# Innovative Passive Treatment Technologies for UK Metal Mine Waters: Results from Field Scale Trials

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**Abstract**

The UK Government's Water and Abandoned Metal Mines (WAMM) Programme was created to clean up the 1,500km of rivers polluted by metal mines in England. Existing mine water treatment technologies typically have high operating costs (active chemical schemes) or take up large areas of land (biochemical reactors relying on bacterial sulphate reduction).

This paper outlines several pilot-scale field trials designed to decrease whole life cycle (financial and carbon) costs of removing zinc from mine waters whilst minimising the land take required. This work has relevance for the design of passive metal mine water treatment schemes across the world.

**Keywords:** Metal Mine Waters, Treatment, Innovation, Pilot Trials

## Introduction

Drainage from abandoned metal mines accounts for approximately 50% of the total load of zinc, lead and cadmium to the freshwaters of England and Wales (Mayes et al, 2013) and is the largest source of metals to the marine environment (Environment Agency, 2023). These mine water discharges can cause significant ecological damage to freshwater ecosystems and without treatment, will continue to pollute rivers for hundreds more years. Most abandoned metal mines in Britain are in remote rural locations with very limited land available to build large passive treatment schemes and where active industrial treatment plants would not be acceptable to planning authorities.

Contaminated groundwater draining from abandoned metal mines is difficult to treat without adding chemicals and energy since treatment has to result in very low concentrations of metals being discharged to receiving waters. Most British mine water discharges have relatively low concentrations of ecotoxic metals and circumneutral pH although there are examples of lower pH and higher metal concentrations (Mayes et al, 2010).

The Water and Abandoned Metal Mines (WAMM) Programme is a partnership between the Environment Agency, the Coal Authority and the Department for Environment, Food and Rural Affairs (Defra) which was created to clean up the 1,500km of rivers polluted by these mines in England. Because the mines closed before 2000, the law says that former mine operators do not have to deal with the water pollution they created. The responsibility for cleaning up this legacy of Britain's industrial revolution therefore falls to the taxpayer. WAMM therefore has a strong emphasis on innovation and R&D with a particular focus on decreasing the footprint and whole life cycle costs of metal mine water treatment systems.

Considerable research has been conducted on treatment technologies based on microbially mediated sulphate reduction to remove metals from mine water as sulphides (Byrne et al, 2012). Since 2014, the WAMM programme has been operating the passive Force Crag compost-based bioreactor system, developed by Newcastle University following lab and pilot-scale research (Gandy et al, 2016), which continues to demonstrate the efficacy of sulphate reduction, removing >90% of Zn and Cd with a hydraulic residence time in the reactive media of about 15 hours. At these residence times, large footprint treatment ponds are required for which land can be difficult to find, and they can be expensive to construct. Removal rates vary, are sensitive to seasonal variations and the availability of reactive organic matter, and in some locations, potential emissions of hydrogen sulphide need to be controlled to avoid nuisance odours. Therefore, identifying and testing technologies that will provide **low-cost**, **low maintenance**, **low hydraulic residence time** (and therefore **small footprint**) passive removal of metals from mine water, is a key driver for applied research.

The majority of mine water treatment studies are carried out at a laboratory scale which allows close control of parameters such as flow rate and temperature. However, testing under field conditions using 'fresh' mine water is essential to avoid changes to the microbiology and geochemistry of the waters during transport, and to understand the influence of seasonal and temperature effects. There are disadvantages to field trials since it is often necessary to have very low flows, often using small tubing, to test representative residence times. Most UK mine sites do not have mains power supply and remote locations means problems such as blockages or variation in flow rates can go unnoticed for days.

The WAMM programme has carried out pilot-scale field trials to assess the performance of various passive treatment substrates which remove metals by a range of processes, many of which are microbially mediated although influenced by the reactive media. This paper presents initial findings of the assessment of our 'long-list' of technologies and/or substrates that have the potential to be deployed at a larger scale for metal mine water treatment along with results to date from various field trials.

## Methodology

Pilot scale field treatment trials have been undertaken at different scales, using two mine water discharges with different concentrations of polluting metals and pH. Field scale reactors (1m$^3$) were constructed in IBC style units by Aquaenviro to evaluate several treatment technologies which are described in Table 1. At sites testing multiple substrates, a 2.4m$^3$ 'header tank' was used as a water balancing tank; this contained high matrix media (HMM) as an iron pre-treatment step to minimise clogging of the main reactors. HMM is the term used by the Coal Authority for plastic filter pack discs with a high surface area (~200m$^2$/m$^3$, see Table 1). The header tank had two water distribution manifolds with fitted globe valves that allowed water to be directed to the IBCs at a determined flow rate. The IBCs were configured with a 2" slotted delivery or drainage pipe network at the base, which was bedded in an inert quartzite gravel drainage layer. In all cases, the reactive media was placed above the quartzite gravel drainage layer, at a predetermined depth. See Plates 1A to 1D for some images of the trials and sites.

Reactors were monitored on a weekly frequency (minimum), when flow rates were checked and amended where required, lines were flushed, levels checked and samples taken. On site water quality parameters were measured with an Aquatroll 500, specifically pH, dissolved oxygen (DO), conductivity (EC, μs/cm$^3$) and temperature. Water samples were taken by Enitial Services and analysed by Socotec UK, a UKAS accredited laboratory. This data is not discussed in this paper but will be used for future modelling and understanding of the different waters.

### *Bridford (Devon):*

A low-flow (<10 l/s) net acidic water, with average concentrations of iron (~56 mg/L), zinc (~11 mg/L) and other metals, which pollutes about 14km of the River Teign. A series of naturally formed 'iron terraces' are encouraging oxidation and precipitation of iron whilst decreasing the pH (see Plate 1D). Trials have been conducted on both the raw mine water, and water discharging from the end of the terraces.

Phase 1 trials put water collected after the iron terraces into a header tank containing HMM before passing through IBCs with either Coir (coconut shell outer fibre), Limestone Bioreactor (LST-BR) or Vertical

Flow reactor (VFR) (down-flow). An up-flow fish bone apatite trial was quickly stopped due to concerns over the high BOD of the media. Phase 2 and 3 investigated an alkaline pre-treatment step using Blast Furnace Slag (BFS), Basic Oxygen Steel Slag (BOSS) and limestone (LST) before a granitic VFR reactor.

*Cambokeels (County Durham):*

A low flow (<10 l/s) net alkaline circumneutral water with elevated zinc (~2 mg/L) and cadmium which pollutes up to 16km of the River Wear. Phase 1 put mine water into a header tank containing HMM, followed by IBCs with coir, LST-BR, BOSS or VFR (down-flow). Phases 2 and 3 involved larger scale (6 $m^3$) reactors which are not presented here.

## Results

*Operation of trials*

The IBC trials were operated for approximately 18 months at Cambokeels and nearly 2 years at Bridford. All trials ran passively, using gravity, siphons and valves to convey the water to the IBCs. Operationally, the systems worked well for 6 to 8 weeks,

***Table 1** Summary of substrates trialled*

| Reactor name | Media/Substrate/information | (Bridford –B, Cambokeels –C) | Material source(s) |
|---|---|---|---|
| Vertical Flow Reactor (VFR) | Fine grained (6mm granite over a 20mm granite gravel drainage layer) developed by D.Sapsford, Cardiff University | B and C | Cloburn Quarry Company, Lanarkshire |
| Limestone (LST) | 20mm single sized calcareous limestone aggregate | C | Heights Quarry, Bardon Aggregate, Westgate, Bishop Auckland |
| | | B | Hanson Aggregates, Batts Combe Quarry, Cheddar, Somerset |
| Limestone Bioreactor (LST-BR) | Organic rich mix of limestone, barley straw and bark, developed by Newcastle University<br>2:1:1 mix of 20mm limestone gravel (calcareous), barley straw, 25-45mm pine bark nuggets | B and C | Limestone as per LST<br>Barley straw: Local Pet centre<br>Bark: 'Maritime Pine', CPA Horticulture |
| Coir | Coconut fibres, various lengths. From untreated lignin-rich coconut husk fibres, a by product of the coconut farming industry | B and C | Fertile Fibre UK |
| Basic Oxygen Steel Slag (BOSS) | Granulated by product from steel production (8 to 14mm). By-product of the steel industry | B and C | Tarmac, Scunthorpe |
| Blast Furnace Slag (BFS) | Granulated by product from iron smelting (20 to 32mm). By-product of the iron industry | B | Tarmac, Scunthorpe |
| High Matrix Media (HMM) | Cascade YTH1170 Filterpak Media (200m2/m3). High surface area plastic filter pack discs | B and C | Veolia |
| Apatite | Fish bone derived apatite (1-2mm ground/granulated). By-product of the cod liver oil industry | B | Pelagia, Grimsby |

after which the systems became less stable. Pipework in both sets of trials became choked with iron oxide which meant flow rates often dropped between sampling events. Pipes were regularly cleaned using a pipeline pig and valves exercised following every sampling event. This led to variation in retention times within the substrates.

We undertook a number of modifications to the system to minimise the water delivery issues, such as running a bleed line to speed up flow through the main delivery pipework, with short spurs from the bleed pipe to the reactor, and also designing a valve less flow control header tank, that has been successfully deployed in the Phase 3 trials.

### *Metal removal results*

Key results from the Bridford and Cambokeels trials are summarised in Tables 2A and 2B along with percent zinc removal at Cambokeels in Figures 1A and 1B. At both sites, the limestone bioreactor (LST-BR) and steel slag (BOSS) proved to be most effective in removing metals. At Bridford, alkalinity pre-treatment followed by a VFR showed promise. The LST-BR reactor harnesses microbial sulphate reduction to remove the metals as sulphides although sorption and precipitation will also play a role. Removal by BOSS system is assumed to be a surface chemistry catalysed mechanism although microbial mediated metal removal cannot be

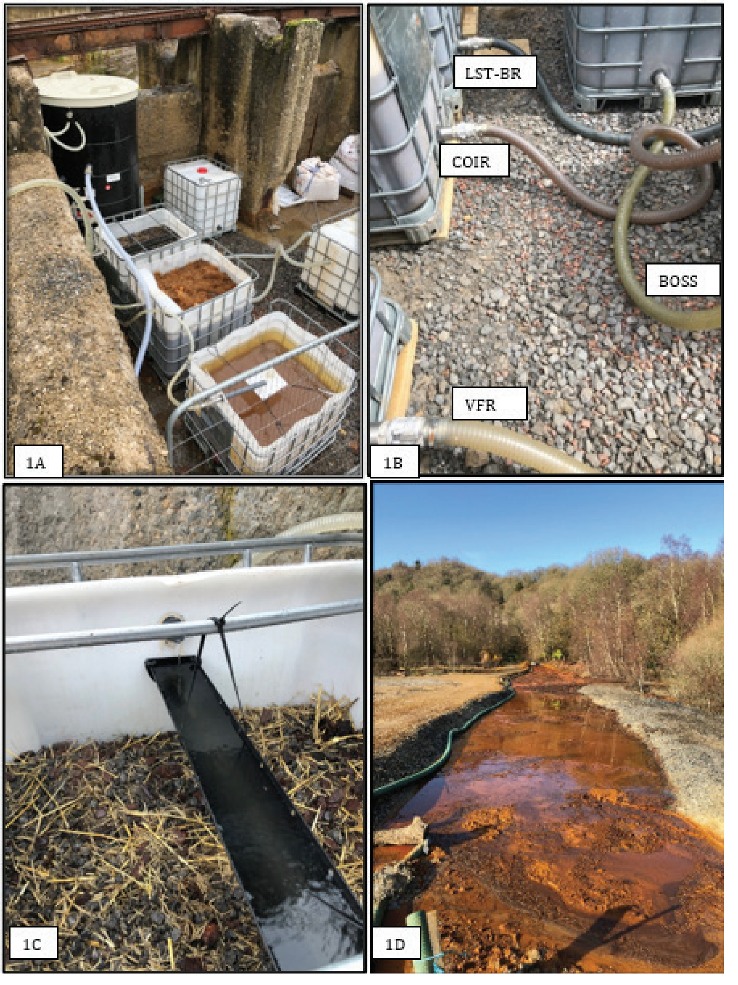


***Plate 1. 1A****: Cambokeels IBC trial.* ***1B****: Cambokeels IBC effluent pipework.* ***1C****: LST-BR substrate with gutter to distribute water.* ***1D****: Bridford 'Iron Terraces'. (Images: Selina Bamforth).*

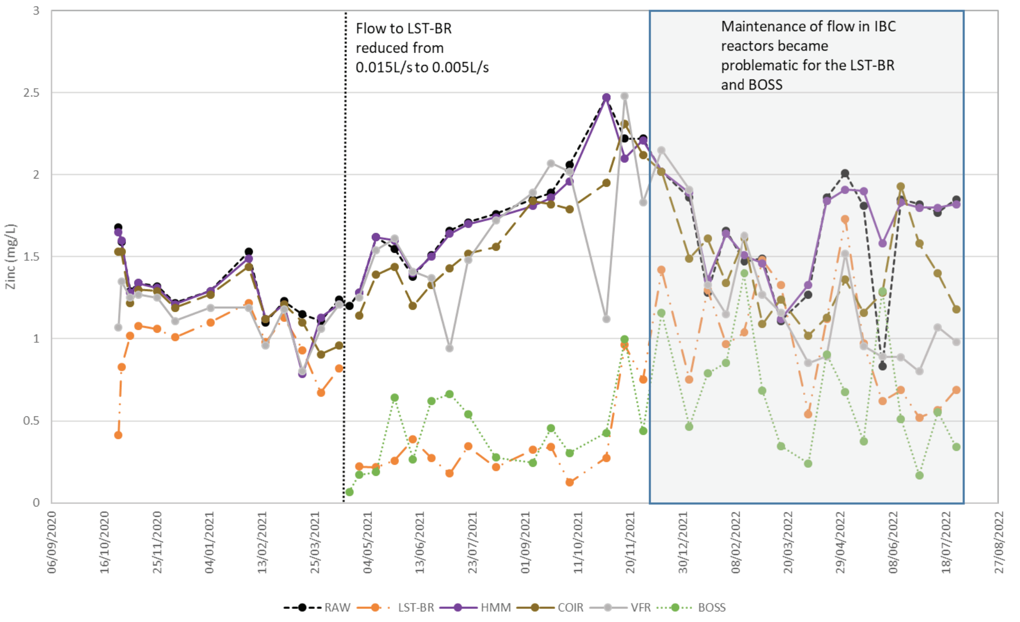


*Figure 1A* Cambokeels: zinc influent and effluents (see Table 1 for substrate descriptions).

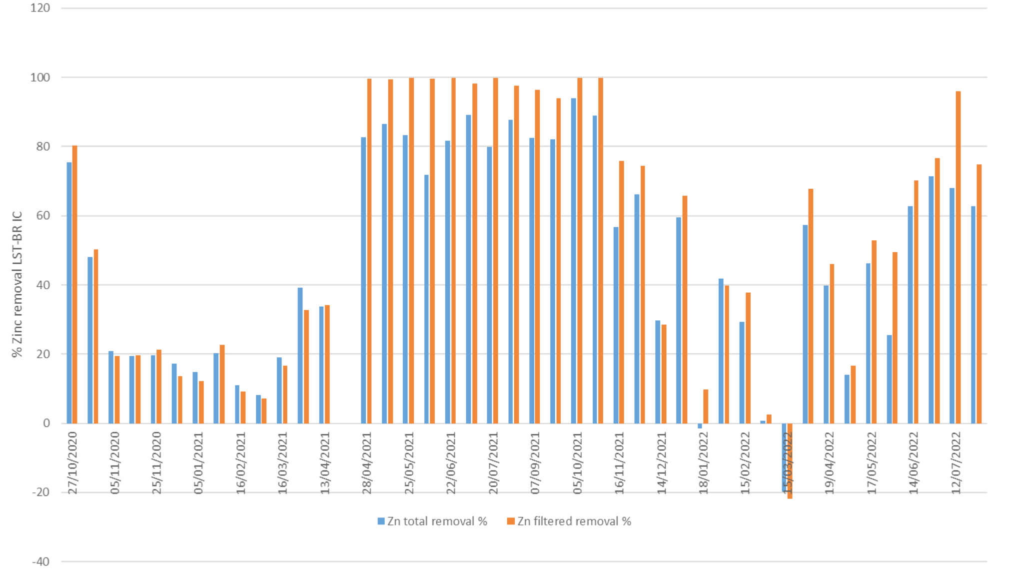


*Figure 1B* Cambokeels: zinc percentage removal in the LST-BR IBC (total and filtered (<0.45μm)).

ruled out; this system may add resilience if used in combination with the LST-BR.

## *Next steps*

Based on the positive results from the 'long-list', longer term and larger scale trials of the LST-BR, BOSS and VFR are currently underway. Key research questions relate to whether hydrogen sulphide emissions need to be managed, seasonal variability in metal removal, effects of residence times and substrate life.

***Table 2A** Summary of results from trials at Bridford January 2020 - November 2021*

| Phase | Date range | Trial type | Flow rate (L/s) | Results summary |
|---|---|---|---|---|
| 1 | January –June 2020 | VFR | 0.05 | Good Fe removal for first 3 months, limited removal of other heavy metals |
| | | Coir | 0.2 | Limited iron and other heavy metal removal |
| | | LST BR | 0.05 | Good Pb and Al removal for first 3 months, limited Zn removal, tracer test conducted highlighting significant short circuiting |
| | January 2020 | Fish bone apatite | 0.015 | Excellent metals removal for first week (nearly 100%), becoming less effective in week 2, with high BOD and ammonia, therefore terminated early |
| 2 | September-December 2020 | pre-treat LST - VFR | 0.005 | Initial zinc removal in LST VFR. Problems with lines blocking, unable to continue. |
| | | BFS pre-treat - VFR | 0.005 | Limited Zn removal in BFS VFR. Problems with lines blocking, unable to continue. |
| | September 2020-November 2021 | LST BR | 0.005 | Good Pb and Cd removal but high variability. Some Zn removal – could; be seasonal patterns (better summer time removal) |
| 3 | March – November 2021 - | LST pre-treat – VFR 1 | 0.005 | Good lead removal, variable Cd, Zn, Pb, As removal. Metals removed in VFR stage more than the pre treat stage but high variability, likely due to flow rate variation |
| | | LST pre-treat – VFR 2 | 0.005 | Good lead removal, variable Cd, Zn, Pb, As removal. Metals removed in VFR stage more than the pre treat stage<br>Up to 100% Fe removal from circa 50mg/L in the VFR element |
| | | BOSS pre-treat - VFR | 0.005 | The BOSS media removed the majority of the heavy metals without the VFR element, good Pb, Cd As, removal variable Zn removal.<br>Up to 100% Fe removal from circa 50mg/L in the VFR element |

***Table 2B** Summary of results from trials at Cambokeels October 2020 - April 2023*

| Phase | Date range | Trial type | Flow rate (L/s) | Results summary |
|---|---|---|---|---|
| 1 | October 2020 – June 2022 | VFR | 0.015 | Good Fe, Al, Mn removal, limited Zn, Cd removal |
| | | Coir | 0.015-0.2 | Limited removal of metals |
| | | LST BR | 0.005-0.015 | Good Zn, Cd, Al removal for first 6 months |
| | April 2021 – June 2022 | BOSS | 0.015 | Variable but promising Zn removal, possible variation due to poor flow control |
| 2 | June 2021-February 2023 | LST BR | 0.7 | Good Zn removal through summer months, higher particulate Zn during winter months |
| 3 | August 2022-present | LST BR | 0.6 | Ongoing |

## Conclusions

The WAMM programme is committed to developing and trialling innovative treatment technologies which require minimal input of chemicals and energy. Initial results presented here indicate that the LST-BR is very effective at removing metals in a higher permeability media than used at the Force Crag scheme. BOSS merits further investigation at larger scale since the small diameter pipework clogged in all trials. For net-acidic mine waters, alkalinity pre-treatment followed by VFR appears to be effective.

Several larger pilot scale trials (6 to >200m$^3$) are underway, being commissioned or are planned including a large VFR trial for the Coombe mine water (www.gov.uk) in Cornwall. The programme is also investigating mitigation options for odour management and different reactive media.

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