The Evaluation of a Pilot Pervious Concrete Treatment System for Acid Mine Drainage Treatment

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Abstract

The high costs involved in Acid Mine Drainage (AMD) remediation have led to a search for low-cost liming alternatives. A pervious concrete (PERVC) reactive barrier system was designed and evaluated for the remediation of AMD at an abandoned coal mine site. The results showed that following treatment with PERVC, the pH increased from 2.6 to 12. Al, Fe, Zn, Ni, Co, Cu, and Mn were effectively removed from the mine water with efficiency levels of 97% to 100%. PERVC offers alternative technology for polluted mine waters that can be marketed to the mining industry for full-scale implementation.

Keywords: Acid mine drainage, contaminant removal, low-cost technology, pervious concrete, pilot study

Introduction

The United Nations recently recognized AMD as the second most critical global issue after climate change, emphasizing the severity of this environmental challenge (Daraz *et al.*, 2023). The primary indicator of AMD contamination in surface water bodies is low pH and high sulfate and metal loading (Kefeni *et al.*, 2015). Most existing AMD treatment regimens make use of active treatment methods. However, these are expensive, generate large amounts of toxic sludge, require a continuous supply of chemicals and substantial energy for production (Seervi *et al.*, 2017; Turingan *et al.*, 2022). Consequently, while addressing AMD, active treatment methods introduce new pollution, rendering them highly unsustainable for environmental management (Yang *et al.*, 2023). Therefore, greater emphasis should be placed on finding the most effective, cost-efficient, and simple methods for successfully treating AMD.

Recent approaches emphasize the use of raw or natural materials to treat AMD, a strategy that is expected to promote greener and more sustainable treatment solutions, such as the use of porous pavements. Porous pavements or pervious concrete (PERVC) have demonstrated high efficiency in the containment of runoff and the reduction of stormwater accumulation in urban areas. They have also been shown to be good pollution sinks owing to their high particle retention capacity. Since porous pavement has minimal environmental impact, the US Environmental Protection Agency (EPA) has endorsed its use for water purification (Lee *et al.*, 2022). PERVC, which is a mixture of granite stone or gravel, cement, little to no sand, and water, has been shown to be highly effective in filtering out metallic micro-pollutants from runoff water. Correctly built PERVC may effectively treat polluted or acidic water by eliminating most of the undesired impurities such as sulfate, Fe, Zn, salt, Mg, Mn, and most other metals, in addition to raising the pH value (Shabalala *et al.*, 2017; Dash and Kar, 2018; Shabalala and Ekolu, 2019). While PERVC has proven to be an effective solution for AMD in controlled laboratory settings, its efficacy in field-scale or pilot studies remains unexplored. The aim of the study was to design and evaluate the application of a PERVC permeable barrier system for the remediation of AMD at an abandoned coal mine site. Furthermore, the study aimed to show that PERVC can effectively treat polluted mine water to meet the national limits applicable to wastewater discharge into a water resource.

Methods

Materials and sample preparation

The concrete mixture was prepared using Ordinary Portland Cement (CEM I 52.5R), 9.5 mm granite aggregates, and Ground granulated blast furnace slag (GGBS). The commercially available South African Portland cement (52.5 R) and GGBS (50 kg) products were purchased from Pretoria Portland Cement Company and AfriSam Ltd, respectively. Before use, the Portland cement and GGBS were milled and sieved until the maximum particle diameter was <90 µm. To achieve optimum porosity, a water-to-cement ratio of 0.27 was used for all mixes. The dry ingredients were mixed for one minute in a 400 L concrete mixer, then water was gradually added and mixed for another minute. Chryso Fluid Premia 310 superplasticizer was added for workability.

Pervious concrete reactive barrier design and installation

A pilot study to evaluate the potential application of PERVC-PRB for the remediation of acid mine drainage was installed at an abandoned coal mine site at Emalahleni, a town located in Mpumalanga, South Africa. The pilot plant consisted of a pre-treatment zone (PTZ) overlying a PERVC reactive barrier zone, as shown in Fig. 1. The dimensions of the PTZ were 7m long, 0.6 m wide, and 0.5m deep. From the PTZ compartment, the AMD seeped into the pervious concrete reactive barrier, which was 7 m long, 1.8 m wide, and 1 m deep. The AMD delivery system consisted of one elevated 2000L tank connected to a pipe system through which the acidic mine water was continuously injected into the gravel layer at a flow rate of 50 ml/min, ultimately through the pervious concrete reactive zone. The performance of the PERVC system was monitored for 180 days. The system was completely passive as all flows relied on gravity, with no need for pumps or electrical components. This also added to the ease of maintenance of the plant.

Analytical methods

The raw and treated AMD samples were analysed for Al, Fe, Zn, Mn, Na, Mg, K, Ca, Mn, Fe, Co, Ni, and Cu using the Perkin Elmer SCIEX (Concord, Ontario, Canada) ELAN 6000 inductively coupled plasma mass spectrometer to accuracy of 0.01 mg/L. The concentration of sulfate was determined using ion chromatography, Dionex QIC-IC (Thermo Fisher Scientific, Massachusetts, USA). Measurement of pH, electrical conductivity and total dissolved solids was conducted using the MP-103 microprocessor-based pH/mV/Temp tester. The mineralogical, and microstructural properties of pervious concrete before and after coming into contact with the AMD were determined using the Pan Analytical X-ray X'pert PRO PW3830 diffractometer (Malvern Panalytical Ltd., Malvern, UK) and the Scanning Electron Microscopy (SEM) coupled with Electron Dispersion Spectroscopy (EDS), TESCAN VEGA3SEM with AZtec EDS (Tescan Orsay Holding, Brno, Czech Republic). Mine tailings and product solids were oven-dried at 50 °C for 24 hours before characterization. Portland cement and pervious concrete samples (0.08 g each) were vacuum-dried, carbon-coated for 30 minutes, and mounted on carbon tape affixed to an aluminum stub for SEM-EDS analysis.

Results and Discussion

The pH of the raw AMD was 2.6, while its composition showed high concentrations of Fe (199 mg/L), Al (73 mg/L), Mn (17 mg/L), and SO_4 (1124 mg/L). Fig. 2a presents the pH results of treated AMD water samples versus time. Upon contact with pervious concrete, the pH value of the untreated AMD increased rapidly from 2.6 and reached a pH value of 11.72 within 24 hours. The pH of the treated mine water remained high throughout the 180 days of treatment being reported. The neutralising capacity of PERVC is attributed to the large quantity of portlandite phase which adds alkalinity to the solution. (Song

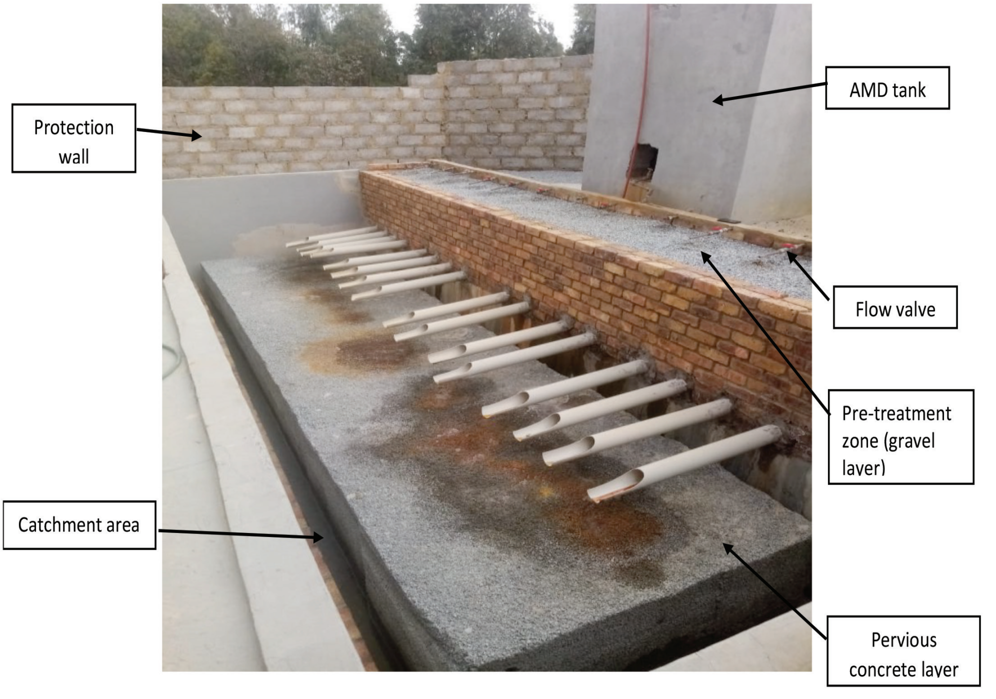

***Figure 1** Pervious concrete reactive barrier system.*

et al., 2021). Fig. 2b gives the change in concentration of Al, Fe and Mn in the mine water after treatment with pervious concrete. Most of the Al, Fe and Mn contained in the AMD precipitated rapidly out of solution due to the formation of Al $(OH)_3$, $Fe(OH)_3$ and $Mn(OH)_2$, respectively. Aluminium in mine water was reduced from 73 mg/l to 0.112 mg/L. The iron concentration in acidic water decreased from 199 mg/l to 0.051 mg/L, which is below the national limits applicable to the discharge of wastewater into a water resource (NWA, 1999). The Fe (III) in AMD may form iron (III) hydroxide ($Fe(OH)_3$) and Hematite (Fe_2O_3) during the treatment, which results in iron removal. Mn was reduced from 17 mg/L to below the detection limit (<0.025 mg/L). Cu, Co, and Ni concentrations in raw AMD were generally low and decreased to undetectable levels after pervious concrete treatment (Fig. 2c). The concentrations of Al, Fe, Mn, Zn, Cu, Co, and Ni decreased as the pH of the solution increased. Precipitation of metal hydroxides and oxides may explain the observed reductions in concentrations of these contaminants. Ni, Cu, and Zn may have precipitated as $Ni(OH)_2$, $Cu(OH)_2$, and $Zn(OH)_2$, respectively. The removal of cobalt is probably due to its adsorption / co-precipitation upon or with iron and aluminium hydroxides and hydrosulfate. At pH values between 8 and 9, Ni is adsorbed onto calcite in solution (Kefeni *et al.*, 2015). An increase in Cu, Co, Ni, and Zn concentrations is observed after day 60 of the experiment. This may be attributed to the seasonal transition from a wet summer to dry winter months, which are characterised by reduced water flow and decreased metal dilution, potentially leading to higher pollutant concentrations. However, the concentration of these metals remained below detection for the 180 days of treatment being reported. After 180 days of running the treatment plant, the concentration of SO_4 had been reduced from 1124 mg/L to 339 mg/L (Fig. 2d). This was possibly caused by the release of calcium ions due to the dissolution of portlandite in concrete, which was then followed by the formation of gypsum ($CaSO_4.2H_2O$). At pH above 3.75, gypsum precipitates out of solution, which results in the removal of sulfate from the acidic water (Chatla *et al.*, 2023). The high neutralising ability of pervious concrete resulted in 69.8% removal of the sulfate content in the raw AMD. Laboratory column studies have indicated that the PERVC barrier has about twice the lifespan of the commonly used ZVI barrier. The minimum expected lifespan of the PERVC treatment system is 10 years (Ekolu & Katadi, 2018).

Removal efficiency

At day 180, pervious concrete effectively removed Al, Fe, Zn, Ni, Co, Cu and Mn with efficiency levels of 97% to 100%. It is clear from Table 1 that the major metals present in AMD were completely removed or reduced to negligible concentrations following treatment with pervious concrete. The concentrations of these metals remained low or below detection during the 180 days of the treatment with PERVC.

Characterization of the pervious concrete before and after exposure to the AMD

The XRD analysis of reacted pervious concrete shows a massive formation of gypsum and close mixtures of gypsum, sodium sulfate and iron oxide (Fig. 3a). These inter-mixtures seem to be metal precipitate complexes from AMD, possibly adsorbed by gypsum. The microstructural feature of concrete after exposure to AMD is seen in Fig. 3b and 3c, and it indicates the presence of an intermixture of alkali metals such as Na, Al, K, Mg, Ca and Si. These observations show that the precipitation of metals with an increase in pH, along with their possible adsorption onto calcium silicate hydrate, are the main mechanisms for metal removal by pervious concrete.

Conclusions

After 180 days of treatment of the AMD with pervious concrete, the levels of Al, Fe, Mn, Co, Cu, Ni, Co, Cu and SO_4 were reduced to limits below the NWA criteria for discharge of wastewater into the environment. The metal removal efficiency levels for Al, Fe, Mn, Zn, Cu, Co and Ni were 99.9%, 99.9%, 99.0%, 97.5%, 97.1%, and 98.2%, respectively, while 69.8% of SO_4 was removed. These findings indicate that pervious concrete technology is effective in treating mine water. However, the pH levels of the treated mine water exceeded the maximum permissible range of 5.5 to 9.0 for

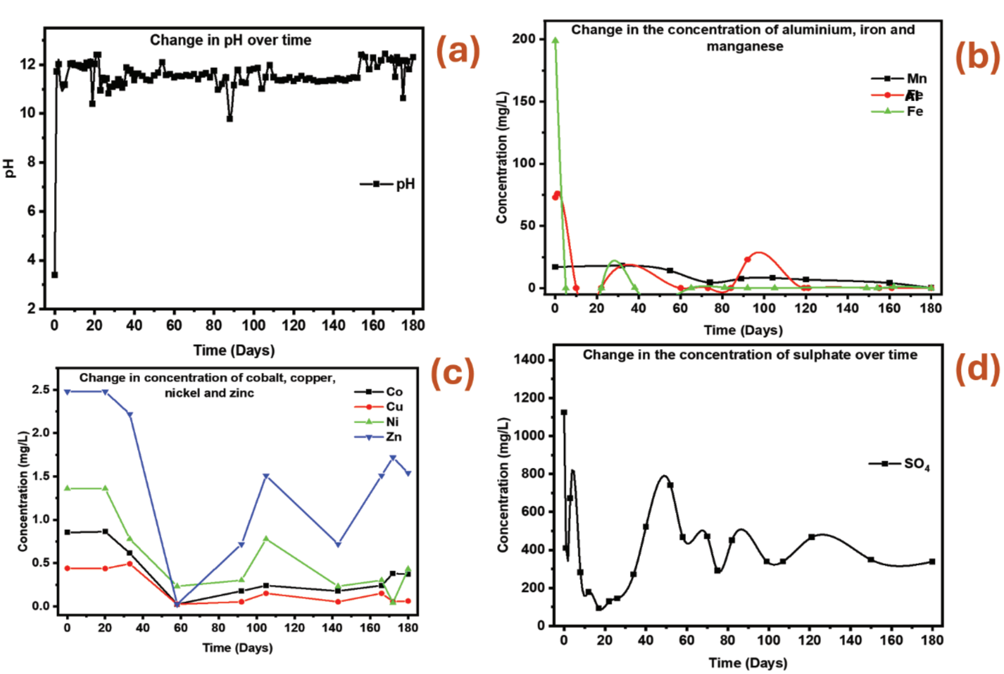

Figure 2 *Change in the pH and the concentrations of Mn, Al, Fe, Co, Cu, Ni, Zn and SO_4 with time.*

Table 1 Contaminant removal efficiency levels of pervious concrete.

	Contaminant Removal Efficiency							
Day	Al (%)	Fe (%)	Mn (%)	SO_4 (%)	Ni (%)	Co (%)	Cu (%)	Zn (%)
33	50.7	99.5	17.7	-10.9	42.8	28.0	-11.8	10.5
105	68.5	99.9	68.2	63.5	42.8	72.0	65.9	39.1
143	69.9	99.9	89.4	54.1	82.9	79.3	88.0	71.1
180	99.9	99.9	99.9	69.8	98.2	97.1	97.5	99.0

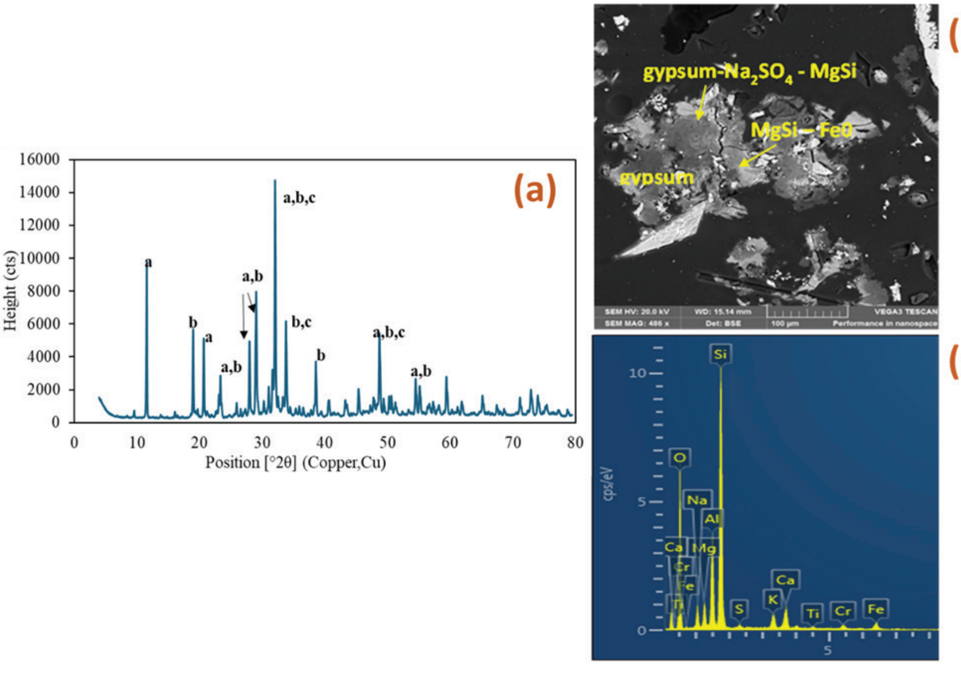

Figure 3 XRD patterns of pervious concrete after exposure to AMD: (a) XRD analysis of residues from: a - gypsum ($CaSO_4{\cdot}2H_2O$); b - Thernadite (Na_2SO_4); c- calcite; (b) and (c) SEM examination of pervious concretes after 180 days of use in acid mine drainage treatment.

the discharge of pollutants to a water resource. Further improvement of the treatment system is required to enable attenuation of the high alkalinity in the treated water.

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