Successful Construction of a Full-Scale Passive Sulfate Treatment System

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Abstract

A passive sulfate reduction system with iron scrubbers was identified as the most viable option for treatment of elevated sulfate within leachate from an old landfill and bench scale trials were established in 2019 at the site to test the theory. This included the use of a Biochemical Reactor (BCR) with different proportions of wood chips, straw, manure, limestone, and biochar to culture sulfate reducing bacteria. In addition the concept of 'bugs on booze' was trialled, using a Fix Bed Anaerobic Bioreactor (FBAR), where alcohol was added to enhance the sulfate reducer activity. In total three BCRs and two FBARs were set up for this stage of the assessment. The resulting treated leachate was then passed through different iron media types (haematite, magnetite and iron filings) and sand filters to remove sulfide/free sulfur generated by the bacteria, with an aerobic wetland/reed bed used to polish the effluent. The success of the bench scale project led to a pilot scale system being constructed and monitored in Spring 2020, the results of which confirmed the success of the bench scale testing and provided useful insights into management of the system. This latest paper updates the project and provides a summary of the full-scale system which is being constructed in 2022/23 and demonstrates the final tier of the successful application of the innovative system.

Keywords: Passive Treatment, Sulfate Reduction, Biochemical Reactor, Wetland, Pilot Plant

Introduction

SLR Consulting (SLR) was appointed by British Gypsum (Saint-Gobain Construction Products UK Ltd trading as British Gypsum) to investigate options for the treatment of leachate emanating from an old landfill disposal site at their property in East Sussex. The options analysis undertaken by SLR highlighted a passive treatment option for the removal of the sulfate, to below discharge standards, was a potential option but that it required treatability/feasibility testing. The concept involved the use of naturally occurring material containing sulfate reducing bacteria to remove the sulfate with the resulting dissolved sulfide in the water being 'scrubbed' by a filter. An aerobic wetland would then be used to polish any final effluent before it is discharged. Full details of the bench and pilot scale can be reviewed in a paper presented in 2021[1], although a summary is presented below.

The Treatment Process Summary

The design of a treatment system should be based on the results of a "staged process" of bench and pilot-scale testing. Typically flow rates of c.5 to 10 mL/min or less is termed "bench-scale" study with a "pilot scale" study as one that would treat about 4 L/min or more.

Bench scale testing is an effective way to advance a project toward to full scale implementation while gaining useful knowledge about appropriate media, reaction rates,

1 J Robinson, I Andrews, J Dodd, L Josselyn, J Gusek and E Clarke (2021) Successful Passive Treatment of Sulfate Rich Waters. Presented at IMWA 2021, Cardiff.

and functionality that increase confidence and overall effectiveness. The typical passive biological treatment process for sulfate reduction utilizes an anaerobic Biochemical Reactor or BCR. While BCRs receiving Mining Impacted Water (MIW) may be configured as "up-flow" or "down-flow", experience has shown that up-flow BCRs are better than down-flow BCRs in treating sulfate rich and metal poor leachates.

The organic substrate comprises hard wood chips, limestone, straw and biochar in varying proportions. 0.1% animal manure is added to provide the naturally occurring sulfate reducing bacteria innoculum. The sulfate in the influent leachate is then consumed by the bacteria and produces sulfide:

$$SO_4^{2-} + 2\,CH_2O = H_2S + 2\,HCO_3^-$$

The lack of suitable metals in the site discharge required a metal ion addition to passively sequester the sulfide generated through the sulfate reduction process. The dissolved sulfide will precipitate as an insoluble metal sulfide or potentially as free sulfur. At the site, iron was added at bench scale via a treatment substrate such that the following reaction (through precipitation of dissolved iron or on metal iron surfaces), in the substrate will occur, shown simplistically below:

$$Fe^{2+} + S^{2-} \rightarrow FeS$$

This metal can be either in the zero-valent state such as scrap iron, or as an oxide. However, care in media selection is warranted. An Aerobic Polishing Wetland (APW), a lined shallow pond filled with soil and locally harvested or cultivated vegetation is used to re-aerate the anoxic effluent from the BCR.

Bench Scale Set Up

To test the theory of a passive wetland treatment solution, a bench scale system was set up at the site to run for 20 weeks (fig. 1). The bench scale system comprised:

- three Biochemical Reactors (BCRs) – pump fed, each filled with a different test mixture comprising different proportions of manure, wood chips, hay, limestone, and biochar,

BCRs and SCRs 1 - 3

FBARs, SCRs and Aeration

Aerobic Polishing Wetland

Figure 1 Bench Scale Test Set Up

- three Sulfide Scrubbers (SCR), each filled with a different test mixture comprising magnetite, hematite, and iron filings,
- three Aerobic Polishing Wetland (APW) cells planted with wetland plants from the site, and
- two Fixed Bed Anaerobic Bioreactors (FBAR) with two Sulfide Scrubbers, Aeration Tub and Settlement Tub.

As part of the treatability, it was also decided to consider the use of a hybrid-passive approach which involves the additional of a soluble form of hydrocarbon, in the form of alcohol to increase the metabolic rate of the bacteria. In this Fixed Bed Anaerobic Reactor (FBAR) small quantities of ethanol is added to a small system to provide a food source for the bacteria. The reasoning being that with a more soluble food source the bacteria will consume more of the sulfate and hence less area will be needed for the treatment at pilot and full-scale. The hybrid system also had an active aeration and settling tank in replacement of the aerobic wetland system to act as a comparison.

Monitoring and Results

The system was monitored for a variety of analytes along with the flows throughout the system. Weekly field-based monitoring of pH, redox and conductivity was undertaken along with sulfate, sulfide, nitrate, calcium and magnesium. At monthly intervals, phosphate, alkalinity, hardness, iron, nickel, zinc and total organic carbon (TOC) was analysed. The flows through the reactor were typically 6 L/d for the BCRs and 25 L/d for the FBARs. The latter was also reduced at the end of the treatment to be closer to the BCR flow rate to act as a comparison. The monitoring of the system was undertaken at weekly intervals where the redox and pH of the various components coupled with the flow rates were taken. The sulfate and other components were analysed at an offsite UKAS accredited laboratory. The results of the treatability study are shown in Figures 2 to 5.

The bench scale test results indicated that both BCRs and FBAR treatment will produce an effluent that would meet a 250 mg/L sulfate discharge limit. In mine water treatment systems sulfate reduction rates typically range from 0.1 – 0.3 moles/m^3 substrate/ day. The rates for this study are shown to be at the upper end of this range. In addition, the FBAR rate of sulfate reduction was c.15 times that of the BCR reduction rate. Consequently, the media volume required to accomplish this with a BCR will be c.15 times greater than for the media volume for an FBAR with an identical treatment capacity. The land area footprint required for an FBAR treatment unit would therefore also be 15 times smaller than that required for a BCR. However, the

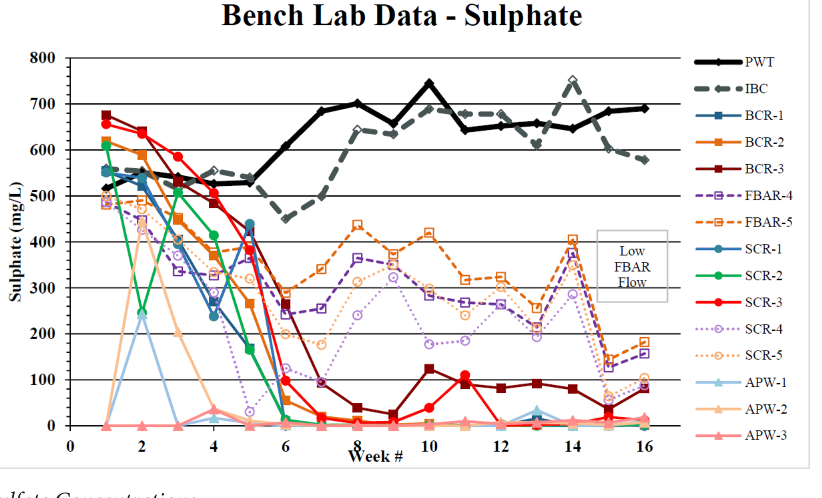

Figure 2 Sulfate Concentrations

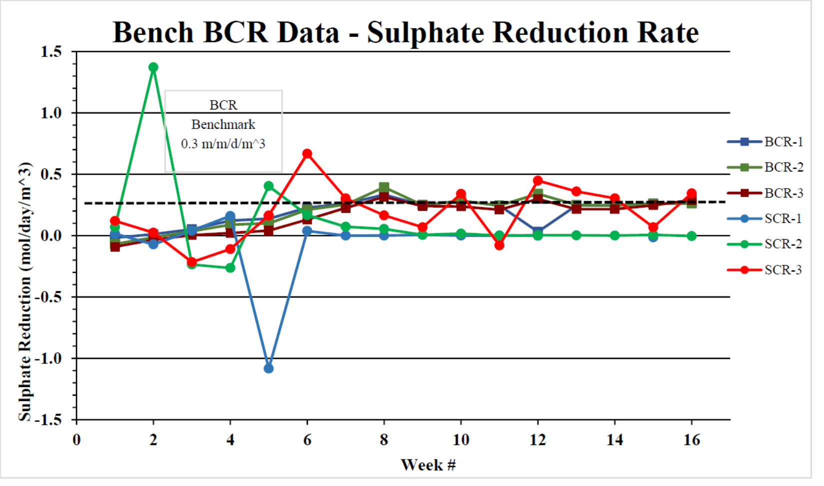

Figure 3 *BCR Sulfate Reduction Rate*

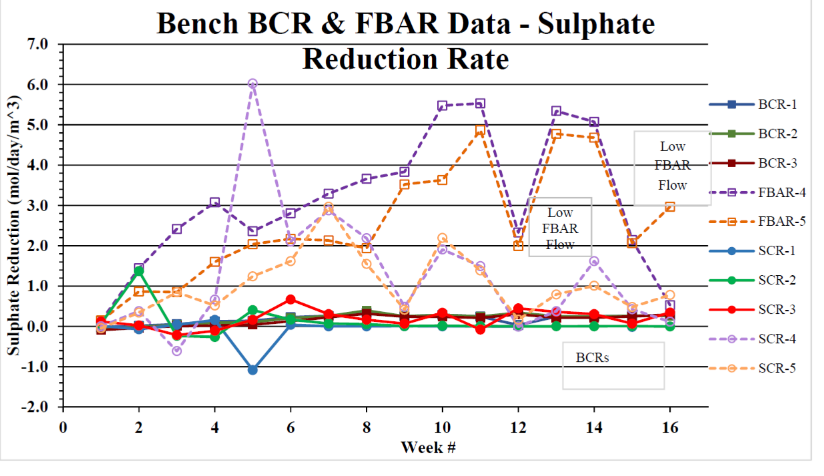

Figure 4 *FBAR and BCR Sulfate Reduction Rate*

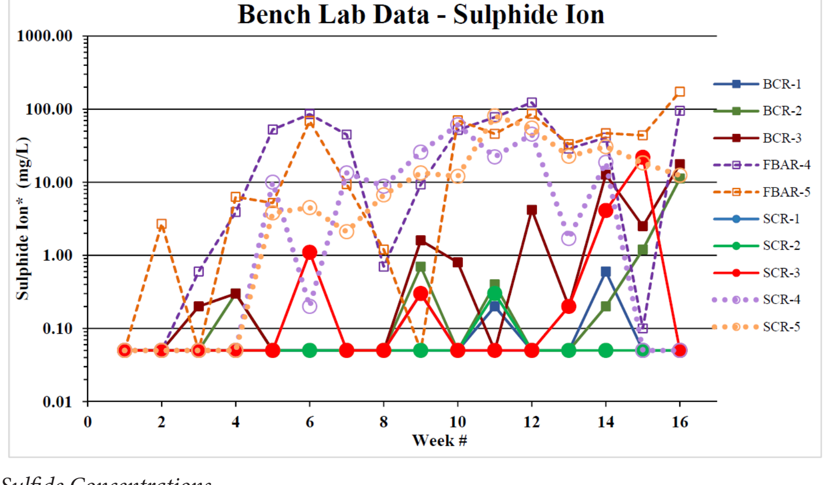

Figure 5 *Sulfide Concentrations*

FBAR process will require the delivery of a steady and reliable supply of alcohol as a microbial nutrient.

The passive BCR process does not require the addition of nutrient, such as alcohol, and therefore is seen as a more practical solution at the site. The scrubbers appeared to sequester sulfide ion present in the BCR and FBAR effluents, although it was also clear that free sulfur was being precipitated in the outfall from the anaerobic systems. The bench scrubbers that received the FBAR effluents, proved to be undersized. The aerobic wetland system was effective in removing the iron leached from the scrubbers and did have a positive impact on the organic carbon which came through the system. The results of the bench scale testing were very encouraging. This has led to the design and development of a pilot scale system at the site.

Pilot Scale Testing

The success of the bench scale trials led to the design and installation of a pilot scale system in Spring 2020 on the site (fig. 6). The purpose of the system was to confirm the success of the bench scale study by using the sulfate removal coefficients and preferred media option. The latter comprised mixing of wood chips, biochar, limestone, wheat straw, bench scale organic material and goat manure inoculum.

The desired flow being introduced into the system was 0.5 L/min and above and there was no addition of alcohol as a nutrient. Review of the bench scale testing showed that free sulfur precipitation dominated and hence the iron scrubbers were not required, although sand filters were included. The pilot scale system had the original orientation of sequential treatment, although three biochemical reactors were established such that variety in flow rate and other parameters could be used to test the system. To construct the pilot plant, shipping containers were used for the three BCRs. These were lined with insulation which also prevented leaks, on the base and sides and reinforced such that they could hold the substrate and the water.

Sampling ports were established such that different horizons in the units could be analyzed if required. The aerobic polishing reed beds were designed with baffles to lengthen the flow length in the wetlands and were designed for the removal of BOD/TOC. Facility was also made to add on the iron-based sulfide sequestering unit should monitoring indicate that sulfide is leaving the system at concentrations which were unsustainable from an environmental perspective.

The pilot system became live through a commissioning phase in Spring 2020 before the COVID emergency, and monitoring has been undertaken by a skeleton staff on site since. A number of sampling points were included in the system including a redox zone depth measurement in the anaerobic material, along with the treatment zones at various locations along the system.

The results of the ongoing monitoring have indicated good sulfate removal with no sulfide detectable in the effluent (fig. 7). Free sulfur has been identified in the system which has the potential to oxidise and release stored sulfur as sulfate, although during the summer/spring there was no evidence this has occurred.

Figure 6 *Passive Treatment Pilot Plant from right to left (Feed Tank; BCR1, 2, 3, 4; Reed bed (APW) 1, 2, discharge holding pond showing purple/white bacteria)*

Elemental sulfur may be the primary product of sulfate reduction in the BCRs. Evidence includes the white cloudiness in the BCR effluents, white deposits in the wetland influent zones, and the purple tinge (likely the bacteria *Chromatium sp*. and *Chlorobium sp*.) in the final pond influent zone (fig. 6). Purple sulfur bacteria produce elemental sulfur as part of their life cycle. Thus far the pilot cell is confirming the results of the bench scale testing with latest influent sulfate of c.800 mg/L being reduced to c.100 mg/L in the effluent, thus providing robust design data for the full-scale system.

In the winter months the treatment efficiency decreased which was believed to be caused by temperature reduction and potential free sulfur re-oxidation. This temperature dependency is a relatively well-known phenomenon with passive systems, with sulfate reduction rates improving in spring and summer months. This aspect of the pilot scheme has been very useful in guiding potential management changes which may need to be included in winter months to maintain the same reduction in sulfate.

The decreased performance of the BCRs over winter months was investigated. The monitoring showed some interesting changes in redox and TOC in the leachate entering the treatment system. Landfills are large anaerobic digesters, and this can result in inconsistent performance (effluent) from the treatment system. Influent TOC ('food' that is 'digestible' for the pilot BCR organisms – like a 'bugs on booze' hybrid system investigated at bench scale) sustain the BCR well. When this food is reduced quickly in the leachate, the whole biosystem in the BCRs is essentially put on starvation mode with knock on lower sulfate reduction rates. This provided very useful information as it might suggest soluble organic matter amendment (as used in the bench scale testing) may be required during the winter months if the sulfate treatment is shown to fall below established permit conditions.

The pilot system operated until Jan 2022, and planning permission for the full sale system was received in late 2021. The design layout of the full-scale system is shown in fig. 8.

It was decided to construct the system atop an old landfill at the site and therefore, additional geotechnical assessments were made regarding the stability of the ground and the potential impact on leachate generation from the additional loading. Given this was an innovative system, the Environment Agency (UK regulatory) required additional information regarding the design and longevity of such systems. Construction of the system will hopefully begin in the spring and the result of the initial work will be presented at the conference.

Acknowledgements

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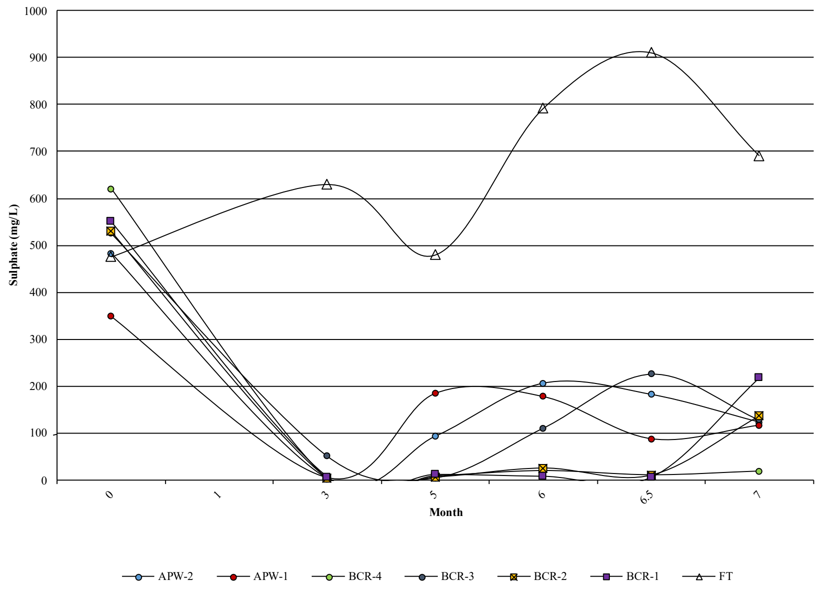

***Figure 7** Example of Sulfate Treatment from the pilot plant operation*

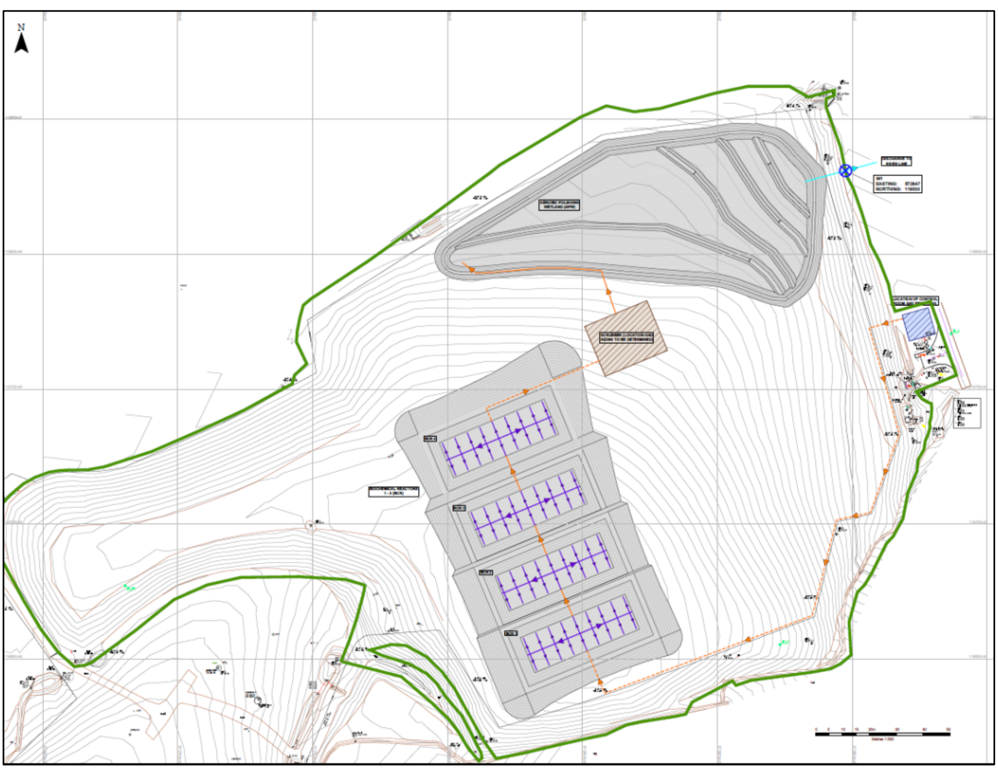

***Figure 8** Proposed Layout of Full-Scale System*