Mine Water Environ (2011) 30:216–230
DOI 10.1007/s10230-011-0142-8

TECHNICAL COMMUNICATION

Lime Treatment of Mine Drainage at the Sarcheshmeh Porphyry Copper Mine, Iran

Mehdi Khorasanipour · Farid Moore ·
Reza Naseh

Received: 25 November 2010 / Accepted: 11 February 2011 / Published online: 23 February 2011

Abstract Laboratory and field treatment tests were performed to evaluate the effectiveness of lime treatment for mitigation of environmental effects of acid mine drainage (AMD) at the Sarcheshmeh porphyry copper mine. AMD associated with the rock waste dumps is contaminated with Al (>36,215 μg/L), Cd (>105 μg/L), Co (>522 μg/L), Cu (>53,250 μg/L), Mn (>42,365 μg/L), Ni (>629 μg/L), and Zn (>12,470 μg/L). The concentrations of other metals (Fe, Mo, Pb, and Se) are low or below detection limits (As, Cr, and Sb). Due to the very high Al and Mn content and the low concentration of Fe, a two-stage lime treatment method was chosen for the laboratory tests. In the first stage, the AMD was treated at four pH set points: 7.5, 8.9, 9, and 10. In the second stage, after removing the sludge at pH 9, treatment was continued at pH 10 and 11. The results indicated that a two-stage treatment method was not necessary because elements such as Al, Cu, Co, and Zn were easily treated at pH 7.5, while complete removal of Cd, Mn, and Ni only required a pH of 10. Increasing pH during the treatment process only caused a slight increase in Al. Field treatment tests support the laboratory results. Lime treatment of highly contaminated AMD from dump 11, using simple low density sludge pilot scale equipment, show that contaminant metals are treatable using this method. The mean treatment efficiency for contaminant metals was 99.4% for Al, % for Cd, 99.6% for Co, 99.7% for Cu, 98.5% for Mn, 99.7% for Ni, 99% for U, and 99.5% for Zn. The optimum pH for AMD treatment by lime was in the range of 9–10. The produced sludge in the treatment process was highly enriched in the contaminant metals, especially Cu (>7.34%), Al (>4.76%), Mn (>2.94%), and Zn (>1.25%). A correlation coefficient matrix indicates that the distribution pattern of the contaminant metals between soluble and precipitated phases is consistent with the hydrochemical behavior of the metals during the lime treatment process.

Keywords Acid mine drainage · Contaminant metals · Sarcheshmeh porphyry copper mine

Introduction

Despite the tremendous appeal of passive treatment, most acid mine drainage (AMD) generated at active mining operations is still treated chemically, in ‘active’ treatment systems, because the effluent quality must consistently meet strict discharge standards. At most sites, this involves the addition of chemical neutralization agents (Coulton and Bullen 2003; Hilson and Murck 2001) such as soda ash, ammonia, caustic soda, pebble quick lime, and hydrated lime (Environment Australia 1997; Kuyucak 2006; SRK et al. 1989; US Department of the Interior 2002; Ziemkiewicz and Skousen 1996). Every mine is unique in terms of mine water characteristics, such as pH, TDS, and trace metal contaminants; thus, the nature and extent of the associated risk, and the feasibility of environmental management approaches and mitigations options vary from site to site (Akcil and Koldas 2006; Kuyucak 2006). Lime [$Ca(OH)_2$] is often preferred over other alkaline reagents (Aubé et al. 2003; Kuyucak 2006; Silverira et al. 2009),

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M. Khorasanipour (✉) · F. Moore
Department of Earth Sciences, College of Sciences,
Shiraz University, 71454 Shiraz, Iran
e-mail: Khorasani_283@yahoo.com

R. Naseh
Research and Development Division,
Sarcheshmeh Copper Complex, Kerman, Iran

due to its high efficiency in removal of dissolved heavy metals, relatively low cost, and insensitivity to seasonal temperature fluctuations (Skousen et al. 1990). The principal reaction in the lime neutralization process can be expressed as:

$$\begin{aligned}&\mathrm{Ca(OH)_{2(S)}} + \mathrm{Me^{2+}/Me^{3+}_{(aq)}} + \mathrm{H_2SO_4}\\&\leftrightarrow \mathrm{Me(OH)_2/Me(OH)_{3(S)}} + \mathrm{CaSO_{4(S)}} + \mathrm{H_2O}\end{aligned}$$

The resulting mixture of $CaSO_4$ (gypsum) and metal hydroxides is typically referred to as 'sludge'. Sludge normally contains a significant amount of water and can contain a high amount of contaminant metals.

The AMD generated at the Sarcheshmeh porphyry copper mine is unusual in that it has relatively low concentrations of Fe, and relatively high concentrations of Al, Cd, Co, Cu, Mn, Ni, and Zn. We conducted laboratory and field treatability tests to investigate how lime treatment could be used to efficiently remove these metals from AMD.

Geology and Site Characteristics

One of the largest porphyry copper deposits in the world is located within the central Iranian volcano-plutonic copper belt, 160 km southwest of Kerman (30°N, 56°E) (Fig. 1a). The geology of this area is dominated by Eocene basic to intermediate volcanic rocks including trachybasalt, trachyandesite, and/or andesite (Dimitrijevic 1973) (Fig. 1b). Mineralization at this Sarcheshmeh deposit mainly forms stockworks and veins that are equally distributed between Eocene volcanic and Oligo-Miocene quartz diorite, quartz monzonite, and granodiorite units (Anonymous 1973; Atapour and Aftabi 2007; Bazin and Hubner 1969; Dimitrijevic 1973; Etminan 1977; Hezarkhani 2006; Shahabpour 1982). The ore body (2,000 m × 900 m) contains 800 M tonnes of ore averaging 1.13% Cu and 0.03% Mo at a cutoff grade of 0.4% Cu (Waterman and Hamilton 1975).

The Sarcheshmeh area is located in an arid to semi-arid region of Iran with mean annual temperatures ranging between −20 and 32°C. The mean annual rainfall is 440 mm and the mean annual evaporation is about 1,170 mm (Sahraei et al. 2005). The Shour stream is the main recipient of the mine effluents including the AMD and industrial wastewaters of the Sarcheshmeh copper complex. This stream discharges into the tailing dam about 18 km north of the mine (Fig. 1b). Rock waste and low oxide ores are usually dumped in natural valleys in the vicinity of the mine. These waste dumps are the principal source of the AMD. Field indicators, such as colorful yellow–red–brown efflorescence and filamentous algae, are well developed in some rock waste drainages and clearly demonstrate the presence of acidic water (Fig. 2).

To date, no study has been carried out on the treatment options for these contaminated waters, especially the highly contaminated AMD of the Sarcheshmeh copper mine. Considering the source and volume of AMD and site-specific characteristics, such as mine topography, extreme annual temperature variations, distance between the mine and the industrial complex, and space limitations, passive treatment is not feasible. Active treatment, especially lime treatment, has many advantages. For example, the treated water can easily be used by the Sarcheshmeh copper complex, and the produced sludge can be mixed with tailings, and transported to the tailings dam.

Materials and Methods

Sampling

Raw AMD was characterized by sampling and analyzing collected samples from five stations (Fig. 1c). As already mentioned, the AMD at the Sarcheshmeh mine is mainly associated with rock waste dumps. Parameters such as pH and electrical conductivity (EC) of water were measured in situ using a multiparametric device (Toledo MP-120 model). Collected samples were immediately filtered through 0.45 μm filter paper (ALBET, Nitrato Celulosa, model), acidified with 63% HNO_3 (to $pH < 2$) and stored at 4°C until analysis. Filtered, unacidified samples were also collected and sent for anion analysis. Finally, unfiltered sub-samples were collected at each station for acidity and alkalinity measurements.

Laboratory Tests

In order to find the optimal pH for precipitation of the pollutant metals, laboratory stepwise tests were conducted in the central laboratory of the Sarcheshmeh copper complex over a wide pH range, at 7.5, 8.5, 9, and 10. Shahabpour and Doorandish (2007) showed that the Mn concentration in the Sarcheshmeh copper mine drainage water is very high. Manganese in its hydroxide form normally starts to precipitate at pH 9.5 or higher (Skousen et al. 1990). On the other hand, high pH values can cause some precipitated elements such as Al to redissolve. Some authors (Skousen et al. 1998) believe that for waters that are high in both Mn and Al, a two stage treatment system may be required. This was tested by first treating the water to a pH of 9 and then, after the precipitated sludge was removed, increasing the pH to 10 and 11. For this purpose, a 5% lime slurry suspension was used to adjust the pH. For each set point of pH, nearly 4 L of raw AMD was used. In order to determine the hydrochemical behavior of the contaminant metals, at each pH, treated water and sludge were separated using gravity separation

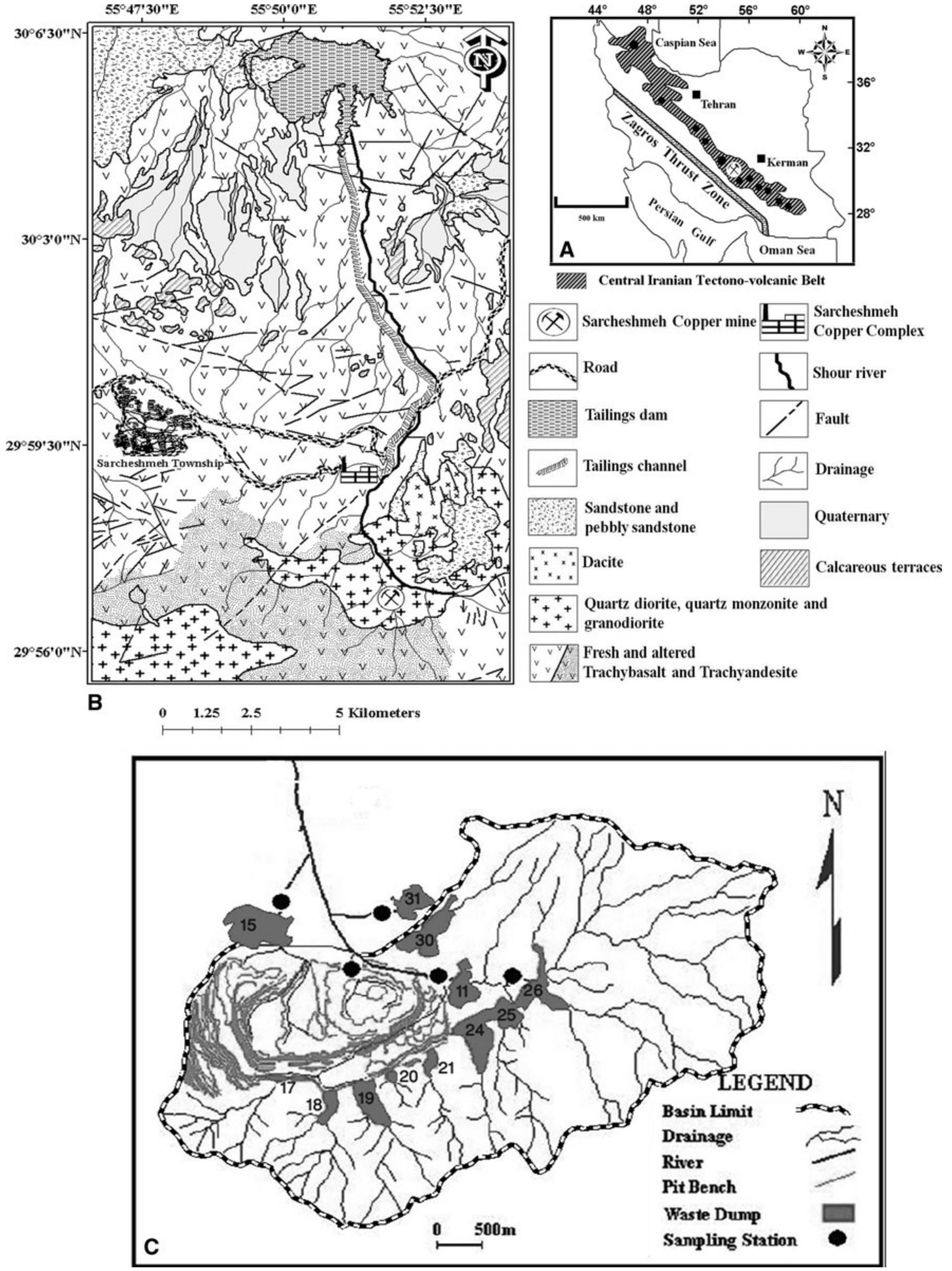

Fig. 1 **a** Location of the Sarcheshmeh porphyry copper mine in the central Iranian volcano-plutonic belt (modified after Shahabpour and Kramers 1987), **b** geologic map showing characteristics of the Sarcheshmeh area (modified after Dimitrijevic 1973), and **c** the Sarcheshmeh pit basin showing AMD sampling locations (modified after Sahraei et al. 2005)

(settling for 2 h) and then centrifuged at 2,500 rpm. The supernatant was filtered through 0.45 μm (ALBET, Nitrato Celulosa, model), and stored for cation and anion analysis. Also, unfiltered treated water samples were taken for acidity and alkalinity measurements. Sludge samples were dried (<50°C) and then digested in aqua regia.

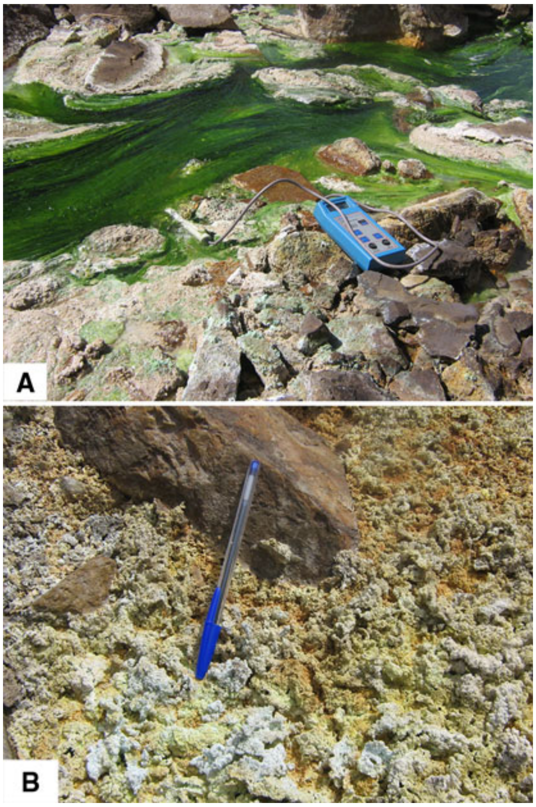

Fig. 2 Field indicators of AMD from rock waste drainages: **a** filamentous algae and secondary minerals and **b** evaporative yellow–red–brown precipitates

Field Treatment Tests

In order to find the efficiency of lime treatment in the field, simple, low-density pilot scale equipment was designed and constructed. As shown in Fig. 3, the equipment basically consists of five tanks of different sizes and a clarifier. All parts of the equipment, including tanks, pipes, pumps, mixers, and aerators, were made from non-corrosive material. Aeration and flocculating (50 mg/L solution of FLOPAM CU 43U) steps were added to the treatment process, and the sludge was recycled by pumping it into the lime slurry tank.

Appropriate chemical treatment depends on both the oxidation state and the concentration of metals in the AMD (US EPA 1983). By oxidizing Fe, As, and Mn, aeration can produce more stable sludge and improve metal removal and treatment efficiency (Kuyucak 2006). Aeration was carried out on the raw AMD and in the flocculation mixing tanks. Field treatability tests were conducted on the AMD from dump 11, based on considerations such as the hydrochemical characteristics of the AMD, accessibility, and availability of electrical power. Field treatability tests were carried out for a week. Each day, the raw AMD, treated water, and sludge were sampled in order to determine treatment efficiency and metal removal. Also, in order to determine the hydrochemical behavior of contaminant metals, the pH set points of the treated water were kept in the range of 9–11. Raw AMD samples were filtered (0.45 μm) and prepared for cation and anion analysis. Also, unfiltered samples were collected for acidity and alkalinity analysis. For comparison with laboratory test results, treated waters from the field tests were collected from the clarifier without centrifuging or filtering, and were sent for analysis. During the treatment period, about 1 L of sludge was collected each day. Sludge samples were dried (<50°C) and after weighing, a fraction was digested in aqua regia.

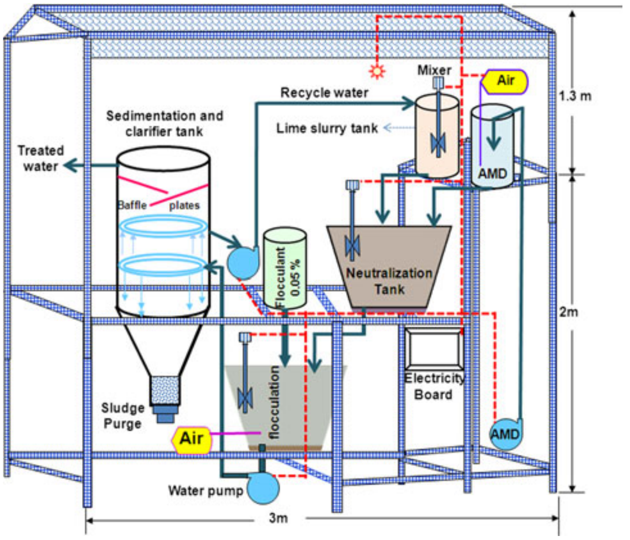

Fig. 3 Schematic presentation of the field AMD treatment test set-up

Analytical Methods

Major cations and trace metals concentrations were determined for the raw AMD and treated water samples using ICP-MS at the accredited Acme Analytical Laboratories, Vancouver BC, Canada. The detection limits for the selected elements are listed (Table 1). Sulfate, bicarbonate, and chlorine were determined using spectrophotometry, titration, and Mohr's methods, respectively. Alkalinity and acidity of raw and treated water were determined using the titration methods proposed by Kirby and Cravotta (2005). Contaminant metals content in the sludge samples were also determined by Acme Analytical Laboratories.

Results and Discussion

Field investigations revealed that AMD in the Sarcheshmeh copper mine was associated with the rock waste dumps. Of

Table 1 Laboratory lime treatment results of contaminant metals (μg/L) for AMD including rock waste drainages and pit mine water during the first (raw AMD to pH 10) and second treatment stages (pH 10 and 11)

Treatment pH	Al	As	Cd	Co	Cr	Cu	Fe	Ni	Pb	Sb	Se	U	Zn
AMD dump 26													
4.1	12,748	0.5	120.75	231.14	0.5	38,383	44	275.6	1.6	1.59	13.2	9.36	9,213
7.5	13	<0.5	103.88	195.18	1.8	202.6	24	221.5	<0.1	1.16	13.2	0.11	5,335
8.5	55	<0.5	56.96	126.09	1.9	53.9	<10	140.4	<0.1	1.16	12.3	0.09	435.4
9	73	0.6	42.57	86.68	0.6	21.3	<10	99.1	<0.1	0.92	12.3	0.09	129.4
10	140	<0.5	<0.05	0.2	<0.5	<0.1	<10	<0.2	<0.1	<0.05	12.00	<0.02	3
10	<1	<0.5	<0.05	0.3	<0.5	<0.1	<10	3	<0.1	<0.05	12.20	<0.02	8
11	<1	<0.5	<0.05	0.2	<0.5	<0.1	<10	5	<0.1	<0.05	12.50	<0.02	5
AMD dump 11													
3.4	43,620	<0.5	144	385	<0.5	76,000	620	962	1.0	<0.05	19.70	22.9	12,225
7.5	<1	<0.5	111	222	<0.5	<0.1	<10	409	0.3	<0.05	18.90	<0.02	4,132
8.5	60	<0.5	9.2	20.4	<0.5	<0.1	<10	50	<0.1	<0.05	18.50	<0.02	25
9	95	<0.5	2.2	0.8	<0.5	<0.1	<10	37	<0.1	<0.05	18.90	<0.02	22
10	250	<0.5	<0.05	0.5	<0.5	<0.1	<10	2	<0.1	<0.05	18.20	<0.02	10
10	<1	<0.5	<0.05	0.7	<0.5	<0.1	<10	3	<0.1	<0.05	19.10	<0.02	7
11	<1	<0.5	<0.05	0.4	<0.5	<0.1	<10	4	<0.1	<0.05	18.80	<0.02	3
Mine pit water													
6.5	<1	6	<0.05	24.4	<0.5	<0.1	6,140	15	0.7	<0.05	<0.5	<0.02	285
7.5	<1	<0.5	<0.05	<0.02	<0.5	<0.1	<10	10	<0.1	<0.05	0.44	0.3	5
8.5	<1	<0.5	<0.05	<0.02	<0.5	<0.1	<10	8	<0.1	<0.05	0.25	0.3	12
9	<1	<0.5	<0.05	<0.02	<0.5	<0.1	<10	3	<0.1	<0.05	<0.5	<0.02	5
10	<1	<0.5	<0.05	<0.02	<0.5	<0.1	<10	<0.2	<0.1	<0.05	0.13	<0.02	4
10	<1	<0.5	<0.05	<0.02	<0.5	<0.1	<10	<0.2	<0.1	<0.05	0.29	<0.02	4
11	<1	<0.5	<0.05	<0.02	<0.5	<0.1	<10	<0.2	<0.1	<0.05	0.22	<0.02	6
AMD dump 31													
3.7	66,980	<0.5	195	1,386	<0.5	104,000	1,000	1,264	14.0	<0.05	8.00	79.8	31,533
7.5	80	<0.5	94.5	554	<0.5	<0.1	<10	449	<0.1	<0.05	4.98	<0.02	1,643
8.5	60	<0.5	2.9	1	<0.5	<0.1	<10	5	<0.1	<0.05	5.06	<0.02	8
9	60	<0.5	0.6	1.1	<0.5	<0.1	<10	<0.2	<0.1	<0.05	5.30	<0.02	4
10	60	<0.5	0.5	1.5	<0.5	<0.1	<10	4	<0.1	<0.05	5.19	0.3	8
10	<1	<0.5	<0.05	0.6	<0.5	<0.1	<10	4	<0.1	<0.05	5.37	<0.02	4
11	<1	<0.5	<0.05	0.7	<0.5	<0.1	<10	<0.2	<0.1	<0.05	5.39	<0.02	3
AMD dump 15													
3.3	11,943	1.1	7.19	75	0.8	14,604.5	469	79.4	4.6	1.44	3.9	1.42	783.6
7.5	11	0.6	6.09	65.92	0.7	202.8	102	68.8	0.1	1.35	3.6	<0.02	360.7
8.5	24	0.9	2.38	37.02	0.5	36.3	<10	41.2	<0.1	1.51	3.7	0.02	45.8
9	59	0.5	1.91	31.81	0.5	12.9	<10	36.6	<0.1	1.19	3.6	<0.02	23
10	120	<0.5	<0.05	0.6	<0.5	<0.1	<10	3	<0.1	<0.05	3.44	<0.02	7
10	<1	<0.5	<0.05	0.3	<0.5	<0.1	<10	<0.2	<0.1	<0.05	3.25	<0.02	9
11	<1	<0.5	<0.05	0.3	<0.5	<0.1	<10	3	<0.1	<0.05	3.39	<0.02	6
US EPA (2009)	50	10	5	100	100	1,000	300	–	–	6	50	30	5,000
WHO (2006)	–	10	3	–	50	–	–	20	10	18	10	15	–

the 32 waste dumps located in natural valleys surrounding the mine, only dumps 11, 15, 26, and 31 discharge considerable AMD, mostly during wet seasons. The pH of the AMD ranges from 3.3 to 4.1 (Table 1). Due to continuous pumping of water from the Sarcheshmeh open pit, the pH of the mine pit water is near-neutral, though it contains high levels of metals. Apparently, only slight oxidation of sulfide minerals occurs below the water level and few metals are leached from above, resulting in environmentally non-aggressive mine water, although acidic water, rich in toxic

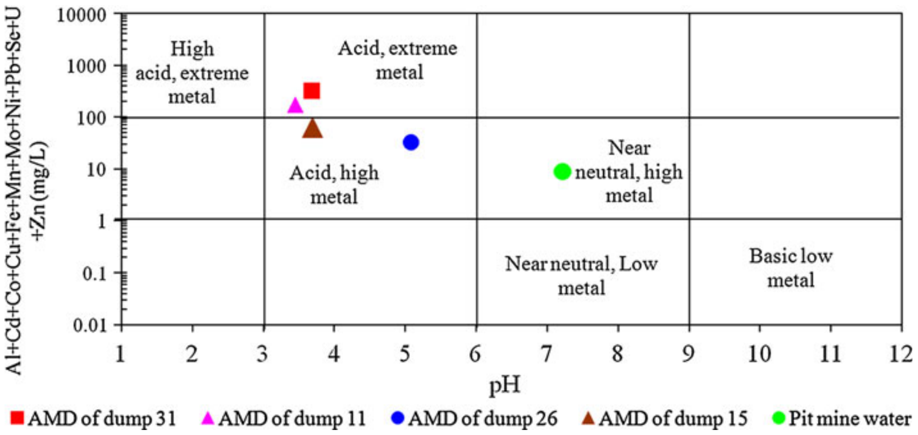

Fig. 4 AMD from Sarcheshmeh plotted on Fichlin et al. (1992) diagram based on pH and metal content (Al + Cd + Co + Cu + Fe + Mn + Mo + Ni + Pb + Se + U + Zn)

metals, will likely be generated if the pumps are turned off and the level of water rises in the pit (Banks et al. 1997; Gammons et al. 2005). The raw AMD from the Sarcheshmeh dumps are categorized as "high metal" or even "extreme metal," according to the classification proposed by Fichlin et al. (1992), which is based on pH and metal concentrations (Fig. 4).

The quality of drainage from mine waste is a function of waste composition, which is variable even within a mine site (Lapakko 2002). The Sarcheshmeh raw AMD contained very high concentrations of Al, Cd, Co, Cu, Mn, Ni, and Zn, while concentrations of elements such as As, Mo, Sb, Se, Fe, and Cr were very low or below detection limits in most of the samples. Molybdenum in AMD can readily hydrolyze and often precipitates as ferrimolybdate (Levinson 1980; Nickel et al. 1979). Dissolved As species also adsorbs onto and precipitates with Fe^{3+} hydroxides, which is an efficient arsenic removal mechanism (Foster et al. 1998; Roddick-Lanzilotta et al. 2002). AMD from dump 31 was the most contaminated sample, with high concentrations of Al (66,980 µg/L), Cd (195 µg/L), Co (1,386 µg/L), Cu (104,000 µg/L), Mn (109,000 µg/L), Ni (1,264 µg/L), U (79.8 µg/L), and Zn (31,533 µg/L).

Laboratory Treatment Results

All AMD sources and the mine pit water were investigated in laboratory treatment tests. Sludge production and lime slurry consumption to reach predefined pH set points were both directly related to the AMD pollution load (Fig. 5a, b). The degree of contamination and metal load of the raw AMD in dump drainages display the following decreasing order: dump 31 (pH = 3.6) > dump 11(pH = 3.4) > dump 26 (pH = 4.1) > dump 15 (pH = 3.3) > mine pit water (pH = 6.5–7).

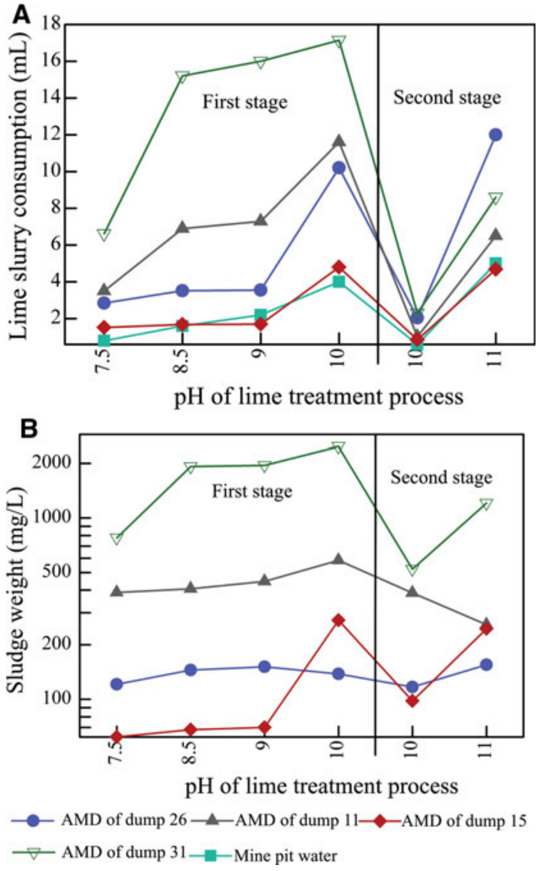

Fig. 5 Lime slurry consumption (**a**) and sludge production (**b**) during the laboratory lime treatment tests

Lime slurry consumption and sludge production correlated well with the metal pollution load. It is clear that a large portion of the alkalinity agent (OH^-) is consumed in removing the metals as hydroxide precipitates.

In order to evaluate the effectiveness of lime treatment in removing contaminant metals from AMD, the

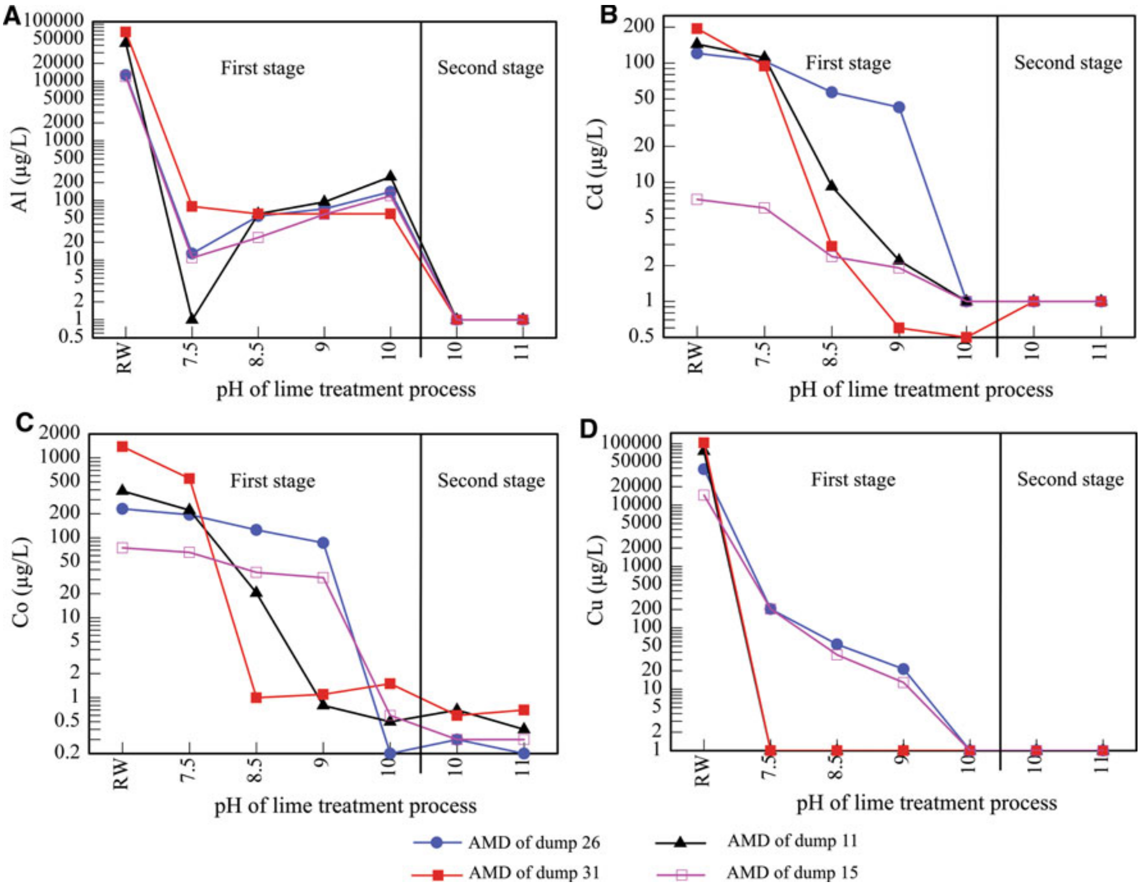

Fig. 6 Treatability trend for Al, Cd, Co, and Cu in laboratory lime treatment tests; the pH of the untreated raw water (RW) was 4.1 for dump 26, 3.4 for dump 11, 3.7 for dump 31, and 3.3 for dump 15

treatability results (Table 1) were compared with drinking water guidelines proposed by the US Environmental Protection Agency (US EPA 2009) and World Health Organization (WHO 2006). The treatment efficiency of AMD depends on many factors, such as the oxidation state of metals, pH of AMD, hydrolysis reactions, metal concentration, alkalinity, and acidity (Kirby and Cravotta 2005). Also, the concentration of metals (such as Fe, Al, and Mn) profoundly affects the treatment process and metal removal efficiency (Hedin et al. 1994; Skousen et al. 1998). The Sarcheshmeh AMD is characterized by very high concentrations of Al, Cd, Co, Cu, Mn, Ni, and Zn. According to Stumm and Morgan (1981), each contaminant metal precipitates at a different pH range. Thus, the optimum pH for AMD treatment is site specific.

The concentrations of Al, Cd, Co, and Cu in the mine pit water were very low, and generally below detection limits, while in rock waste drainage, the concentrations were very high. Figure 6 shows the treatability behavior of these elements during the lime treatment process. Most Al-bearing minerals are soluble at low pH, and relatively low concentrations of dissolved Al can be toxic to some organisms (Elder 1988). Al precipitates as a hydroxide at pH 5.5, but begins to redissolve when the pH is increased above 8.5 or 9 (Kuyucak 2006). Treatment results show that maximum removal efficiency of Al was reached at pH 7.5. During the first stage of treatment, at increasing pH from 7.5 to 10, a slight increase in Al concentration was observed for most of the treated waters. However, if the sludge was removed, the Al concentration remained below the detection limit ($<1\ \mu gL^{-1}$) during the second stage of treatment, even at pH 11. It has already been noted that Al can be removed from water by keeping the pH between 5 and 8, where $Al(OH)_3$ is highly insoluble, and that oxidizing or reducing environments has no effect on Al concentrations (Costello 2003).

In most AMD samples (except for the AMD from dump 26), Cd was readily removed at pH 9. In the first stage of treatment, the concentration of Cd was lowered below both guideline values and detection limits. In some reported cases, such as at the Samatosun treatment plant, lime neutralization at pH 10.5 is required to reduce Cd concentration to $<0.01\ mgL^{-1}$ in treated tailings water (Kuyucak 2006).

Co values in all AMD waters were reduced to acceptable level at the end of the first stage of treatment at pH 9 (in some cases, pH 8.5).

The more oxidized Cu^{2+} is the dominant form of Cu in natural waters (Cotton and Wilkinson 1988). In some cases, such as drainage from dump 31, the concentration of Cu in the raw AMD reaches 104 mg/L. Yet, the Cu content was reduced below detection limits and a considerable fraction of the dissolved Cu was precipitated as a hydroxide when the pH was increased to pH 7.5.

Figure 7 presents treatability trends for Mn, Ni, and Zn in the AMD and mine pit water. While Mn can theoretically exist in numerous states, only Mn^{2+} and Mn^{4+} are relatively stable in natural waters (Stumm and Morgan 1970). This element forms oxide, hydroxide, or carbonate compounds depending on pH and Eh conditions (Ehrlich 1990). Precipitation of Mn as a hydroxide is variable due to its oxidation state, but will generally occur at pH 9–9.5 (Skousen et al. 1990). In some cases, complete removal of Mn is very difficult to attain and may requite a solution pH of 10.5, which can cause other elements, such as Al, to redissolve (Kuyucak 2006).

As already mentioned, Mn concentrations in the Sarcheshmeh mine waters were very high, even at neutral pH (Table 1), compared with drinking water guidelines. Laboratory test results showed that a high pH (pH 10) was required to decrease the concentration of Mn to acceptable levels. Mn concentrations did not differ considerably at pH set points of 7.5, 8.5, and 9 during the first stage of treatment in the AMD from dumps 26 and 15. In contrast, Ni concentrations in AMD from dumps 26, 11, and 15 decreased to an acceptable level (<20 μg/L) at pH 10.

The concentration of Zn readily reached acceptable levels, even at a pH of 7.5, although with increasing pH, the concentration of Zn decreased dramatically. Zinc can form complexes with numerous anions in aerobic natural waters, but those that influence Zn solubility are carbonate and hydroxyl ions (Morel and Hering 1993).

In general, the laboratory test results indicated that a two-stage lime treatment was not necessary for treating most metals. Only Mn, Ni, and Cd required higher pH values (≈10) to reach acceptable concentrations. According to Kuyucak (2006), a pH range of 10.5–11 is needed to effectively precipitate Cd and Ni as a hydroxide.

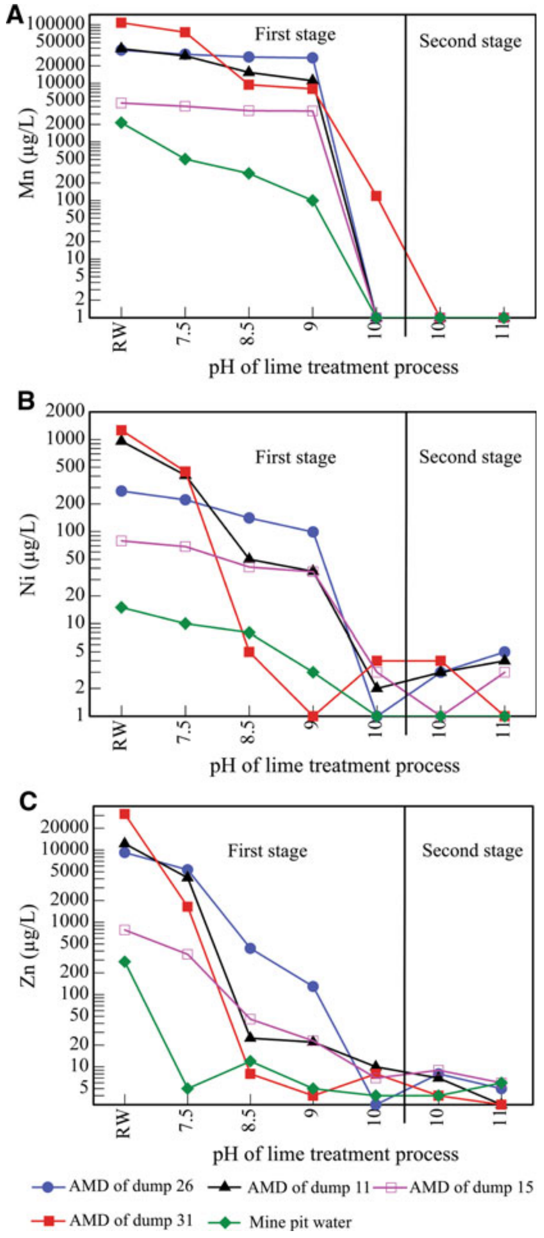

Fig. 7 Treatability trend for Mn, Ni, and Zn in laboratory lime treatment tests; the pH of the untreated raw water (RW) was 4.1 for dump 26, 3.4 for dump 11, 3.7 for dump 31, 3.3 for dump 15, and 6.5 for the pit water

Fe and U in some AMD, such as dumps 31, 11 and the pit water, were higher than acceptable values, even though, when compared with other analyzed metals, their concentrations were not considerable. Both metals were readily removed at pH 7.5. Lime treatment efficiency was observed to increase for samples with higher Fe content. For example, efficiency for precipitating Cd, Co, Cu, and Zn was better for AMD from dumps 31 and 11. When AMD is generated, iron is generally present in the ferrous state (the more soluble form) but exists in the ferric state in acid, oxidizing conditions (Nordstrom and Alpers 1999; Rose and Cravotta 1998). Ferric iron precipitates at a pH of 3.5 or higher as oxy-hydroxide compounds (Costello 2003). This reaction tends to control the mobility and availability of other metals through sorption and co-precipitation processes (Skousen et al. 1990). Unfortunately, iron concentrations in Sarcheshmeh AMD are low and some metals, such as Mn, Ni, and Cd, tend to remain in solution even at high pH values (≈10). Skousen et al.

(1990) demonstrated that Mn can be mostly removed from water at pH 8 if the Fe concentration in water is at least four times that of the Mn.

As, Cr, Mo, Pb, Sb, and Se had low concentrations in Sarcheshmeh AMD. With increasing pH in the laboratory lime treatment tests, the concentration of these elements either fell to below detection limits (Cr and Pb) or did not change considerably (As, Cr, Mo, Sb, and Se). Arsenic and Mo are not easily controlled by pH (lime treatment) and must be co-precipitated with other metals, typically ferric iron or base metals, such as Cu and Zn (Aubé et al. 2003). Also, elements such as As, Mo, Sb, and Se usually require additional chemicals (Kuyucak and Payant 1996). Fortunately, due to the low concentration of these elements, they do not pose an environmental concern at the Sarcheshmeh copper mine.

In evaluating the lime treatment process, other water characteristics, such as EC, TDS, TH, HCO^{3-}, CO_3^{2-}, SO_4^{2-}, alkalinity, acidity, and Cl were also determined (Table 2). In general, with increasing pH, the EC, TDS, and TH also increased, although the differences in the first stage of treatment were not considerable. For all treated AMD samples, the maximum increase in EC, TDS, and TH occurred at a pH of 11 in the second stage of treatment. The concentration of Cl and SO_4^{2-} ions did not change considerably. The fact that lime treatment does not lower SO_4^{2-} concentrations below a relatively high concentration is a disadvantage. Even though several methods, such as precipitation with barium, ion exchange, biological sulfate reduction, and aluminum hydroxide are available to reduce SO_4^{2-} concentrations (Kuyucak 2000), these methods are not used widely to treat mine effluents due to technical or economical constraints (Kuyucak et al. 2001).

The acidity (as mg/L $CaCO_3$) of raw AMD is strongly related to its metal load. Among the investigated AMD samples, water from dumps 31 and 11 had the highest acidity (1,150 and 890 as mg/L $CaCO_3$, respectively). It is noteworthy that the pit water (pH 7) had a higher acidity than AMD from dump 15 (pH 3.3). Cravotta III et al. (1999) suggest that metal-laden mine waters with considerable alkalinity or acidity are important because pH can increase or decrease after equilibrium with the atmosphere. The acidity of near-neutral AMD results mainly from the potential for hydrolysis of dissolved Fe^{2+}, Fe^{3+}, Al, and Mn^{2+} and the precipitation of associated solid hydroxide compounds (Cravotta III and Kirby 2004).

Field Treatment Tests

Field treatment tests were conducted for a week on the AMD from dump 11. The mean pH of raw AMD and treated waters were 3.3 and 10, respectively. Raw AMD samples from dump 11 were highly polluted, containing 49,985.1 μg/L Al, 208.7 μg/L Cd, 508.6 μg/L Co, 85,287.7 μg/L Cu, 51,103.3 μg/L Mn, 1,375.1 μg/L Ni, 18.8 μg/L U, and 14,041.1 μg/L Zn (mean values). Table 3 shows the lime treatment results and indicate that the pilot equipment can effectively remove contaminant metals from AMD. The treatment efficiency for most contaminant metals was higher than 99%. The mean treatment efficiency values were 99.4% for Al, 99% for Cd, 99.6% for Co, 99.7% for Cu, 98.5% for Mn, 99.7% for Ni, 99% for U, and 99.5% for Zn. Treated samples were collected from the clarifier and sent for analysis without filtering or centrifuging; thus, some minuscule particles of sludge were probably present in the treated samples. The treatment efficiency, especially for elements like Al and Mn, would undoubtedly increase if the treated waters were filtered. In comparison with guideline values, the concentration of Cd, Co, Cu, Ni, U, and Zn in the treated samples were below drinking water standards, while in some cases, the Mn content (especially at $pH < 10$) was higher. With increased pH, Mn concentrations decreased and Al concentrations slightly increased.

Concentrations of As, Bi, Cr, Fe, Hg, Mo, and Sn were below detection limits in AMD from dump 11, while concentrations of Pb, Se, and Sb were less than drinking water standards. Similar to what was seen in the laboratory tests, with increasing pH, the Pb content decreased below the detection limit, while the concentration of other elements (As, Bi, Cr, Fe, Hg, Mo, Sn, Sb, and Se) remained almost unchanged.

Table 4 presents EC and TDS, TH, HCO^{3-}, CO_3^{2-}, SO_4^{2-}, alkalinity, acidity, and Cl in raw and treated waters from dump 11. EC, TDS, and TH increased with increasing pH. SO_4^{2-} and Cl concentrations did not change considerably during the treatment period, similar to what was observed in the laboratory tests. The mean EC, TDS, and SO_4^{2-} values of the treated water were 2,170 μs/cm, 1,488, and 886 mg/L, respectively. The measured values, especially for EC and TDS, exceeded the recommended values for drinking water.

Sludge Characteristics

The resulting sludge from lime treatment was metal rich and contained a large volume of water (Table 5). It had very high mean concentrations of Cu, Al, Mn, and Zn: 7.34, 4.76, 2.94, and 1.25%, respectively. Other metals, such as Cd, Co, Ni, and U, were also concentrated in the sludge. The concentration of metals in the sludge from the laboratory lime treatment tests mainly reflected the hydrochemical behavior of the elements. For example, among the sludge samples that were taken at each pH set point, the maximum concentration of Al occurred at pH 7.5. At higher pH, Al concentrations

Table 2 EC (μS/cm) and TDS (mg/L), TH (as $CaCO_3$), HCO^{3-} (mg/L), CO_3^{2-} (mg/L), SO_4^{2-} (mg/L), alkalinity (mg/L $CaCO_3$), acidity (mg/L $CaCO_3$), and Cl (mg/L) content of raw and laboratory treated waters

Lime treatment process	pH	EC	TDS	TH	HCO_3	CO_3^{2-}	SO_4^{2-}	Acidity	Alkalinity	Cl
AMD dump 26										
Raw water	4.1	2,290	1,464	1,070	30.5	0	2,105	1.4	0	14.2
First stage	7.5	2,400	1,532	1,120	36.6	0	2,080	1.8	18	17.8
	8.5	2,380	1,520	1,115	36.5	0	2,093	1.6	21	14.2
	9	2,380	1,512	1,115	42.7	0	2,105	1.5	22.5	17.7
	10	2,375	1,524	1,135	18.3	12	2,193	1.3	67	17.7
Second stage	10	2,390	1,534	1,145	30.5	6	2,108	3.2	68	17.8
	11	2,640	1,615	1,215	140.3	39	2,110	4.8	269	27.5
AMD dump 11										
Raw water	3.4	1,525	975	710	0	0	690	890	0	32
First stage	7.5	1,750	1,120	825	36.6	0	792	3.5	25	14.2
	8.5	1,781	1,140	840	48.8	0	790	1.8	33	17.8
	9	1,800	1,152	850	42.7	0	802	3.2	48	21.3
	10	1,750	1,120	825	18.3	9	770	2.8	55	21.3
Second stage	10	1,795	1,145	855	18.3	6	802	3.3	59	17.8
	11	2,020	1,290	960	48.8	21	835	7.1	202	21.3
Mine pit water										
Raw water	6.5	1,340	858	625	164.7	0	500	12.3	257	10.7
First stage	7.5	1,325	848	605	170.8	0	490	10.1	260	10.7
	8.5	1,234	790	565	61	0	523	2.2	89	14.2
	9	1,196	765	545	12.2	3	543	0.7	44	10.7
	10	1,217	779	555	12.2	12	540	0.2	24	14.2
Second stage	10	1,218	780	545	12.2	12	540	0.5	29	14.2
	11	1,700	1,088	775	48.8	33	643	11.8	38	21.3
AMD of dump 31										
Raw water	3.7	2,250	1,440	685	0	0	880	1,150	0	14.5
First stage	7.5	2,350	1,505	1,095	30.5	0	1,085	5.9	1.8	14.2
	8.5	2,280	1,460	1,105	24.4	3	1,045	0.2	2.4	14.2
	9	2,260	1,430	1,100	22.4	3.2	1,030	0.04	2.9	15.2
	10	2,250	1,440	1,090	10.4	6	1,018	0.04	3.8	17.7
Second stage	10	2,318	1,480	1,125	12.2	3	1,065	0.4	21	17.7
	11	2,356	1,508	1,140	18.3	12	1,055	1.2	94	17.7
AMD of dump 15										
Raw water	3.3	1,040	664	495	24.5	0	1,105	1	0	10.6
First stage	7.5	1,050	672	500	24.5	0	1,160	0.07	5.5	10.7
	8.5	970	620	460	24.4	0	1,133	0.07	5	10.6
	9	1,000	640	475	30.5	0	1,144	0.1	7	10.6
	10	1,330	850	635	12.2	3	1,195	0.6	25	17.8
Second stage	10	1,315	842	630	6.1	6	1,190	1.3	25	14.2
	11	1,545	988	745	42.7	18	1,120	1.9	187	24.9
Drinking water standard		–	500[a,b]	–	–	–	250[a]; 500[b]	–	–	–

[a] US EPA (2009), [b] WHO (2006)

decreased. Conversely, with increasing pH, the Mn concentration in the laboratory sludge samples increased. The geochemical and hydrochemical behavior of metals and sludge stability must all be considered during remediation and environmental management of sludge to avoid release of metal contaminants (Fiset et al. 2003; Payette et al. 1991; Zinck et al. 1996). In some cases, depending on the sludge characteristics and site specific requirements, sludge may be stabilized by mixing it with cement or lime prior to disposal (Kuyucak 1995; Zinck 2006).

Table 3 Field treatability results of contaminant metals (μg/L) in AMD from dump 11

Treatment description	Al	Cd	Co	Cu	Mn	Ni	U	Zn
Day 1								
Raw AMD (pH = 3.12)	50,965	207.19	517.41	83,247.6	50,058.6	1,352	17.52	13,679.9
Treated AMD (pH = 9.11)	140	2.33	0.66	3.7	1,784.9	<0.2	0.37	11.7
Treatability (%)	**99.7**	**98.9**	**99.9**	**100**	**96.4**	**100**	**97.9**	**99.9**
Day 2								
Raw AMD (pH = 3.42)	49,280	201.1	500.7	85,396.6	50,710.0	1,346.5	18.87	13,789.9
Treated AMD (pH = 11)	120	<0.05	<.2	75	125.21	<0.2	<0.02	50.1
Treatability (%)	**99.8**	**100**	**100**	**99.9**	**99.8**	**100**	**100**	**99.6**
Day 3								
Raw AMD (pH = 3.33)	49,688	208.8	518.5	87,807	51,162.5	1,386.7	18.45	14,320.4
Treated AMD (pH = 9.2)	102	3.19	2.81	538.3	1,006.9	6	0.57	98.9
Treatability (%)	**99.8**	**98.47**	**99.46**	**99.4**	**98.0**	**99.57**	**96.91**	**99.3**
Day 4								
Raw AMD (pH = 3.43)	50,018	215.6	517.1	85,401.7	51,406.6	1,381.3	18.6	14,303.8
Treated AMD (pH = 11)	106	<0.05	<.02	39.2	29.53	<0.2	0.05	7.1
Treatability (%)	**99.8**	**100**	**100**	**100**	**99.9**	**100**	**99.73**	**99.9**
Day 5								
Raw AMD (pH = 3.4)	49,608	205.2	496.9	85,522.7	51,604.7	1,389.2	18.36	14,001.9
Treated AMD (pH = 10.37)	166	6.12	8.43	595.9	572.47	20	0.1	251
Treatability (%)	**99.7**	**97.02**	**98.30**	**99.3**	**97.0**	**98.6**	**99.5**	**98.2**
Day 6								
Raw AMD (pH = 3)	49,706	211.4	509.3	84,170.5	51,022.9	1,390.6	19.08	14,007.6
Treated AMD (pH = 10.32)	340	1.15	0.23	142.6	537.2	2.7	<0.02	52.4
Treatability (%)	**99.3**	**99.5**	**100**	**99.8**	**99.0**	**99.8**	**100**	**99.6**
Day 7								
Raw AMD (pH = 3.4)	50,631	211.5	500.2	85,467.5	51,757.3	1,379.2	20.3	14,190.2
Treated AMD (pH = 10.27)	248	1.41	0.67	131.8	487.5	0.6	0.2	29.8
Treatability (%)	**98.3**	**99.3**	**99.9**	**99.9**	**99.1**	**100**	**99.0**	**99.8**
Drinking water acceptable level	50[a]	5[a]; 3[b]	100[a]	1000[a]	50[a]; 400[b]	20[b]	30[a]; 15[b]	5,000[a]

The treatability percent for each contaminant metal was highlighted

[a] US EPA (2009), [b] WHO (2006)

The correlation between certain contaminants (Al, Cu, Cd, Co, Mn, Ni, U, and Zn) in the Sarcheshmeh sludge was significant (Table 6). In contrast, other elements, including As, Cr, Fe, Mo, Sb, and Se, were weakly associated with contaminant metals. Cd, Ni, and Mn were weakly correlated with Al, probably due to the hydrochemical behavior of these metals during lime treatment, since during the treatment process, the efficiency of Cd, Ni, and Mn removal increased with increasing pH, while Al redissolved.

Sludge may contain 1–30% solids (Kuyucak 2006). During field treatment, the solid fraction of sludge samples ranged from 10.2 to 18.47 g/L (1.02–1.84%), which puts the sludge in the low-density category (less than 2% solids). There are several options for disposal of lime treatment sludge including disposal in mine workings, with tailings, in engineered ponds, on waste rock piles, under water cover, or in natural dispersions (Aubé et al. 2003). Several factors, such as regulatory considerations, sludge stability, sludge generation rate, space availability, budget, and aesthetic considerations, can affect disposal options (Aubé et al. 2003). Based on the site characteristics of the Sarcheshmeh copper mine, especially the climatic conditions, sources and volume of AMD, topography, and the short distance (<2 km) between the mine and the concentration plants, treatment of AMD with lime, and mixing the produced sludge with tailings appears to be a reasonable method for mitigating the environmental concerns.

Conclusions

AMD in the Sarcheshmeh copper mine is associated with rock waste dumps and is characterized by high

Table 4 EC (μS/cm) and TDS (mg/L), TH (as $CaCO_3$), HCO^{3-} (mg/L), CO_3^{2-} (mg/L), SO_4^{2-} (mg/L), alkalinity (mg/L $CaCO_3$), acidity (mg/L $CaCO_3$) and Cl (mg/L) content of raw and treated waters in field treatability tests

Treatment description	EC	TDS	TH	HCO_3	CO_3^{2-}	SO_4^{2-}	Acidity	Alkalinity	Cl
Day 1									
Raw AMD (pH = 3.12)	2,010	1,286	955	0	0	820	428	0	106.5
Treated AMD (pH = 9.11)	1,980	1,268	925	24.4	4.5	895	2.3	39	14.2
Day 2									
Raw AMD (pH = 3.42)	1,920	1,230	900	0	0	765	415	0	113.6
Treated AMD (pH = 11)	2,240	1,435	1,035	30.5	51	870	6.4	169	14.2
Day 3									
Raw AMD (pH = 3.33)	1,960	1,255	920	0	0	922	420	0	14.2
Treated AMD (pH = 9.2)	1,940	1,240	895	48.8	4.5	855	0.7	33	17.8
Day 4									
Raw AMD (pH = 3.43)	1,950	1,250	920	0	0	715	435	0	163.3
Treated AMD (pH = 11)	3,000	1,920	1,415	24.4	133.5	925	31.7	447	49.7
Day 5									
Raw AMD (pH = 3.4)	1,960	1,254	930	0	0	915	450	0	21.3
Treated AMD (pH = 10.37)	1,990	1,273	895	30.5	12	870	2.5	63	17.8
Day 6									
Raw AMD (pH = 3)	2,080	1,330	990	0	0	870	455	0	95.8
Treated AMD (pH = 10.32)	2,010	1,985	905	24.4	13	875	2.1	46	17.8
Day 7									
Raw AMD (pH = 3.4)	1,980	1,270	940	0	0	850	430	0	74.6
Treated AMD (pH = 10.27)	2,030	1,300	930	30.5	4.5	915	1.4	78	14.2
Drinking water acceptable level		$500^{a,b}$				250^{a}; 500^{b}			

[a] US EPA (2009), [b] WHO (2006)

concentrations of Al, Cd, Co, Cu, Mn, Ni, U, and Zn. Other metals such as As, Cr, Fe, Mo, Pb, Sb, and Se are present at relatively low concentrations. This blend of contaminant metals strongly influences lime treatment strategy since the different hydrochemical behavior of elements such as Al and Mn, together with the low Fe concentrations, affects lime treatment efficiency. The acidity of the raw AMD (as mg/L of $CaCO_3$) was associated with metal loading, which determines lime slurry consumption and sludge volume. According to the laboratory results, a pH of 7.5 is adequate to reduce the concentration of elements such as Al, Cu, U, and Zn to permissible drinking water levels, while complete removal of Mn, Cd, and Ni requires a higher pH (≈ 10). The results also indicated that a two-stage strategy sometimes used in lime treatment, in which the sludge is removed at pH 9, is not essential, and only increases the capital cost and complexity of the process. In the field treatment tests, the following percentages of contaminant metals were removed: 99.4% for Al, 99% for Cd, 99.6% for Co, 99.7% for Cu, 98.5% for Mn, 99.7% for Ni, 99% for U, and 99.5% for Zn. Both laboratory and field tests indicated that the optimum pH for removing the important contaminants was between 9 and 10. At this range of pH, elements such as Mn, Ni, and Cd were efficiently removed, and only a negligible fraction of Al redissolved. The concentration of other metals, such as Fe and Pb, was either reduced to below detection limits or, as in the case of As, Cr, Mo, Sb, and Se, did not change considerably during lime treatment.

Increased EC, TDS, and TH, associated with lime treatment at high pH (>10), can cause scaling during industrial purposes. High remnant SO_4 concentrations are another disadvantage of lime treatment.

Contaminant metals, especially Cu, Al, Mn, and Zn, were highly concentrated in the sludge. The concentrations of Al, Cd, Co, Cu, Mn, Ni, U, and Zn in the sludge reflected the geochemical and hydrochemical behavior of these elements. Most of these metals correlated well. The low correlation between Al and elements such as Cd, Mn, and Ni, clearly demonstrated the different hydrochemical behavior of these metals.

Environmental management practices at the Sarcheshmeh copper mine should focus on controlling dissolution reactions (AMD prevention), collecting contaminated water, lime treatment, and management of the sludge. Treatment of the collected waters with lime and mixing the

Table 5 Contaminant metals concentrations in sludge samples in laboratory (a) and field treatment tests (b); Al, Cu, Mn and Zn are in %; other elements are in mg/L

Treatment pH	Al	Cu	Mn	Zn	Co	Cr	Cd	Fe	As	Mo	Ni	Pb	Sb	Se	U
(a)															
Dump 26															
7.5	8.62	23.53	29.34	2.84	294.8	12.2	112.7	985.0	16.1	9.7	446.3	13.5	0.73	4.9	54.7
8.5	7.97	24.03	50.12	5.33	688.8	13.2	394.3	1,065.5	31.2	7.6	928.3	17.4	1.11	5.6	60.6
9	7.98	23.60	61.04	5.43	947.1	11.6	498.3	1,030.7	18.5	8.0	1,206.5	17.1	0.57	6.1	65.4
10	2.27	6.31	83.32	2.08	673.2	5.3	741.8	1,192.6	15.0	14.6	770.1	13.8	2.79	13.4	42.7
10	0.20	0.08	4.29	0.02	10.1	3.3	5.7	737.8	19.8	14.9	30.1	10.2	4.34	22.6	3.4
11	0.47	0.16	5.31	0.03	14.6	14.8	9.2	2,376.8	19.7	14.1	53.3	9.6	3.69	11.8	8.9
Dump 11															
7.5	10.22	14.89	21.43	1.78	374.4	5.9	168.6	2,228.6	7.5	7.0	1,019.9	14.4	1.29	11.7	108.6
8.5	8.63	12.78	41.33	2.11	665.1	6.4	505.0	1,996.9	8.8	7.1	1,427.1	8.9	1.00	10.4	95.8
9	7.56	11.22	43.88	1.88	574.5	5.3	466.0	1,875.6	7.8	8.8	1,233.3	6.8	0.85	11.0	84.9
10	5.59	8.44	45.69	1.34	391.0	5.0	368.0	1,553.9	5.3	5.4	836.1	5.8	0.49	7.8	65.7
10	0.47	0.20	14.52	0.03	10.0	25.0	26.2	662.5	9.9	20.0	48.7	6.0	0.72	7.2	3.0
11	1.03	0.18	9.06	0.03	9.8	6.1	25.9	1,123.2	13.6	5.8	27.6	6.8	2.03	9.3	6.0
Pit water															
7.5	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
8.5	0.05	0.01	3.19	0.04	34.0	1.9	1.3	20,193.3	20.9	2.8	16.9	1.8	0.70	2.4	1.1
9	0.10	0.06	3.79	0.05	39.1	2.0	3.6	19,835.8	20.3	2.4	24.2	2.1	0.65	1.9	2.4
10	0.09	0.03	2.99	0.04	30.3	2.8	1.9	17,513.3	21.9	3.3	20.7	2.1	0.60	2.1	2.3
10	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND
11	0.27	0.10	0.75	0.03	10.0	8.4	3.7	1,642.1	37.9	17.2	14.7	9.5	4.11	5.7	5.2
Dump 31															
7.5	7.30	9.58	38.87	2.89	721.3	4.1	218.1	1,608.3	4.8	4.6	645.2	30.4	0.75	8.4	167.9
8.5	3.46	4.50	45.88	1.37	435.3	2.6	175.5	880.2	2.9	2.7	373.8	14.3	0.38	4.1	81.4
9	4.61	5.99	57.09	1.80	596.7	3.4	222.4	1,185.0	3.6	3.1	513.2	20.4	0.31	4.7	110.8
10	4.24	5.45	58.74	1.63	523.2	4.3	227.1	1,282.8	4.2	3.0	441.9	18.6	0.49	5.4	102.4
10	0.18	0.03	12.47	0.01	4.3	1.6	13.8	334.4	6.9	6.0	5.4	4.0	2.21	5.1	2.6
11	0.11	0.00	5.38	0.00	0.6	6.7	6.0	504.9	4.2	3.8	4.4	3.1	1.72	1.9	1.9
Dump 15															
7.5	15.74	16.93	6.91	0.66	115.0	15.5	14.1	4,729.5	29.6	2.4	155.5	32.9	0.47	4.2	16.0
8.5	13.94	11.68	9.31	0.68	290.5	10.8	37.6	3,203.0	20.3	1.5	299.4	21.1	0.62	2.3	10.9
9	13.76	15.39	12.27	0.89	382.9	14.2	49.6	4,222.1	26.7	1.9	394.6	27.9	0.81	3.0	14.4
10	12.25	9.81	19.71	1.08	210.2	7.8	82.7	2,775.9	18.6	11.0	539.5	16.4	1.61	10.4	15.8
10	0.73	0.05	9.47	0.02	17.7	4.3	8.1	1,109.2	25.2	17.4	71.7	15.2	5.95	17.4	3.1
11	0.52	0.12	4.95	0.03	17.9	6.1	8.7	1,127.2	15.0	8.3	34.7	9.2	2.00	6.8	5.8
(b)															
9.1	4.85	8.89	5.22	1.69	510.0	9.1	196.2	1,684.8	19.4	13.6	1,333.8	22.2	0.97	3.0	19.1
11	4.33	8.23	4.86	1.51	460.2	11.8	182.3	2,559.5	14.0	6.0	1,236.8	16.8	0.61	2.5	18.3
9.2	2.82	4.98	3.02	0.93	274.6	9.5	107.1	1,436.7	7.3	2.6	738.9	6.9	0.39	1.7	11.3
11	4.19	7.40	4.52	1.36	427.1	10.3	169.9	1,734.0	8.1	3.9	1,172.0	7.2	0.61	2.0	17.0
10.4	4.06	7.35	4.45	1.36	422.1	9.5	176.1	1,561.1	7.0	3.8	1,193.7	6.6	0.43	2.0	17.8
10.3	4.08	7.71	4.77	1.44	409.7	10.3	185.0	1,890.1	7.6	3.9	1,231.5	7.6	0.45	1.3	18.6
10.3	4.06	7.13	4.34	1.34	385.4	9.8	175.1	1,562.8	5.3	1.7	1,175.8	4.9	0.28	1.3	19.1

ND not detected

Table 6 Correlation matrix between contaminant metals in sludge samples

Correlation	Al	Cd	Co	Cu	Mn	Ni	U	Zn	As	Cr	Fe	Mo	Pb	Sb	Se
Al	1														
Cd	0.23	1													
Co	**0.45**^{b}	**0.84**^{b}	1												
Cu	**0.8**^{b}	**0.45**^{b}	**0.67**^{b}	1											
Mn	0.17	**0.84**^{b}	**0.87**^{b}	**0.44**^{b}	1										
Ni	0.36^{a}	**0.70**^{b}	**0.80**^{b}	**0.56**^{b}	**0.77**^{b}	1									
U	**0.41**^{a}	**0.55**^{b}	**0.70**^{b}	**0.45**^{b}	**0.54**^{b}	0.4	1								
Zn	**0.44**^{b}	**0.71**^{b}	**0.87**^{b}	**0.83**^{b}	**0.7**^{b}	**0.65**^{b}	**0.6**^{b}	1							
As	0.14	−0.25	−0.3	0.13	**−0.43**^{b}	−0.34	−0.42^{a}	−0.04	1						
Cr	0.31	−0.05	0.3	0.34^{a}	−0.11	0.13	−0.23	0.15	0.23	1					
Fe	−0.18	−0.28	−0.3	−0.3	−0.08	−0.31	−0.26	−0.3	0.3	−0.29	1				
Mo	0.29	0.04	0.19	−0.17	0.09	−0.15	−0.14	−0.08	0.35^{a}	0.26	−0.3	1			
Pb	**0.70**^{b}	0.12	**0.42**^{b}	**0.54**^{b}	0.21	0.12	0.44^{b}	0.37^{a}	0.25	0.23	−0.29	−0.04	1		
Sb	−0.4^{a}	−0.21	**0.45**^{b}	0.41^{a}	−0.38^{a}	**0.43**^{b}	−0.3	−0.35^{a}	0.42^{a}	−0.15	−0.19	**0.7**^{b}	−0.08	1	
Se	−0.08	0.16	0.07	−0.11	−0.08	−0.15	0.18	−0.04	0.12	−0.17	−0.29	−0.29	**0.65**^{b}	**0.72**^{b}	1

The significant correlations were highlighted

[a] Correlation is significant at the 0.01 level (2-tailed), [b] correlation is significant at the 0.05 level (2-tailed)

sludge with the tailings can provide a reasonable amount of water for industrial purposes and reduce pollution.

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