Sewage Sludge as an Electron Donor in Biological Mine Wastewater Treatment: Development of the Rhodes BioSURE Process®

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Abstract.

The use of sewage sludge as a carbon and electron donor source for sulphate reduction in biological mine wastewater treatment has been considered for some time, and the application has been evaluated at pilot-scale in this study. Results have shown that sewage sludge may be converted to VFA as a feedstock for sulphate reducing proaryote growth at an efficiency of 32-37% of available COD. Where the contact time is optimized this estimate approaches 50%, which compares well with bench-scale experiments. Continuous operation of the pilot plant showed up to 80% sulphate removal, with ~90% potential removal achievable in the fully optimized process. These observations have been confirmed in full-scale application studies currently in progress.

Introduction

Pyrite and arsenopyrites may constitute up to 9% of gold bearing ore bodies in the Witwatersrand, and the oxidation of these ores, giving rise to acid formation and heavy metal solubilisation, has been comprehensively dealt with by Kuenen and Robertson (1992), Robb (1994), Johnson (1995), and more recently Lens et al. (2000). Large-scale dewatering of the East and Central Rand gold mines in South Africa, has resulted in the draw down of good quality surface water and the pumping out of bad. However, modeling studies by Scott (1995) have shown that the problem will persist after final closure of the last operating mines, which is now pending. Filling is likely to be more rapid than formerly thought (< 10 years in the East

Rand Basin) and, due to hydraulic gradients, a diffuse daily discharge of >100 ML, or more, of poor quality water to the, already stressed, Vaal River system, may be anticipated across the Witwatersrand. Rising salinity in the water supply to this landlocked industrial hub of the country has been a subject of growing concern for many years (Commission 1970; Stander 1987; Du Plessis 1990 and DEAT 1999). Younger et al. (1997) have shown that mine flushing may be anticipated to last for many decades to several centuries, and the need for a solution commensurate with the size of this problem, and sustainable over the long-term, has become a matter of urgency.

The potential of biological treatment of acid mine drainage (AMD) wastewaters has been considered by Gadd and White 1993, Barton 1995, Johnson 1995, and Lens et al. (2000), and early studies in this area were reported by Maree and Strydom (1985). However, the cost and supply of the carbon source, as well as appropriate reactor design, has constrained widespread application of these systems in the treatment of large-volume AMD flows. Use of waste carbon sources to support the growth of sulphate reducing prokaryotes (SRP) has been fairly widely considered (Rose et al., 1998), with the possible first reports of sewage sludge as a growth medium for these organisms by Butlin et al. (1956).

Investigations in the potential linkage of the sewage disposal system and AMD treatment, as a long-term sustainable solution to the mine water problems of the Witwatersrand, commenced in the mid-1990s with the threatened closure of Grootlei Mine, the last operating mine on the East Rand (Rose et al. 2004). With dewatering of the East Rand Basin now dependent entirely on the pump station at the mine's No 3 Shaft, at times over 130 $ML.day^{-1}$ minewater required pumping and treatment before disharge to the Blesbokspruit wetland, a Ramsar site of international significance.

Studies in the enhanced hydrolysis of complex organic carbon substrates in biosulphidogenic environments had been reported for tannery ponding systems by Rose et al. (1998 and 2004), Dunn (1998) and Boshoff (1999), and Whittington-Jones (2000), Molepane (1999) and Molwantwa (2003) showed that enhanced hydrolysis of sewage sludge could be successfully linked to biological sulphate reduction activity. The enzymology of the enhanced hydrolysis reaction in sewage has been reported by Whiteley et al. (2002a&b), Pletschke et al. (2002) and Enongene (2004).

Corbett (2001) and Rose et al. (2004) have reported the development of the dual-stage Rhodes BioSURE Process® using primary sewage sludge in the biodesalination of mine drainage wastewaters.

Process Development

The Recycling Sludge Bed Reactor (RSBR), as the core unit operation of the Process, was conceptualised on the basis of studies of the microbial ecology and sulphur cycle in tannery ponds (Dunn 1998). The system was experimentally modeled by Whittington-Jones (2000), who showed that more than 50% of particulate chemical oxygen demand (CODp) had been solubilised into a from readily available to SRP consumption (Figure 1). This value exceeded previous reports by about 20%, and the results suggested that enhanced hydrolysis of the substrate and the sulphate reduction reactions would be best effected in separate unit operations.

This hypothesis was tested in 2L and 10L bench-scale reactor studies (Figure 2) by Whittington-Jones (2000) Whittington-Jones et al. (2002), and evaluated in a $1M^3$ reactor by Molepane (2000). Following threatened closure of the Grootvlei Mine by the Department of Mineral and Energy Affairs, the BioSURE Process® was selected with a group of four other technologies for competitive pilot-scale evaluation on-site at the mine.

A $50m^3$ pilot plant of the BioSURE Process® was constructed and commissioned on site at Grootvei Mine (Figure 3). Enhanced hydrolysis in the RSBR ($23m^3$) was followed by sulphate reduction in an adapted Anaerobic Baffle Reactor (ABR) of $25m^3$, and final treatment was effected in an Algal High Rate Pond (HRAP) raceway (Figure 4).

Materials and Methods

Analytical determination of chemical oxygen (COD), volatile fatty acids (VFA), and settleable solids was according to Standard Methods (APHA 1989). Sulphate was determined using the Spectroquant system (Merck), and faecal coliform by South African Bureau of Standards Method SABS 228.

The system was fed with mine water following lime treatment, and sewage sludge was provided by the Springs Municipality. Plant feed was made up by blending sewage sludge with mine water to establish a 2:1 COD:SO_4 ratio, and fed at a rate of 1.04m^3.hour.

Results and Discussion

Commissioning

Although active sulphate reduction commenced soon after initiating plant loading, commissioning activities ran over nearly three months, mainly due to shutdowns and perturbations in the mine water supply. Uninterrupted steady state operation was achieved after day 85, and Table 1 reports plant performance for the end of the commissioning period, days 90-118. While sulphate reduction averaged 66% over this period, the results show the major fraction of COD removal occurring in the RSBR, and of sulphate reduction in the ABR. Around 98% of settleable COD was removed in the RSBR.

Process Operation

Following commissioning, the plant was monitored for a further 8 months of steady state operation, and sulphate reduction and COD consumption performance values are reported in Figures 5 and 6. Fairly wide fluctuation in the sulphate concentration of the mine water, and in the COD of the sewage sludge, were experienced throughout the piloting operation. Average process performance across the full 240 day period is reported in Table 2 and shows 67% sulphate removal and 72% COD consumption. Faecal coliform bacteria and Ascaris ova were completely removed in the process.

Despite the reactors being constructed as closed systems, the reoxidation of sulphide was observed with the formation of a copious floating sulphur biofilm on the surface of both units. Towards the end of the pilot study the reactors were sealed and a nitrogen delivery system installed to sparge the headspace of each unit. During this operation sulphate reduction increased to over 80% with an average of 75% for the full month of operation.

Process Performance

The hydrolysis and solubilisation reactions, as the initial steps in which complex organic structures, such as primary sewage sludge, are made available to the biological processes, are of central importance. In order to measure the efficiency of the process in mobilising sewage sludge as an SRP substrate, the combined products of hydrolysis and acidogenesis may be measured directly as total VFA. However, since both production and consumption are occurring simultaneously, process efficiency may also be calculated theoretically from stoichiometric sulphate reduction values within the system (COD:SO_4 = 0.61:1) based on equation 1 (Hansford 2004), and expressed as acetate equivalents.

$$CH_3COOH + H_2SO_4 = H_2S + 2CO_2 + 2H_2O \qquad (1)$$

Since the products of acidogenesis would also have been consumed by organisms other than SRP, the process efficiency factor derived in this way from total sulphate reduced, presents both a crude and minimum value for VFA generated in the hydrolysis/acidogenesis reactions. Figure 7 reports VFA production from primary sewage sludge in the Process showing the combination of direct measurement and calculation of acetate equivalents based on values of sulphate reduced.

Based on this approach, the COD:SO_4 consumption/reduction ratio was found to range from 2.6-4.5:1 in the RSBR and 0.57-0.82:1 in the ABR. Given the close approximation, in the ABR, of the measured and theoretical values, it may be broadly assumed that sulphate reduction in the ABR was largely driven by VFA products generated by sewage sludge hydrolysis, occurring mainly in the RSBR. An efficiency for conversion of sewage sludge into acetate equivalents of 32%-37% was achieved across the piloting period. This rises to ~50% in the fully optimized process and compares well to bench study values reported by Whittington-Jones (2000).

Process efficiency in terms of sulphate reduction achieved may also be measured as a function of hydraulic retention time (HRT). While the plant was operated at a fixed HRT of 46 hours (8hrs in RSBR;38hrs in ABR), it was apparent that residual COD could support additional sulphate reduction, but probably on a basis of diminishing returns. An estimate of HRT required to achieve maximum sulphate conversion was undertaken in flask experiments in which the final effluent from the ABR was incubated for a further 216 hours. Figures 8 and 9 show that both VFA production and sulphate removal reach a plateau by 96 hours, and in this period achieving a sulphate reduction of ~90%. Where this level of removal is desired, and large water volumes are to be treated, the efficiency of retention within a ponding system may be considered as an appropriate reaction environment following the RSBR hydrolysis unit operation.

Conclusion

Based on the above results the BioSURE Process® has been further scaled-up at the ERWAT Ancor Sewage Works located some 2.5 km from Grootvlei Mine. A dedicated pipeline connecting the mine and the sewage works has been constructed and delivers mine water to site, and sewage sludge is sourced directly from the primary settling tanks. In this system a RSBR of $180m^3$ is linked to a stirred tank reactor instead of using the ABR design. These studies are currently running at the time of writing, and plans have been drawn for the construction of a $10ML.day^{-1}$ mine water treatment plant.

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