

Pyrite oxidation in the Sarcheshmeh copper mine tailings dam, Kerman, Iran

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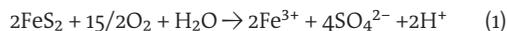
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Abstract This paper investigates pyrite oxidation and related environmental problems associated with the sulphide mine tailings dam produced by the copper processing plant at Sarcheshmeh mine in Kerman, Iran. The Sarcheshmeh copper mine tailings are rich in pyrite. Oxidation of pyrite-containing tails causes the well-known problem of acid mine drainage. Depending on the rate of pyrite oxidation, availability of moisture and oxygen within the tailings, the pH of the drainage is often very low. Depth sampling was conducted over the tailings materials with a spacing of 0.5 m. The samples were analysed using an AA-670 Shimadzu atomic adsorption to determine major elements and the fraction of pyrite remained within the tailings particles. The concentrations of heavy metals were determined using ICP-MS. The results show that the pyrite oxidation in tailings materials has lowered the pH of the tailings to a range varied between 2.9 and 3.5. The oxidation process caused elevated concentrations of SO₄, Fe and heavy metals. The results of such investigations can be used for designing an effective environmental management program.

Key Words Tailings dam, Pyrite oxidation, Acid mine drainage, Sarcheshmeh porphyry copper mine

Introduction

The Sarcheshmeh copper mine is located in the Central Iranian Volcanic Belt (CIVB), in Kerman Province, southeast of Iran (Shahabpour and Doorandish 2008). This deposit is recognised to be the fourth largest porphyry copper mine in the world contains 1 billion tonnes copper (0.9 %) and molybdenum (0.03 %) (Banisi and Finch 2001). Mining activity and mineral processing operation has placed many low grade waste dumps and tailings materials that can cause many environmental problems (Doulati Ardejani *et al.* 2008 a). The tailings dam contains reactive sulphide minerals in particular pyrite. When pyrite is exposed to the atmosphere and water, it rapidly oxidises and produces acid mine drainage (AMD) (Atkins and Pooley 1982). The overall stoichiometric reaction describing the oxidation of pyrite and AMD generation is given as:



As Eq. 1 shows, pyrite is initially oxidised by the atmospheric O₂, producing H⁺, SO₄²⁻, and Fe²⁺ (Singer and Stumm 1970, Doulati Ardejani *et al.* 2008 b). The ferrous iron (Fe²⁺) can be further oxidised by O₂ into Fe³⁺, which in turn either oxidises pyrite at low pH or hydrolyses into amorphous iron hydroxide, accompanied by the release of additional H⁺ ions into the environment at high pH. When pH is less than 3.5, the system is under saturation with respect to Fe (OH)₃,

and a significant amount of Fe³⁺ can remain in the solution phase to react with pyrite. For pH values greater than 3.5, the system is saturated with respect to Fe (OH)₃, and amorphous iron hydroxide mineral tends to precipitate.

AMD is usually characterised with high concentrations of Fe, SO₄ and low pH. It can carry potentially toxic metals and other dissolved materials away from the tailings dam site (Williams 1975). AMD has detrimental effect on surface waters, groundwater aquifers and soils (Walter *et al.* 1994 a, b; Dinelli *et al.* 2001).

Many physical, chemical and biological processes are involved in the oxidation of sulphide minerals and generation of acid mine drainage including transport of atmospheric oxygen through the waste materials, sulphide mineral oxidation, bacterially mediated oxidation reaction, pH-buffering reaction due to dissolution of mineral phases, precipitation of secondary minerals, transportation of the oxidation products and their interaction with solid phase (Morin *et al.* 1988). Study of such processes provides useful information for development of an effective treatment scheme and environmental management program for tailings dam sites.

This paper presents the geochemical characterisation of the tailings materials in the Sarcheshmeh porphyry copper mine to evaluate pyrite oxidation and AMD generation.

Methods

Sampling and analysis

Twenty eight samples each 2 kg in weight were collected with a spacing of 0.5 m from different depths of two trenches dug in the tailings dam (Trench A: 30° 0.5' 57.9" N; 55° 50' 30.1"E; and Trench B 30° 0.5' 56.4" N; 55° 50' 32.3"E) which is located in the north of the Sarcheshmeh copper mine (fig. 1). Two trenches had about 4.20 m depth. The samples were oven dried at 105 degrees of centigrade and then sieved to obtain the particle sizes of <200 mesh. In order to investigate pyrite oxidation process, the samples were analysed for geochemical parameters including anions and cations in the laboratory of National Iranian Copper Industries Company (NICICO) and heavy metals using an inductively coupled plasma mass spectrometer (ICP-MS) by Lab West Minerals Analysis Pty Ltd., Australia.

Pyrite oxidation and mineralogical studies

Pyrite oxidation process generates AMD as the source of acidification of mine spoils. Therefore, it is very important to investigate this process in the tailings of the Sarcheshmeh copper mine. Recent investigations show that pyrite oxidation process is very complex due to its involving chem-

ical, biological, and electrochemical reactions, and varies with environmental conditions (Evangelou and Zhang 1994; Evangelou 1995). Four methods including inorganic/biochemical reaction approach, electrochemical reaction approach, reaction kinetics approach and computer simulation approach have been proposed to investigate pyrite oxidation process (Evangelou 1995). In this paper, we apply geochemical and mineralogical studies to consider pyrite oxidation problem.

A method presented by ASTM (Gladfelter and Dickerhoof 1976; Doulati Ardejani *et al.* 2010) was employed to determine organic pyrite from the non-organic pyrite. Hydrochloric Acid (HCl) was used to dissolve sulphates and then the pyrite was extracted from the remained acidic solution using Nitric Acid (HNO₃). An AA-670 Shimadzu atomic absorption at Shahrood University of Technology was used to measure iron in the solution. It was then employed to determine the content of pyrite that remained in the tailings particles. Fig. 2 (right) shows the percent of pyrite remained within the tailings particles versus depth. As it shows, in zones where oxygen is present in the pore spaces of the tailings, the pyrite was oxidised. The oxidation reaction decreased sharply at lower depths up to 1 m. The oxidation process decreased gradually at depths between of 1 to 4 m, where little oxygen is available to oxidise pyrite. It was completely ceased below 4 m.

A mineralogical analysis was conducted to qualitatively investigate the pyrite oxidation process at various depths of the tailings materials. The study indicates depletion of pyrite in the oxidised zone and its presence in the un-oxidised zone. At the tailings surface, oxygen is readily available. So, the rate of pyrite oxidation is very high. The polished section from the tailings surface (fig. 2, a) shows no pyrite. Due to the rapid reduction in oxygen diffusion with depth, the pyrite oxidation decreased from the surface to a depth of 1 m (fig. 2, b). Pyrite can be easily seen in the polished section from a depth of 4 m (fig. 2, c), where no oxygen is available to oxidise pyrite.

Quantitative analysis using XRF method

A X-ray fluorescence (XRF) analysis was performed. An average XRF result show the major oxides including SiO₂ (60%), Al₂O₃ (19%), Fe₂O₃ (5%), K₂O (4%), Na₂O (1%), MgO (0.1%), SO₃ (5%) and L.O.I (1%).

Geochemical studies of samples

Pyrite oxidation and AMD generation often cause the concentrations of heavy metals to be elevated. An investigation of the geochemistry of heavy metals is important for comprehensive assessment of the potential environmental impacts of mine drainages. For this reason, a geochemical

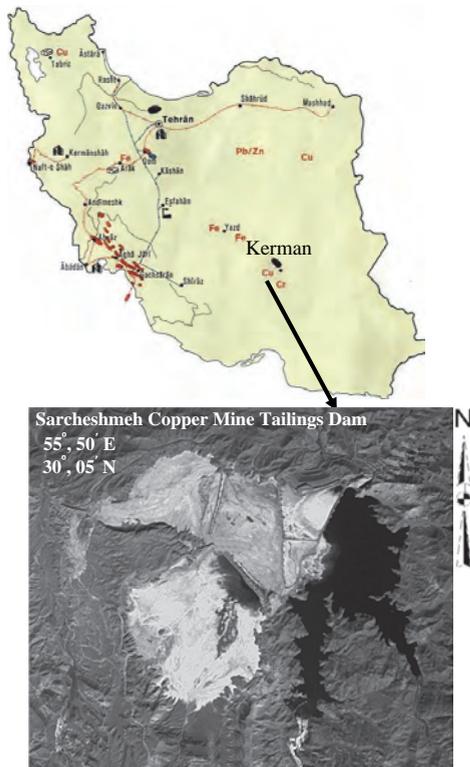


Figure 1 Location map of the Sarcheshmeh copper mine tailings dam.

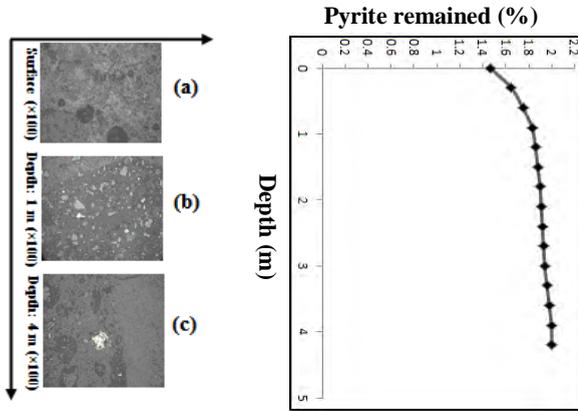


Figure 2 Polished sections of tailings samples (left), showing pyrite depletion in surface layers of tailings. The sample was taken at (a) the dam surface, (b) a depth of 1 m, (c) a depth of 4 m. Pyrite content remained within the waste particles (right) versus depth.

analysis was carried out to measure the concentrations of major elements (tab. 1) and heavy metals (tab. 2) in tailings materials. The results show that the concentration of HCO₃ in the samples was very low. The acid released from pyrite oxidation has been enough to deplete carbonate minerals in the tailings profile, so a zero concentration was detected for. The pH of the samples varies from 2.9 to 3.5. Low value of pH and high concentrations of SO₄ and Fe in the samples is attributed to the oxidation of pyrite. SO₄ concentration in the samples varies between 538 and 2319 ppm. Pick concentration of sulphate was observed at depth 3.30 m. Considering tab. 2, the concentrations of the most of heavy metals are very high. Pyrite oxidation at

the surface layers of tailings has resulted in the elevated concentration of Fe (from 22900 to 53100 ppm at depth 60 cm). Ag shows a pick concentration at depth 60 cm.

Conclusions

Pyrite oxidation causes acid mine drainage generation in the Sarcheshmeh copper mine tailings. A geochemical study of pyrite oxidation and release of the oxidation products can provide useful information for designing an appropriate mine plan which results the minimum environmental problems. A geochemical study was carried out to investigate pyrite oxidation and chemically characterise the tailings materials. The results

Samples no.	SO ₄ ²⁻	K ⁺	Ca ²⁺	Mg ²⁺	Na ⁺	T.D.S	T.S.S	T.H
<i>Location A (Depth m)</i>								
A30	844	58.0	28.80	18.50	11.70	>5800	93.80	134
A60	866	84.3	30.40	18.60	4.50	>5800	94.78	153
A90	874	42.0	32.40	18.80	3.70	>5800	90.26	158
A120	928	59.3	45.60	13.90	3.80	>5800	92.70	172
A150	901	28.8	32.00	19.00	2.10	>5800	96.12	159
A180	699	76.8	22.80	20.00	4.30	>5800	91.10	188
A210	863	39.8	26.40	21.90	3.20	>5800	94.72	157
A240	808	43.7	38.40	22.80	2.90	>5800	94.52	191
A270	1106	23.0	31.20	11.50	2.00	>5800	95.14	76
A300	835	22.3	30.40	18.50	2.00	>5800	95.60	153
A330	715	23.0	22.80	9.40	1.90	>5800	93.32	96
A360	915	28.7	31.20	20.40	2.20	>5800	94.20	188
A390	1024	13.7	25.60	18.30	1.70	>5800	97.08	140
A420	1095	11.2	30.40	32.40	2.10	>5800	95.96	211
<i>Location B (Depth m)</i>								
B30	538	34.2	31.20	27.00	8.60	>5800	93.92	191
B60	923	28.4	22.80	20.40	7.60	>5800	86.44	142
B90	721	34.4	24.00	20.20	4.50	>5800	93.96	144
B120	570	40.6	30.40	24.50	4.20	>5800	90.96	178
B150	728	26.3	15.20	18.50	2.60	>5800	93.96	115
B180	607	17.9	15.20	18.50	1.70	>5800	92.68	115
B210	653	24.7	12.40	10.80	1.80	>5800	89.00	76
B240	634	100.0	38.80	22.60	400	>5800	88.80	191
B270	558	100.0	23.20	22.80	400	>5800	92.12	153
B300	687	100.0	23.20	21.10	400	>5800	88.56	146
B330	2319	100.0	34.80	25.20	400	>5800	92.28	172
B360	644.0	100.0	34.00	16.30	400	>5800	91.52	153
B390	801.0	250.0	30.40	19.70	450	>5800	94.08	158
B420	725.0	100.0	22.80	15.10	400	>5800	95.40	145

Table 1 Geochemical analysis of samples for major elements taken from two trenches A and B in the Sarcheshmeh copper mine tailings dam (ppm).

Samples no.	Ag	Al	Co	Cr	Cu	Mo	Pb	Zn	Fe
	Location A (Depth in m)								
A30	0.53	85257	34.0	44	1294.8	173.0	36.4	272.3	53100
A60	0.46	85212	33.2	48	1203.7	94.6	39.7	210.2	49000
A90	0.34	82299	18.8	63	782.4	122.0	30.1	107.0	37800
A120	0.47	75676	24.8	29	1446.0	159.0	46.4	200.3	31900
A150	0.51	74905	24.3	28	1681.9	181.0	50.8	186.0	27800
A180	0.33	83324	24.9	26	1110.1	77.9	41.9	150.8	34200
A210	0.30	80134	19.4	31	1190.6	94.0	47.8	129.1	30700
A240	0.33	80083	23.8	34	1245.4	113.9	53.9	152.2	35100
A270	0.36	81371	37.4	39	1163.7	74.5	27.9	188.5	44200
A300	0.33	80067	28.3	29	912.9	66.1	43.3	146.7	34000
A330	0.28	78473	22.5	24	781.4	82.5	36.9	154.2	30600
A360	0.36	85062	31.7	43	1306.5	74.8	34.3	244.9	48000
A390	0.27	82926	32.2	46	1158.3	62.6	36.3	135.2	43300
A420	0.29	79578	34.9	53	1049.1	92.4	51.3	133.5	43100
	Location B (Depth in m)								
B30	0.55	89998	28.4	42	1196.2	144.6	48.8	221.1	38600
B60	0.73	81809	35.4	57	2174.3	137.7	48.5	230.7	44600
B90	0.59	84042	33.2	51	1310.4	96.7	38.0	205.5	41900
B120	0.49	82052	26.6	48	1263.2	94.9	38.8	186.7	34700
B150	0.43	76154	21.6	33	1100.2	129.2	35.1	164.9	27600
B180	0.55	73080	27.3	27	1774.9	183.8	45.1	224.1	27000
B210	0.46	76787	29.8	27	1606.6	109.8	41.8	178.5	30700
B240	0.35	73184	23.6	23	1374.3	82.8	34.9	146.0	29400
B270	0.33	76877	18.2	31	1263.8	93.0	46.7	122.6	29700
B300	0.32	75662	23.5	27	1072.1	84.3	53.5	147.6	29400
B330	0.35	72366	35.5	35	1328.7	83.9	28.8	174.9	44200
B360	0.35	73266	26.4	27	1240.6	84.6	42.7	143.4	34000
B390	0.24	77591	17.6	21	658.7	55.6	44.7	115.4	22900
B420	0.33	82080	30.2	35	1270.4	89.7	48.8	246.1	41800

Table 2 Heavy metal concentrations in the Sarcheshmeh copper mine tailings dam (ppm).

show that the pyrite oxidation in tailings materials has lowered the pH of the tailings to a range between 2.9 and 3.5. The oxidation process caused elevated concentrations of SO_4^{2-} , Fe and heavy metals. The results further show that the concentration of HCO_3^- in the samples was very low. The acid released from pyrite oxidation has been enough to deplete carbonate minerals in the tailings materials, so the concentration of was very low.

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References

Atkins AS, Pooley FD (1982) The effects of bio-mechanisms on acidic mine drainage in coal mining. *Mine Water Environ* 1: 31–44

Banisi S, Finch JA (2001) Testing a floatation column at the Sarcheshmeh copper mine. *Mineral Eng.* 14 (7): 785–789

Dinelli E, Lucchhini F, Fabbri M, Cortecchi G (2001) Metal distribution and environmental problems related to sulfide oxidation in the Libiola copper mine area (Ligurian Apennines, Italy). *Journal of Geochemical Exploration* 74, 141–152.

Doulati Ardejani F, Karami GH, Bani Assadi A, Atash Dehghan R (2008 a) Hydrogeochemical investigations of the Shour River and groundwater affected by acid mine drainage in Sarcheshmeh porphyry copper mine. 10th International Mine Water As-

sociation Congress, June 2–5, 2008, Karlovy Vary, Czech Republic, pp. 235–238.

Doulati Ardejani F, Jodeiri Shokri B, Moradzadeh A, Soleimani E, Ansari Jafari M, (2008 b) A combined mathematical geophysical model for prediction of pyrite oxidation and pollutant leaching associated with a coal washing waste dump. *Int. J. Environ. Sci. Tech.* 5 (4): 517–526

Doulati Ardejani F, Jodeiri Shokri B, Bagheri M, Soleimani E, (2010) Investigation of pyrite oxidation and acid mine drainage characterization associated with Razi active coal mine and coal washing waste dumps in the Azad shahr–Ramian region, northeast Iran. *Environ Earth Sci.* 61: 1547–1560

Evangelou VP, Zhang YL (1994) A review: pyrite oxidation mechanisms and acid mine drainage prevention: *Environ. Sci Tech* 25: 141–199

Evangelou V.P, (1995) Potential microencapsulation of pyrite by artificial inducement of $FePO_4$ coatings: The International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acid Drainage, Pittsburgh 2, 96–103

Gladfelter WL, Dickerhoof DW (1976) Use of atomic absorption spectrometry for iron determinations in coals. *Fuel* 55 (4): 360–361

Morin KA, Cherry JA, Dave NK, Lime TP, Vivjurka AJ (1988) Migration of acidic groundwater seepage from uranium-tailing impoundments, 1. Filed study and conceptual hydrogeochemical model. *J Contaminant Hydrogeology* 2: 271–303

Shahabpour J, Doorandish M (2008) Mine drainage

-
- water from the Sarcheshmeh porphyry copper mine, Kerman, IR Iran. *Environ Monit Assess* 141: 105–120
- Singer PC, Stumm W (1970) Acid mine drainage, rate determining step: *Science* 167, 1121–1123
- Walter AL, Frind EO, Blowes DW, Ptacek CJ, Molson JW (1994a) Modelling of multicomponent reactive transport in groundwater, 1. Model development and evaluation. *Water Resour Res* 30 (11): 3137–3148
- Walter AL, Frind EO, Blowes DW, Ptacek CJ, Molson JW (1994b) Modelling of multicomponent reactive transport in groundwater, 2. Metal mobility in aquifers impacted by acidic mine water discharge. *Water Resour Res* 30(11): 3149–3158
- Williams RE (1975) Waste production and disposal in mining, milling, and metallurgical industries. Miller-Freeman Publishing Company, San Francisco, California, 485 pp

