ALKALINITY PRODUCING COVER MATERIALS FOR PROVIDING SUSTAINED IMPROVEMENT IN WATER QUALITY FROM WASTE ROCK PILES[1].

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Abstract. Acidic and Metalliferous Drainage (AMD) from sulfidic waste rock piles is a major issue facing the mining industry worldwide. Existing dry cover systems are designed to minimize the acid load discharged from waste rock piles by lowering infiltration rates. The strategic blending of alkaline amendments, such as limestone, within waste rock piles is also used to minimize the acid load discharged. The benefit of this blending is limited in most cases due to armoring (passivation) of limestone by precipitates.

Armoring can be overcome by placing limestone on top of the waste rock piles, where it only interacts with rain water. Alkalinity released from the limestone-bearing covers can react with acid and metallic salts along preferential flow pathways within a waste rock pile to create inert, precipitate-coated channels that inhibit further reaction (ie. acid release). Due to the low solubility and slow dissolution rates of limestone, acid generation is not completely prevented and may still occur within the waste rock pile. Nevertheless, an overall reduction in the physical interaction between water and acid producing materials can sometimes be achieved using limestone-bearing covers. This mechanism has proven successful at the Freeport mine in Indonesia, which is characterized by very high rainfall. However, the effectiveness of limestone-bearing covers is limited under most climatic conditions, as a result of the low solubility and slow dissolution rates of limestone in near-neutral rainwater.

New magnesium-based materials with superior solubility and dissolution rate characteristics to limestone have been developed for use in waste rock covers. These materials will permit the controlled release of alkalinity to infiltrating rainwater over a wide range of climatic conditions.

The required amount of the magnesium-based alkalinity producing material in a waste rock cover will be insignificant relative to the amount of acid producing material in the waste rock. As a result, the magnesium-based cover materials represent an innovative and cost-effective solution to *minimization*, rather than *treatment*, of acid drainage from waste rock piles.

The new materials being developed are based on calcium-enriched caustic magnesia (MgO) with controlled calcination grades and grain sizes to maximize both solubility and dissolution kinetics. Alkalinity concentrations of up to 510 mg/L $CaCO_3$ equivalent in pure water can be achieved with the new materials (c.f. only 10-15 mg/L for limestone), with a typical saturation pH of 9.0-9.5 (c.f. only 8.0-8.5 for limestone).

Compared to limestone it is envisaged that relatively small amounts of these new magnesium-based materials can be deployed within existing and new cover systems to minimize short, medium and long term acid discharges, thereby providing a significant advance in the control of AMD (acid and metalliferous drainage) from waste rock piles.

Additional Key Words: store and release covers, alkalinity producing cover materials, caustic magnesia, acid and metalliferous drainage (AMD), acid and metalliferous drainage.

Introduction

Acid and Metalliferous Drainage (AMD) is the single biggest environmental issue facing the mining industry worldwide. It affects essentially all sites containing sulfide minerals, including both metal and coal mines. Currently the most common methods used to control AMD from mine waste materials are to lower water infiltration or limit O_2 diffusion by installing low permeability dry or water-saturated covers. Dry cover systems that provide long-term effectiveness remain difficult to achieve, despite a great deal of research and many installations.

With an increasing realization that *best practice* water shedding and store-and-release covers display a highly varied ability to control acid discharges, alkaline amendments are being used in a supporting role to provide some neutralizing capacity when infiltration does occur. With the careful deployment of appropriate materials, recent work (Miller et al., 2003) has demonstrated that a sustainable reduction in the rate of acid discharge from mine wastes can be achieved in some climatic and geological settings.

Alkaline amendments such as mineral carbonates (eg. limestone $CaCO_3$, dolomite $MgCO_3$ and magnesite $MgCO_3$) are widely used for AMD control in waste rock piles. Such carbonates are either naturally present or are "blended" with wastes to neutralize acidic pore waters. When intimately mixed with acid generating material, most alkaline amendments become coated with various metal precipitates and rapidly become chemically inactive, a process called armoring. To overcome this problem, in recent times amendments have been placed above acid generating wastes so that they are only exposed to circum-neutral rainwater. For commonly used amendments such as limestone, low solubilities and slow dissolution rates in near neutral water mean that, in most environments, unrealistically large quantities are required or they have little effect. The objective of this paper is to investigate the suitability of other alkaline cover amendments to provide cost effective and sustained improvement in water quality from waste rock piles in a range of climatic conditions.

Alkalinity Producing Cover Systems – A Brief Background

Concept

Alkalinity producing cover systems are defined here as soil covers (eg. water shedding or store-and-release covers) that have an additional "alkalinity generating" component deployed above, within or at the base of the cover. The overall aim is to minimize infiltration where possible and ensure that any water that does migrate into deeper and more acidic parts of a waste rock pile contains substantial alkalinity. The sluggish dissolution kinetics and very low solubility of natural carbonate minerals renders this approach either ineffective or extremely slow in all but very rare circumstances. Thus, in settings where the annual rainfall exceeds 3 m per annum and a significant proportion of the waste rock pile is comprised of limestone, there is some potential for effective alkalinity transfer into deeper parts of the waste rock pile.

This concept is innovative and differs from the traditional concept of "blending". To be successful, the intimate blending of mineral carbonates with sulphidic waste rock requires the addition of a significant excess of neutralizing reagent in order to account for all of the potential acidity, as well as the armoring and grain size effects (eg. Miller et al., 2003). However, alkalinity producing cover systems require much less alkaline material to achieve a water quality improvement because the intention is not to treat all of the acid produced within the waste rock

pile, but to prevent infiltrating water from interacting with acid and metal salts by coating preferential pathways with inert precipitates.

Preferential Fluid Flow Pathways

It has been reported that due to the heterogeneity in composition and grain size within waste rock piles, the majority of the fluid that percolates through piles flows along preferential hydrological or fluid pathways (Fines et al., 2003 and references therein). The presence of these pathways means that a significant percentage of the waste rock pile is not routinely flushed by infiltrating waters, and as a result sulfide oxidation products or acid salts within these parts of the waste rock pile contribute little to the acid load in seepage from the waste rock piles. It therefore appears that most water passing through a waste rock pile interacts with only a small mass of waste material. If the reaction of infiltrating waters with this limited mass of acid forming materials can be reduced further, then significant reductions in the acid load exiting via seeps can be expected. Interestingly, it is the operation of preferential pathways that is predicted to render "blending" largely ineffective. Fluid migrating through "blended" piles appears to interact with neither all of the acid generating material nor all of the acid neutralizing material.

Thus, the concept of preferential fluid flow pathways is crucial to understanding the operation of alkalinity producing covers: as alkaline water migrates down into a waste rock pile, it will follow these preferential pathways and react with the acid and metallic salts that it encounters. The effect of these reactions will be the neutralization of acid and the precipitation of metal hydroxides. These precipitates are likely to coat the walls of the flow path, effectively enhancing the insulation of acid producing materials from subsequent infiltrating water through an armoring process.

In addition, narrow preferential pathways and those proximal to strongly acidic sources may become totally blocked with (aluminous) precipitates, resulting in enhanced water shedding around sulphidic zones in waste rock piles. Moreover, in-situ neutralization and precipitation of metal hydroxides will immobilize metals within the pile and therefore no additional handling or disposal of precipitates will be required. Over time, the continual infiltration of alkaline water through the pore spaces will also reduce sulfide oxidation rates and therefore lower the rate of acid production.

Evidence from the Papua Province of Indonesia (Miller et al., 2003) and Tasmania in Australia (Ray and Kent, 2004) supports the conclusion that alkalinity producing covers have the potential to progressively and sustainably minimize acidity discharges from waste rock piles over time. The key parameter to examine is the rate at which alkalinity can be transferred into a rock pile. The amount of alkalinity introduced from an "alkalinity generating" material will be a function of the solubility and dissolution rate of the material, along with the amount and rate of infiltration. Without very high rainfall and carbonate-rich covers over waste rock piles, natural mineral carbonates are limited in their ability to deliver measurable improvements in acidity discharges from waste rock piles and thus are often found to perform poorly in most settings.

Limestone as an Alkaline Amendment - The Freeport Example

Miller et al., (2003) reported the successful use of an alkalinity producing cover at the Grasberg Mine in the Papua Province of Indonesia. At Grasberg a number of test pads (waste rock test piles) were constructed from acid producing waste blended with limestone, with the latter comprising up to 50 wt% of the pile. Subsequently, one of these pads containing 25 wt%

blended limestone was also capped with a 2 meter thick limestone cover some time after the construction of the pads.

The pH of leachate from each of the test pads was monitored regularly over several years.

A significant improvement was recorded in the pH of waters exiting the limestone-covered pad within 2.5 years. This was attributed largely due to the armoring and passivation of preferential flow paths by neutralization precipitates. The armoring process was achieved by maintaining near-neutral conditions in pore waters due to the dissolution of limestone. Excavation of one of the limestone-covered pads revealed an irregular reaction/precipitation front moving down through the waste rock. This reaction front is believed to follow preferential fluid pathways (Miller pers. comm.).

Key factors contributing to the short-term success of the limestone cover at the Freeport mine include the high annual rainfall (3,000-5,000 mm) that results in continuous dissolution of the limestone, and the high carbonate content within the waste rock (blended) and cover system (2 meter thick limestone cover). A comparable response rate is far less likely in areas of lower rainfall due to the very low solubility and slow dissolution rate of limestone.

Hence, the ability of alkalinity generating cover materials to sustainably lower acidity discharges from waste rock piles can be significant under relatively unique conditions (very high rainfall and carbonate-rich waste rock and cover). However, alkaline amendments with the potential to achieve similar improvements in the quality of seepage at mine sites in essentially any geological or climatic setting are not currently available.

Alternative Alkaline Amendments

The concept of acid load reduction from waste rock leachate by strategic deployment of alkalinity generating materials into waste rock covers is limited in its application due to low solubility and slow dissolution rate of carbonates. If alkalinity producing covers are to be used successfully at more mine sites, alternative reagents are necessary. The optimum characteristics for an alkaline amendment suitable for use in conventional cover designs include:

1. An effective saturation pH of ≤ 10.
2. A relatively rapid dissolution rate in near-neutral water.
3. Sustained and high levels of alkalinity release over years, rather than days (e.g. hydrated lime) or centuries (e.g. limestone, $CaCO_3$).
4. No tendency to react in-situ to form less soluble mineral phases (eg. form carbonate assemblages in the presence of atmospheric CO_2).
5. Some control over the release of alkalinity by modification of some physical and/or chemical parameter.
6. Widely available compound.
7. Broadly comparable in cost to burnt lime compounds.

Burnt lime products, including hydrated lime ($Ca(OH)_2$) and quicklime (CaO), have been occasionally used to overcome the solubility constraints of limestone ($CaCO_3$). Unfortunately, the use of burnt lime compounds in covers is rarely cost effective, generally short-lived and has the potential to generate spikes of toxic alkalinity when used in acid generating wastes. The reason for this is that burnt lime compounds have a relatively high solubility and dissolve rapidly, raising the pH of pore water up to 12.4. In addition, hydrated lime slurry or saturated

solutions react readily with ambient concentrations of carbon dioxide and revert within hours to calcium carbonate (ie. limestone).

A range of other potential alkaline amendments include:

1. Cement kiln dust (CKD).
2. Lime kiln Dust (LKD) (e.g. Rose et. al., 1995).
3. Precipitated calcium carbonate (PCC).
4. Fly Ash (containing some Ca and Mg oxides and hydroxides) (e.g. Hamic, 1993).
5. Seawater neutralized Red Mud (key active ingredient $Mg(OH)_2$) (e.g. McConchie et. al., 2003).
6. Conventional Caustic Magnesia (MgO).
7. Enhanced Caustic Magnesia (MgO).

Of these proposed amendments CKD, LKD and PCC are composed primarily of CaO or $CaCO_3$ and as a result have the same drawbacks as burnt lime products and limestone.

Fly Ash, depending on its source, has variable amounts of Ca and Mg oxides and hydroxides, with higher Ca content fly ash suffers from similar problems to other Ca based amendments. Impurities in Fly Ash can also inhibit the effectiveness of this material, by potentially introducing new contaminants to the waste rock leachate. Another key issue is the limited availability of Fly Ash at some sites.

The key active ingredient in Seawater neutralized Red Mud is predicted to be $Mg(OH)_2$ and in some circumstances this material may prove a beneficial amendment. However, its limited availability, low active ingredient content and relatively high cost may prohibit its use at many sites.

Conventional Caustic Magnesia (MgO) is more widely available than other sources of MgO, such as Fly Ash and Red Mud. Conventional Caustic Magnesia is a commercially produced material that is most commonly used in the refractory industry. As such, the material is produced under high-temperature conditions that result in low solubility characteristics (e.g. approximately 1 mg/L $CaCO_3$ equivalent). The applications of Conventional Caustic Magnesia, as an alkalinity producing material, can in many situations be more limited than limestone.

Due to limitations of the alkaline amendments discussed above, Earth Systems undertook research work with Queensland Magnesia Pty. Ltd. (QMAG) to develop new products (Enhanced Caustic Magnesia), with improved solubility and dissolution characteristics, which are specifically designed for waste rock cover applications. Enhanced Caustic Magnesia has been developed by manipulating the calcination temperatures, the composition of raw materials (relative proportions of Mg and Ca), and the grain size, to achieve desirable alkalinity release characteristics. Enhanced Caustic Magnesia is a promising alternative to Conventional Caustic Magnesia and has the potential to achieve each of the "optimum characteristics" listed above.

Earth Systems and QMAG are working to commercialize Enhanced Caustic Magnesia products for use by mining companies worldwide. Some mineral process details remain commercial-in-confidence. However, this paper presents the results of recent testwork that documents key properties and the performance of Enhanced Caustic Magnesia as an alkalinity producing material.

Enhanced Caustic Magnesia

Research work has proven that products based on caustic magnesia (magnesium oxide – MgO) can be modified to achieve the optimum alkalinity release characteristics and thus are an ideal candidate for use in alkalinity producing covers.

Caustic magnesia is the calcined product of magnesite or magnesium carbonate ($MgCO_3$). Being a natural mineral, magnesite often also contains lesser amounts of calcium carbonate (limestone) and calcium-magnesium carbonate (dolomite). The magnesite ore is fired in kilns at specific temperatures to convert the carbonate starting products to alkali metal oxides. Commercially available caustic magnesia is not specifically optimized for rapid dissolution and high solubility, and is in fact generally unsuitable as an alkalinity producing material. However, by modifying the calcination regime and selecting specific starting carbonate compositions (ie. relative proportions of Mg- and Ca-based carbonates), enhanced forms of caustic magnesia can be produced that display ideal alkalinity release characteristics.

On interaction with fresh water, the outer layer of caustic magnesia (light pink; MgO) particles is converted to magnesium hydroxide (whitish; $Mg(OH)_2$), which progressively dissolves in the water. Caustic magnesia particles remain coherent when mixed with water, unlike quicklime (CaO) that generally reacts vigorously (exothermically) and disintegrates due to molar volume increases. In addition, unlike hydrated lime ($Ca(OH)_2$) there is presently no evidence that $Mg(OH)_2$ reacts to form a less soluble carbonate by interaction with CO_2 from the atmosphere. Unlike burnt lime-based reagents (with a saturation pH of 12.4), caustic magnesia produces an equilibrium saturation pH of around 10.8 (in laboratory conditions) or 9-9.5 (in field conditions), avoiding the risk of passively overdosing acidic waste. At pH 9-9.5, essentially all of the problematic soluble metals associated with AMD, including manganese, will precipitate as hydroxides and be immobilized.

Experimental Method

Earth Systems and QMAG prepared a range of Enhanced Caustic Magnesia materials (ie. magnesium oxide, MgO) using different calcination temperatures, starting material compositions (relative proportions of Mg and Ca) and grain sizes.

A series of solubility and dissolution rate laboratory experiments were designed to investigate the alkalinity release characteristics of the various Enhanced Caustic Magnesia preparations. Specifically, the experiments were intended to identify the optimum calcination temperature, composition and grain size characteristics for maximum alkalinity release rates.

Solubility and dissolution rate experiments were conducted at room temperature (23 ±2°C), using 2 liter conical flasks to mix a known mass of Enhanced Caustic Magnesia with a known volume of deionized water (Table 1), to model the interaction between rain water and an alkaline cover material.

The solutions were mixed continuously using a mechanical stirrer throughout each experiment, for a duration of 7 days. Conductivity and pH were monitored at regular intervals using an automatic data logging system. A recording interval of 2 seconds was set on commencement of the experiments. This interval was increased throughout each experiment to a final interval of 360 seconds. During each experiment, 10 mL aliquots were withdrawn at regular intervals and analyzed for alkalinity, dissolved Mg, Ca, K and Na concentrations.

Table 1. Solid to fluid ratios used in the solubility and dissolution rate experiments.

Solid to fluid ratio	Mass of Enhanced Caustic Magnesia	Volume of Deionized Water
10 g/L (1% w/v)	20.0 g	2000 mL
30 g/L (3% w/v)	60.0 g	2000 mL
57.5 g/L (5.75% w/v)	115.0 g	2000 mL

This paper presents a small portion of the results of laboratory experiments conducted on three preparations of Enhanced Caustic Magnesia, which differ according to their temperature of calcination. For the three experiments discussed in this paper, the starting material for each form of Enhanced Caustic Magnesia was kept constant (ie. constant grain size and relative proportions of Mg- and Ca-based carbonates) and a 1% w/v solid to fluid ratio was used. The exact composition and calcination temperature of the starting materials is currently proprietary.

Results

Figures 1 and 2 provide results of the testwork conducted using three forms of Enhanced Caustic Magnesia, which differ according to their temperature of calcination.

Figure 1 displays the evolution of pH and electrical conductivity (EC) of deionized water in contact with the three preparations of Enhanced Caustic Magnesia (ie. different calcination grades T_x) with time. Trends within these diagrams for all calcination temperatures (T_1 – low temperature, T_2 – moderate temperature and T_3 - high temperature) indicate a rapid initial spike in pH within the first minute of mixing, followed by a slow decline in pH over a few hours. EC also shows a rapid spike followed by a gradual decline to a minimum (over 2-4 days), after which there is a gradual increase. The pH and EC maxima and minima, along with the time these are attained, vary as a function of calcination temperature.

Figure 2 shows the variation in alkalinity (mg $CaCO_3$/L equivalent) and dissolved Mg and Ca concentrations for the same three calcination grades (T_1, T_2 and T_3) and compositions as depicted in Fig. 1. All diagrams show an initial rapid increase in Ca concentration which progressively decreases as Mg concentrations rise. Similarly, elevated initial alkalinities decrease to a minimum (around 50 mg/L $CaCO_3$ equivalent, corresponding to pH 10.8), followed by a steady rise. The value of the alkalinity minimum and the time at which it is achieved varies according to the calcination grade. The slight exception to these general trends occurs in sample T_1, where the initial alkalinity and calcium spike occurs 4 hours after the commencement of the experiment (whereas the spikes occurred much earlier for the T_2 and T_3 samples). In all examples the alkalinity and magnesium concentrations were still rising at the completion of the testwork.

Key conclusions from the solubility and dissolution rate testwork include:

- The initial pH (>11.4) and EC maxima (ref. Fig. 1a, c and e) are due to the rapid dissolution of CaO phases within the Enhanced Caustic Magnesia ($Mg(OH)_2$). These elevated pH conditions prevent the dissolution of $Mg(OH)_2$ in the early stages of the

tests. As atmospheric CO_2 reacts with dissolved Ca, $CaCO_3$ is progressively precipitated and the pH gradually falls below the saturation pH for $Mg(OH)_2$ (i.e. pH 10.8).

- The EC reaches minima (ref. Fig. 1b, d and f) at roughly the equilibrium saturation pH for $Mg(OH)_2$ (10.8). After this time, the EC rises (as the pH continues to fall) due to the onset of $Mg(OH)_2$ dissolution.

- The systematic changes in EC are reflecting the variation in Ca and Mg concentrations over time as displayed in Fig. 2 (T_1-T_3).

- The experiments were not conducted for long enough to reach a peak solubility value for any of the materials tested. The maximum alkalinity value achieved for Enhanced Caustic Magnesia was 510 mg $CaCO_3$/L (not in data provided), but trends in Fig. 2 indicate that alkalinity values were still increasing when the testwork was terminated.

- Lower calcination grade material generates higher alkalinity values (up to nearly 100 mg/L $CaCO_3$ equivalent; Fig. 2a) in a far shorter period of time.

- Higher initial pH values are achieved at higher calcination temperatures due to the higher CaO:$CaCO_3$ ratios in the Enhanced Caustic Magnesia, which enable the water to more closely approach saturation with respect to CaO.

- Higher initial EC values are obtained at higher calcination temperatures due to the higher CaO:$CaCO_3$ ratios in the Enhanced Caustic Magnesia.

- Elevated Ca concentrations in Enhanced Caustic Magnesia provide an initial rapid peak in alkalinity release, which is quickly depleted but followed by a more subdued and sustained release in magnesium-based alkalinity.

It is clear from the testwork that the optimum calcination temperature for Enhanced Caustic Magnesia is significantly less than that used to produce typical commercial caustic magnesia products. Lowering the calcination temperature can significantly raise the solubility and enhance the alkalinity release (dissolution) rate for caustic magnesia, which is a pre-requisite for potential long-term applications associated with covers over sulfidic waste rock piles. Utilizing Enhanced Caustic Magnesia with a small proportion of Ca is expected to provide a short-lived surge of alkalinity to infiltrating waters that should rapidly kick-start the passivation of preferential pathways.

The testwork demonstrates that very fine-grained, calcium-enriched caustic magnesia produced at relatively low calcination temperatures (ie. Enhanced Caustic Magnesia) is chemically well suited to perform as an alkaline amendment for waste rock cover systems.
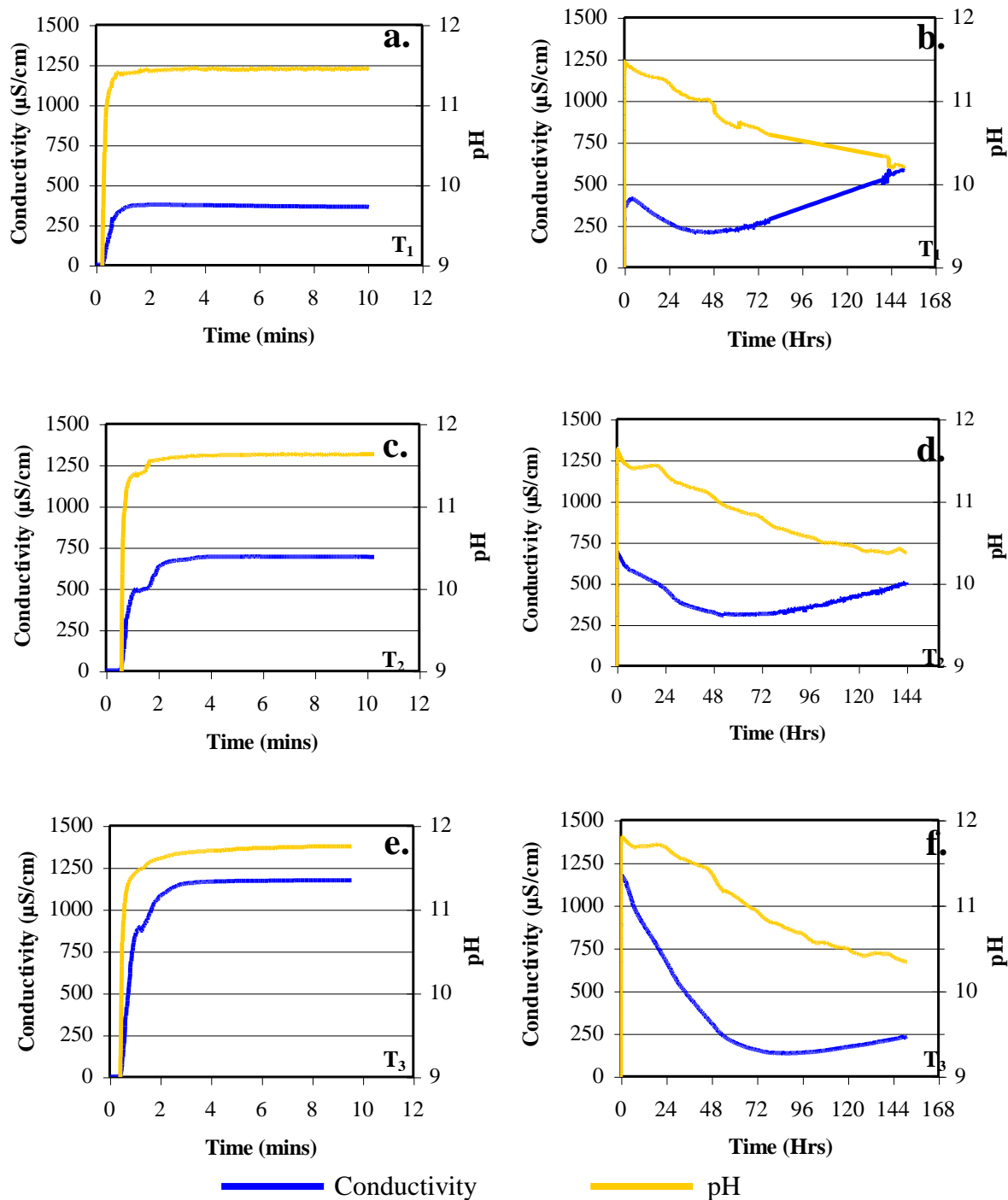
Figure 1a-f: Dissolution plots of 3 calcination grades (T_{1-3}) of Enhanced Caustic Magnesia. Plots show conductivity (µS/cm) and pH of a solution containing 10g/L Enhanced Caustic Magnesia. Changes in conductivity reflect the dissolution of the solid Enhanced Caustic Magnesia to form primarily Mg and Ca aqueous species. Rise in pH of the solution is due to the reaction of the Enhanced Caustic Magnesia with water to form $Mg(OH)_2$ and $Ca(OH)_2$. (a) and (b) Low calcination temperature Enhanced Caustic Magnesia (T_1) over the first 10 minutes and 7 days respectively. (c) and (d) Moderate calcination temperature Enhanced Caustic Magnesia (T_2) over the first 10 minutes and 7 days respectively. (e) and (f) High calcination temperature Enhanced Caustic Magnesia (T_1) over the first 10 minutes and 7 days respectively. See text for explanation of conductivity and pH curves.
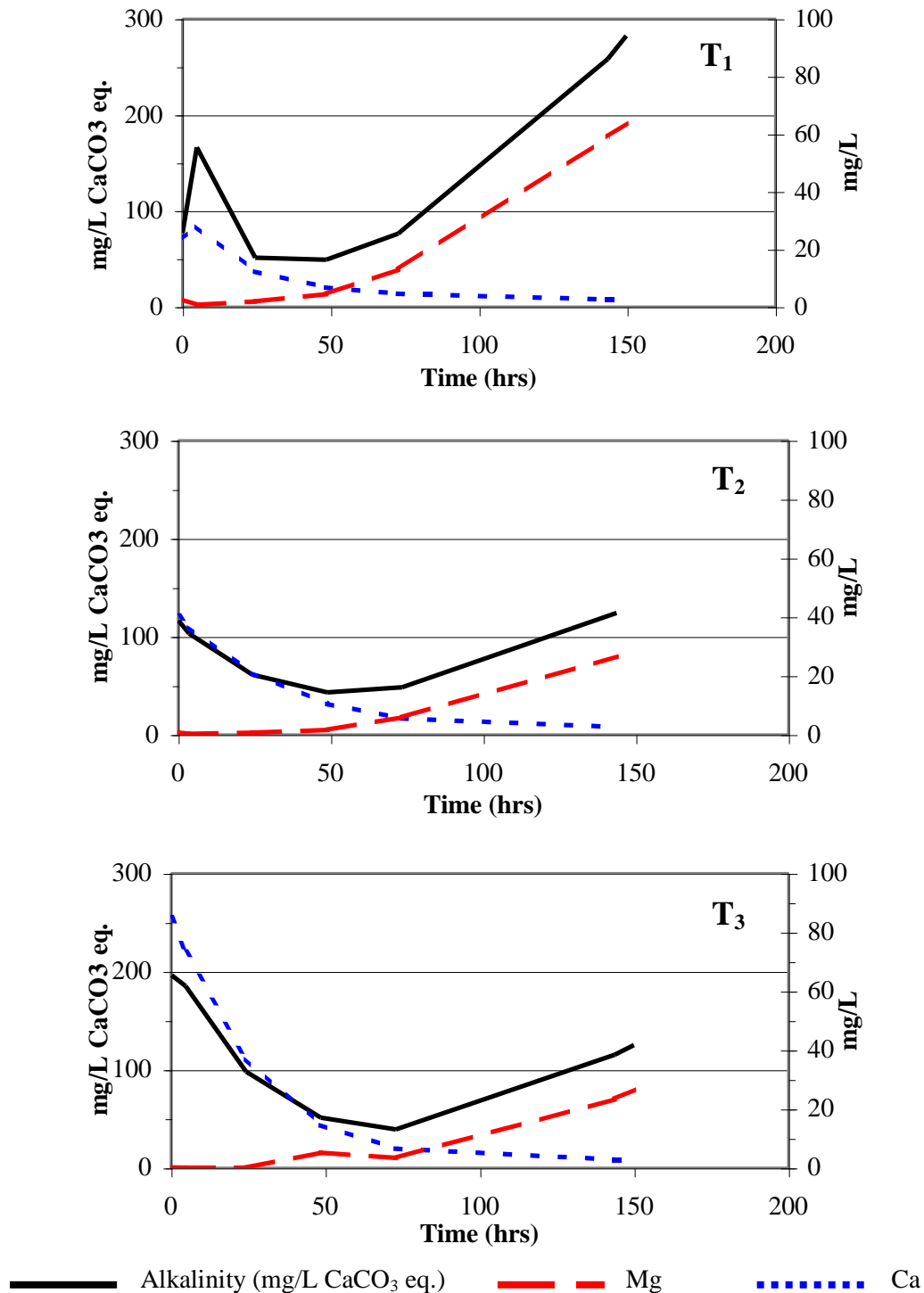
Figure 2: Changes in alkalinity, calcium and magnesium concentrations over time in a solution initially containing 10g/L Enhanced Caustic Magnesia. Experiments with three different calcination grades, low temperature (top), moderate temperature (middle), and high temperature (bottom), indicate that lower calcination temperatures show significantly greater rates of alkalinity release.

<u>Predicted performance in field situations</u>

In any given field situation, water saturated with Enhanced Caustic Magnesia is calculated to deliver at least 20 times more alkalinity to infiltrating waters per unit time relative to water saturated with limestone. In particular, in settings where annual rainfall is approximately 1.0 m (~40 inches), a 2 mm (0.08 inches) layer of MgO within a cover should release all of its alkalinity (assuming 300 mg $CaCO_3$/L) in 30 years, assuming complete infiltration. Under the same conditions, a 2 mm layer of limestone (assuming 14 mg $CaCO_3$/L) would take more than 200 years to dissolve completely and provide negligible reduction in acidity loads over that period.

It is expected that a typical Enhanced Caustic Magnesia installation will involve the deployment of a mass of MgO equivalent to a 1-3 mm thick layer within a cover system. This corresponds to approximately 18-55 tonnes of amendment per hectare (7-22 tons per acre), which is expected to cost between AUD$10,000-30,000 per hectare (~US$3,000-9,000/acre).

As a result of the very rapid dissolution rate of Enhanced Caustic Magnesia, at typical infiltration rates it is estimated that a 1-3 mm thick layer of Enhanced Caustic Magnesia would provide sufficient contact time to achieve saturation, as compared with a 1 meter thick layer of limestone. If this is an accurate estimate, the installation of a 1 meter layer of limestone could be up to 25 times more expensive (and still less effective) than a 2 mm thick Enhanced Caustic Magnesia layer.

If a 2 mm thick layer of Enhanced Caustic Magnesia is deployed at the base of a "store and release" cover, any pore water that unavoidably passes through the cover and into the waste rock would become saturated with respect to $Mg(OH)_2$. The initial slug of alkalinity delivered into the pile would react with any sulfide oxidation products encountered along preferential pathways and result in the precipitation of Fe, Al and various other inert metal hydroxides. The next slug of alkaline pore water would migrate past these "inert precipitates" before further neutralization and precipitation would occur along the next section of preferential pathway encountered. Successive alkalinity bearing infiltrates would enable the "inert precipitate" front to migrate down the pile, progressively passivating fluid pathways. (A similar mechanism has been demonstrated in the test pads excavated at the Freeport site.) Once most of the major fluid conduits have been effectively lined with "inert precipitates", a substantial reduction in pollutant release rates can be expected.

Conclusions

Carefully calcined, Ca-enriched, fine-grained caustic magnesia (Enhanced Caustic Magnesia) has all the necessary solubility and dissolution rate characteristics to work very effectively at dramatically, rapidly, cost-effectively and sustainably lowering acidity loads from waste rock piles. Enhanced Caustic Magnesia, produced at calcination temperatures below those typically used to create Conventional Caustic Magnesia, can transform the product into an effective material for use in alkalinity producing covers.

Enhanced Caustic Magnesia is not intended to replace the need for conventional waste rock covers, but may be used in conjunction with existing technologies that aim to decrease water infiltration rates into waste rock piles, e.g. "store-and-release" covers. The mass of alkalinity required from Enhanced Caustic Magnesia to provide a sustained reduction in acidity loads from waste rock represents only a small fraction of the total potential acidity stored in the pile.

Therefore, Enhanced Caustic Magnesia is not regarded as a treatment additive, but a controlled alkalinity release technology for AMD minimization.

Properly constructed, such covers are predicted to:

- Lower the cost and improve the performance of AMD management in waste rock piles.

- Substantially lower medium to long term AMD liabilities for mining companies by rapidly and sustainably lowering pollutant discharges from waste rock piles under most climatic conditions.

- Permit the controlled release of alkalinity over relatively short periods of time by manipulation of the composition, calcination temperature and grain sizes of Enhanced Caustic Magnesia.

- Significantly retard pollution release rates from mine wastes by passively lining preferential pathways with inert neutralisation precipitates.

- Assist in retarding pollution generation rates (ie. sulfide oxidation rates) from mine wastes by raising the pH of pore waters and thereby lower the generation of soluble ferric iron available to accelerate sulfide oxidation.

- Improve the water shedding capacity of some piles, (or water holding capacity of some covers), by totally blocking some preferential pathways.

- Provide the most cost effective, environmentally benign and widely available supplement for AMD management in waste rock piles currently available.

- Provide an AMD minimization technology that could be applied pro-actively to new waste rock piles or retrospectively to uncovered or polluting piles at derelict mine sites.

- Facilitate the relinquishment of mining leases post-closure by sustainably improving off-site discharges.

- Minimize or avoid medium to long term AMD treatment costs and store some treatment precipitates within the waste.

- Substantially lower the cost and improve the effectiveness of AMD minimization relative to the intimate blending of carbonate minerals within acid generating wastes.

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