Mine Water Environ (2013) 32:56–70
DOI 10.1007/s10230-012-0212-6

TECHNICAL ARTICLE

Long Term Performance of Hydrogeochemical Riverine Mine Tailings Deposition at Freeport Indonesia

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Received: 24 March 2012 / Accepted: 21 November 2012 / Published online: 11 January 2013

Abstract Steep terrain, intense rainfall, and seismic activity precluded use of conventional tailings storage facilities at the PT Freeport Indonesia (PTFI) copper–gold mine, in Papua, Indonesia. A controlled river tailings system was adopted as the only feasible way to manage the tailings. The tailings are transported to an engineered 230 km^2 deposition area, which is bounded by levees on the east and west sides and is open on the south side to allow transport water and surges of rainfall to exit the area. We evaluated the performance of the ore-fed blending strategy for managing potential acid rock drainage formation of the tailings. Long-term leaching column tests and monitoring of deposited tailings provided insight on the reactivity, leaching behaviours, and neutralizing potential of the samples, and the ratio of acid neutralizing capacity (ANC): maximum potential acidity (MPA) that would ensure that the deposited tailings remain non-acid forming. We concluded that an ANC/MPA ratio >1.5 provides an adequate factor of safety to prevent acid generation and ensure long-term geochemical stability of the deposited tailings.

Electronic supplementary material The online version of this article (doi:10.1007/s10230-012-0212-6) contains supplementary material, which is available to authorized users.

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Keywords Copper gold mine · Papua · Leach test · ANC/MPA

Introduction

PT Freeport Indonesia (PTFI), one of the world's largest copper–gold mines, is located in the high equatorial mountains of the Indonesian province of Papua on the western half of the island of New Guinea. The southern part of New Guinea is part of the ancient and stable Australian continental plate. The mountains are the result of relatively recent uplifts, where the Australian Plate moved north against the Indo-Pacific Plate, pushing up crustal rocks along the plate margins. The overall result is a series of sub-parallel mountain ranges running in an east–west direction across the island (Murray et al. 2001).

Seismicity is related primarily to the convergence of the north-moving Australian Plate and the south moving Indo-Pacific Plate. Although earthquakes shake the PTFI Ertsberg District in Papua a few times a year, the magnitude and frequency of earthquakes in this part of New Guinea is substantially less than in the surrounding areas, with very few earthquakes originating in this area. For comparison, earthquake activity rates across Papua, New Guinea (PNG, which is the eastern half of the same island and not part of Indonesia) are among the highest in the world, with about two earthquakes of Richter magnitude 7.0 or more per annum (Ripper and Letz 1993).

The south side of the island includes the Central Mountain Range, which is characterized by extremely steep, rugged topography with streams confined to deeply-incised narrow V-shaped valleys, the result of centuries of erosion. These are subject to flash flooding, high rates of erosion, and associated valley wall instability, often combined with near-vertical karstic limestone cliffs in the elevated regions. However, despite the large, natural sediment loads carried from the mountains to the lowlands by the highland rivers, the rivers commonly have a sediment carrying capacity in excess of the sediment load because of the high velocity and turbulence. Glaciers, seismic activity, high rainfall, and natural erosion have generated tremendous sediment loads that have settled in the alluvial floodplain and been carried out into the estuary and the Arafura Sea, creating a massive natural area of deposited sediment.

Riverine deposition is practiced today by mining companies that are situated in areas of high rainfall, high seismic activity condition, steep terrain, and frequent natural hazards that make other tailings management options unsuitable and potentially dangerous (International Institute for Environment and Development (IIED) and World Business Council for Sustainable Development (WBCSD) 2002a, b, c). The combination of social, environmental, and engineering factors are unique to each tailings disposal site and vary with time.

The Bougainville copper mine in eastern PNG was the first (1967) modern large-scale mine to utilize a riverine tailings disposal system, which effectively resulted in shallow coastal ocean disposal of much of the tailings. Pilot studies for placement of thickened tailings in the shallow ocean were underway in the later stages of operation. Due to civil unrest, the mine was closed in 1989 (Murray et al. 2001). PTFI began operations in 1970 on the western side of New Guinea and Ok Tedi copper/gold commenced in 1983 in PNG. Both have used riverine tailings management. Ok Tedi has been a particularly difficult operation, in large part due to the combined impact of riverine tailings and waste rock disposal. The Ok Tedi case highlights the different perspectives of developed and developing countries and conflicts between local interests and the international community. The local interest and perspective resulted in the willingness of the PNG government to accept the environmental impacts in an exchange for foreign investment, employment, and to foster regional development. This was in contrast with the international community, specifically NGOs in the developed world, which advocated for its closure (Murray et al. 2001). The Porgera gold mine, which commenced operations in 1990, has also attracted attention due to the riverine disposal of mine tailings and difficult social setting.

The elevation of mining in PNG is relatively modest (the mill site at Ok Tedi is at 2,000 m elevation, the Porgera mill at 2,400 m) compared with the elevation at the PTFI, which in excess of 4,000 m (Murray et al. 2001). The Grasberg mine site lies at the collision point of two tectonic plates, the Indo-Australian plate to the south and the Pacific plate to the north. Puncak Jaya, the tallest peak between the Andes and the Himalayas, is occupied by one of the three remaining equatorial glaciers in the world. In contrast to the mountainous regions, there are extensive areas of relatively flat coastal plains across the island. The southern coastal plain is part of the stable Australian tectonic plate and has relatively low seismic activity.

The PTFI contract of work (CoW) area extends from the ridgeline of the Jaya Wijaya Mountain Range in the north at approximately 4,600 m above mean sea level (AMSL) to the Arafura Sea in the south (Fig. 1). Two major physiographic regions dissect the CoW area—the Central Mountain Range (the mountainous highland zone from 600 to about 4,880 m AMSL) and the Southern Coastal Plains (the lowland zone extending from sea level to an elevation of about 600 m AMSL). The climate is alpine/sub-alpine with little seasonal variation in temperature or rainfall in the highland, and tropical rainy monsoon climate in the lowland. Annual precipitation gradually increases with elevation across the lowlands (about 4 to 7.5 m/year), then rises sharply in the mountain foothills to a maximum annual precipitation of about 11 m/year at about 500 to 1,500 m AMSL. It then decreases above 1,500 m AMSL to approximately 3 to 4 m per year.

The PTFI project area stretches from the Grasberg mining complex in the central highlands south to a port facility on the coast of the Arafura Sea. This north–south corridor of operations traverses a mangrove coastal zone, sago forest, tropical rain forest, cloud forest, and sub-alpine regions over the relatively short distance of 130 km. Tailings originate at the mill facility, located in a narrow valley just below the mining area, at an elevation of approximately 2,700 m.

The ore bodies are porphyry copper–gold deposits. The main ore bodies that have been or will be mined are the Grasberg and Ertsberg open pits, and underground deposits at the Deep Grasberg Block Cave (DGBC), East Ertsberg Skarn System (EESS), Gunung Bijih Timur (GBT), Intermediate Ore Zone (IOZ), Deep Ore Zone DOZ), Big Gossan, and Kucing Liar (Fig. 2). The Ertsberg open pit was mined between 1972 and 1984. Underground mining of the East Ertsberg Skarn System began in 1980 and mining of the Grasberg open pit began in 1990. Mining of the Grasberg open pit will be completed by about 2016, at which time ore production will be exclusively from underground operations.

The Grasberg porphyry copper–gold deposit, also referred to as the Grasberg igneous complex, is a cone shaped deposit, with an elliptical surface expression. Copper mineralization is primarily in the form of chalcopyrite with some bornite, chalcocite, and covellite. Pyrite is less abundant than copper sulphides in most GIC ore zones. However, in the Kucing Liar ore body and in portions of the Deep Grasberg Block Cave ore body, pyrite is much

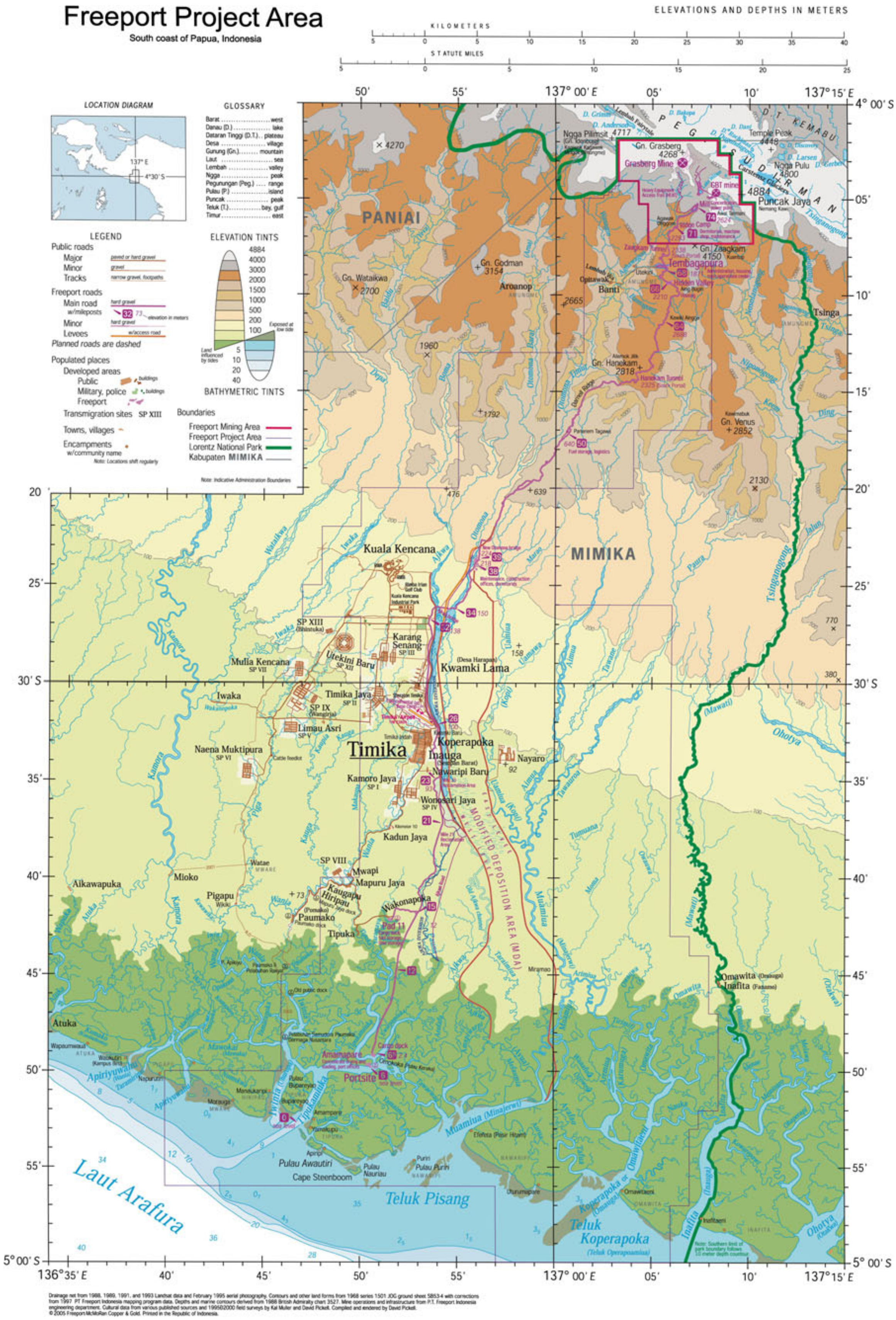

Fig. 1 Map of PTFI copper–gold project area in the Indonesian province of Papua

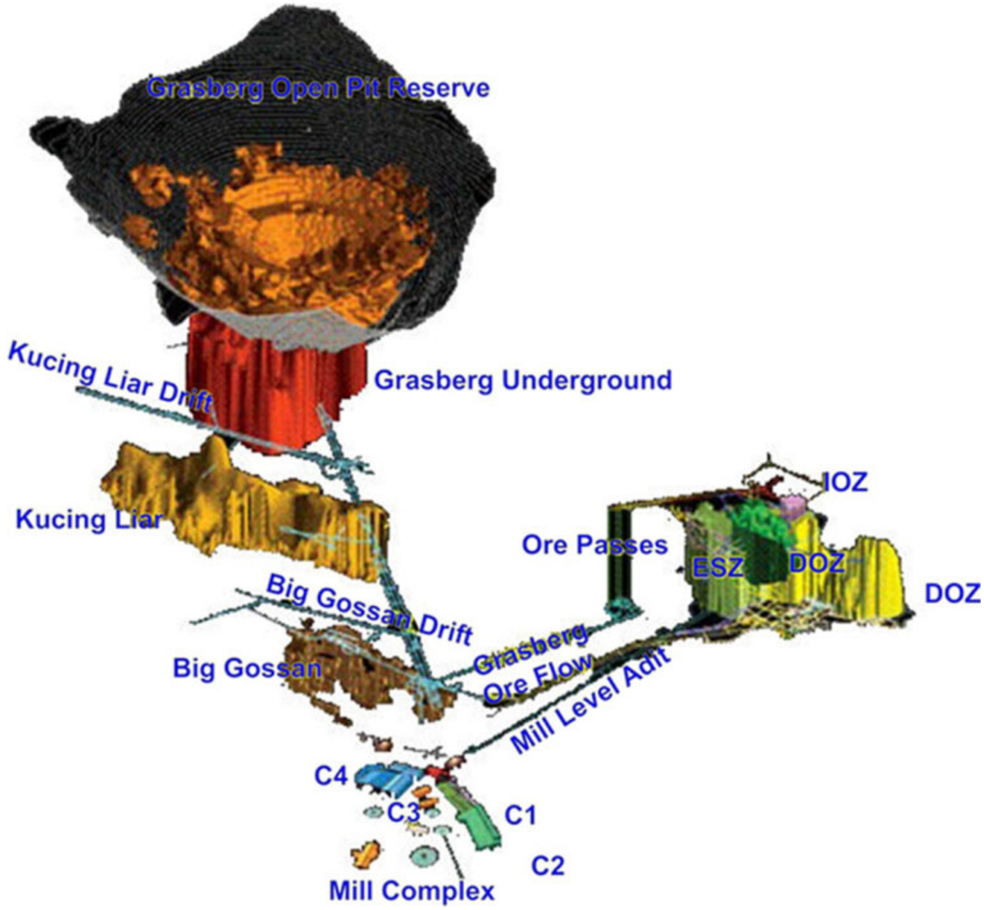

Fig. 2 PTFI current and future ore bodies

more abundant. Other ore bodies in the area, including the Ertsberg open pit, the East Ertsberg Skarn System, and the Big Gossan, are hosted in copper skarns where pyrite is subordinate to copper sulphides and there is abundant carbonate minerals present. At this time (2012), ore production of about 225,000 tonnes (t) per day is approximately 65 % from the Grasberg open pit and 35 % from Ertsberg underground mines. The ore is processed at the nearby mill and the tailings are transported to the deposition area by the local river.

The tailings discharged from the mill are largely quartz, carbonate, and feldspar with generally less than 5 % sulphide minerals. Chalcopyrite, pyrite, and bornite are the predominant sulphide minerals observed in the tailings samples characterized to date. Lesser amount of sphalerite and covellite are also present. Calcite and dolomite are the main carbonate components. The predominant non-sulphide gangue minerals are magnetite (ranging from 3–7 %), sulphate/anhydrite (7 %), and silicates (up to 65 %).

PTFI transports $\approx$225,000 t/day of tailings via a section of the Otomona River to a designated area in the lowlands and coastal zone, called the modified deposition area (ModADA, PTFI 2009). This area is an engineered managed system for the deposition and control of tailings and natural sediment in the floodplain of the Otomona River. The system includes lateral containment structures (levees), approximately 55 km long, on both sides of the deposition area (Fig. 3). The tailings management system was selected following a series of comprehensive interdisciplinary studies of 14 alternative tailings transport and disposal options including highland, midland, and lowland storage areas, river transport and run-of-river deposition, river transport with sand re-handling, pipeline with off-channel deposition in lowlands area, pipeline to north side of Papua with subaqueous disposal, and pipeline south with subaqueous discharge in the Arafura Sea.

Conventional storage was rejected due to the lack of a suitable area, since building a high dam(s) in a seismically active area with high amounts of precipitation would create unacceptable risks. The terrain is extremely steep and rugged with steep, deeply incised valleys and sharp peaks. The high precipitation (3.5 to 10 m annually, depending on altitude and aspect) exposes sites to high potential slope stability problems. Pipeline options were rejected because construction and installation in the harsh terrain would result in significant environmental impacts to the canyon systems. Additionally, the integrity of the pipeline would

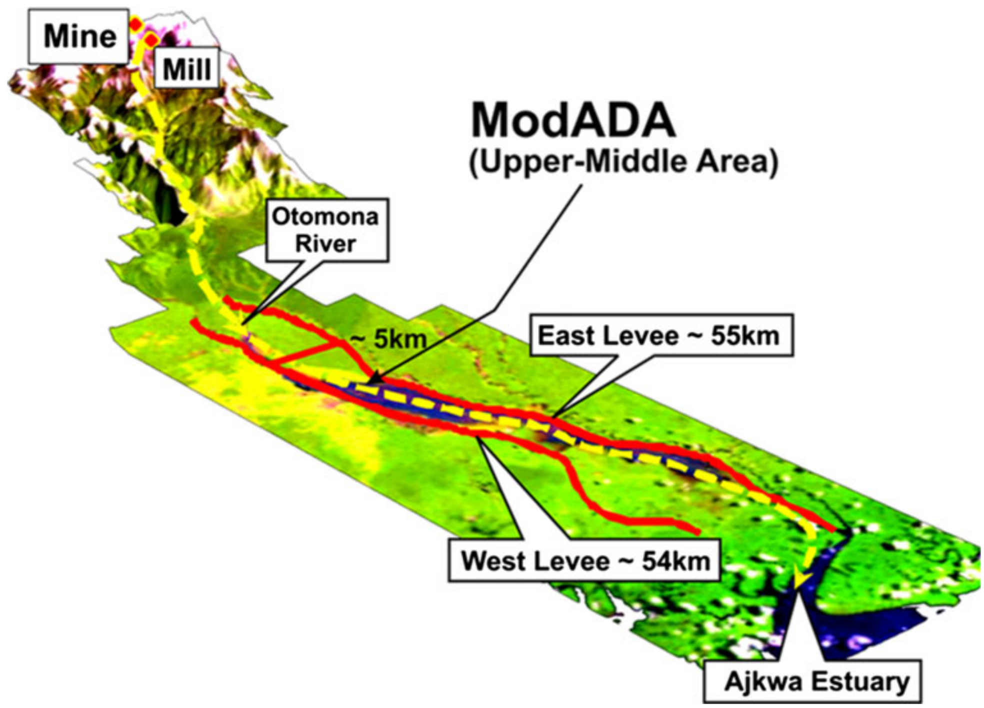

Fig. 3 Schematic figure of PTFI tailing deposition area (ModADA) at floodplain of Otomona River, Papua

be jeopardized by extreme natural events such as landslides, floods, and earthquakes. Deep water (subaqueous) discharge in the Arafura Sea was not feasible due to the presence of a wide shelf and shallow water for many miles offshore. The current system, using the river channel to transport tailings from the high mountains to the lowlands deposition site, enables naturally high-alkaline runoff to mix with the tailings in the river channel, thus adding additional buffering capacity and reducing acid-generating potential. Studies and subsequent independent environmental audits of the system have concluded that the company's tailings management system is the best alternative, considering the applicable geotechnical, topographic, climatological, seismic, and water quality conditions.

The controlled riverine tailing management system requires careful monitoring of the blended ores in the mill processes to ensure that the final tailings have an appropriate factor of safety with respect to excess carbonate neutralizing capacity since the geochemistry of these tailings could affect the long-term water quality of the river and aquatic life (Salim 2003; Hettler et al. 1997; IIED and WBCSD 2002d). To minimize risk, the deposited material should be capable of neutralizing at least 50 % more acid than the maximum amount that could be generated. This requirement, which is based on internal studies, addresses the potential for adverse environmental impacts that could arise due to the physical transport of tailings by the river and prolonged residence time of the sulphidic tailings deposited in the river sediments. In this paper, we review the performance of this tailings management strategy and procedures that can be taken to ensure that tailings deposited in the ModADA remain non-acid forming (NAF).

Materials and Methods

Sampling

Tailings samples are collected daily at the mill, and at the entrance and exit of the ModADA to determine acid-forming characteristics. Transects are sampled on a semi-annual basis across the ModADA. Approximately 400 profile tailing locations have been sampled annually since 1998 along 40 transects from the north to the south of ModADA (Fig. 4). Depth profile samples of tailings solids have been collected at each site down to a maximum depth of 500 mm from transect location MA 230 at the ModADA inlet to transect location MA 155, approximately 30 km downstream of the ModADA inlet.

Geochemical and Mineralogical Methods

Assays used to geochemically characterize tailings sediment included pH, electrical conductivity (EC), net acid generation (NAG), acid neutralizing capacity (ANC), copper (Cu), and total sulphur (S). These assays and kinetic (leach column) tests were performed at the PT FI environmental laboratory on site in Papua. Measurements of total S content were used to calculate the maximum

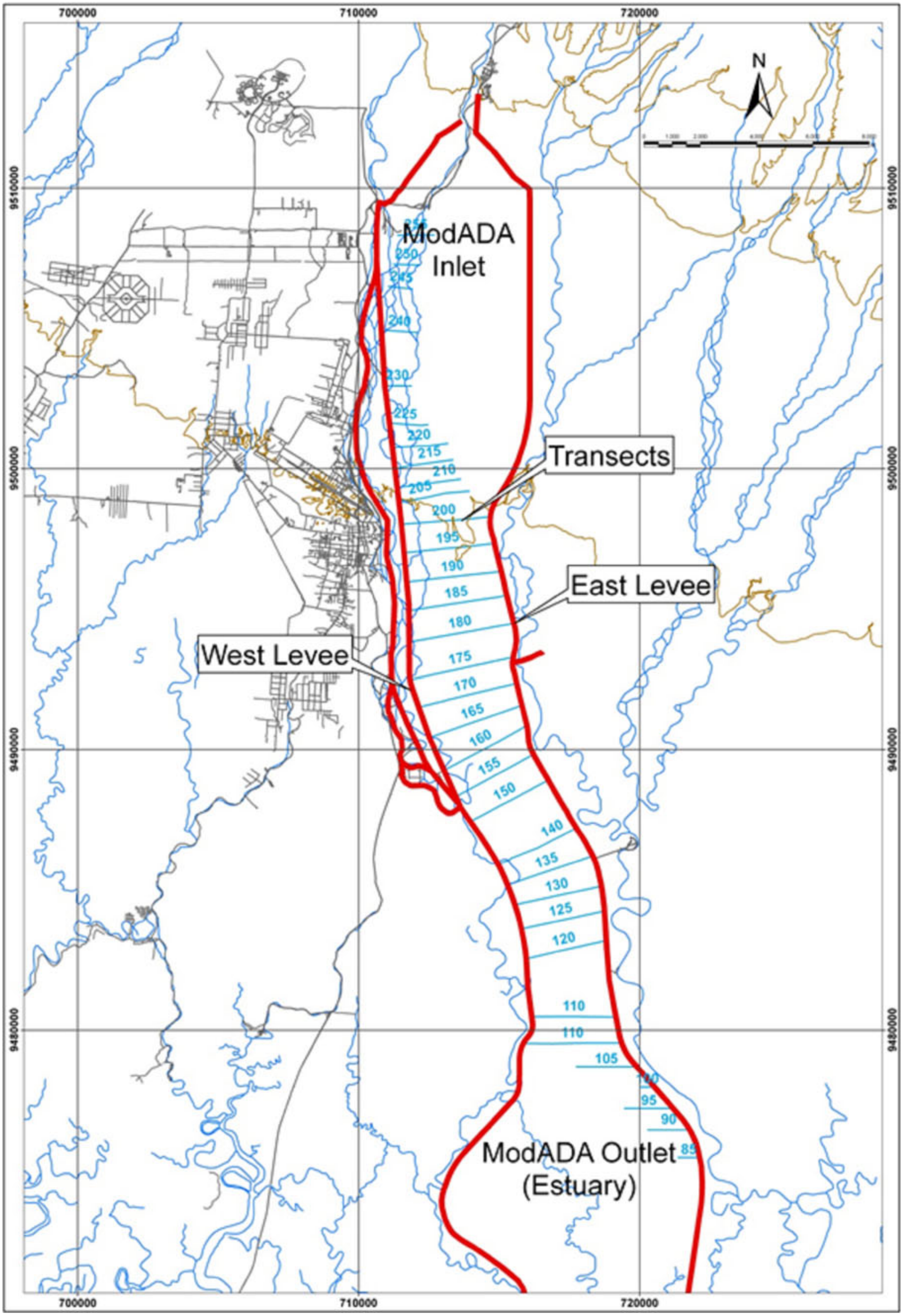

Fig. 4 ModADA layout and its 40 transect sampling locations

potential acidity (MPA) that a sample can theoretically produce. ANC was determined using a modified Sobek method (AMIRA International 2002; Sobek et al. 1978). The difference between ANC and MPA results in the NAG.

Geochemical analysis involved (and involves) the following steps: tailing samples are oven-dried for 12 h at 60 °C, sieved to 250 μm, and splits are removed for geochemical and elemental analysis. Approximately 50 g of sample are used for geochemical analyses and 10 g for particle size and elemental analysis. A 15 g sample in 30 mL of deionized (DI) water is stirred for an hour and measured for pH and EC. A known amount of standardized hydrochloric acid (HCl) is added to an accurately weighed sample. This mixture is allowed to react with heat, and then back titrated using sodium hydroxide (NaOH) to determine the amount of HCl consumed by the reaction. The NAG testing procedure is similar to that developed and used by Miller (1996). Total sulphur is analyzed by a LECO analyzer. Particle size analysis is carried out using a laser particle size analyzer in which 100–200 mg samples were analyzed. For elemental analyses, one gram samples are mixed with acid [5–10 mL of HCl and nitric acid (HNO3)] and digested using a microwave digester. Samples are then diluted to 40 mL with DI water and analyzed using inductively couple plasma (ICP) for elements such as aluminum (Al), arsenic (As), calcium (Ca), cadmium (Cd), Cu, iron (Fe), magnesium (Mg), manganese (Mn), lead (Pb), selenium (Se), and S.

Mineralogical analysis provided information on the species of sulphide-bearing and sulphide-neutralizing minerals that contribute to the total S and sulphur fractions. X-ray diffraction (XRD) was carried out using a Rigaku Miniflex machine equipped with a scintillation detector, Cu-K radiation, and K filter to determine the sulphide mineral content, and in particular, the contribution of pyrite in the sulphide mineral suite.

Long-term Laboratory Column Leaching Test

Leaching Tests

In addition to the geochemical tests performed on each of these tailings samples to quickly predict if a sample could be acid producing after exposure to weathering, kinetic tests using repeated cycles of humidity or aqueous solutions are applied over a period of time (Blowes et al. 2003). The kinetic tests provide information on weathering rates and leachate water chemistry that are not obtainable from a static test since they allow the materials to react on a real-time basis (Blowes et al. 2003; Dold and Fontbonte 2001, 2002).

Thirty-eight long-term kinetic free-draining leach column tests conducted with six samples of mill tailings discharge, natural sediment carried in the river system upstream of the ModADA (1 sample), tailings from Upper and Middle ModADA (21 samples), and pilot plant samples representing future tailings (10 samples) have been monitored since Nov. 2000. These tests were designed to: (1) provide information on long-term geochemical behaviour and chemical leaching from current and future tailings; (2) assess the ANC/MPA ratio required to ensure tailings depositing within the ModADA remain NAF; (3) assess the benefits of limestone addition to potentially acid-forming (PAF) tailings, and: (4) investigate whether grain size significantly changes the effectiveness of added limestone.

Leach column test procedures (AMIRA International 2002) consisting of free-draining columns leached with DI water were applied to sets of columns to create a range of conditions under which the oxidation of sulphidic minerals within the tailings could occur without being limited by a lack of atmospheric oxygen. The columns were conventional plastic Buchner Funnels with a diameter of 150 mm and a height of 120 mm. Each funnel was filled with approximately 2 kg of tailings solids; the leachates drained into collection bottles. The columns operated on a four-week leach cycle intended to wet all of the tailings within the column once a week and to thoroughly flush the tailings once a month. To achieve this, 200 mL of DI was applied to the top of each column once a week for each of the first 3 weeks in the four-week cycle. The water was applied slowly and on each watering occasion, the surface of the tailings was initially reworked to remove any cracks that developed during the previous week of drying. At the end of each four-week period, the columns were weighed, flushed with 800 mL of rain water, and allowed to drain for a few days until leachate flow stopped. The volume of leachate collected over the 4 week period was then recorded and the leachate sample retained for analysis.

Description of Columns

Geochemically, 8 samples (column 2, 3, 14, 17, 31, 35, and 37) had ANC/MPA ratios less than 1, two samples (column 19 and 24) had a value between 1 and 1.5, and all other samples (column 1, 4 to 13, 15, 16, 18, 20 to 23, 25 to 30, 32 to 36, and 38) had crushed limestone added, yielding ANC/MPA ratios greater than 1.5. Fine, medium, and coarse crushed limestone was added to the Upper and Middle ModADA, mill, and future ore types tailings in varying amounts to produce tailings with target ANC/MPA ratios of 1.5, 2.0, and 2.5 to assess the minimum ANC/MPA ratio required to ensure that tailings depositing within the ModADA would remain NAF. Table 1 presents the sample descriptions and limestone treatments. Column 1

Table 1 Sample descriptions and acid forming characteristics of the 38 columns

No.	Tailings group	Ls addition (kg/t)	Ls grind	Target ANC/MPA ratio	Actual ANC/MPA ratio	Acid–base analysis				pH	NAG Test		pH
						Tot.S %	MPA	ANC	NAPP		pH 4.5	pH 7.0	
1	Control	–	–	–	114	<0.01	0	35		8.4	0.0	0.0	7.3
2		–	–	–	0.95	1.54	47	45	2	4.6	0.0	2.0	7.2
3		–	–	–	0.85	1.5	46	39	7	4.7	0.0	2.0	7.3
4		41	Fine	1.5	1.68	1.5	46	77	−31	8.2	0.0	0.0	7.5
5		41	Med.	1.5	1.58	1.55	47	75	−28	7.8	0.0	0.0	7.4
6		41	Med.	1.5	1.75	1.42	43	76	−33	8.1	0.0	0.0	7.4
7		41	Coarse	1.5	1.63	1.54	47	77	−30	7.3	0.0	0.0	7.5
8		66	Med.	2.0	2.07	1.45	44	92	−48	8.3	0.0	0.0	7.6
9	Upper	66	Med.	2.0	2.12	1.42	43	92	−49	8.3	0.0	0.0	7.6
10	ModADA	90	Fine	2.5	2.60	1.38	42	110	−68	8.2	0.0	0.0	7.4
11		90	Med.	2.5	2.50	1.44	44	110	−66	8.3	0.0	0.0	7.5
12		90	Med.	2.5	2.46	1.46	45	110	−65	8.3	0.0	0.0	7.5
13		90	Coarse	2.5	2.46	1.46	45	110	−65	8.3	0.0	0.0	7.6
14		–	–	–	0.77	1.57	48	37	11	3.9	<1	4.0	7.2
15		62	Med.	2.0	1.87	1.4	43	80	−37	7.9	0.0	0.0	7.6
16		62	Med.	2.0	1.62	1.55	47	77	−30	7.9	0.0	0.0	7.6
17		–	–	–	0.63	1.76	54	34	20	4.2	<1	3.0	7.3
18		67	Med.	2.0	1.27	1.7	52	66	−14	7.9	0.0	0.0	7.6
19	Middle ModADA	–	–	–	1.67	0.88	27	45	−18	7.9	0.0	0.0	7.6
20		8	Med.	2.0	2.09	0.86	26	55	−29	4.1	<1	3.0	7.7
21		–	–	–	2.15	0.76	23	50	−27	7.8	0.0	0.0	7.7
22		7	Med.	2.0	2.49	0.76	23	58	−35	7.9	0.0	0.0	7.7
23		–	–	–	2.76	0.84	26	71	−45	8.1	0.0	0.0	7.8
24		–	–	–	1.15	0.74	23	26	−3	4.5	0.0	3.0	3.8
25	Mill	23	Med.	2.0	2.21	0.71	22	48	−26	8.2	0.0	0.0	7.6
26		–	–	–	1.71	0.69	21	36	−15	4.6	0.0	2.0	7.6
27		13	Med.	2.0	2.21	0.71	22	48	−26	8.1	0.0	0.0	7.8
28		–	–	–	2.88	0.67	21	59	−38	8.2	0.0	0.0	7.8
29													
	–	–	–	2.39	0.41	13	30	−17	8.2	0.0	0.0	7.9	
30		–	–	–	8.66	1.17	36	310	−274	8.2	0.0	0.0	7.8
31		–	–	–	0.34	3.6	110	38	72	8.0	0.0	0.0	7.4
32		184	Med.	2.0	1.93	3.05	93	180	−87	8.0	0.0	0.0	7.5
33	Future	–	–	–	0.23	1.58	48	11	37	6.1	0.0	<1	7.3
34	Ore types	90	Med.	2.0	1.92	1.48	45	87	−42	8.1	0.0	0.0	7.5
35		–	–	–	0.18	3.88	119	21	98	7.7	0.0	0.0	7.4
36		217	Med.	2.0	1.93	3.05	93	180	−87	7.9	0.0	0.0	7.5
37		–	–	–	0.29	1.7	52	15	37	7.8	0.0	0.0	7.7
38		86	Med.	2.0	2.02	1.52	47	94	−47	8.1	0.0	0.0	7.6

pH measured on day 3,922 (22 Aug. 2011); MPA, ANC, NAPP and NAG test results at pH 4.5 and 7.0 were measured in kg of H_2SO_4/t of tailings

Ls limestone; – indicates that no limestone was added

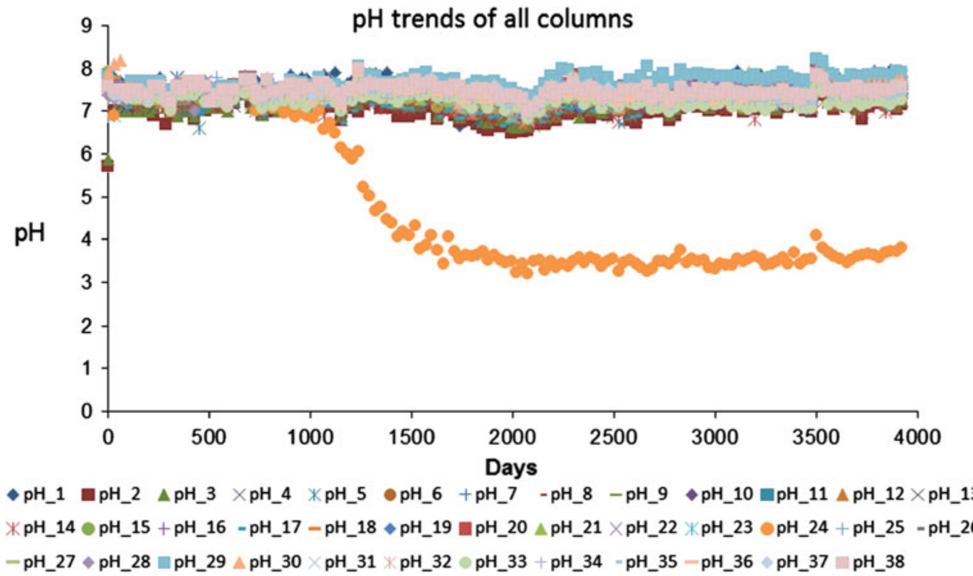

Fig. 5 The pH trend during the 4,000 days leach test

represented the natural sediment typically transported in the river system upstream of the ModADA and was included as a control. The sand contained <0.01 % S and moderate ANC (35 kg H_2SO_4/t). The column results show that the leachate from this material was pH 7.5 with an alkalinity between 12 and 60 mg $CaCO_3$/L. The dissolved sulphate concentration in the leachate was relatively steady and averaged 12 mg/L over the 11 year test period.

Column 2 to 18 represented deposited tailings at the upper ModADA (MA 210–MA 249). Three tailing samples, columns 2, 14, and 17, represented the as-received samples. Column 3 was the duplicate of column 2.

The other 13 columns (columns 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 15, 16, and 18) were the as-received tailings columns treated with limestone. Geochemical characterisation indicates that the as-received samples had positive net acid producing potential (NAPP) values (i.e. 2, 11 and 20 kg H_2SO_4/t) and that columns 14 and 17 had NAGpH values less than 4.5 (as a general rule, a positive NAPP indicates that a material is likely to be acid generating). Therefore, these two columns were classified as PAF but with a low acid-generating capacity (PAF_LC). Column 2 had a NAGpH of 4.6, indicating that the sample is classified as uncertain (UC) but is expected to also be PAF_LC. The corresponding ANC/MPA ratios for the samples (columns 2, 14, and 17) were 0.95, 0.77, and 0.63 respectively. Note that these samples were specifically selected to represent PAF tailings from the Upper ModADA and do not represent the bulk of the deposited tailings that were NAF at the time of sampling in 2000. Meanwhile, columns with limestone addition show negative NAPP (i.e. ranging from −14 to −68) and NAGpH $>$ 4.5 and were classified as NAF.

Columns 19 to 22 represented tailings samples from the Middle ModADA (MA145-160). Each sample was evaluated with and without limestone addition, as described in Table 1. Acid–base and NAG testing indicate that the as-received and as-received treated with limestone samples will be NAF, having negative NAPP values and NAG-pH $>$ 4.5. The as-received samples (column 19 and 21) have an ANC/MPA ratio of 1.7 and 2.2, respectively, while samples treated with limestone (column 20 and 22) have an ANC/MPA ratio of 2.09 and 2.49, respectively, slightly higher than the as-received samples. The ANCs of column 19 and 21 (as-received samples) of Middle ModADA tailings samples are comparable to the ANCs of the as received Upper ModADA tailings, but the sulphur contents are lower at 0.88 and 0.76 % S.

Columns 23 to 28 were designed to represent the tailings discharge from the mill, during which approximately 8 % of the feed ore was sourced from the underground mine. Four mill tailings samples of column 23, 24, 26, and 28 were tested as received samples and two other columns (column 25 and 27) were tested with limestone addition. Table 1 shows that only column 24 was classified as uncertain but expected to be PAF-LC; all of the other columns had negative NAPP values and NAGpH $\geq$ 4.5 and were classified NAF.

Columns 29 to 38 were designed to represent samples of future flotation tailings by pilot plant processing of six different ore types from the Grasberg Deep deposit. Six samples (column 29, 30, 31, 33, 35, and 37) were prepared without limestone addition while four of the samples (column 32, 34, 36, and 38) had limestone added. Without added limestone, the as-received tailings are classified PAF with low ANC/MPA values of 0.18 to 0.34.

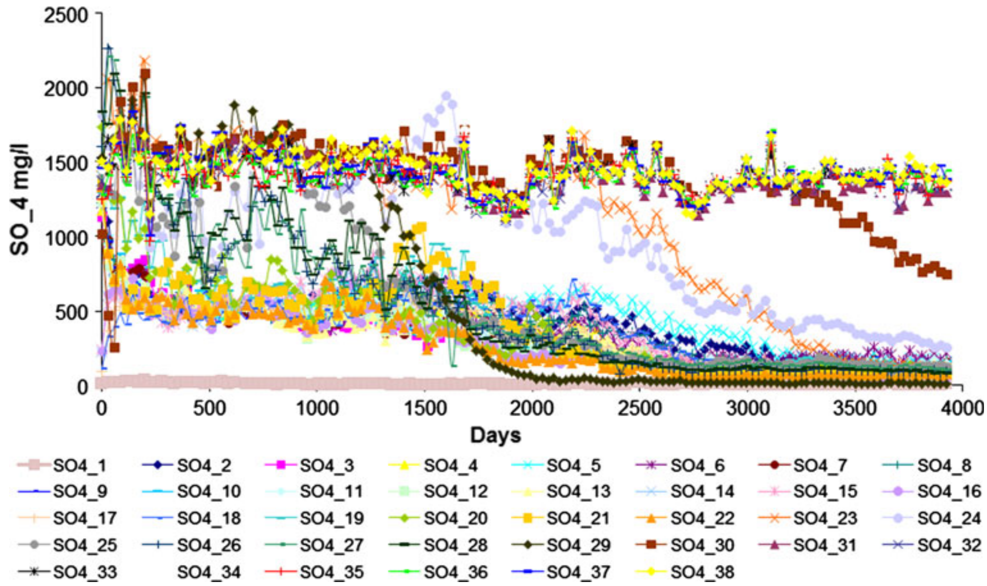

Fig. 6 Sulphate release trend of all tailings samples during the 4,000 days leach test

Results

Long-term Column Leaching Test

After 4,000 days of operation, the column tests provide an understanding of the reactivity and leaching behaviors of the samples, their neutralizing potential, and the required ANC/MPA ratio to ensure that tailings deposited within the ModADA will remain non-acid forming. Figure 6 shows pH trends for tailings column samples. Only column 24 (ex-mill tailings with an ANC/MPA of 1.1) has acidified during the 11 year test period. In contrast, columns 2, 3, 14, 17, 18, 31, 33, 35, and 37 have an ANC/MPA < 1 but the leachate has remained neutral (Fig. 5). The high proportion of anhydrite content (columns 31, 33, 35, and 37) determined the neutral pH; Table 1 indicates that despite the low ANC/MPA ratio, the NAGpH remains alkaline. Columns containing coarser sized particles (columns 2, 3, 14, 17, and 18) released higher leachate volumes than columns with finer-sized particles (i.e. column 24) for the same flushing volume. Column 24 maintains higher moisture content, resulting in higher oxidation rates than the columns that contain coarser particles. This was confirmed by the higher sulphate release from column 24. Columns 31, 33, 35, and 37 have higher S contents but this largely consisted of non-reactive anhydrite.

Sulphate release of all columns varied except for the natural sample (column 1), which consistently had a low release rate due to the absence of sulphur (Fig. 6). The upper (columns 2–18) and middle (columns 19–22) ModADA samples both showed a gradually decreasing release of sulphate to the leachate. However, samples from the upper ModADA took about 2,500 days to reach a concentration of 200–250 mg/L, which the lower samples reached in about 2,000 days (see supplemental figures 1 and 2, which all subscribers can access for free in the

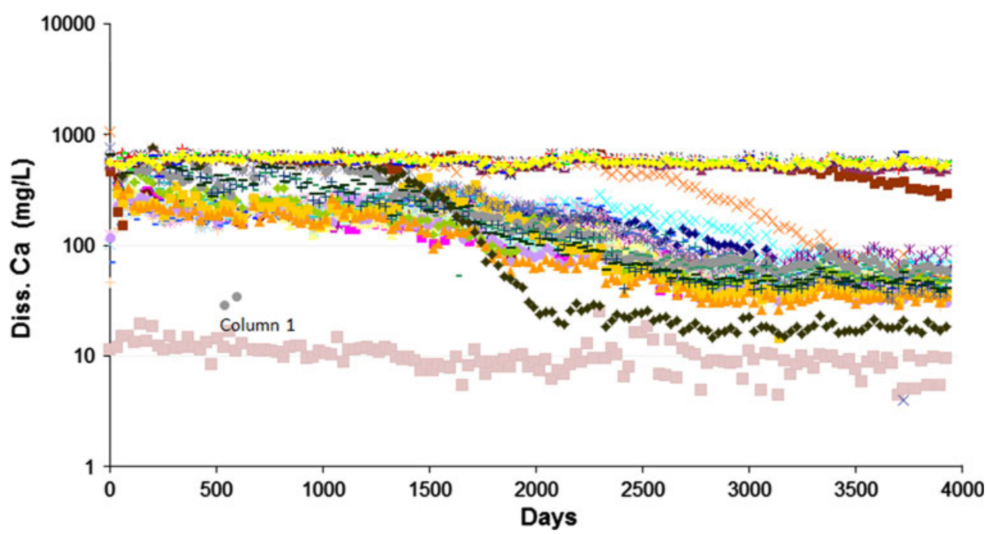

Fig. 7 Ca concentration trends of all columns

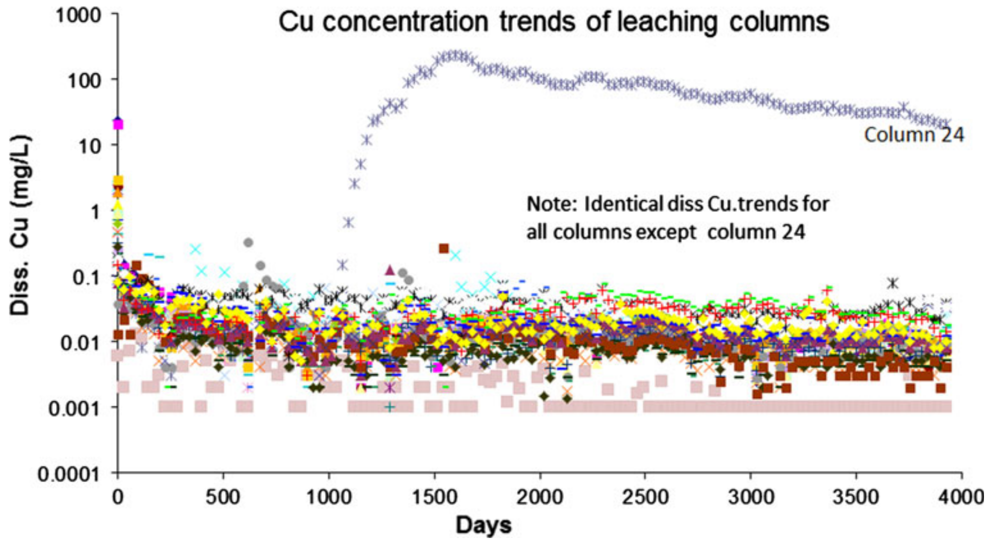

Fig. 8 Cu concentration trends of all columns, similar trend was shown for Fe

electronic version of this paper). This difference is probably due to the difference in total sulphur content (1.4–1.76 % for the upper vs. 0.76–0.88 % for the lower). The upper ModADA tailings sulphate release trend showed an initial sulphate concentration release of 200–1,300 mg/L, which decreased to 200 mg/L after 2,500 to 3,000 days. The middle ModADA tailings sulphate release trend showed an initial sulphate concentration release of 1,300-1,750 mg/L, which decreased after 2,000 days to a rate below 200 mg/L.

Mill samples (column 23 to 28) had different sulphate trends than the upper and middle ModADA samples, as indicated by higher initial release rates; however, periods of decrease of sulphate release appear to occur at a similar time (after 2,000–2,500 days). Unlike all of the other samples, the sulphate release rate remained high (1,500 mg/L) for the future tailing samples (column 29 to 38), except for column 29. The release rate is largely attributed to the S content and proportion of reactive and non-reactive S within the samples; column 29 has the lowest S content of the future tailings samples. Mill tailings (columns 23–28) had higher initial sulphate release (supplemental figure 3) than the upper and middle tailings samples. Column 23 and 24 had higher sulphate release rates (above 1,200 mg/L) until 2,500 days, compared with column 25, 26, 27, and 28, which showed a rapid reduction of sulphate release rate to below 300 mg/L after 2,500 days. This is likely due to the relatively higher reactive sulphur content and different ANC content of column 23 and 24 (Table 1). Sample column 24 was the only one to acidify within the leach test period.

Future tailing samples (columns 30–38) retained a high sulphate release rates (1,300–1,600 mg/L) after 3,000 days except for Column 29, which had the lowest S content (0.41 %) and had a sulphate release that rapidly decreased after approximately 1,300 days of operation, after the reactive sulphur had been oxidized (supplemental 4).

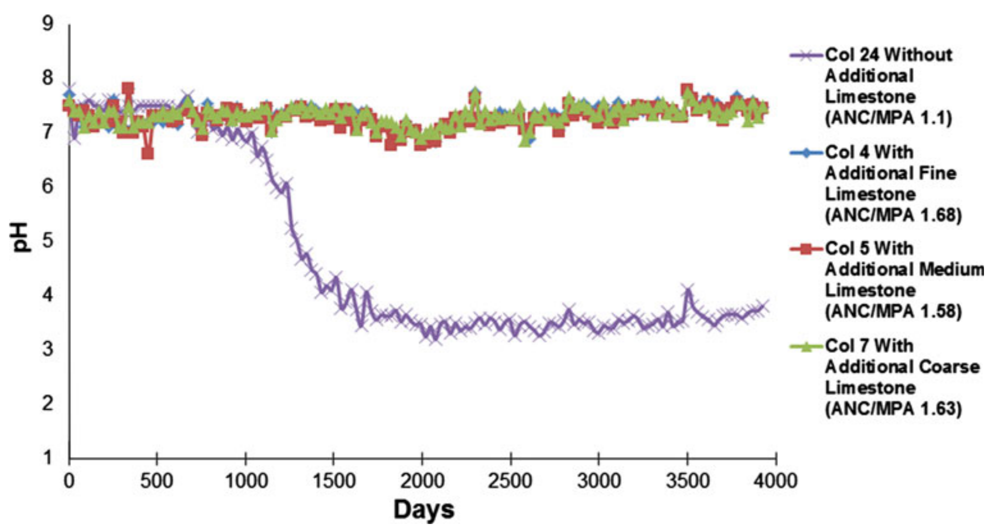

Fig. 9 pH trends for tailing columns with addition of crushed limestone

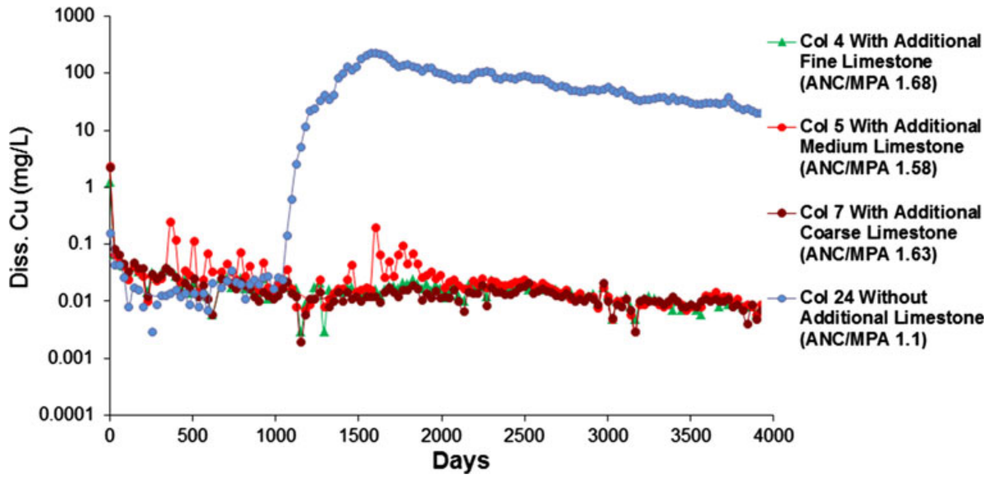

Fig. 10 Cu concentration trends for tailing columns with addition of crushed limestone and Fe also shows a similar trend

Calcium (Ca) release trends (Fig. 7) essentially followed the chemistry implied in the above discussion of sulphate. Ca concentrations from the natural sample (column 1) remained low, while the Ca release from future tailings was stable and high, except for column 29, which had the low S assay. Other columns (the mill, upper, and middle ModADA samples) showed relatively similar trends of Ca concentration, e.g. a slow decrease after 1,500 days of leaching. The Ca release trends reflect ANC depletion from reactions with pyrite-generated acidity, and, to some extent, dissolution of calcite through pore water flushing.

Release of Cu and Fe had relatively similar trends, except for column 24, which showed a dramatic increase of Cu and Fe solubility after 1,000 days (Fig. 8). The sample acidified due to the depletion of carbonates, which caused an increase in the dissolution potential of metals.

The tests also provided insight into the benefits of limestone addition to PAF tailings, and whether grain-size significantly changes the effectiveness of the added limestone. The addition of crushed limestone to the experimental leach column tests increased the ANC/MPA ratio of the Upper ModADA tailings to a minimum of 1.3 and a maximum of 2.6 (i.e. column 18 and 10, respectively). Column 24 (ex-tailings sample without limestone addition, with an ANC/MPA value of 1.1) is the only one of the 38 columns to acidify within the test period of 11 years. The pH trend for this sample showed a 3 year lag before the pH begins to decrease, reaching pH 4 after 4 years (Fig. 9). Figure 9 also shows that all of the other samples with additional limestone maintained circumneutral pH throughout the test period.

The acid–base accounting and NAG test results indicated that all of the limestone-amended columns are NAF. Leachate quality data confirm the NAF nature of the limestone-amended tailings, with leachates typically averaging a pH of about 7.0 to 8.0.

The Cu and Fe concentrations trends for column 4, 5, 7, and 24 (Fig. 10) clearly demonstrate a dramatic increase in Cu and Fe concentrations in column 24 as the pH dropped below 6; by pH 4, dissolved Cu and Fe concentrations exceeded 100 and 10 mg/L, respectively. On the other hand, columns 4, 5 and 7, which had limestone added, showed low Cu and Fe concentrations, at 0.01 and 0.001, respectively.

Results also indicate that sulphide oxidation is occurring, with average SO_4 concentrations of about 400 to 600 mg/L, and average alkalinities between 20 and 30 mg/L, as $CaCO_3$. There were no discernible differences between columns containing different limestone grinds (fine, medium, and coarse). The S release trends suggest that, at the current rates of oxidation and release, all S would be removed before depletion of ANC, confirming that these samples are NAF and will not generate ARD. Sulphate release from column 24 (without additional limestone, the ANC/MPA ratio was 1.1) was higher than columns with additional limestone and an ANC/MPA ratio >1.5. The results indicate that an ANC/MPA ratio of 1.5 provides a high factor of safety for long-term control of ARD.

Particle Size Distribution

Results from sampling of transects showed that the deposited tailings is largely (85 to 100 %) comprised of a material size fraction smaller than 0.3 mm with the remaining portion fraction between 0.3–0.6 mm. Natural segregation of the different particle sizes due to their weight and specific densities is observed as tailings are transported along the river from the mill to the lowlands. The coarser and denser particles tend to settle upstream in the ModADA as the velocity decreases, whereas the finer and lighter particles remain suspended and finally settle in the lower reaches of ModADA.

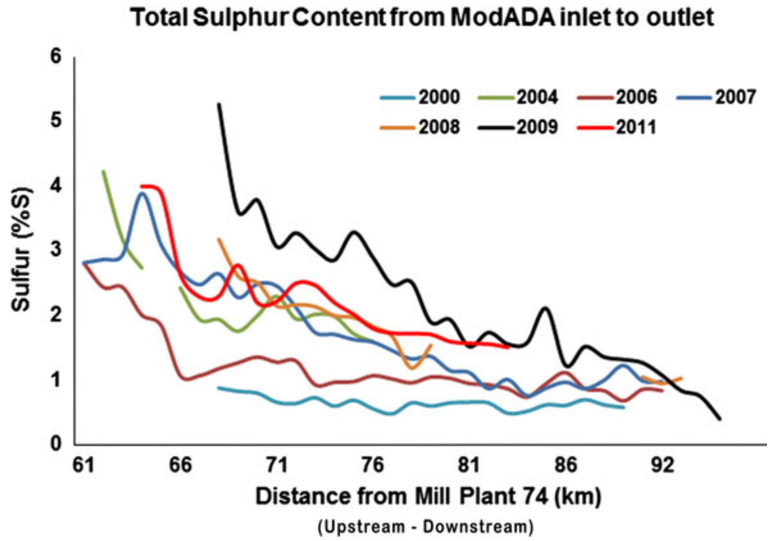

Fig. 11 Preferential deposition of sulphide due to the high specific gravity

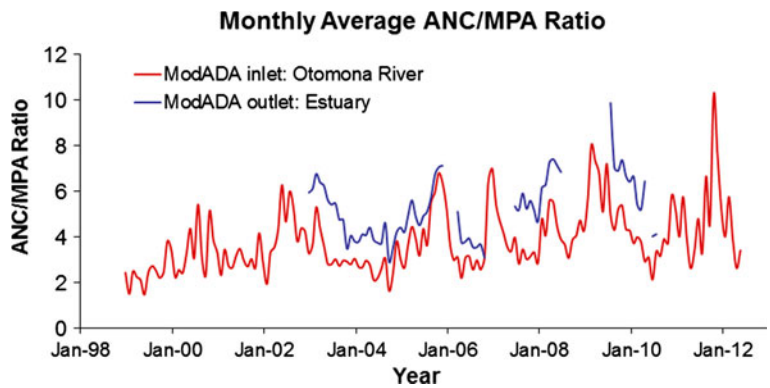

Fig. 12 Monthly average ANC/MPA of the ModADA inlet and outlet

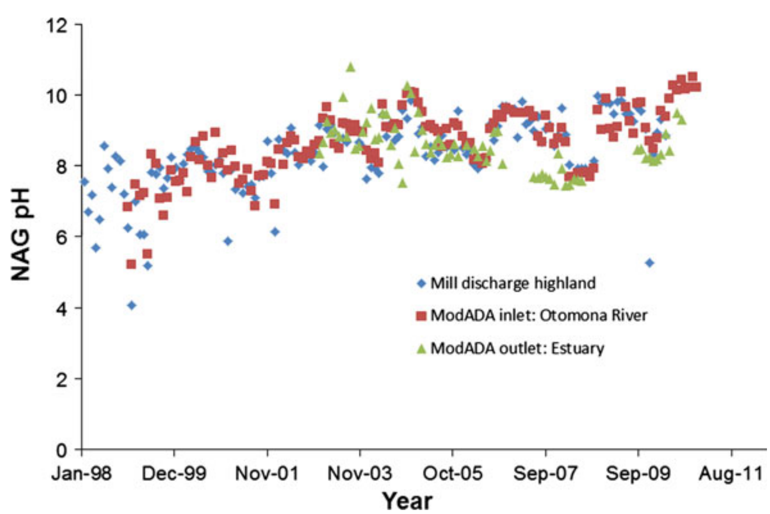

Fig. 13 Monthly average NAG pH of the ModADA inlet (Otomona Bridge)

Results of geochemical analysis of the ModADA tailings samples confirm the role of specific density in preferential S deposition in ModADA (Fig. 11). The S content in the upper reach is generally higher than in the rest of the ModADA due to the higher specific gravity of sulphides.

Unlike S, the ANCs of suspended tailings at the ModADA outlet are similar to the results for the ModADA inlet; hence, there appears to be no preferential settling of carbonate mineralogy. Consequently, this produces small localized areas of tailings in the upper ModADA that are PAF, even when overall, the ModADA inlet and outlet tailings are NAF. The combined effect is that ModADA outlet tailings have an ANC/MPA ratio that is higher than the ModADA inlet tailings (Fig. 12). This may imply a favourable condition for material that discharges into the estuary, although this can be a concern for the sediment captured within the upper reach of ModADA in that the acid potential there will be slightly higher. Nonetheless, the upper ModADA also contains sufficient carbonate buffering, which will prevent acid formation in the short term (the average ANC/MPA ratio of deposition areas >2). Furthermore, the upper ModADA is a high energy reach of the river system, which is regularly remobilized by high flows; therefore, this is unlikely to be a concern during operation.

Monitoring results indicate that the sediment that passes the ModADA inlet (Otomona Bridge) are NAF, have a high factor of safety for the prevention of acid generation, and pose minimal risk of developing acid generating hot spots within the ModADA. The pH trends for the Mill station in the Highlands, ModADA inlet (Otomona Bridge), and ModADA outlet (Estuary) are presented in Fig. 13. The increasing trend shows that the NAGpH is generally alkaline, which indicates a low risk of acid generation.

Conclusion

The long term leaching column tests provided an understanding of the reactivity and leaching behaviors of the samples, neutralizing potential, and the required ANC/MPA ratio to ensure that tailings deposited within the ModADA will remain NAF. Results showed that columns with an ANC/MPA < 1.1 remain neutral; the one column with an ANC/MPA of 1.1 acidified after 3 years.

The percentages of reactive S and anhydrite content in the samples appeared to largely determine the pH. The pH trends for columns (column 24) with a high content of reactive S (ANC/MPA 1.1) acidified, while columns 31, 33, 35, and 37, which have a higher anhydrite content, remain neutral despite an ANC/MPA < 1.0. The leaching column tests also showed the benefits and effectiveness of added limestone. The addition of crushed limestone increased the ANC/MPA ratio of the Upper ModADA tailings to a minimum of 1.3 and a maximum of 2.6 (i.e. columns 18 and 10, respectively), whereas the one column without added limestone (column 24, ex-tailings sample) with an ANC/MPA value of 1.1, was the only one of the 38 columns to acidify within the 11 year test period. Columns consisting of coarser particles (columns 2, 3, 14, 17, and 18) released higher leachate volumes than columns consisting of finer particles (i.e. column 24) for the same flushing volume. Consequently, column 24 retained more moisture (but was not saturated) in the column, resulting in higher oxidation rates than columns that contain coarser particles. Consistent results were shown by columns with ANC/MPA >1.5, which have maintained circumneutral pHs throughout the test period.

Geochemical analysis of the ModADA tailings samples confirm some segregation of S in the ModaADA, as the S content at the upper reach is generally higher than in the rest of the ModADA. Unlike S, the ANCs of suspended tailings at the ModADA outlet is comparable to the results for the ModADA inlet; hence, there appears to be no preferential settling of carbonates. Consequently, small localized areas of tailings with lower ANC/MPA ratios than the average deposition areas (ANC/MPA ratio >2) may develop in the upper ModADA.

However, overall monitoring results indicate that the sediments passing the ModADA inlet are NAF and have a high factor of safety for the prevention of acid generation. Although localized areas with relatively low ANC/MPA ratios may exist at the inlet, most of these still contain significant ANC and would require a long period of exposure to atmospheric conditions before an onset of acid conditions.

Thus, the current ore-feed blending has resulted in the tailings being NAF, with an excess of ANC. An ANC/MPA ratio of 1.5 appears to provide an adequate factor of safety to prevent long term generation of acid and metal leaching of the tailings deposited in the ModADA. This result suggests that this blending strategy has achieved the objective of ensuring the geochemical stability of the tailings deposited in the ModADA.

Acknowledgments The authors thank PT Freeport Indonesia for their financial support of this project.

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