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Control of ochreous deposits in mine water treatment

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Abstract

This paper briefly reviews the accumulation of ochreous deposits by sedimentation and accretion at mine water treatment operations. It introduces an ongoing survey of deposition and management options for ochreous sludges in the UK. The results of pilot scale testwork carried out at the Bullhouse mine water treatment system to control accretion by sodium dithionite dosing are discussed in comparison with observations of high pressure 'jetting' and 'pigging' operations employed on the 800 m pipeline which conveys raw mine water to the treatment lagoon. The relative merits of physical and chemical control of accretion are considered.

Key words: iron, mine water, ochre, sludge, waste, wetland

INTRODUCTION

Ochre arises in mine water discharges mainly from the oxidation of dissolved ferrous iron and precipitation of red-brown hydrated iron(III) oxide (ferrihydrite). Lagoons and wetlands are increasingly employed to prevent this ochre from reaching the environment. Accumulation of ochre from flowing mine water occurs by two primary mechanisms: sedimentation and accretion. Sedimentation provides the main method of retaining ochre in mine water treatment plants. From an operational point of view, the technique is tried and trusted. However, long-term management of sludge remains an issue. Accretion contributes variably to ochre retention, mainly with adverse practical effects. In particular, build-up of ochre in pipelines by accretion represents a major operational problem.

Sedimentation normally occurs as the gravity settling of suspended particles when linear flow velocities decrease to <1 cm/s on entrance to a pond, lagoon or wetland. Particles smaller than 0.1 mm do not settle readily, but may be retained by flow restriction and aggregation, particularly in wetlands. Gravity sedimentation generally yields a deposit of low solids content (<15%), although slow consolidation may follow, and leads to relatively large volumes of sludge. For instance, a flow of 100 L/s containing 20 mg/L Fe would yield about 3 m^3 sludge per day. Systems of large capacity are required to provide low enough flow velocities and long enough residence times for efficient sedimentation, plus sufficient room to contain the sludge. Sequences of lagoons and wetlands are increasingly employed, in which most of the sludge is retained in one or more lagoon(s). The wetlands function as 'polishing systems' to remove fine-sized solids carried over from the lagoons.

Accretion takes place when suspended particles impact with, and adhere to, solid surfaces in contact with the flow, e.g. pipe walls, the stems of wetland plants or suspended particles. The process also occurs via surface adsorption of ferrous ions and oxygen, followed by *in situ* oxidation – an example of surface catalysis. Particles apparently adhere or adsorb over a wide range of linear water flow rates, probably up to about 4 m/s in pipes. The product is a relatively consolidated deposit of higher solids content (typically 20–25%), particularly in turbulent pipe flow which tends to anneal and dewater the deposit. When pumping raw mine water, the thickness of deposited ochre may increase by about 1–2 mm per week. To keep the pipe clear, physical cleaning by 'jetting-out' or 'pigging' can be undertaken periodically. However, different forms of chemical cleaning by use of a polyphosphate dispersant or reductive leachant may also be possible.

This paper reports briefly on recent studies to assess sludge accumulation and management in lagoons and wetlands in the UK, and to compare chemical dosing with physical methods of accretion control in pipelines.

OCHRE ACCUMULATION AND MANAGEMENT

Sampling and analysis

Table 1 summarises analyses of raw mine water and

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ochre sludge taken from 17 selected former colliery sites in England, Scotland and Wales during February–October 2001. At the time of sampling, mine water treatment was operational at all except six of the sites (itemised in the table as discharges).

Table 1 includes representative data on mine water flow and iron concentration, from which overall iron and sludge quantities could be estimated. It also includes analyses of the dried sludge for iron, manganese and the main toxic elements. These formed a basis for discussing possible applications and problems in marketing, rather than disposing of, ochreous sludge. The flow rates were estimated from meter readings, timed volumes and/or archival data. The iron concentrations were measured spectrophotometrically on-site. Similar data were obtained for a further 24 sites, not shown in Table 1. As expected, flows and concentrations (and therefore sludge quantities) varied greatly from site to site. They were also expected to vary from time to time on account of varying catchment rainfall, chance events underground and/or operational changes. Additionally, longer term drifts in concentration might or might not occur. For instance, the relatively recent pumped system at Woolley contained approximately 80, 30 and 12 mg/L Fe in 1995, 1998 and 2001, respectively, whereas the ancient gravity system at Bullhouse remained essentially stable at 55–60 mg/L Fe during at least the last decade. Notwithstanding such differences, calculations based on data relevant to operating and proposed mine water treatment schemes indicated a total production of about 2.84×10^4 t/yr raw ochreous sludge (1.56×10^3 t/yr iron content) during the next 10–30 years. This quantity will be largely confined to five geographical areas in Scotland (41%); Northumberland and Durham (5%); Lancashire (15%); Derbyshire and Yorkshire (9%) and Wales (30%). Of course, additional quantities can be

Table 1. Summary of mine water and ochreous sludge compositions at selected sites

Site	Flow	Fe	Fe	Mn	As	Cd	Pb	Zn	Cu	Ni
	L/s	mg/L	mg/g dried sludge							
Bullhouse Sump	25	56	463 510	0.09 0.24	0.035 0.068	<0.003 <0.003	0.030 <0.015	0.036 0.013	0.027 0.025	<0.005 <0.005
Sheephouse Wood Disch.	12	45	277 422	0.05 0.13	0.018 0.010	<0.003 <0.003	0.015 <0.015	0.028 0.040	0.067 0.025	0.010 <0.005
Woolley Lagoon	120	12	500 505	3.38 0.89	0.010 0.017	<0.003 <0.003	<0.015 <0.015	0.165 0.467	0.017 0.026	0.020 0.017
Silkstone Lagoon	5	17	486	0.53	0.036	0.014	0.018	0.020	0.001	0.015
Old Meadows Lagoon	60	21	336	10.3	0.096	0.014	0.017	0.322	0.010	0.282
Edmondsley Wetland	4	16	518	0.46	0.016	0.012	0.012	0.179	0.044	0.040
Fender Wetland	28	10	409	0.72	0.023	0.010	0.025	0.078	0.006	0.020
Kames Wetland	15	17	534	1.06	0.039	0.014	0.005	0.008	0.002	0.006
Polkemmet Wetland	85	69	388	2.38	0.006	0.007	0.016	0.112	0.011	0.024
Monktonhall Lagoon	30	68	235	24.3	0.003	0.004	0.013	0.196	0.012	0.329
Monktonhall Wetland	–	–	198	8.51	0.002	0.002	0.020	0.282	0.016	0.141
Morlais Discharge	120	48	499	0.99	0.050	0.015	0.017	0.039	0.001	0.014
Pontlandfraith Discharge	55	25	455	5.53	0.024	0.014	0.017	0.126	0.026	0.112
Rhymney Discharge	200	11	443	3.37	0.024	0.017	0.017	0.069	0.001	0.084
Taff Merthyr Lagoon	60	12	437	2.53	0.049	0.014	0.017	0.115	0.003	0.022
Six Bells Discharge	35	45	433	0.94	0.008	0.011	0.014	0.008	0.000	0.009
Craig y Aber Discharge	20	23	467	3.79	0.034	0.013	0.024	0.690	0.006	0.071
Ynysarwed Wetland	17	160	348	4.92	0.096	0.014	0.017	0.062	0.003	0.318

anticipated in the same general areas as new mine water treatment sites are developed.

A classical analysis of a calcined sludge sample from Woolley gave:

Fe_2O_3	89.6
SiO_2	4.14
CaO	2.56
Al_2O_3	1.06
K_2O	0.43
MgO	0.25
Na_2O	0.11
ZnO	0.11
MnO	0.095
SrO	0.078
TiO_2	0.033
P_2O_5	0.03
BaO	0.02
Total	98.52%

The comparative analytical data in Table 1 were obtained by a simpler method of sludge drying, dilute acid leaching and ICP measurement. In the interests of clarity, seven elements were selected for display out of the total of 26 or 27 determined in each case. Leachable iron was seen to comprise 40–50% of most of the dried sludges, usually (but not exclusively) from lagoon samples. The remainder contained 20–40% Fe. Thus, iron oxide contents were generally dominant but highly variable. Variability was further exemplified in the table by several analyses of sludge samples taken from the same site at different times and from different locations at the same site. For instance, the iron content at Monktonhall was some 16% greater in the lagoon than in the wetland. Other elements comprised a small fraction of the iron content, but with similar or greater variability. For instance, arsenic varied from 10–290 mg/kg Fe (Monktonhall wetland – Ynysarwed wetland), lead from 9.4–65 mg/kg Fe (Kames wetland-Bullhouse sump) and zinc from 15–1480 mg/kg Fe (Kames wetland – Craig y Aber discharge), respectively. The observed sludge variability could be attributed largely to different, unquantifiable, conditions underground. However, particular process operations can have a significant effect, e.g. at Old Meadows, where the low sludge iron content may be the result of caustic soda dosing.

The analyses above, and direct observation, highlight the quantity and quality control problems faced with ochre. The total sludge quantities may appear to be large and high in iron content, but are actually small in industrial terms, widely distributed, high in water content, variable in mineralogy, awkward to handle and of low or negative value. In particular, the small, but often significant, levels of arsenic and other toxic elements may preclude use of ochre sludge in added-value applications. Nevertheless the sludge needs to be disposed of, or utilised sustainably, as each treatment system becomes filled. The traditional method of disposal (landfill) is now very expensive, requires suitable pre-drying of sludge and is not sustainable in the long term. In principle, methods of utilisation entailing overall costs less than those of landfill merit reconsideration. Of course, regulatory issues – particularly classification of modified ochre materials as 'wastes' or 'products' – need parallel attention.

Management

Ochre has been marketed occasionally, particularly as a cement and brick additive by the former British Coal. Various other outlets have received serious consideration, including conversion to iron coagulants, utilisation in the steel industry and application as an absorbant of hydrogen sulphide in septic wastewater or in coking processes. Currently there are no consistent outlets in the UK.

To foster new approaches to industry, a survey was undertaken of brick, steel, cement and concrete works located within the five areas mentioned above. The results are summarised in Table 2. Although the table is not comprehensive, it is clear that many relevant operations are located near mine water treatment plants, particularly in ready mixed concrete. Limited progress has been made in identifying companies prepared in principle to utilise lagoon sludge in brick or concrete production, as it becomes available in sufficient quantity. Ochre can be delivered in dewatered/dried form by excavation and trucking from drying beds, or as a slurry by pumping and tankering direct from lagoons. Both options represent established technology and have well-known general advantages and drawbacks. However, specific developments seem to be essential to interface effectively with potential customers. For instance, if tankering is adopted it is likely to be important to pump the sludge at its maximum settled density (about 15–20% solids) and blend it directly with other components at a customer's site. For these purposes, modified procedures will be needed to reduce the phenomenon of 'vortexing' during pumping, and on-site testwork will be required to optimise the feed and blending processes.

Simple experiment shows that partially dewatered ochre dissolves readily in heated sulphuric acid to form a concentrated solution of iron(III) sulphate having similar properties to those of commercial coagulants used in potable water treatment. A filtered sample containing 13% Fe w/w prepared from Bullhouse ochre and tested at E.A. West (Grimsby), gave satisfactory coagulation. However, it was not consistent with BS EN 890:1999 on account of small concentrations of

Table 2. Geographic distribution of brick, steel and cement works in the mine water areas

	Bricks	Steel	Cement	Concrete
Scotland	10	2	5	21
Wales	6	4	2	16
England (Lancashire)	4	–	1	19
England (Yorkshire/ Derbyshire)	6	4	2	31
England (Northumberland/ Durham)	4	1	1	13
Totals	30	11	14	100

arsenic and (marginally) cadmium, lead and mercury. While the proportions of toxic elements might be reduced sufficiently in practice by blending with the normal plant feed, the implied risk would probably be unacceptable. Similar samples were tested as a wastewater coagulant to enhance primary sedimentation – where trace impurities would be of less consequence. Studies carried out at the Yorkshire Water Bradley Laboratory and at Silkstone STW indicated that ochre-derived and commercial coagulants enhanced primary sedimentation equally, when used in conjunction with a polyelectrolyte. Reductions in suspended solids, phosphate and COD were 3–4, 2–4 and 2–3 fold, respectively, for a dosage of 20–35 mg/L Fe and 0.3 mg/L Allied Colloids Magnafloc 155 – similar to the results of analogous experiments reported in the literature (e.g. Harlemann 1991). Unfiltered coagulants, which would be less expensive to produce, were as effective as filtered ones. Wastewater coagulation is employed at a number of locations, notably Canada and Scandinavia, and is of increasing interest in the UK for phosphate control. Thus, ochre might find an outlet in wastewater treatment if chemical dosing becomes generally more widespread.

A different study at the Imperial College Silwood Park field station in Berkshire indicates a possible application of ochreous sludge in artificial soil formulations. At Silwood Park a 200 year-old lake/wetland system accumulates ochreous sludge – similar to that in mine water wetlands – via iron leached naturally from ‘iron pan’ interlayered with sand in the surrounding Bagshot Sands (Carlile and Dudeney 2000). To avoid the lake becoming completely choked with sludge about 30–40 years from now, trials are being carried out to establish that – if the sludge can be pumped ashore and suitably mixed with local sand and wood debris – it could contribute to the surrounding growing medium without causing environmental damage. Early laboratory and field trials with the perennial grass species *Lolium perenne cv Prophet* indicate that growth is sustainable in various artificial soil compositions containing ochre, and that the ochre itself soon becomes visually indistinguishable from indigenous soil. More comprehensive trials are planned at Woolley to demonstrate the more general applicability of the technique to brownfield site restoration. The work will be based on coal spoil, ochre and digested sewage sludge, in combination with a variety of plant species typically employed in tip restoration. The main response variables will be the vigour of plant growth (in comparison with controls) and stability against metal leaching. A complementary study just beginning involves blending fine sized solids such as ochre, pfa and digested sewage sludge with coarse materials and encapsulating them in engineering foundations.

ACCRETION CONTROL IN PIPELINES

Techniques

Table 3 summarises options for controlling ochre accretions in pipelines conveying raw mine water. The physical methods of jetting and pigging have been observed over several years at the Bullhouse Mine water treatment system, where an 800 m dual Hep30 plastic pipeline (200 mm and 160 mm od) has been carrying some 25 L/s mine water containing 55–60 mg/L Fe (about 40 mg/L ferrous iron) since August 1998 (Laine and Dudeney 2000; Dudeney *et al.* 2000). Initially, high-pressure water jetting was carried out at roughly six month intervals. Access was achieved via hatchboxes located at 100 m intervals along the pipe-

Table 3. Options for managing ochre accretions in pipework

Method	Advantages	Disadvantages
Jetting	Well established and simple operation	Needs access via hatchboxes every 100 m, possible environmental hazard, problem with complicated pipe geometry
Pigging	Clean and simple operation	Needs launch and receiving equipment, possible scouring of plastic pipe surfaces, problem with complicated pipe geometry
Dispersion	Applicable regardless of pipe material or geometry	Needs dosing facilities for both dispersion and subsequent flocculation
Prevention	Applicable regardless of pipe material or geometry	Untried technology, needs new dosing equipment

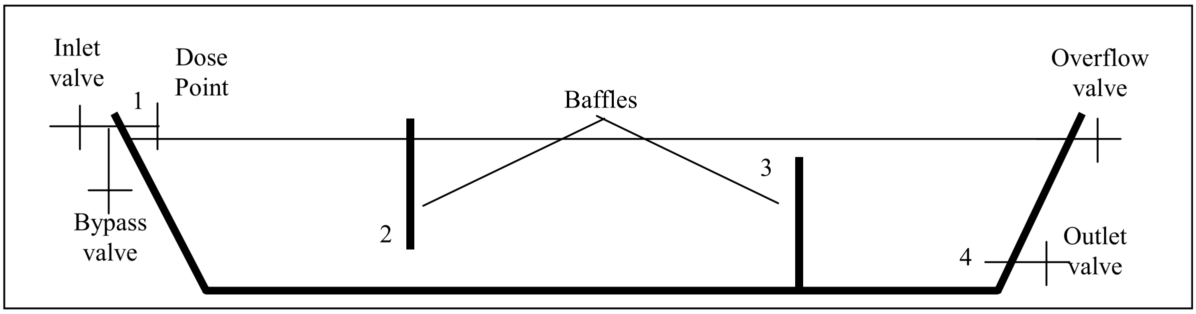

Figure 1. The 225 L tank and fittings used in dithionite dosing testwork

line. The process removed a layer of up to 2–3 cm ochre but required several days of work, created ochreous contamination at surface and could not satisfactorily reach remote parts, particularly of the 160 mm pipe. In 2001 a pigging inlet system designed by IMC Consultants was installed beside the pumphouse. This provides access to insert a pig – a composite foam and scraper construction shaped like a naval shell – into either pipeline via short detachable sections of pipe. Once re-assembled and pumping, the pig is driven along the pipeline with the water flow (1–2 m/s), removing the surface layer of ochre in the process, and is caught in a net at the far end. Pigs of slightly different diameter allow the ochre to be removed in stages. As access is required only at the beginning and end of the pipeline, the process successfully removes ochre without creating ochre spillage at surface. However, it needs carrying out more frequently (approximately monthly) than jetting, to avoid the possibility of a pig becoming wedged in thick ochre. The pigs also suffer damage, presumably on passage through the hatchboxes, around corners or at the outlet, and plastic pipework is probably subject to scouring, particularly on bends.

Chemical dosing with proprietary phosphate-based dispersants has been marketed by Applied Chemicals Ltd. Such chemicals may easily be dosed into a sump or injected directly into a pipeline and will undoubtedly remove ochre scale. However, the need subsequently to break the dispersion and sediment the ochre represents an additional cost. Dosing with reductive leachants, e.g. sodium dithionite, has received little attention, even though the technique is used widely in other sectors of industry, e.g. in china clay bleaching, to convert ochreous deposits to soluble ferrous iron. Actually, the reagent first removes residual dissolved oxygen and then reduces iron(III). The potential advantage is that a relatively small dose rate should be sufficient in many cases. This is because mine water emerging from underground is normally in a largely reduced state. Given a sufficiently small dosage, treated water exiting from the pipeline should be satisfactorily aerated in an existing cascade system, e.g. Bullhouse, or in current chemical precipitation procedures, e.g. Old Meadows, and thus obviate the need for a second dosing procedure at the pipe outlet. The objective of the work reported was to test the practicality of dithionite dosing.

Dithionite dosing

Preliminary work confirmed that small quantities of technical sodium dithionite (Merck Eurolab), dosed as a powder or solution to flowing mine water, rapidly scavenged dissolved oxygen and precluded iron oxidation and accretion, providing that the mine water was free of suspended particles. Thus, dissolved oxygen could be reduced to <10% of full saturation by means of about the theoretically required dose within a few minutes – much less than the normal residence time in the Bullhouse sump (1–2 hours) or pipeline (6–8 minutes). The de-aerated solutions could be readily re-aerated by several simple cascades, e.g. by pouring the water repeatedly from one beaker to another. Larger quantities of reagent dissolved any ochre particles in suspension and could thus prevent impact accretion. However, in this case re-aeration required ten or more cascades. On the basis of these results, a pilot-scale system (Figure 1), designed primarily to de-aerate mine water, was constructed in a wagon container beside the pumphouse at Bullhouse. The system consisted of a 225 L glass-reinforced plastic tank fitted with inlet, bypass, outlet and overflow valves, and reinforced flexible plastic pipework. Mine water was supplied as a 2 L/min. bleed from a separate valve in the pig inlet system outlined above. This gave a tank residence time of approximately two hours – similar to that of the mine water sump (which varies in the range 1–2 hours). Baffles were inserted to reduce back-mixing. Dosing was by simple gravity feed at Point 1 (Figure 1) of a solution containing 127 g sodium dithionite in 12 L water (see below). Time-course measurements of dissolved oxygen were made with a portable DO probe (not shown) inserted at set intervals at Points 1–4. Samples, normally of volume 200 mL, were withdrawn from Point 1 (inlet) and Point 4 (outlet) at suitable intervals over 22 hours for determination of pH (by probe) and iron concentration (by spectrophotometry).

The results (Table 4) show that careful dithionite dosing in the range 12–100 mg/L mine water reduced the DO of the mine water efficiently to insignificant levels (<10%), even though passage through the sump had initially increased the raw mine water DO from 42% to 63–69%. Interpolation of the data indicated that 100 mg/min (50 mg/L mine water or 100 kg/day of full scale flow) sodium dithionite would be optimal. As the DO was largely uniform at Points 2, 3 and 4 (Figure 1, Table 4), the dithionite reacted before passing the first baffle, i.e. within 40 min.

However, progressive decomposition of the dithionite stock solution occurred, as was evident from the ineffectiveness of de-aeration after 12 hours. Analysis of Samples 1–6 indicated that the mine water pH was essentially constant throughout. Despite occasional inconsistencies in analysis, the iron concentrations were also observed to be largely unchanged. However, the turbid/yellow appearance of the water after passage through sump indicated the incipient impact accretion and precipitation, and a small quantity of sediment was observed on the bottom of the tank during final clean-up.

Re-aeration was tested as outlined above. The inlet sample (equivalent to that normally aerated in the lagoon cascade) required four cascades between beakers to achieve >90% DO, while the outlet sample (initially 4–6% DO) similarly required five cascades. Thus, optimal dosing did not appreciably inhibit re-aeration, and it is probable that the lagoon cascade would achieve satisfactory re-aeration after dosing on the full scale.

Selected samples were retained for ageing (sedimentation) tests in the presence of air. Table 5 shows values of pH, iron concentration and percentage of iron sedimented in the tank inlet and outlet samples, before leaving Bullhouse (Day 0–1), at Imperial College on the three subsequent days (Days 1–2, 2–3 and 3–4) and after the Christmas break (Day 15). The results were not comprehensive and were occasionally erratic, but it was clear that >50% of the iron had precipitated after three days in all cases and essentially all had precipitated by day 15. Undosed samples sedimented relatively quickly, but not significantly more quickly, as the normal residence time in the Bullhouse lagoon is >20 days. The relatively high laboratory temperature (17°C) was of no consequence, because ochre from undosed mine water is known to sediment in the lagoon in both summer and winter. A decrease in pH was observed in all cases, particularly in the optimally dosed outlet Samples 4 and 5 (pH 3.6 and 3.7, respectively). A decrease to pH 4.2–5.0 is normal in the lagoon, as reflected in the aged inlet samples. However, the effects of pH <4 would need careful evaluation,

Table 4. Results of systematic dithionite dosing of 2 L/min post-sump mine water at 10°C

Spl. no	Elapsed time (hours)	Dithionite dose rate (mg/min)	Dissolved oxygen (%)				pH (inlet)	pH (outlet)	Fe(II),Fe(T) (inlet) (mg/L)	Fe(II),Fe(T) (outlet) (mg/L)
			1*	2	3	4				
1	0	42	63	–	–	69	5.7	5.8	24, 52	28, 58
	2	26	–	48	48	50				
2	3	26	63	–	–	58	5.9	6.0	39, 55	26, 53
	4	93	–	36	37	41				
3	6	70	–	34	33	35	5.9	5.9	44, 57	41, 54
4	8	162	–	4	4	5	5.9	5.9	47, 60	36, 57
	9	128	–	4	4	6				
	12	93	–	10	10	11				
5	13		69	14	14	15	5.9	5.8	40, 60	37, 56
	14		–	22	21	23				
	16	70	–	38	37	38				
	18	116	–	47	44	43				
	19	313	–	45	44	46				
6	22	zero	67	67	66	65	–	6.0	–	–
Adit	–	–	42**				5.9**		47, 58**	

*Numbers refer to points in Fig. 1. **Figures relate to pre-sump adit (sump inlet) sample.

Table 5. Results of ageing of mine water samples in air before and after dithionite dosing

Age/days	T/°C		Adit	Inlet samples	Outlet samples					
					1	2	3	4	5	6
0–1	7	pH	5.7	5.9	5.8	6.0	5.9	5.9	5.8	–
		Fe(II)	47	24–47	28	26	41	36	37	–
		Fe(T)	58	52–60	58	53	54	57	58	–
		%ppt	Insignificant							
1–2	16	pH	6.0	6.0	6.2	6.1	6.2	6.0	6.0	6.1
		Fe(II)	31	31	35	31	26	32	29	35
		Fe(T)	54	52	47	50	44	47	45	54
		%ppt	7	13	19	6	19	18	22	–
2–3	17	pH	5.9	5.9	5.8	5.9	5.9	5.9	5.9	5.9
		Fe(II)	17	17	13	26	21	22	18	21
		Fe(T)	31	30	19	35	31	32	30	42
		%ppt	47	50	67	34	43	47	48	–
3–4	17	pH	5.4	5.4	5.2	5.3	5.3	5.3	5.3	5.4
		Fe(II)	6	6	2	12	2	11	16	16
		Fe(T)	10	9	4	24	22	16	25	29
		%ppt	83	85	93	55	56	72	57	–
15	17	pH	4.7	4.9	5.0	4.4	3.9	3.6	3.7	4.0
		Fe(II)	0.2	0.1	–	0.1	–	0.2	0.0	–
		Fe(T)	0.1	0.0	–	0.1	–	0.7	0.3	–
		%ppt	Essentially all							

particularly with regard to the buffer capacity of the Upper River Don. Thus, dosing had slightly negative but probably not prohibitive effects on sedimentation.

The results show that sodium dithionite dosing can, in principle, be used to keep pipelines free of ochre accretions by reversibly de-aerating raw mine water. Under optimal conditions, surprisingly little detriment to ochre separation seems likely. Subsequent precipitation by aeration (as at Bullhouse) or alkali addition (as at Old Meadows) would apparently be feasible. However, the reagent presents a number of problems: it now has to be imported at premium prices (nominally £3–4 K/tonne); although readily handled, it requires special dosing equipment to ensure an optimal dose rate; and it does not limit impact accretion or adsorption by suspended particles unless dosed in excess – under which circumstances subsequent ochre precipitation is inhibited.

CONCLUSIONS

In conclusion, the technique can only be recommended in special cases where emergent mine water contains very little suspended solid and physical cleaning methods fail, e.g. in pipelines which have complicated geometry and/or are blocked with hardened ochre. Despite the problems mentioned here relating to physical cleaning, pigging and subsidiary jetting continue to represent the state-of-the-art, and systems having simple geometry should be designed to accommodate them.

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