AMD has been found to be carcinogenic.

Extent of the problem in South Africa

AMD is an extensive problem with coal and gold mining, as marcasite and pyrite (or "fools gold" as it is often known) is highly prevalent in the mine wastes and surrounding mineralogy. South Africa has notably large deposits of these sulfur rich natural resources. The AMD problem faced by the mines in Johannesburg is being further accentuated with the gold mining operations ceasing and mines not being maintained after closure. This is resulting in uncontrolled amounts of AMD welling up inside the mine voids left from deep excavations as the ground water level is no longer being drawn down and controlled to allow for mining along the reef. To put things into perspective , the potential volume of AMD produced by the Witwatersrand Goldfields alone amounts to an approximated 350ML/day which is around 10% of the daily supply of potable water by Rand Water according to Hobbs et al (2009).

There is huge concern regarding the state of the water level at the central basin in Witwatersrand as ground water with high concentrations of AMD has been rising at an average rate of 0.59 metres per day (m/d) since July 2009 which translates to approximately 15m/month (Akcil and Koldas, 2006).

If this rising water level is not treated and controlled it would threaten to flood the low lying tourist areas of the mine at Gold Reef City and of more consequence, pollute and compromise the shallow ground water resources along with causing damage to the dolomitic strata. This will ultimately affect the dolomites ability to sustain loadings in the southeast part of Johannesburg according to Coetzee et al. (2010). One of the largest concerns of AMD is the accelerated karstification of dolomite (which is soluble in acid) resulting in potentially large sinkholes and soil subsidence coupled with the consequential contamination of aquifers and decanting into waterways. This ultimately pollutes and impacts all types of biodiversity including with time our drinking water. This same threat is faced by the cradle of humankind in Krugersdorp and is of huge concern as the structural stability of the

surrounding areas are in question threatening the heritage site and the artefacts contained within its soil as the dolomitic aquifers carry more and more highly acidic AMD into the area (Durand et al. 2010).

According to Case studies done by Hochmann et al. (2010) on coal mining in South Africa, an account of the mining community living at the Maguqa township near an open cast coal mine in the Brugspruit valley was given, where AMD carrying toxic heavy metals is flowing into the Brugspruit stream and from there into the Olifant's river system. The children of the township play soccer on the flat white surfaces of sulfate salt precipitates left by the AMD, oblivious to the potential health risks. Therefore there is a need for a rapid temporary solution which has the potential to reduce the risk to such impacted communities whilst a long term solution is sought.

Treating AMD

Treatment of AMD is complex, costly and requires a fairly large amount of capital and infrastructure to be put in place for the treatment methods to be implemented (Hobbs et al., 2009). There are a number of effective treatment techniques, all of which can be broadly characterised as either active or passive. Active treatments are those treatments which involve ongoing and continual input and often involve electrical and mechanical implementations that are highly sophisticated and engineered which make use of chemical dosing or similar techniques to ensure the remediation of the contaminated water [Shabalala (2013) , Skousen et al. (2000)]. Passive treatment techniques are those which can operate with little to no input over the long term and often require longer periods of time/processing in order to reach the same level of effectiveness as an active system and don't often involve chemicals or mechanical equipment (Jennings and Blicker 2008). Some of the more commonly used passive methods are discussed further below.

Anaerobic wetlands

This system is a modification of an aerobic wetland and incorporates a bed of limestone with a thick layer of organic rich medium above it to promote bacterial growth. This system creates anaerobic conditions when the AMD permeates through the organic material due to microbial activity leading to high oxygen demand. It is thus described as a sub-surface treatment method as it requires sub surface flow of the AMD to be effective unlike the aerobic wetlands where the AMD can flow along the surface. This system can thus treat highly acidic AMD through the dissolution of the fluid due to a limestone layer. This system however requires a large surface area and extended residence time within the ponds for effective treatment with low/slow flow rates [Skousen et al. (2000), Zipper et al. (2011)].

Experiments conducted by Sexstone et al. (1993) involving anaerobic wetland setups resulted in good pH reduction resulting in almost neutral levels upon exiting the wetland (pH of 6.5) which was largely attributed to the limestone. The tests were run for a period of four years over which it was observed the systems became less and less effective with metal retention and pH reduction due to the system having a finite capacity and thus highlight the need for larger areas as smaller setups are less effective and have a shorter life span than respectively larger setups. Wieder (1992) documented that the performance of wetlands are different depending on the season and age of the wetland which was attributed to factors such as bacteria activity, current loading of the wetland and ability of the aquatic plants to absorb precipitated heavy metals.

Permeable reactive barriers (PRBs)

Permeable reactive barriers are essentially a permeable obstruction placed typically below surface which intersects the AMD plume as it flows along with ground water and treats the influent as it passes through the barrier. The treatment is achieved in the majority of cases through the use of Iron metal and silica sand, with some instances using organic matter to treat nitrate and sulfates depending on the AMD that is to be treated (Powell et. al, 1998). According to work done by Blowes et al. (2000) the use

of solid organic matter such as wood chips, sawdust, compost and leaves have positive effects on sulfate reduction in AMD due to the proliferation of sulfate reducing bacteria which reduce sulfate to sulfide which in turn leads to the formation of insoluble metal sulfides. However one of the most important considerations of using a PRB for treatment is the fact that sulfides have low solubility in anaerobic conditions and thus if oxidation occurred metals could be released by the barrier (Blowes et al., 2000). Another drawback is the Installation of a PRB is quite costly as often impermeable structures are constructed to channel the AMD to the Barrier and these can be quite large and long such as a slurry piled wall.

One of the limiting factors according to Taylor et al. (2005) is the finite amount of reactive substrate available and the need for the AMD to have low oxygen content upon entering the system to prevent clogging. The organic substrate is consumed in the treatment process which creates void spaces that are then filled with the metal precipitates - compaction and the filling of these void spaces can lead to reduced porosity and effectiveness of the system.

Bioreactors and (SRB) Sulfate reducing bacteria

Most passive treatments that target AMD with a high sulfate content will make use of sulfate reducing bacteria (SRB). The bacteria consume organic forms of carbon (CH_20) under anaerobic conditions to produce bicarbonate; which promotes neutralization of the AMD; and H_2S which creates an environment where low solubility metals will precipitate out as shown in the Equation 1 [Shabalala (2013), Younger et al. (2002)]:

$$SO_4^{2-} + 2CH_2O \rightarrow H_2S + HCO_3^- \quad (1)$$

This process is highly dependent on the availability of an organic feedstock for the bacteria to proliferate and become increasingly effective. Temperature also plays a role with the bacterial activity where they become increasingly more active at higher temperatures and less so at lower temperatures [Akcil & Koldas (2006), Younger et al. (2002)].

Bioreactors essentially create a concentrated carbon rich environment where these SRBs can thrive and proliferate in order to effectively remove sulfates and heavy metals of fluids that pass through them. Bioreactors are commonly used with most sludge and waste water treatment facilities. The problem with some bioreactors arises where they become inundated with metal precipitations and lose their effectiveness. Replenishment of the carbon source is sometimes needed and removal of the heavy metal rich sludge can be costly and expensive to dispose of.

Use of Concrete in AMD treatment

The use of concrete in the treatment of AMD has not been extensively tested and its use in conjunction with biological layers is novel. There has been some experimental work done by Ekolu et al. (2013) with concrete in the removal of heavy metals, where it was shown that removal of iron content in the order of 95-99% was achieved through a single pass through a concrete cube. It was also found to have effectiveness in reduction of other such heavy metals and approximately 30% removal of sulfate content. It is also expected that the lime within the Portland cement will react to increase the pH of the AMD solution. Permeable concrete is most effective for the purposes of the research presented here as it will allow AMD fluids to pass through the cube while retaining heavy metals within its macro porous structure. The concrete cube will have a finite life much like the Alkali Limestone Drains solutions due to armouring and preferential flow paths forming through the cube.

METHODOLOGY

Filters were constructed out of permeable concrete and organic material in an attempt to combine the benefits of anaerobic wetland conditions, permeable reactive barriers, along with the benefits of heavy metal reducing concrete to achieve a low cost yet effective remediation system aimed at the local communities such as those in Johannesburg that are hard hit by rapidly proliferating AMD. Two phases of testing were undertaken. The first phase was aimed at finding a suitable medium for SRB proliferation and tests were conducted over a 2-3 week period to determine effectiveness of the biological layers. Once an effective medium was found, phase one testing was stopped and a long term filtration system was setup for phase 2. These long term setups have a drip system to pass AMD through them continuously and sulfate reduction levels will be monitored over time for a period of 3-6 months in order to gauge/quantify the effectiveness and ability to perform over the short to medium term. These phase 2 experiments are currently underway and are ongoing.

Permeable concrete

Concrete cubes and cylinders for the filters were batched using Sure build Afrisam 42,5 PPC cement, no fines and 9.5mm dolerite aggregates. Dolerite aggregates were chosen due to their hardness and resistance to acidity which is expected to increase the lifespan of the concrete in AMD remediation. Research conducted by Ekolu et al. (2013) showed that greater sulfate reduction was obtained with dolerites as opposed to granite and limestone. The mix design proportions used for the research are given in the table below:

Table 1 Mix design proportions

Material	**Quantities Used**
Portland Cement	325 kg/m^3
Fine Aggregates	0 kg/m^3
Coarse Aggregate (9.5mm aggregates)	1500kg/m^3
Water/Cement Ratio	0.3

These values are based on the need for greater permeability to allow movement of the AMD through the concrete while still maintaining workability and ease of placement along with maintaining suitable concrete strength. Once the concrete had been cast it was immediately covered to prevent any moisture loss and allowed to set for 24 hours. Thereafter casts were submerged and allowed to cure for 28 days as per standard cement curing processes.

Filtration systems

Filters for the first phase were constructed out of Perspex sheets and were rectangular with an internal dimension of 105mm in order to accommodate a standard 100x100x100mm concrete cube and have a length of 450mm in order to allow for sufficient space for two concrete cubes and a 200mm thick composting layer in between them. The experimental rigs were placed vertically and AMD was passed through the filter under gravitational force. The base plate as well as the midpoint of the filter has a nozzle to allow samples to be taken during filtration. An example of the phase one setup can be seen in Figure 1.



Figure 1: Short term experimental rigs in operation

An AMD taken from coal mine tailings in Mpumalanga with exceptionally high sulfate content (8200ppm) was used to test the effectiveness of the phase one setups. The composting layers used were varied in order to ascertain an effective medium which maximized SRB population growth and activity while not adding any adverse chemicals or metals to the system. The layers tested consisted of leaf compost, wood chips, kraal manure, chicken manure, zoo manure, elephant dung, sawdust and straw. Combinations of the above along with additions of lime were also tested once an effective medium had been established.

Samples and testing

For the short term experiments samples were taken at 3, 7, 10, 14 and finally at 21 days. These preliminary phase 1 tests were stopped after 21 days as results were showing trend lines of favourable (or otherwise) at this point. Samples were extracted from the bottom, midpoint as well as the top of the filter during phase 1 testing. The samples were tested for sulfate concentration through the use of barium chloride, standard solutions and a spectrograph as per the test methodology stipulated in the sulfate testing methods IS:3025 (Part 24) - Reaffirmed 2003 and ASTM D516 methods.

RESULTS AND DISCUSSION

The results presented are an average of the three samples taken from the top, middle and bottom of the filters. The pH of the samples was checked and it was found that the concrete cubes were very effective at raising the pH of the AMD from 3 to an average of 7.68. The test setup with only permeable concrete cubes in them had a pH of 11 after 21 days.

In Figure 2, the data presented indicates that a mixture of kraal manure with sawdust in the proportions 80%:20% had the most significant remedial effect (a kraal is a South African word for an enclosure normally used to house cattle). The manure sourced from the Johannesburg zoo also had a significant effect on sulfate removal but is hard to come by and in short supply. Chicken manure and a mixture of zoo leaf compost with sawdust had the least effect.

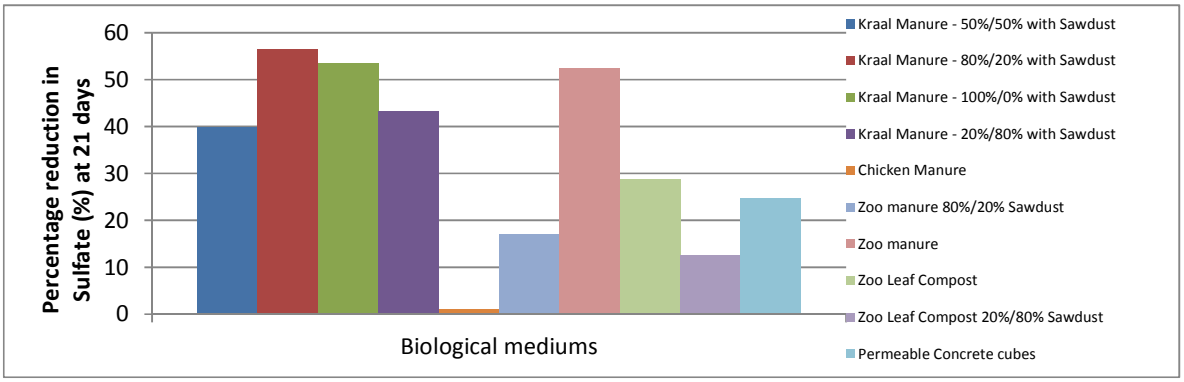


Figure 2: Sulfate removal after 21 days of operation for different organic feedstocks

The effect of residence time on the removal of sulfate for 5 selected scenarios is presented in Figure 3. Similarly to the data shown in Figure 2, kraal and zoo manure were the fastest removers of AMD with chicken manure having almost no effect after 7 days. This could be as a result of the ruminant bacteria which would occur in cattle, elephant, buffalo, and other herbivorous animal dung (which would not be present in the chicken manure). The sharp initial drop in sulfate concentration at the start of the experiment (shown as the difference between AMD and the series) is attributed to the absorption of sulfates into the permeable concrete and organic materials. This effect, however, is short lived as the filter quickly becomes saturated and sulfate concentrations rise before DSR (Dissimilatory sulphite reductase) begins.

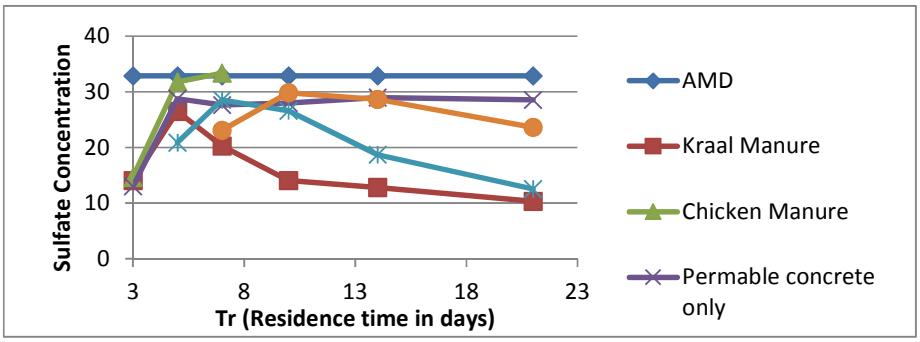


Figure 3.Effect of residence time on sulfate reduction

The permeable concrete cubes were able to reduce sulfates by 25% which is regarded as significant, as well as being effective at raising the pH of the passing AMD. The kraal manure was selected as the best performer and candidate for long term testing due to is ease of sourcing across Southern Africa, especially within the rural mining communities and areas, and is considered the best biological medium for the filters. As can be seen the organic medium typically becomes more effective at sulfate removal with time which correlates to the proliferation of SRBs and the curves typically represent a steady growth rate resulting in accelerated sulfate removal with time. The permeable concrete setups also show the initial drop in sulfates but show steady reduction of approximately 25% throughout the testing cycle which correlates well with the sulphate reductions found by Ekolu et al. (2013) in their experiments.

CONCLUSION

From the results of the research it is concluded that kraal manure is the most effective and readily available on a large scale of the organic feedstocks and when coupled with permeable concrete is able to effectively remove sulfates in a relatively short time frame (favourable results in 2-3 weeks) while raising the pH to almost neutral. The costs of the materials needed to construct these filters is significantly lower than other current passive solutions, and thus the filter system shows great promise as a low cost temporary solution to communities such as those like Maguqa township and others in Johannesburg where AMD is proliferating at high rates.

Due to the promise shown by the research over the short term it will be test further to ascertain the ability of the system to provide favourable remediation over longer periods, while quantifying limitations, capacities and performance of the filter system. The authors have already commenced with this long term testing, and it is ongoing.

Permanent long term solutions in South Africa more often than not require enormous capital outlay and infrastructure from government or mining bodies, and may take a number of years to be implemented. The hope is that the proposed filter system would be able to offer some short term relief to heavily affected receptors, especially in poor and/or rural communities.

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