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ORIGINAL ARTICLE

ARD generation and corrosion potential of exposed roadside rockmass at Boeun and Mujoo, South Korea

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Abstract Acid rock drainage (ARD) is a longstanding problem often associated with the resulting corrosion due to the acidity generated from sulfidic oxidation. To evaluate characteristics of ARD and corrosion, samples from the road side rock mass of Boeun and Mujoo were analysed using X-ray diffraction, acid/base accounting and Leaching tests. The results indicated that many samples had a pyritic origin and can be regarded as acid-generating rocks. The Leaching test showed that the average pH of the leachates of samples from both Boeun and Mujoo were moderately acidic, ranging from 3 to 4. Interestingly, as acidity increases from pH 4, the SO_{4-}, Fe, Al and Mg concentrations increase abnormally. Samples from roadside slope of Mujoo showed high corrosive potential. Maximum sulfide oxidation rate of a sample taken from Mujoo was as high as 5,166 mg/kg/week.

Keywords Acid rock drainage · Construction hazards · Boeun · Mujoo · Korea

Introduction

As urbanisation increases, road construction and other development increases all over the world. New construction in rocky, mountainous terrane increases acid rock drainage (ARD). Acid rock drainage has significant deleterious effects, some of which are as below:

1. Increased acidity has the potential to both carry and leach nutrients that can contribute to increased eutrophication.
2. Acidity increases the solubility of the ions of a concrete structure, inducing micro passages in the concrete matrix and speeding up weathering. Similarly, acidity increases cation exchange of metals in steel.
3. Acidity may induce decolouration and reduce aesthetic value.
4. Increased weathering as a result of ARD will increase maintenance costs and reduce safety.

ARD release is enhanced by increased surface area of the rock. High temperature differentials induce cracking, creating opportunities for increased oxidation and excess water to carry more H+ ions. While not all rocks contribute to increased acidity, pyrritic rocks having loose association of sulfur in the complex of elements and radicals can result in net acidity in excess of the inherent alkalinity of the rock. Conventionally, ARD is considered to be the carrier of non-critical metallic cations like Fe, Mg, Ca and Zn, but ARD also may carry potentially toxic metal pollutants like Cu, Mn, Zn, As and Pb.

ARD today is a global phenomenon. Orndorff (2001) lists examples of ARD occurrences worldwide (Table 1). Hydrothermally altered andesite due to acid sulfate weathering was reported by Kim et al. (2000). ARD was considered to be a cause for reduced service life of concrete by Clifton (1991). Toxicity from ARD of Ankeesta formation leachates contributed to habitat

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Table 1 Summary of engineering problems by ARD (Orndorff 2001)

Location	Materials	Problems
Buchanan, Georgia, USA	py bearing schist (Sandy Springs group)	Decline in local water quality due to acid drainage
Central Pyrenees, Spain	po and py bearing schist	Concrete degradation due to formation of expansive sulfates in the aggregate
Sainte-Foy, Quebec, Canada	py bearing black shale (Sainte-Foy formation)	Concrete floor slab heaved more than 10 cm
Barcelona, Spain	po and py bearing shales and limestone	Concrete degradation due to formation of expansive sulfates in the aggregate
Southwest Pennsylvania, USA	py bearing coals and shales (dominantly the Conemaugh and Monongahela formations)	Structural damage due to heaving
Nova Scotia, Canada	po bearing slate	Decline in local water quality due to acid drainage
Ottowa, Ontario, Canada	py bearing black shale (Eastview formation)	Basement floor heaved up to 6.3 cm sulfate attack on concrete
Cardiff, UK	py bearing black mudstone (Westbury formation)	Heaving in the floor slab
Central Japan	py bearing rhyolite	Acidification of reservoir water
North Carolina, USA	py bearing black shales (Anakeesta formation)	Metalliferous, acid leachage destroyed aquatic ecological systems
Texas, USA	py bearing sediments (Weches and Queen City formations)	Vegetative failure, causing increased erosion, on road banks
North Carolina & Tenn., USA	py bearing black shales (Anakeesta formation)	Metalliferous, acid leachate destroyed aquatic ecological systems
Oslo, Norway	po in slightly metamorphosed shales (alum shales, alum slates)	Concrete deterioration due to sulfate attack foundation upheaval
Kansas City, Missouri, USA	py bearing black shales (Upper Pennsylanian beds)	Building floor heave up to 10 inches mine floor heave up to 8 inches
Ottowa, Ontario, Canada	py bearing black shale (Billings formation)	Basement floor slab cracked by 10.2 cm of differential heave
Redding, California, USA	Massive py ore	Thermal expansion and deformation due to heat from oxidation reactions
Derbyshire, UK	py bearing black shale (Namurian shale)	Collapse of a shale embankment from volumetric changes due to acid leaching
Ottowa, Ontario, Canada	py bearing black shale (Lorraine formation)	Interior columns heaved up to 7.6 cm
Malaysia	py bearing granite, hornfels	Disintegration of road aggregates
Liddell, New South Wales	Framboidal py in siltstone	Rapid weathering of excavated siltstone due to acidity and expansion effects
Netherlands	Unspecified sulfides	Corrosion of concrete piles poured in situ (unsatisfactory hardening due to sulfates)
Derbyshire, UK	py bearing black shale (Namurian shale)	Slope instability, landslides, and acid drainage along roadcut

py pyrite; *po* pyrrhotite

destruction of the shovel-nosed salamander 8 km from the worksite (Mathews and Morgan 1982). Several such instances of ARD effects in highway and construction activities were reported by Daniels and Orndroff (2003), about managing ARD by Hutchison and Ellsion (1992) and about pit disposal of acid leachate by Orava (1997).

ARD Determination

The two primary objectives of predictive testing are to: (1) determine if a discrete volume of rock/waste will generate acid and (2) predict the quality of the drainage based on the rate of acid formation. Proper procedure should be as follows:

1. Scientific and representative samples are collected from the field for analytical testing.
2. An appropriate analytic test method is selected depending upon the expected characteristics of the rock mass.

Results from any analytical test are only as reliable as the samples used. Once the sampling strategy is defined, an appropriate analytical method (or methods) can be selected.

Methods used to predict the ARD potential are classified as either static or kinetic. A static test determines both the total acid generating and total acid neutralising potential of a sample. The static tests are one-time characterisation of the rock samples and the methods are enumerated by many (Sobek et al. 1978; Coastech 1989; Duncan and Bruynesteyn 1979; Sobek et al. 2000). Factors affecting the selection of the sampling regime and analytical method for static tests include knowledge of the geology, rock mass or material, costs and length of time to conduct the test. Several sample methodology and analytical tests may be used to predict acid generation potential.

The following components describe the solid phase composition and mass reaction environment of sulfidic rock and minerals contributing to ARD potential. Potential criteria components can be individually obtained by separate methods.

Components affecting the total capacity to generate acid include:

- Amount of acid generating (sulfide) minerals (assumes total dissolvable oxidation of all sulfide minerals) and whether there are other potential sources of acidity like carbonate or organic matter. Knowledge of the non-sulfidic acidity contribution of rocks and minerals is still limited.
- Amount of acid-neutralising minerals. This measurement indicates whether net acidity or net alkalinity is likely to prevail.
- Amount and type of one or more critical contaminants (heavy metals, etc.).

Components affecting the rate of net ARD include:

- Type of acidity generating and oxidisable sulfide mineral (Geidel and Caruccio 2000; Lapakko 1988; Sobek et al. 2000).
- Type of carbonate mineral (and other neutralising minerals as appropriate).
- Mineral surface area available for reaction, including occurrence of the mineral grains in the waste (i.e. included, liberated) and particle size of the waste.
- Availability of water and air and their accessibility in the rock body.
- Bacterial influence, if any.

The capacity of the sample to generate acidic drainage is calculated as either the difference of the values or as a ratio of the values (Ferguson and Morin 1991; Lapakko 1993a).These tests are not intended to predict the rate of acid generation, only the potential to produce acid as a mass (or gross) characteristic. Static tests can be conducted quickly and are inexpensive compared to kinetic tests.

Kinetic tests obviously provide time-dependent characteristics dependent upon how much ARD is already discharged, how many remains to be discharged and what are the existing environmental parameters, like flow, temperature, pressure, etc. (Lapakko 1993b). For example, the rate of discharge depends on the available acidity, i.e. total acidity minus acidity already discharged. A first order differential equation can be written as:

$$\mathrm{d}At/\mathrm{d}t = -kAt$$

or by integration,

$$At = Ao(1 - \mathrm{e}^{-kt}), \tag{1}$$

where At is the acid generation capacity left, k is the reaction rate, time^{-1} and Ao is the ultimate or complete acidity.

Test results are used to classify wastes or materials according to acid generating potential. This information can be collected and evaluated during the economic analysis of infrastructure construction. Decisions can then be made with respect to specific mitigation practices.

Sampling

Proper selection of samples directly impacts subsequent acid prediction testing. The purpose of testing rock material is to allow classification and planning for waste disposal based on the predicted drainage quality. Samples must characterise both the type and volume of rock materials and also account for variability of materials that will eventually be exposed. When to collect samples for testing is an equally important consideration. Sampling and testing should be concurrent with resource evaluation and mine or construction planning (Lapakko 1992). Sampling techniques used to evaluate recoverable mineral resources (assay samples) are similar to those required for prediction of acid generation potential. Active mining operations for which predictive tests were not conducted in advance lack the advantage of front end planning; however, samples and other information may still be used to establish acid generating potential.

There are many opinions concerning the number of samples to be collected in a fixed-frequency sampling program. In one instance about 8–12 samples of each significant rock type, or one sample for each one million tons, at a minimum, was recommended (Schafer 1993). In this case a significant rock type represents 1 or 2% of the total rock volume. USDA Forest Service suggests that one sample (about 1,500 g) be collected per 20,000 tons of waste rock, or about 50 samples for each one million tons (USDA Forest Service 1993). These samples would be collected by compositing from individual drill hole cuttings. The British Columbia AMD Task Force (1989) recommends a minimum number of samples based on the mass of the geologic unit. Their recommended minimum sample number is 25 for a one million ton geologic unit, or one sample for every 40,000 tons. Using the British Columbia method, as waste volume increases, the number of samples decreases. For example, for a unit of 10 million tons, the minimum sample number is 80, or one sample for every 125,000 tons (British Columbia AMD Task Force 1989).

There are reservations to prescribing a fixed number of samples per volume of material. This is particularly true for existing mines when samples are from waste rock for acid generation potential tests. Waste rock dumps are usually constructed by dumping of rock from trucks and excavators, creating heterogeneous and changing deposits. The determination of how many samples should be taken at any one time depends on variability of the site's geology and how the site will be developed. Due to general uncertainty regarding ARD predictive methods, it may be prudent to sample wastes or material throughout the life of the project.

Factors to consider in a sampling program for existing or planned mines and excavated sites include the method of sample collection, length of time samples are to be (or have been) stored and the sample storage environment. Each can affect the physical and chemical characteristics of a sample. Samples collected from cores exposed to the environment may be physically and/or chemically altered. Sample contamination can be restricted if a lubricant was used, or if lime was added during milling.

Samples of rock were collected from roadside slopes for this current example. The study was conducted in four locations: two road cut slopes at Boeun and the Mujoo, in a waste rock pile of an abandoned mine in Samtan and in an operating non-metallic mine.

ARD static test

One underlying assumption of ARD static testing is to assume that a rock will generally have constituents that will provide acidity and alkalinity (also known as neutralisation potential) together at the same time, and pass them in solution. Static tests predict drainage quality by comparing the sample's maximum acid production potential (AP) with its maximum neutralisation potential (NP). The AP is determined by multiplying the percent of total sulfur or sulfide sulfur (depending on the test) in the sample by a conversion factor (AP = 31.25 × % S, unit: kg $CaCO_3$/ton). NP is a measure of the carbonate material available to neutralise acid (unit: kg $CaCO_3$/ton). The value for NP is determined either by adding acid to a sample and back titrating to determine the amount of acid

Fig. 1 Oxidation marks at the road cut slope in the vicinity of Boeun area

consumed or by direct acid titration of the sample; the endpoint pH is usually 3.5 (Ferguson and Morin 1991; Lapakko 1993a). Lapakko (1992) reported that using an endpoint pH of 3.5 measures a sample's acid neutralising potential below 6.0, but noted that a drainage pH in the range of 3.5 may not be environmentally acceptable. The net neutralisation potential (NNP), or acid/base account (ABA) is determined by subtracting the AP from the NP (NNP = NP – AP, unit: kg CaCO$_3$/ton). A ratio of NP to AP is also used. An NNP of 0 is equivalent to an AP/NP ratio of 1 (Ferguson and Morin 1991). Units for static test results (AP, NP and NNP) are typically expressed in mass (kg, metric ton, etc.) of calcium carbonate (CaCO$_3$) per 1,000 metric tons of rock, parts per thousand. If the difference between NP and AP is negative then the potential exists for the waste to form acid. If it is positive then there may be lower risk. Prediction of the acid potential when the NNP is between –20 and 20 is more difficult. If ratios are used, when the ratio of a sample's neutralisation potential and acid production potential is greater than 3:1, there is lower risk for acid drainage to develop (Brodie et al. 1991). For ratios between 3:1 and 1:1, referred to as the zone of uncertainty, additional kinetic testing is usually recommended. Those samples with a ratio of 1:1 or less are more likely to generate acid. Prediction of drainage quality for a sample based

Fig. 2 Oxidation marks at the road cut slope in the vicinity of Mujoo area

Table 2 Mineral composition and sulfur contents of collected samples

No.	S (%)	Mineral	No.	S (%)	Mineral
BW-1	7,860	mus, qtz, clino, py	Sh-14	890	qtz, mus, clino, pyro, micro
BW-2	8,950	qtz, mus, clino, py	Sh-15	440	qtz, clino, mus, pyro, micro
BF-3	16,300	qtz, clino, mus, py	Py	263,000	py, qtz, pyro, kao
MW-1	6,640	mus, qtz, clino, albite	SS-1	230	qtz, mus, clino
MW-2	14,700	stilbite, qtz, mont, laumo, mus, clino, gypsum, albite, micro, py	SS-2	480	qtz, mus, pyro, clino
			SS-3	280	qtz, pyro, mus, clino
MW-3	32,900	mus, clino, qtz, gypsum, clino	SS-4	90	qtz, pyro, mus, clino
Sh-1	860	–	SS-5	90	qtz, mus, clino, pyro
Sh-2	700	–	SS-6	690	qtz, mus, clino, pyro
Sh-3	840	–	SS-7	250	qtz, mus, pyro, clino
Sh-4	800	–	SS-8	340	qtz, mus, clino
Sh-5	480	–	SS-9	110	qtz, mus, pyro, clino
Sh-6	13,100	qtz, clino, mus, pyro, micro, py	SS-10	140	pyro, qtz, mus, clino
Sh-7	4,100	qtz, mus, pyro, clino, py, micro	A-1	13,070	qtz, py, clino, calcite
Sh-8	10,500	qtz, pyro, clino, mus, py	A-2	tr	qtz, mus
Sh-9	2,400	qtz, mus, pyro, clino, micro	A-3	2,720	qtz, clino, py, mus
Sh-10	2,470	qtz, pyro, mus, clino, py, micro	A-4	13,860	qtz, py, sanidine, mus, clino
Sh-11	4,180	qtz, mus, clino, pyro, micro	A-5	730	qtz, albite, clino, laumo, pyro
Sh-12	520	qtz, clino, mus, pyro, micro	A-6	8,330	qtz, pyro, py
Sh-13	6,040	qtz, mus, clino, pyro, micro	A-7	15,660	qtz, py, mus

B Boeun, *M* Mujoo, *A* mine A, *W* weathered, *F* fresh, *Sh* shale, *SS* sandstone, *Py* pyrite dyke, *qtz* quartz, *mus* muscovite, *mon* montmorillonite, *kao* kaolinite, *py* pyrite, *clino* clinochlore, *pyro* pyrophyllite, *micro* microcline, *laumo* laumontite

Table 3 Results of ABA test

Samples	NP (kg $CaCO_3$/ton)	AP (kg $CaCO_3$/ton)	AP/NP
Sh-1	0.8	2.7	3.6
Sh-2	5.8	2.2	0.4
Sh-3	1.0	2.6	2.6
Sh-4	1.8	2.5	1.4
Sh-5	1.3	1.5	1.2
Sh-6	23.8	40.9	1.7
Sh-7	3.7	12.8	3.4
Sh-8	17.5	328.1	18.8
Sh-9	8.8	7.5	0.9
Sh-10	346.3	7.7	0.0
Sh-11	–23.8	13.1	–0.6
Sh-12	4.5	1.6	0.4
Sh-13	23.8	18.9	0.8
Sh-14	6.3	2.8	0.4
Sh-15	7.8	1.4	0.2
Py	36.3	821.9	22.7
SS-1	49.8	0.7	0.0
SS-2	24.0	1.5	0.1
SS-3	2.8	0.9	0.3
SS-4	7.3	0.3	0.0
SS-5	1.8	0.3	0.2
SS-6	1.5	2.2	1.4
SS-7	0.8	0.8	1.0
SS-8	3.5	1.1	0.3
SS-9	2.0	0.3	0.2
SS-10	1.5	0.4	0.3
MW-1	137.5	20.8	0.2
MW-2	–53.8	45.9	–0.9
MW-3	8.8	102.8	11.8
BW-1	51.3	24.6	0.5
BW-2	–6.3	28.0	–4.5
BF-3	–18.8	50.9	–2.7
A-1	31.8	40.8	1.3
A-2	49.1	0.2	0.0
A-3	32.8	8.5	0.3
A-4	43.5	43.3	1.0
A-5	47.0	2.3	0.0
A-6	6.3	26.0	4.2
A-7	3.3	48.9	15.1

on these values requires assumptions that reaction rates are similar and that the acid consuming minerals will dissolve (Lapakko 1992). When reviewing data on static tests, an important consideration is the particle size of the sample material and how it is different from the waste or unit being characterised. Information on these and other static acid prediction tests, including summaries of test results (Coastech 1989; Lapakko 1992, 1993b) is available in US EPA 530-R-94-036 (1994).

Acidity generating potential

Figures 1 and 2 provide images of ARD discharges on the roadside concrete surface. Wherever seepage water contacts the concrete surface, yellow ochre signatures are visible. Considering high slopes and high rainfall, similar signatures can be extensive over a construction.

Table 4 Values of NP, AP and ∑AP/∑NP

Sample	NP (kg $CaCO_3$/ton)	AP (kg $CaCO_3$/ton)	∑AP/∑NP
Samtan Shale (*n* = 15)	28.6 (–23.8 to 346.3)	29.8 (1.4–328.1)	2.3 (–0.6 to 22.7)
Samtan Sandstone (*n* = 10)	9.5 (0.8–49.8)	0.8 (0.3–2.2)	0.4 (0.0–1.4)
Mujoo Shale (*n* = 3)	30.8 (–53.8 to 137.5)	56.5 (20.8–102.8)	3.7 (–0.9 to 11.8)
Boeun Phyllite (*n* = 3)	8.8 (–18.8 to 51.3)	34.5 (24.6–50.9)	2.2 (–4.5 to 0.5)
"A"(*n* = 7)	30.5 (3.3–49.1)	24.3 (0.2–48.9)	3.1 (0.0–15.1)

The overall mineral composition and sulfur percentage were found for a sufficient number of samples (Table 2). Table 3 provides the results of the acid–base accounting tests for all samples. A summary of the result with range values of NP, AP and AP/NP are given in the Table 4. Figure 3 is a plot of AP/NP values for the sample from the four locations. The plot suggests that although most of the ratio of values of the samples is within 0–1, usually signifying little net acidity potential, higher values also suggest acidity sufficient to damage the structure may possibly be generated. The plot for AP/NP in Fig. 4 suggests that regional correlation of the values of AP/NP with pH may exist. For example, both samples from Samtan AP/NP vary almost directly with pH. In the cases of Boeun and Mujoo, the relationship is too weak to suggest any characteristic. In the case of mine A, the relationship is quasi-log linear. More investigation related to this relationship is required.

Sulfatic corrosion

The pyritic sulfur in the rock matrix is understood to be released as sulfatic ion in the aqueous solution. Sulfates present in soils, groundwater, seawater, decaying organic matter and industrial effluent surrounding a concrete structure may pose a major threat to the long term durability of the concrete. Sulfate attack of concrete may lead to cracking, spalling, increased permeability and strength loss. Thus, a measurement of vulnerability of concrete to sulfate attack is integral to ensure its satisfactory performance over time. In the presence of calcium hydroxide (CH) and water (H), monosulfate hydrate ($C_3A \cdot C\$ \cdot H_{18}$)and calcium aluminate hydrate ($C_3A \cdot C \cdot H_{18}$) react with the sulfate (\$)to produce ettringite ($C_3A \cdot 3C\$ \cdot H_{32}$)(Mehta and Monteiro 1993):

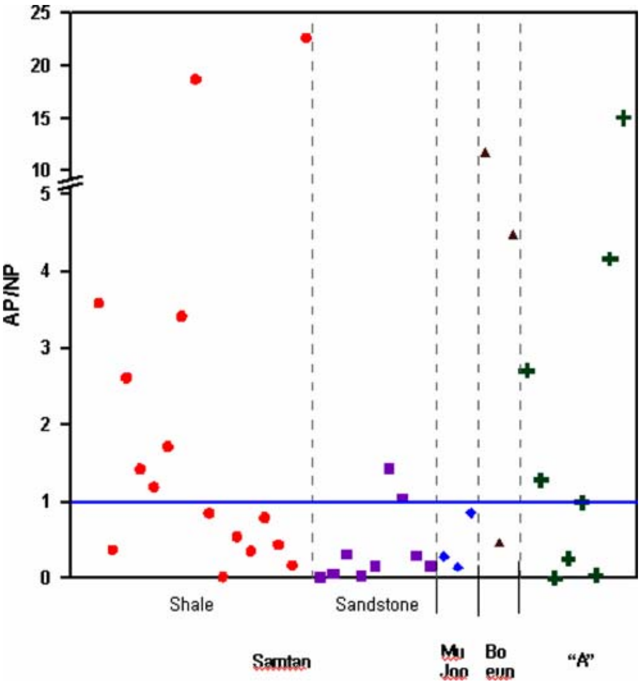

Fig. 3 AP/NP in each sample groups

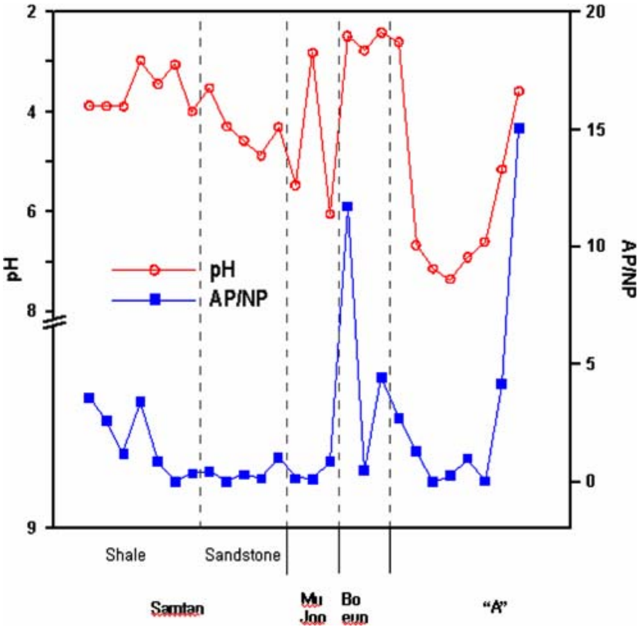

Fig. 4 Relation of AP/NP and pH

$$C_3A \cdot C\$ \cdot H_{18} + 2CH + 2\$ + 12H'C_3A \cdot 3C\$ \cdot H_{32} \quad (2)$$

$$C_3A \cdot CH \cdot H_{18} + 2CH + 2\$ + 12H'C_3A \cdot 3C\$ \cdot H_{32} \quad (3)$$

where C = CaO, A = Al_2O_3, \$ = SO_3,H = H_2O.

In hardened concrete, the formation of ettringite by sulfate attack can, but does not always, results in expansion and leads to cracking of the concrete. The conditions under which ettringite formation produces damage in the concrete are uncertain.

Corrosion potential

To determine the corrosion potential, sulfate concentration is found. About 1 kg of the sample is taken and sieved with a no. 50 seive. About 1 kg of rock sample was put in 500 ml of distilled water under airtight conditions. After a week, 500 ml of water was recovered by draining and measurement. Then the pH, Eh and salinity were measured and SO_4^{2-}, Fe, Al, Ca and Mg were determined. The complete results are given in Table 5 and the average and range values are given in Table 6. The plot of sulfate concentration at various solution pH is given in Fig. 5. Figures 6 and 7 provide respectively Fe and Al concentrations, and Ca and Mg concentrations at different solution pH.

Sulfide oxidation rate

Sulfide oxidation rate (SOR) is calculated by the sulfate determined by acid soluble method (US Army, C 403-71) and is given by

Table 5 Results of leachate experiment

	pH	Eh (mV)	SO_4^{2-} (mg/l)	Fe (mg/l)	Al (mg/l)	Ca (mg/l)	Mg (mg/l)
Sh-1	3.87	387	28.5	0.04	0.4	3.45	1.27
Sh-3	3.88	381	24.8	0.03	0.28	3.06	1.07
Sh-5	3.89	384	23.9	0.01	0.29	2.69	1.05
Sh-7	2.97	422	130	9.4	5.21	4.74	3.08
Sh-9	3.44	411	58	0.53	2.72	3.77	2.92
Sh-10	3.05	423	112	4.66	5.16	4.83	3.32
Sh-12	3.99	360	36	0.08	2.1	3	1.95
Sh-14	3.52	356	50	0.94	2.57	2.92	2.4
SS-1	4.29	358	11.1	0.08	0.1	1.51	0.39
SS-3	4.57	352	8.99	0.05	0.05	1.26	0.4
SS-5	4.87	341	8.01	0.03	0.05	1.27	0.32
SS-7	4.3	368	14.8	0.07	0.14	2.07	0.8
SS-9	5.47	317	8.94	0.02	0	1.9	0.68
MW-1	2.81	420	476	11.6	38.7	12.8	17
MW-2	6.04	268	645	4.77	0	200	17.4
MW-3	2.48	411	4,170	662	162	248	207
BW-1	2.77	440	634	58.8	31.5	15.5	28.3
BW-2	2.41	446	940	77.9	21.6	108	22
BF-3	2.6	410	725	98.9	35.8	15.4	27.1
A-1	6.67	280	5.62	0.08	0.04	15.1	0.14
A-2	7.14	261	3.37	0.02	0.06	7.99	0.01
A-3	7.35	245	6.68	0.01	0	7.6	0.01
A-4	6.91	256	137	0.03	0	38.5	0.34
A-5	6.6	248	21.8	0.01	0	24.3	0.51
A-6	5.15	252	219	4.18	1.17	72	1.93
A-7	3.58	363	197	8.18	2.08	57.2	0.66

Table 6 Average of each sample group in the result of leachate experiment

Sample	pH	Eh (mV)	SO_4^{2-} (mg/l)	Fe (mg/l)	Al (mg/l)	Ca (mg/l)	Mg (mg/l)
Samtan Shale (*n* = 15)	3.58 (2.97–3.99)	390.50 (360–423)	57.90 (36–130)	1.96 (0.01–9.4)	2.34 (0.28–5.21)	3.56 (2.69–4.83)	2.13 (1.05–3.32)
Samtan Sandstone (*n* = 10)	4.7 (4.29–5.47)	347.2 (317–368)	10.37 (8.01–14.8)	0.05 (0.02–0.08)	0.07 (0.0–0.14)	1.602 (1.26–2.07)	0.52 (0.32–0.8)
Mujoo Shale (*n* = 3)	3.78 (2.48–6.04)	366.33 (268–420)	1763.67 (476–4170)	226.12 (4.77–662)	66.90 (0.0–162)	153.60 (12.8–248)	80.47 (17–207)
Boeun Phyllite (*n* = 3)	3 (2.41–2.77)	432 (410–446)	766 (634–940)	79 (58.8–98.9)	30 (21.6–35.8)	46 (15.4–108)	26 (22–28.3)
"A" (*n* = 7)	6.2 (3.58–7.35)	272.1 (245–363)	84.4 (3.37–219)	1.8 (0.01–8.18)	0.5 (0.0–2.08)	31.8 (7.6–57.2)	0.5 (0.01–1.93)

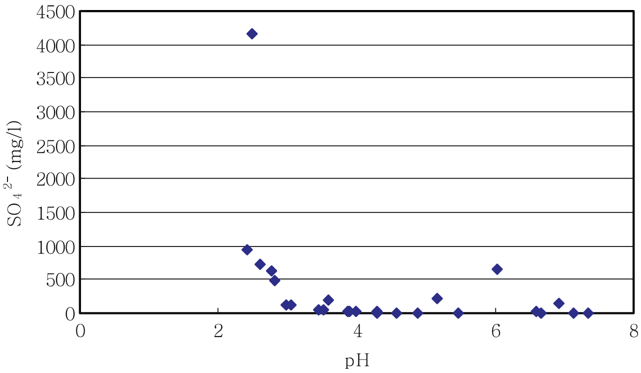

Fig. 5 pH versus SO_4^{2-} concentration in the leachates

$$\text{Amount of } SO_4^{2-}(\text{mg/kg/week}) = SO_4^{2-}(\text{mg/l}) \times \text{volume of water recovery (ml)} \div \text{weight of rock sample (kg)}. \quad (4)$$

Time to sulfide depletion

Time to sulfide depletion (TSD) is calculated by dividing the cumulative extractable sulfide in weeks until the sulfide leached to water becomes negligible by the average sulfide leached per week.

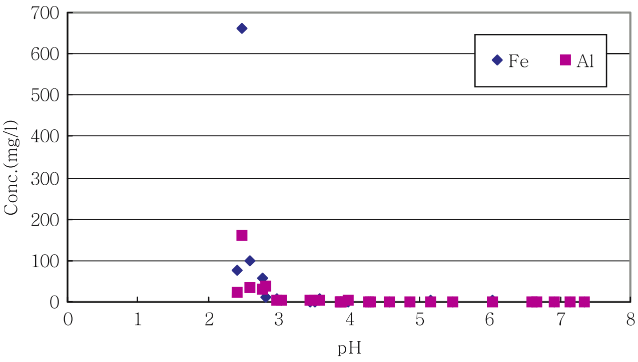

Fig. 6 pH versus Fe and Al concentration in the leachates

$$\text{Sulfide depletion (weeks)} = \text{Total sulfide mineral content (as } SO_4^{2-}) \div \text{Amount of } SO_4^{2-}(\text{mg/kg/week}). \quad (5)$$

Neutralisation potential depletion rate

From the values of Ca and Mg, neutralisation potential depletion rate (NPDR) is calculated as follows:

$$\text{NPDR (g}\,CaCO_3/\text{kg/week)} = [\text{Ca (g/L)} \times (\text{moles Ca}/40\,\text{g}) + \text{Mg (g/L)} \times (\text{moles Mg}/24.3\,\text{g})] \times \text{volume of water (L)} \div \text{weight of rock sample (kg)}. \quad (6)$$

Time to NP depletion

As in the case of TSD, time to NP depletion (TNPD) is found out as:

$$\text{TNPD (weeks)} = \text{Total NP content } (\text{g}\,CaCO_3/\text{kg sample}) \div \text{NP depletion rate } (\text{g } CaCO_3/\text{kg/week}). \quad (7)$$

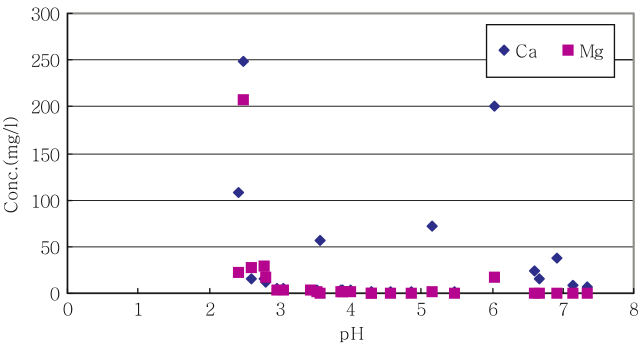

Fig. 7 pH versus Fe and Al concentration in the leachates

Table 7 Results of the sulfide oxidation rate (SOR) test

Sample	SOR (mg/kg/ week)	TSD (weeks)	NPDR (g $CaCO_3$/kg/ week)	TNPD (weeks)
Sh-1	34	77	163	0.005
Sh-3	30	83	148	0.007
Sh-5	28	51	131	0.010
Sh-7	151	81	286	0.013
Sh-9	69	104	256	0.034
Sh-10	134	55	308	1.126
Sh-12	42	37	180	0.025
Sh-14	61	44	209	0.030
SS-1	13	53	63	0.792
SS-3	11	80	56	0.049
SS-5	10	28	54	0.033
SS-7	18	42	103	0.007
SS-9	10	32	86	0.023
MW-1	591	34	1,265	0.109
MW-2	817	54	7,236	–0.007
MW-3	5166	19	18,235	0.000
BW-1	789	30	1,932	0.027
BW-2	1164	23	4,464	–0.001
BF-3	867	56	1,795	–0.010
A-1	7	5,499	486	0.065
A-2	4	35	255	0.193
A-3	9	947	246	0.133
A-4	175	238	1,246	0.035
A-5	28	78	806	0.058
A-6	280	89	2,401	0.003
A-7	254	185	1,876	0.002

SOR Sulfide oxidation rate, *TSD* time to sulfide depletion, *NPDR* NP depletion, *TNP* time to NP depletion

Table 8 Hydro-chemical factors of the corrosion indicator

Aggressive components	Effect
pH	Corrosion increased under the pH 7
DO	Accelerate corrosion in acidic, neutral and weak alkaline
H_2S	Corrosion accelerated with hydrogen sulfide increased
TDS	Corrosion accelerated with salinity increased, especially over 1,000 mg/l
Temperature	Acceleration of corrosion in high temperature

Table 9 Threshold values for assessment of waters aggressive to concrete (DIN 4030))

Aggressive components	Corrosion strength			Concentration
	Weak	Strong	Very strong	
pH	5.5–6.5	4.5–5.5	4.5	2.41–7.35
Mg^{2+} (mg/l)	100–300	300–1,500	1,500	0.01–27.1
SO_4^{2-} (mg/l)	200–600	600–3,000	3,000<	3.37–4,171
Corrosion strength				Weak–strong

The values of SOR, TSD, NPDR and TNPD for the samples from the four sites are given in Table 7. Tables 8, 9 and 10 and Fig. 8 provide guidelines to corrosion potential related the concentrations of various parameters of water present or in contact with concrete.

Engineering implications

Exposed rock bearing sulfate can corrode various engineering structures and even be a cause of small and large failures. As these are mostly areas where engineering constructions have taken place or will take place, gradual corrosion by ARD can cause concern. Results from acid–base accounting indicated that AP/NPs of shale sampled from Muju and Samtan, phyllite from Boeun and sandstone from Samtan were 3.7, 3.1, 2.3, 2.2 and 0.4, respectively. All the samples except sandstone could be classified as acid-producing rocks. Amounts of sulfate determined by acid soluble method for shales from three locations reached a maximum of 5,166 mg/kg/week. In the case of sandstone, the value reached 18 mg/kg/week. Results from leaching tests showed that leachate pH ranged between 3 and 4 (acidic). Leachates from samples taken from road cut slope at Mujoo and Boeun had high levels of sulfate, Fe, and Al. Due to continued weathering process near the road cut slopes, these elements and the sulfate radical have already been accumulating on the surface as soluble salts that can lead to corrosion.

Conclusions

In this study, highly weathered rock samples taken from road cut slopes, together with samples from uncontrolled waste rock dumps and fresh rock samples from an active underground mine were evaluated for acid-producing potential and sulfide oxidation rates. In rehabilitation of waste rock impoundments or new engineering works accompanying excavation and movement of rock mass, acid rock drainage is a concern, depending on mineralogical composition and site-specific conditions. When reclamation of abandoned

Table 10 The selection guidelines of cement and admixture for concrete exposed on the sulfate salts [American Concrete Institute (ACI 318)]

Exposure	Water soluble sulfate salts in soil (%)	Sulfate (mg/l)	Cement
Not consider	0.00–0.01	0–150	–
Normal	0.1–0.2	150–1,500	Type II, Type I + pozzolan, slag, Type V
Serious	0.2–2.0	1,500–10,000	Type II + pozzolan, slag
Very serious	2.0<	10,000	Type V + pozzolan, slag

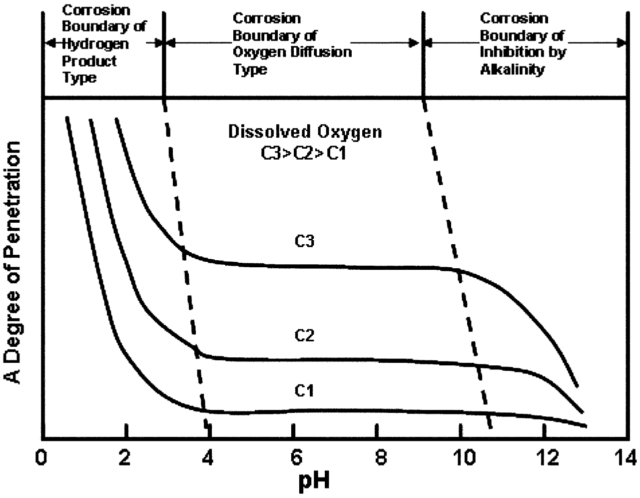

Fig. 8 Effect of pH and dissolved oxygen on the iron corrosion (LG Construction Ltd. 1999)

mines and civil works accompanies excavation and back-filling, either current or anticipated prediction of ARD occurrence might give a preview of the site-specific challenges of construction.

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