Pilot plant testing to determine the process implications of treating net alkaline mine water using the high density sludge process

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Abstract

Old Fordell Adit in Dalkeith, Scotland discharges near neutral, net-alkaline mine water into the River South Esk causing discoloration, water pollution and deposition of iron ochre on the river bed. The Coal Authority concluded that the optimum option was to treat this discharge using the high density sludge (HDS) process. A HDS pilot plant trial was incorporated into the design stage to improve understanding of how CO_2 stripping, reagent consumption and precipitate generation would influence the scheme's design and equipment selection for this mine water.

This trial demonstrated that the optimum degassing ratio was 3:1. Iron removal, > 99.1%, was achieved over the pH range studied. Trial results allowed the equipment to be correctly sized and specified for the project's construction. It also provided a set of operational parameters that will be used for plant commissioning.

Keywords: Active treatment, high density sludge, pilot plant

Introduction

The former Bilston Glen coalfield covered an area of about 30 km2. It extends from Dalkeith and Loanhead in the north, Newtongrange and Rosewell to the south and Easthouses and Bilston to the east and west respectively. Bilston Glen Colliery, Dalkeith, Midlothian, Scotland, UK, closed in 1998, and its mine water discharges via Old Fordell Adit into the River South Esk. Due to the complexity of the underground connections between the collieries in the Bilston Glen area, the origin of the water discharging at the Old Fordell Adit is unknown. Since January 2019, sampling data suggested that the deeper and poorer quality mine water was discharging at surface. For the period 2020-2023, the discharging mine water contained 43.4 mg/L total iron (mean) and 4.6 mg/L total manganese (mean) with concentrations predicted to increase to 80 mg/L iron and 8 mg/L manganese. Treatment to reduce the concentration of manganese in the discharge to a target concentration of 1.2 mg/L may be required to ensure compliance with the annual average bioavailable environmental quality standard of 123 µg/L in the river. Based on prior measurements and modelling, it has been agreed with key stakeholders that flow rates up to 200 L/s will be treated prior to discharge into the river. Modelling of a passive scheme to treat the discharge considered either the treatment of iron only or the treatment of both iron and manganese. For iron removal, the scheme requires a land area of 62,000 m^2. To remove both iron and manganese, the scheme requires 112,000 m2 of land. This much larger land need is influenced by the interactions that promote manganese removal in UK passive schemes, as identified by Moorhouse-Parry and Satterley (2022), namely

- Iron concentrations must be low (ideally ≤ 5 mg/L) before manganese removal will take place in reed beds.
- Manganese removal tends to be seasonal with greater concentrations typically removed in the warmer months.
- Manganese removal will likely only commence once reed beds have established.

Table 1 Components of HDS pilot plant

Component	Description	Volume m^3	Component	Description	Volume m^3
Stage 1	Degassing	0.67	Stage 4	Flocculant dosing	0.05
Stage 2	Sludge addition	0.67	Stage 5	Flash mixer	0.05
Stage 3	Lime dosing	0.67	Stage 6	Lamellar clarifier[1]	3.5 m^2
Lime Tank	5 %w/w lime storage	0.190	Flocculant tank	0.05 %w/w flocculant storage	0.09

[1] this is its effective settlement area

A passive treatment scheme required substantial areas of land and the lack of suitable land in the Dalkeith area led to the consideration of an active treatment option that could be built on a much smaller site owned by the Coal Authority of approximately 8000 m^2.

The UK Coal Authority has been responsible for three active, mine water treatment plants for over 15 years – Ynysarwed (Neath Port Talbot, Wales), Wheal Jane (Cornwall, (see Coulton et al. 2003)) and Dawdon (County Durham). The latter two plants precipitate metal contaminants using a High Density Sludge (HDS) process. The last HDS plant that was designed and built for the Coal Authority was Dawdon in 2008. Advantages of the HDS process over a conventional precipitation process are that the ferric hydroxide precipitate has a high sludge settlement velocity, it has a low settled sludge volume and can be mechanically dewatered in excess of 50% solids in a filter press/centrifuge (Coulton et al. 2004). Experience gained in operating these plants was used to propose a preliminary design for a HDS plant for Dalkeith. To confirm the assumptions used in the preliminary design a pilot plant trial was undertaken at the Dalkeith site for three weeks.

Pilot Plant Trial

The HDS pilot plant was built in a 6.05 m shipping container; its components are described in Table 1 and a diagram of its layout is shown in Fig. 1.

Hydrated lime powder (95% pure) was manually mixed to 5 %w/w lime solution. A 0.05 %w/w flocculant solution was made with BASF Magnafloc 155. Mine water was pumped from Old Fordell Adit to the pilot plant. To ensure the delivery of a consistent flow to the plant a control loop was established between the feed pump variable speed drive

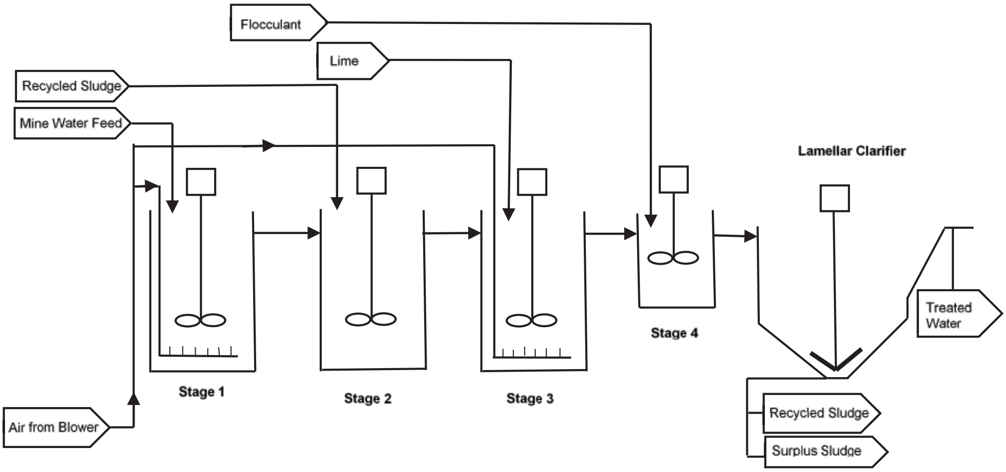

Figure 1 Layout of HDS pilot plant

and the magnetic flow meter. This delivered a steady flow (25 L/min) throughout the trial independent of both flow and level changes in the adit. The trial was carried out in two stages, firstly, to determine the optimum degassing ratio and secondly to determine the optimum parameters for HDS formation.

Optimisation of Degassing Ratio

The purpose of the degassing stage is to remove entrained/dissolved CO_2 from the raw mine water. This decreases the concentration of total inorganic carbon present in the water which improves the process efficiency by reducing the number of carbonate equilibrium system reactions. Consequently, calcium carbonate precipitation decreases. Free dissolved CO_2 is rapidly interchangeable with carbonic acid, so the species are combined in the term $H_2CO_3^*$, and also with the bicarbonate ion as shown below (Kirby and Cravotta 2005),

$$CO_2 + H_2O \rightleftharpoons H_2CO_3^* \qquad (1)$$
$$HCO_3^- \rightleftharpoons CO_2 + OH^- \qquad (2)$$

Vigorous aeration of the water improves gas transfer and enables displacement of the CO_2 to the atmosphere. However, increased aeration rates require larger equipment and increased energy consumption and so optimisation to ensure efficient operation is required.

To confirm the optimum degassing ratio, the plant was operated in single pass mode (degassing, oxidation, precipitation and settlement) which allowed for the degassing to achieve a steady state in a relatively short space of time without the process inertia present in a HDS plant. The degassing air flow rate was varied to achieve degassing ratios between 0:1 to 4.5:1(degassing air flow: mine water flow) and to study the effect of the degassing ratio on the mine water acidity.

Due to the circum neutral pH of the mine water (Table 2, selected mine water chemistry), the dissolved inorganic carbon is present as both dissolved CO_2 and bicarbonate ions, and because of the limited retention time in stage 1, only the dissolved CO_2 was removed by degassing. Fig. 2 shows the effect of varying degassing ratios on the acidity of the mine water. Compared to the raw mine water's acidity the removal of dissolved CO_2 decreased the acidity within the degassing reactor. As the degassing ratio increased the residual acidity trended to a minimum. Degassing of CO_2 increased the mine water pH and it reached approximately pH 6.9 as the degassing ratio increased (Fig. 3). At this pH, bicarbonate is the predominant species and further degassing increased the pH further which inhibited the equilibrium reaction (Equation 2) for bicarbonate dissociating into dissolved CO_2 and hydroxide ions. Consequently, CO_2 degassing became limited as the pH increased.

Choosing an optimum degassing ratio is a compromise between efficiency of CO_2 removal and the costs of purchasing the correctly sized blowers and their associated operational costs. A degassing ratio of 3:1 was deemed optimal and used for the second part of the trial.

Optimisation of high density sludge process conditions.

In the second part of the trial, the stage 3 precipitation pH was varied in the range pH 7.5–9.3 to investigate its effect on iron and manganese removal, lime consumption and sludge generation. For this work, the mine water flow was 25 L/min and the degassing air flow was 75 L/min to maintain a degassing air ratio of 3:1. A summary of the process performance at the chosen precipitation pH is in Table 2.

Oxidation and precipitation of dissolved iron was > 99.1% across the pH range, therefore operating the proposed treatment plant at pH 7.5 would minimise lime use when iron only removal is required. Manganese precipitation (> 85.1%) occurred when the target precipitation was pH 8.5 or higher. To achieve < 1 mg/L manganese in the discharge, a target precipitation pH of pH 8.75 would be required (Fig. 4), however, this may require further optimisation. If a manganese concentration much less than 1.2 mg/L is required at the discharge, the stage 3 precipitation pH would have to be increased and the treated water could require pH correction prior to discharge to meet the anticipated environmental permit requirements.

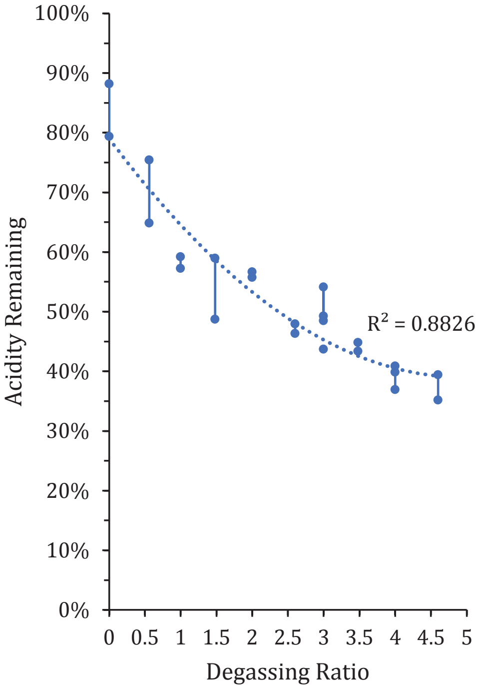

Figure 2 Acidity remaining after degassing

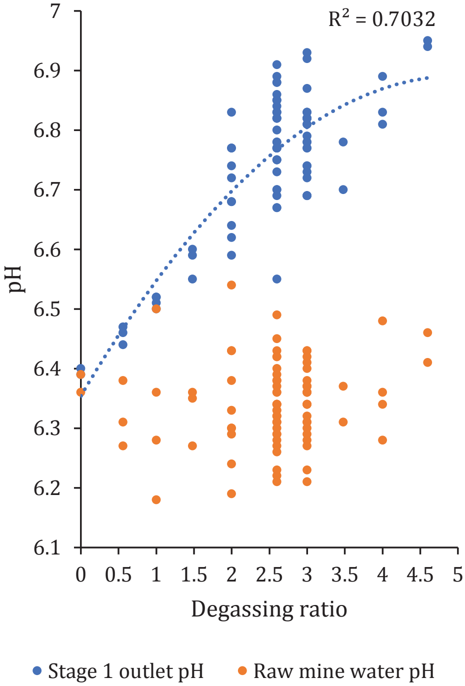

Figure 3 pH variation by degassing ratio

Lime consumption during the trial was monitored continuously. Consumption varied to achieve the precipitation pH and also to changes in the inlet mine water chemistry and the quantity of sludge recirculating within the system, with the removal of sludge resulting in an increase in lime demand. Lime consumption is shown in Fig. 5 relative to both the target precipitation pH and the degassing ratio.

Sludge production increased as the precipitation pH increased. This was studied, on-site, by titrating a sample of degassed mine water, from stage 1, with lime water to the required pH and it was maintained at this pH for 25 minutes. The resulting solid was isolated, dried and weighed (Fig. 6). Between pH 7 and pH 8 there was a gradual increase in the sludge generated.

Above pH 8.5, there was a substantial increase in the mass of sludge generated which coincided with the co-precipitation of calcium carbonate caused by the reaction between the bicarbonate / carbonate equilibrium and the calcium ions from the added lime. This was confirmed by the analysis of the isolated solids. The sludge density ranged from 11.05–11.24 kg/m³ and

Table 2 Process performance at chosen stage 3 precipitation pH

Chosen pH	Raw Mine Water			Treated Water			
	pH	Total Fe mg/L	Total Mn mg/L	pH	Total Fe mg/L	Dissolve Fe mg/L	Total Mn mg/L
7.50	6.4	53.1	4.86	7.8	2.76	0.03	3.79
8.00	6.3	52.3	4.71	8.1	4.30	0.06	4.13
8.50	6.3	61.5	4.77	8.3	0.16	0.01	0.64
8.75	6.4	54.5	4.79	8.3	0.12	0.01	0.71
9.30	6.4	52.6	4.44	8.9	0.45	0.41	0.49

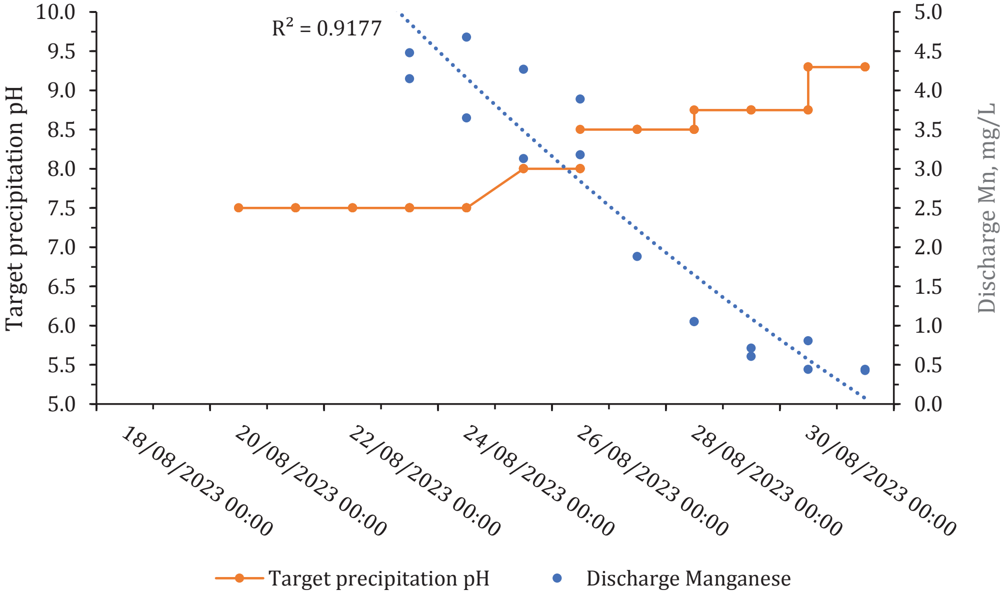

Figure 4 *Effect of precipitation pH on manganese concentration in discharge*

averaged 11.18 kg/m³ compared to a set point of 11.25 kg/m³.

Conclusions

Prior laboratory work suggested that the optimum degassing air flow: mine water flow ratio for CO_2 degassing was in the range 3:1–5:1. It also suggested that if the HDS process operated at greater than pH 8.2 a target discharge manganese concentration of <1 mg/L would be achieved.

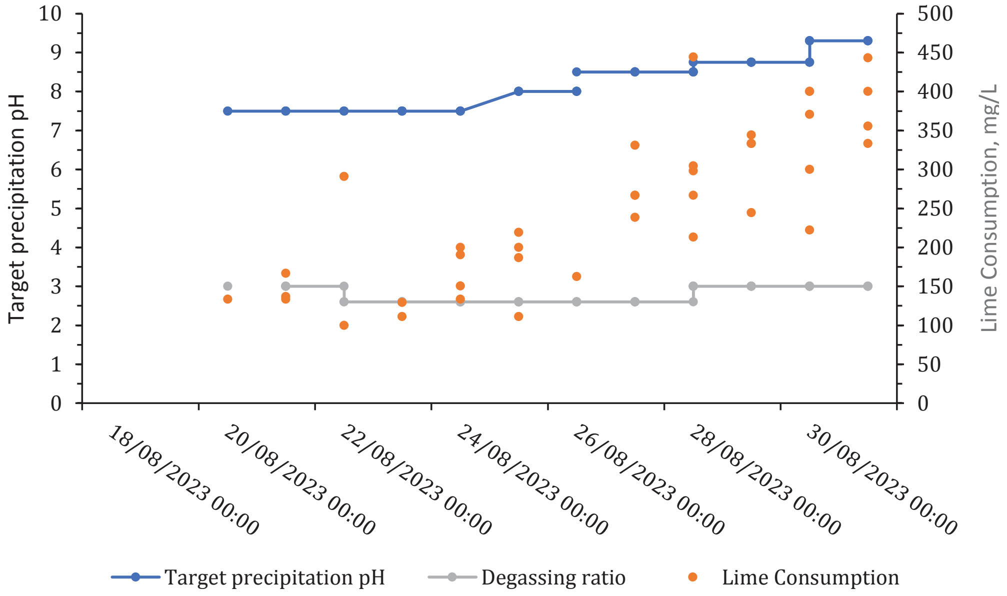

Figure 5 *Lime consumption variation with precipitation pH*

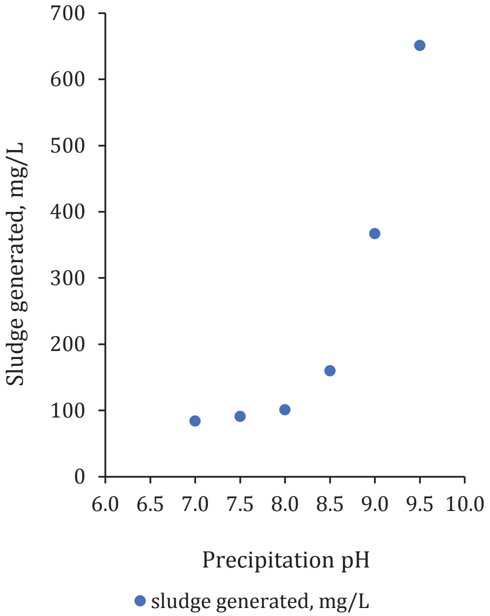

Figure 6 *Sludge production varying with pH*

This trial demonstrated that the optimum degassing ratio of 3:1 achieved a 40–50% decrease in dissolved CO_2 which was in agreement with the laboratory results. Iron removal, >99.1%, was achieved over the pH range studied, however, operating at pH 7.5 minimised lime consumption for iron only precipitation. To achieve a manganese concentration of <1 mg/L trial results suggested operating at pH 8.75, higher than the pH indicated by the laboratory work.

Prior to this work, the Coal Authority relied on best available information from its other HDS plants for its preliminary design work. The pilot plant trial allowed the equipment for the proposed plant to be correctly sized and specified for the build stage of the project. It also provided a set of operational parameters that will be used for plant commissioning.

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