

ACID SULFATE ROCK MANAGEMENT IN EARTHWORKS FOR ROADS

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ABSTRACT

Acid sulfate rocks (ASR) have elevated levels of reduced sulfur, usually as pyrite or other sulfide minerals, and in NSW occur in the lower Sydney Basin and other areas. When exposed to water and oxygen a series of chemical reactions lead to the formation of acid leachates and sulfate salts, and the acidic conditions can also produce high levels of metals in solution. These products can be damaging to both the environment and engineering elements of roads such as concrete and steel bridge foundations and culverts, geotechnical reinforcements such as reinforced soil wall straps and rockbolts, cut batters and pavement materials. This paper presents experiences with ASR in road projects including an overview of the basic science, investigation and test methods, ASR characterisation, design considerations, management plans and construction issues. The Conjola Mountain realignment project on the Princes Highway in southern NSW is presented as a case study together with some research work undertaken on this project.

1 INTRODUCTION

NSW Roads and Maritime Services (RMS) manages about 18,000 km of state roads in NSW and acid sulfate rock (ASR) occurs in fills and cuttings of some of its existing and planned new roads, requiring measures to manage risks to road infrastructure and its surroundings. ASR contains acidity or potential acidity, by virtue of sulfide mineral content, typically fine grained pyrite, that when oxidised produces sulfuric acid. ASR is known to occur in parts of the lower stratigraphic sequences of the Sydney Basin within and below the Permian age coal measures, and at other locations in NSW. Over the past two decades awareness in the roads field of ASR has grown with the increased emphasis on environmental issues and legislation, with the acceleration of high standard often dual carriageway road project construction having deep cuttings into fresh rock zones, and with increased awareness of the engineering risks.

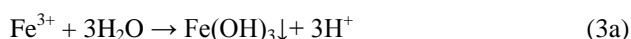
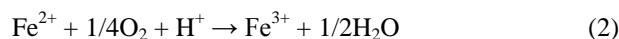
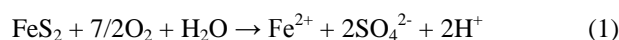
Techniques and management methods for ASR in road earthworks have largely come from the fields of acid mine drainage (AMD) and acid sulfate soils. These provide excellent testing and characterisation protocols and environmental management practices, but offer less guidance for risks to engineering elements. Nevertheless over the past 1 to 2 decades there have been significant advances and research in the civil engineering and related fields.

2 ACID SULFATE ROCK - CHEMISTRY AND STANDARDS

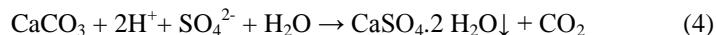
Acid sulfate rocks (ASR) are rocks that have either developed significant acidity as result of natural weathering of sulfides, or have the potential to develop significant acidity if they are exposed to oxygen and water (potential acid sulfate rock - PASR). The sulfide minerals in ASR can develop during the laying down of sediments in a reducing environment, in igneous or metamorphic crystallisation, or by secondary processes such as hydrothermal veining or alteration. Most ASR in NSW is sedimentary or metasedimentary. Pyrite (FeS_2) is the most common sulfide mineral for PASR because it is relatively abundant and it is reactive in the presence of oxygen and water. Pyrrhotite ($\sim\text{Fe}_7\text{S}_8$) is less common and is highly reactive. Galena (PbS) and sphalerite (ZnS) have low reactivities or may even consume acid (AMIRA, 2002). Elemental and organic sulfur are not normally acid producing (AMIRA, 2002; QASSIT, 2004).

Acid sulfate soils (ASS) have similar chemical behaviour related to sulfide content, and in eastern Australia generally occur at shallow elevations in coastal floodplain areas within estuarine or marine sediments which are of Holocene or Pleistocene age. ASS can also occur in elevated, older non lithified sediments over greater elevation ranges, with examples being in the eastern USA (Fanning *et al.*, 2004) and southern UK (Higgins *et al.*, 2002). ASR generally reacts more slowly than ASS but its exposure by excavation and necessity as a construction material poses more variable and longer term environmental risks and higher risks to engineering elements.

When acid sulfate rock (and soils) containing pyrite is exposed to oxygen and water, the following basic reaction sequence can occur and may be catalysed by bacteria (Byerly, 1996; GARDGuide, 2008; QASSIT, 2004):



Pyrite is oxidised (initiating reaction 1) to ferrous iron and sulfuric acid and ferrous iron is oxidised to ferric iron (rate limiting reaction 2). In propagating reactions, at pH > 4 to 4.5 ferric iron hydrolyses to ferrihydrite and acid (3a) and at pH < 4 to 4.5 ferric iron oxidises pyrite to ferrous iron and acid (3b). There are variations in the literature on these reactions and the catalysing role of bacteria. Other reactions produce goethite (FeO.OH), jarosite (KFe₃(SO₄)₂(OH)₆), typical of yellow staining in ASR, and oxidised products of these sulfate salts, along with more acid. Acid neutralising reactions, by minerals present or added, consume acid. Calcite consumes sulfuric acid forming gypsum (reaction 4):



As can be seen these reactions produce acid at various stages. Below pH 4 to 4.5 oxidation by ferric iron (reaction 3b) increases the rate of acid production provided there is a continuing supply of ferric iron, often catalysed by bacteria, typically *Acidithiobacillus ferrooxidans*, (hence the limiting reaction 2). At these pH levels metals go into solution as potential contaminants. Neutralising agents, typically calcium carbonate, can consume acid and buffer the pH, so that the true extent of acidity and other effects can be delayed (GARDGuide, 2008), with typical pH plateaux at pH 6 to 8, 4, 3 and 2 associated with carbonates at high pH through various buffer minerals to aluminosilicates at low pH.

ASR reactions can be expansive with calculated volume increases at mineral level of 115% and 170% for reactions of pyrite to jarosite and ferric sulfate respectively (Nixon, 1978) and 350% for pyrite to amorphous ferrous sulfate. (Fasiska *et al.*, 1974). Formation of gypsum from reaction 4 can increase the volume of the material and may result in cracking of fragments or heave (Hawkins, 2012). The addition of lime or cement, together with other minerals and high pH, can produce ettringite (Ca₆[Al(OH)₆]₂.(SO₄)₃.26H₂O) or thaumasite (2CaSiO₃.CaCO₃.CaSO₄.15H₂O), which again increase the volume and are known to cause heave and swelling problems for concrete, pavements and stabilised earthworks (Reid *et al.*, 2005; Higgins *et al.*, 2002; Harris *et al.*, 2004).

The forms of pyrite (or other sulfides) influence the rate of oxidation reactions. Pyrite reacts more rapidly in smaller and framboidal forms in comparison with larger or crystalline forms, the former factors giving higher specific surface area at the mineral grain level. Amorphous pyrite reacts more rapidly than its crystalline form. Also the rates of reaction will depend on the specific surface area of the rock material, that is the surface area per unit volume of rock material reflected by the degree of its breakup during excavation and compaction, the permeability of the individual rock fragments, the ongoing supply of air (oxygen) and water, the presence of catalysing bacteria and other factors such as temperature and ongoing pH (GARDGuide, 2008).

Relevant standards and guidelines include the Acid Sulfate Soils Laboratory Methods Guidelines (QASSIT, 2004), AMIRA ARD Test Handbook (2002), TRL Report on Sulfate Specification for Structural Backfills (Reid *et al.*, 2005), the GARDGuide (2008), the Acid and Metalliferous Drainage handbook (DITR, 2007), the RTA (now RMS) Guidelines for the Management of Acid Sulfate Materials: Acid Sulfate Soils, Acid Sulfate Rock and Monosulfidic Black Oozes (2005) and the FHWA guide for Handling Excavated Acid-Producing Materials (Byerly, 1990). Typical upper limits for reduced sulfur for structural backfills for steel and concrete are 0.01 to 0.04% (Reid *et al.*, 2005), and for untreated earthworks 0.05 to 0.15% for recent RMS projects and about 0.15 to 0.2% for US cases (Byerly, 1996).

3 TESTING FOR ACID SULFATE ROCK

Testing schemes for acid sulfate rocks are similar to those for acid sulfate soils. The types of testing used are influenced by whether an indication is required for filtering out benign materials or more definitive tests are needed to determine potential amount and timing of acid leachate generation. Most tests samples are prepared by pulverising to -75 micron size, although the longer term tests mostly use crushed rock, and field trials generally use rock as excavated. Indicative tests include:

- pH in water (pH_w) and peroxide (pH_{ox}) for existing and potential acidity respectively
- pH as part of the Total Actual Acidity (TAA) and Net Acid Generation (NAG) tests for existing and potential acidity respectively
- Electrical conductivity (EC) for salinity including sulfates
- pH and EC tests can be done in the field with less risk of sample oxidation, or more accurately in a lab
- Sulfur (mass %), usually total (TS) or reduced (TRS) - see Table 1.

Quantitative testing enables the total potential acid production to be calculated:

- Sulfur, singly or in combination (Reid *et al.*, 2005) as in Table 1, to quantify potential acid production – usually TRS assuming little sample oxidation or TS if some of the sulfide may have reacted since sampling
- Total Actual Acidity (TAA) by back titration for existing acidity
- Acid Neutralising Capacity (ANC) by back titration for carbonates and other bases.

By Acid Base Accounting (ABA) quantities are placed on an equivalent scale of kg H₂SO₄ / t of rock material for:

- Net acid producing potential NAPP = TRS - ANC (as kg H₂SO₄ / t)
- Net Acidity NA = TAA + NAPP = TAA + (TRS - ANC) (as kg H₂SO₄ / t)
- Neutralising requirement kg CaCO₃ / t, approx. equivalent to kg H₂SO₄ / t (~2% different)

Table 1: Sulfur Tests (mostly based on Reid *et al.*, 2005)

Test	Includes	Excludes	Relevance
Water soluble sulfur (WSS)	Highly reactive sulfates such as epsomite	Gypsum, jarosite	Short term reactive sulfates
Acid soluble sulfur (ASS)	Slower reacting sulfates – eg gypsum, anhydrite and jarosite	Non reactive species such as baryte and celestine	Long term slow reacting sulfates by ASS - WSS
Total reduced sulfur (TRS)	Disulfides such as pyrite, monosulfides such as pyrrhotite and elemental sulfur	Organic sulfur	Good indicator of oxidisable sulfide. Some sulfides eg galena not acid forming. Elemental sulfur not common in nature.
Total sulfur (TS)	Reduced sulfur, sulfates, elemental sulfur and organic sulfur	Nil	Quick indicator. Also used if some sampled sulfide may have oxidised. Elemental & organic S don't usually produce acid.
Monosulfide (MS)	Typically pyrrhotite, also galena	Disulfides such as pyrite, marcasite	Extension of acid soluble sulfate method. Monosulfide often highly reactive.
Organic sulfur (OS) calculated	By calculation TS – (TRS + ASS) assuming no unreactive sulfates		Not normally reactive, but may be expressed in the NAG test, requiring adjustment.

This allows quantification of the potential acidity assuming all sulfides are oxidised to acid and all ANC can be utilised. In reality other factors may limit oxidation of the pyrite, and ANC may also not be fully utilised due to grain size, reaction blinding and availability (location). Also variable rates and delays may apply to acid producing and neutralising reactions. To account for these a Factor of Safety (FOS), minimum 1.5 to 2, is often applied to the ANC and neutralising requirement, and may be applied to the TRS or NAPP (Batchelder, 2012; QASSIT, 2004).

Check tests include the Net Acid Generation test (NAG), providing a check on the ABA by strongly oxidising a sample and titrating back to pH6.5. The kg H₂SO₄ / t NAG result reflects the existing and sulfide generated acidity, and the acid neutralising content and so may be compared with Net Acidity, however it also includes organic sulfur as evolved acid, which does not usually occur in the field and for which an adjustment may be needed.

Tests to address rates and delays in reactions, and metal production, take considerable time, of the order of 3 to 12 plus months, and include (AMIRA, 2002; DITR, 2007; Morin *et al.*, 2003):

- Kinetic single stage NAG tests with continuous pH and temperature measurements
- Sequential NAG tests where the remaining rock sample material is filtered and subject to multiple cycles of oxidation and titration – particularly for S > 1% and high ANC
- Column leach tests, in which a column of crushed rock or aggregate is repeatedly rinsed and aired, with measurement of pH and dissolved salts and metals of the liquor to indicate rates and periods of reaction
- Humidity cell tests
- Field trials where barrels or piles of excavated rock are exposed to rain or a water source and the leachate is gathered and analysed.

4 POTENTIAL ENVIRONMENTAL AND ENGINEERING EFFECTS OF ASR

The potential products from the oxidation of ASR include acid leachates, sulfate salts, iron hydroxides, and dissolved metals. The potential environmental effects are fish kills, vegetation scalding, metals in water and the food chain, effects on water quality for humans, agriculture and animals, and sedimentation in waterways due to excessive breakdown of exposed cut faces (Arup, 2005; RTA, 2005).

The potential engineering effects are a result of the generation of acid leachates, the chemical breakdown of some rock materials by the various chemical reactions associated with sulfides, and physical breakdown and heave by swelling reactions such as production of gypsum, jarosite, ettringite and thaumasite. They include:

- Corrosion of steel in corrugated steel culverts, concrete reinforcement, steel strips in reinforced soil walls (RSW), rockbolts and anchors (Reid *et al.*, 2005)
- Corrosion of concrete in bridge foundations, retaining structures, pipes, kerbs and 'V' drains (Reid *et al.*, 2005)
- Heave of pavement support layers of earthworks, especially if lime or cement is added (Higgins *et al.*, 2002)
- Swelling, blistering, cracking and sulfate salt efflorescence for pavements containing acid sulfate rock material (Bannerman, 2005)
- Leaching or neutralisation of binders in earthworks or stabilised pavement materials

- Swelling, spalling and loss of strength of exposed ASR cut batters leading to spalling, rockfalls and instability (Arup, 2005), and loss of batter shape and bench widths
- Rapid weathering and erosion of poorly vegetated (scalded) cut and fill ASR batters leading to disruption of drainage from sedimentation and precipitate clogging (RTA, 2005)
- Acid leachates resulting from rainfall runoff from, and seepage through, ASR in cut and embankment batters
- Mitigation measures complicating earthworks sequencing and materials handling, including limiting the locations and uses of ASR (Arup, 2005), for example proscribing its use as rockfill or drainage material.

5 EXAMPLES OF ROAD PROJECTS INVOLVING ACID SULFATE ROCK

One of the most well known road projects involving PASR is the 'Skytop' project in Tennessee USA, in which a cutting of more than 750,000 cubic metres was constructed through what was in effect an orebody (Hammarstrom *et al.*, 2004). Its existence, together with the extent of pyrite occurrence in the groundmass and as vein concentrations, was not anticipated. Selected rock samples contained up to 28% sulfur. Once excavated and exposed, the cutting face and embankment and stockpiled materials generated large amounts of acid leachates and heavy metals which polluted waterways and killed fish. Remediation is understood to have cost of the order of US\$80 million, and to have included liming and spoiling of already placed fills and stockpiles, covering of batters with heavy waterproof barriers and extensive treatment of drainage and runoff waters for acid and metals.

For the Oyster River to Tsolum River section of the Vancouver Island Highway Project in Canada (Morin *et al.*, 2003) excavated PASR with up to 2% sulfur was encapsulated by glacial till in the highway fill embankment, with leachate drainage and treatment. Testing, including humidity cell, indicated significant ANC, supported by relatively high pH (generally >6) and sulfate (from pyrite) in leachate waters. With a history of AMD and damage to salmon spawning areas, long term monitoring was necessary.

Byerly (1990) reports a trial in the eastern US of encapsulated PASR road embankments treated with crushed limestone spread between 0.6 m thick fill lifts at 90 to 95% standard compaction, together with limestone rock underdrainage. Drilling and mineralogical testing of PASR fill materials showed significantly improved drainage chemistry and inhibited PASR reactions for the encapsulated treated embankments relative to a control untreated embankment.

RMS incidents include bridge pier corrosion near Lithgow by PASR backfill treated by excavation cleanoff and encapsulation by sulphite resistant concrete (1970s to 1980s), rapid rock batter weathering and spalling at Lidsdale (from late 1980s), steel culvert corrosion by PASR fill leachates near Marulan (late 1970s), and acidic runoff from imported PASR select material near Raymond Terrace (early 2000s). Planned designs and treatments include at Lidsdale encapsulation of PASR fill embankment by bentonite geocomposite and inert fill (mid 2000s), at Buladelah Bypass mapping and spoiling of excavated PASR with ABA determined aglime treatment (late 2010 to 2012), and at Kempsey Bypass mapping of excavated cuttings and pretreatment with peroxide of PASR select stockpile samples prior to mechanical testing (2012). On the Federal Highway Sutton to ACT project PASR dacite occurred in an area proposed for a low wet cutting, interchange with RSWs and 400 m creek diversion culvert, for which integrated rockfill drainage layers and foundations were designed and constructed (late 1990s to early 2000s). Limestone lined drains were used for discharge waters and PASR was placed in designated fill zones away from RSWs and well above fill foundations.

6 ASR PRECONSTRUCTION REQUIREMENTS FOR ROAD PROJECTS

In the preliminary stages of road projects the main actions are to undertake a literature and mapping study for any records of ASR in the area or any association of rock types or formations with ASR. A site visit would concentrate on visual indications of ASR such as yellow staining and iron oxide precipitates on or adjacent to fresher rock surfaces, particularly those exposed by human activity or active cliff formation. During drilling investigation, discolouration and deterioration of core and rusting on core boxes are further indicators. Testing of water for pH and EC, on creeks and rivers, ponds and runoff water from roads, as well as seepage waters and groundwater, is a useful indicator of general levels of acidity or salinity which may be related to rocks in the area, and also provides preconstruction levels.

Tests for pH may be conducted, in the field or laboratory, on soil or pulverised rock samples mixed with water and hydrogen peroxide. The former can indicate elevated actual acid levels that may be the product of natural weathering oxidation of sulfides, and the latter can indicate potential acidity levels from future oxidation of sulfides in rock. Another useful index and quantitative test is sulfur (total or reduced), requiring a laboratory. Typical screening tests limits are $\text{pH}_w < 5$, $\text{pH}_{\text{ox}} < 3$, $\text{pH}_w - \text{pH}_{\text{ox}} > 2$, $S > 0.05\%$, as well as a positive peroxide fizz test (QASSIT, 2004).

For concept and detailed design stages, investigations and tests are aimed at defining the distribution of acid sulfate rock and the form and concentration of sulfides so that the management of this material during and after construction can be planned, and so there is enough information to enable road constructors to assess risks and estimate methods and costs. Typical investigations and tests additional to those used in the preliminary stages include:

- detailed drilling and mapping to define the distribution of ASR and controlling geological factors
- maximised sampling of the ASR stratigraphic sequence, eg vertical and/or angled cored boreholes
- sampling on a systematic basis, including sampling for testing to take account of uneven distributions of sulfide (and acid neutralising) minerals
- additional cored boreholes dedicated for providing test samples
- consideration of 100% sampling of core, with crushing and blending, to better achieve averaged sulfide and ANC contents, prior to subsampling for testing
- procedures to minimise oxidation of sulfides between disturbance and testing, such as storing at less than 4°C or oven drying and sealing (QASSIT, 2004; Reid *et al.*, 2005)
- the full suite of indicative and quantitative tests, thus maximising characterisation of the materials and allowing cross checking of results, e.g. pH_{ox} v %S, ABA v NAG
- column leach or other longer term tests for field performance of the ASR and indications of heavy metals.

The design of earthworks with PASR (or ASR) should take account of the quantities and net acidities of PASR, excavation and placement locations and their sequencing, locations and protection of PASR in stockpiles and dumps, placement zones and treatments for PASR fills, treatment of cutting faces, and protection of higher risk elements from acid leachates. Other considerations are drainage design for cuts and fills, and treatment of seepage and runoff waters. Alternative treatments, such as burial below the water table, spoiling and liming may be considered.

Where PASR is identified as a significant risk or factor in a road project a PASR Management Plan is needed to set out the methods and procedures for managing ASR in earthworks. This may be developed by the principal, constructor or both. The principal's plan sets the benchmark and direction for the contractor, and also tests the feasibility of the project with respect to PASR. A comprehensive PASR Management Plan may contain features such as identification and classification of material types (for PASR), testing schemes, placement zones for different materials, liming rates and drainage treatments, construction and monitoring controls (including runoff water), and post construction monitoring and maintenance. Information on the results of preconstruction investigation and testing may also be presented.

7 CASE HISTORY – CONJOLA MOUNTAIN REALIGNMENT PROJECT

The Conjola Mountain Realignment project is 45 km south of Nowra on the Princes Highway in the NSW south coast region. It lies in fine to medium quartz sandstone, with minor siltstone and claystone, of the Snapper Point Formation of the lower Permian margin of the Sydney Basin. The 2.4 km project descends 110 m vertically from a plateau to Conjola Creek and was constructed in steep sidelong terrain from 2008 to 2010 (Figures 1, 2 and 4), with cuttings up to 28 m high and side fills on steep slopes up to 40 m high. The 28 m wide road formation includes two northbound climbing lanes and one descending southbound lane, shoulders and verge areas. Structures include a 120 m viaduct, reinforced soil walls up to 18 m high as bridge abutments and on the sides of some fills and a concrete arch underpass.

Preliminary drilling and testing indicated PASR in deep cuts, quantified by later investigation at 82,000 m³ of PASR excavation in the fresh to slightly weathered lower zone with %S_{cr} up to 1%, overlain by 175,000 m³ of a generally 7 to 11 m thick mostly highly weathered nonPASR upper zone with very low %S_{cr}. A detailed program of ASR investigation and testing by RMS and consultants (Batchelder, 2012) included three full depth cored boreholes in each of two large cuts, with comprehensive indicator and quantitative tests – see Figure 5 for %S_{cr} against depth for all samples from these later boreholes. Sampling of core was undertaken by crushing and blending each metre of the entire rock core, oven drying, sealing in plastic bags (to minimise oxidation) and subsampling for laboratory testing. Tests (QASSIT, 2004) on each metre sample included:

- pH in water and peroxide, and pH for the TAA test and (where done) the NAG test
- reduced inorganic sulfur (TRS) percentage by chromium II method - %S_{cr}
- total actual acidity (TAA) by back titration
- acid neutralising capacity (ANC) by back titration
- acid base accounting (ABA) for Net Acidity (NA) – with a FOS of 2 for ANC

Plots of results against depth in boreholes (see example in Figure 6) showed good correlations of:

- lower pH (4.5-5.8) in water in the upper weathered zone, reflecting remnant acidity from oxidation of pyrite
- low pH (~2) in peroxide against increased sulfur percentage in the deeper fresh to slightly weathered zone
- higher pH (about 6-9) in peroxide, water and TAA where there was significant ANC or very low sulfur.



Figure 1: Conjola Mountain Fill 2, grey PASR in Cut 2.



Figure 2: Fill 2 grey PASR and brown cover being placed.

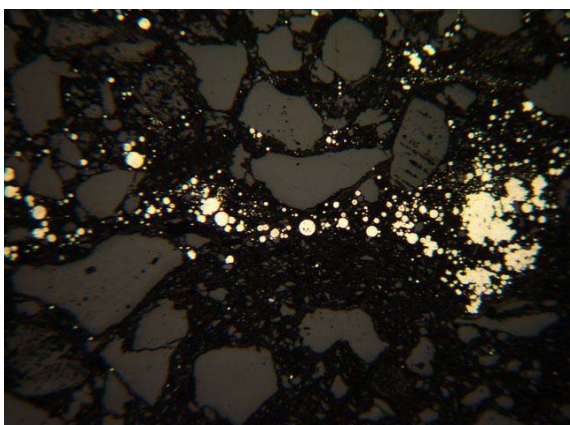


Figure 3: Framboidal pyrite in sandstone matrix - reflected light petrographic slide.



Figure 4: Cut 2 excavation of PASR - note iron oxide from oxidation of pyrite at right above first bench.

A plot of pH in peroxide against net acidity (see Figure 7) indicates a general division between the upper weathered and lower fresher rocks at pH in peroxide of 3 or 2.8 and net acidity (NA) of 2.5 kg H₂SO₄/t, although some fresher rock with higher pHs and negative NAs are associated with high ANC, linked to fossil calcite bivalves observed in rock core. This is supported by plots of %S_{cr} against NA (see Figure 8) with fresher rocks having some results of lower NA than the %S_{cr} would indicate. On the same graph results from older boreholes, sampled and tested about 1 year after drilling, show the effects of oxidation, acid generation and loss of sulfur over the 1 year period. Table 2 shows means and ranges of test results for mostly highly weathered upper and slightly weathered to fresh lower zones.

Table 2: ASR Test Results For Conjola Mountain - Detailed Design Stage Investigation***

Test Type	Stat.	pH		Chemical Analysis mass %		Acid Base Accounting (ABA) - kgH ₂ SO ₄ /t			kgH ₂ SO ₄ /t	
		Water	Perox.	TRS* (S _{cr})	ANC* (CaCO ₃)	TAA*	TRS*	ANC*	NA**	NAG**
Upper Weathered	mean	5.1	3.3	0.02	0.03	0.9	0.64	0.02	1.6	4.0
	range	3.9-5.8	1.9-4.9	<0.005-0.39	<0.05-0.12	0-2.9	0-11.9	0-1.2	-0.6-13.6	3.2-4.5
Lower SW-Fr	mean	6.1	2.6	0.47	0.84	0.4	14.2	8.0	10.6	9.3
	range	3.6-8.7	1.5-8.1	<0.005-1.01	<0.05-7.52	0-3.6	0.5-30.9	0-73.7	-31.3-27.0	0.9-21.1

*TAA – Total actual acidity, TRS – Total reduced (inorganic) sulfur, ANC – Acid neutralising capacity (%CaCO₃ for chemical analysis, kgH₂SO₄/t for ABA).

** NA – Net acidity (FOS 2 for ANC) = TAA+TRS-(0.5xANC), NAG - Net acid generation - tests only on about 7 % of samples.

*** Freshly drilled and sampled core. Results from preliminary investigation, sampled and tested up to 1 year later, were more scattered and are excluded.

Thin section petrography on rock cores revealed abundant fine framboidal pyrite, associated with carbonaceous clay matrix (see Figure 3). A column leach test on crushed core produced pH values down to 3.1 (generally in the range 3.2 to 3.8), which after 38 cycles (88 pore flushes) and 3 drying cycles over 14 weeks had consumed about 10% of the net acidity. Limited NAG testing had higher values than the NA (FOS 1) for the same samples, interpreted as caused by either organic sulfur contributing to the acid in the NAG test, or the NAG test mobilising only some of the ANC.

Grey PASR rock was to be excavated from two large 26 to 28m deep cuttings (Cuts 2 and 4) and from bored bridge foundations, and placed in two large side fills up to about 40m high (Fills 2 and 4) as core materials with encapsulation

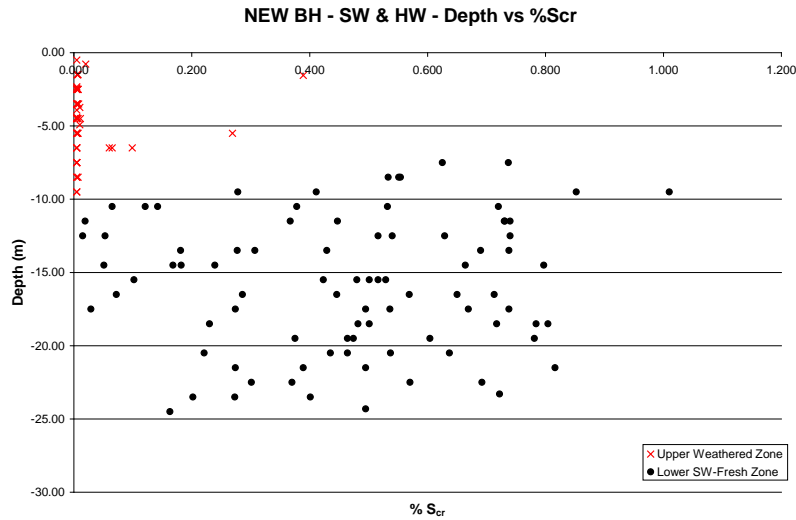


Figure 5: %Scr v depth for all detailed design stage borehole samples.

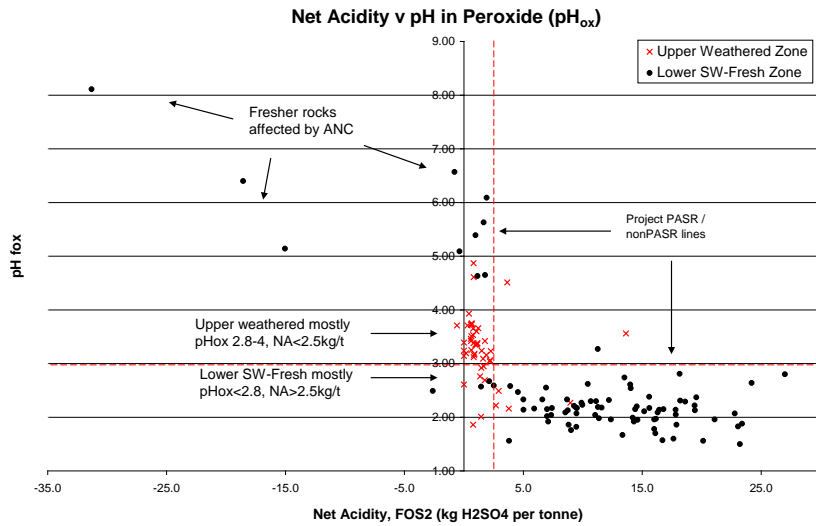


Figure 7: Net Acidity v pH in peroxide (pH_{ox}) – detailed stage samples.

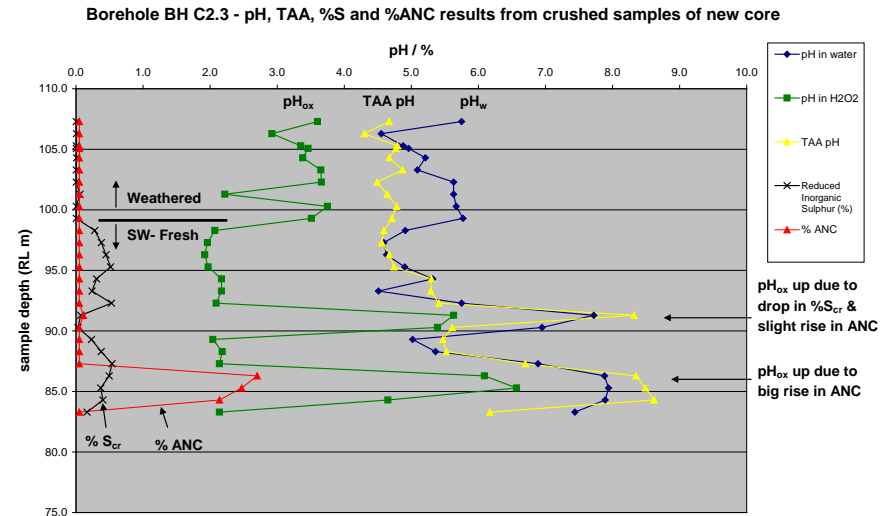


Figure 6: Example BH C2.3 (Cut 2) test results v depth.

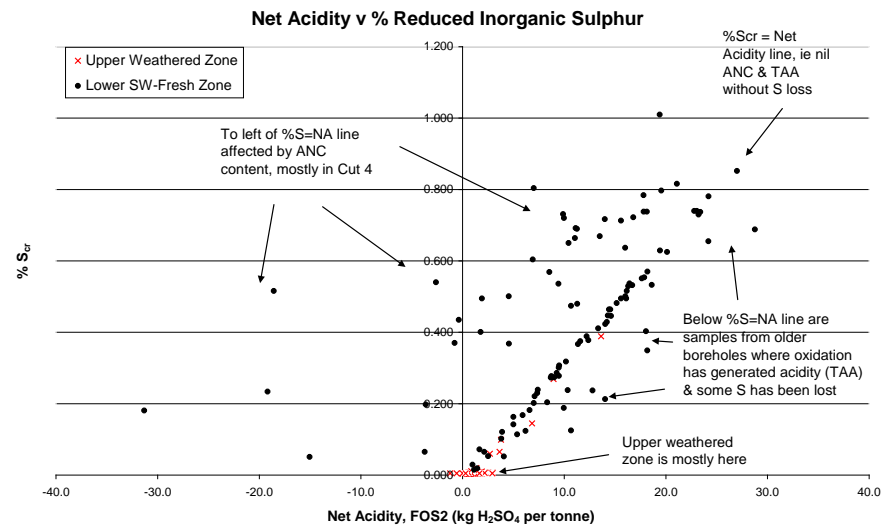


Figure 8: Net Acidity v $\%S_{cr}$ – detailed and preliminary stage samples.

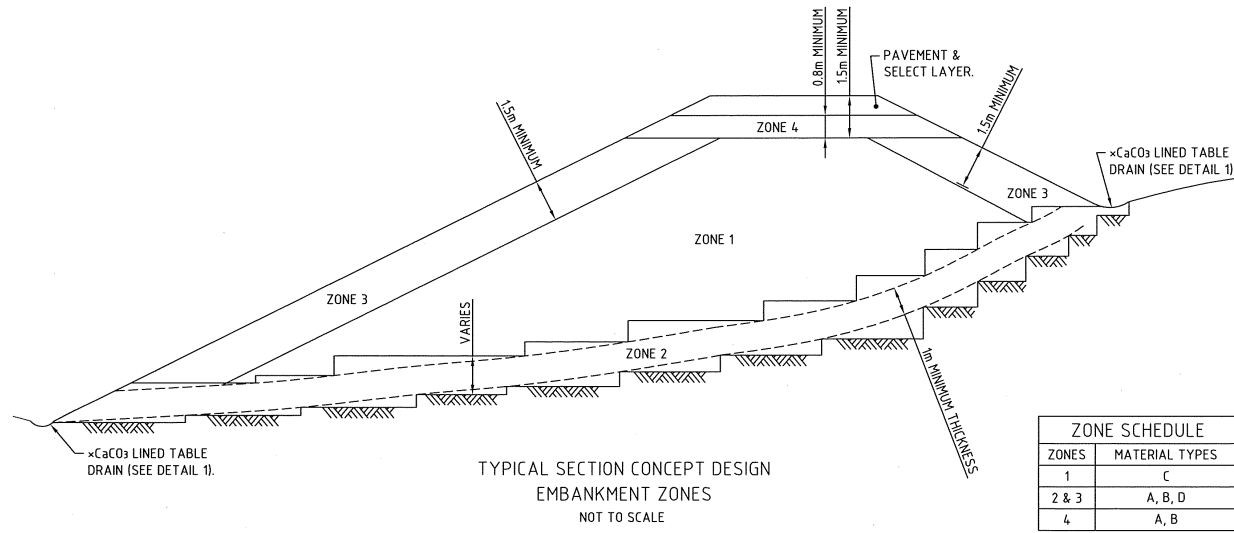


Figure 9: Encapsulated PASR embankment concept design – note actual embankments were side fills.

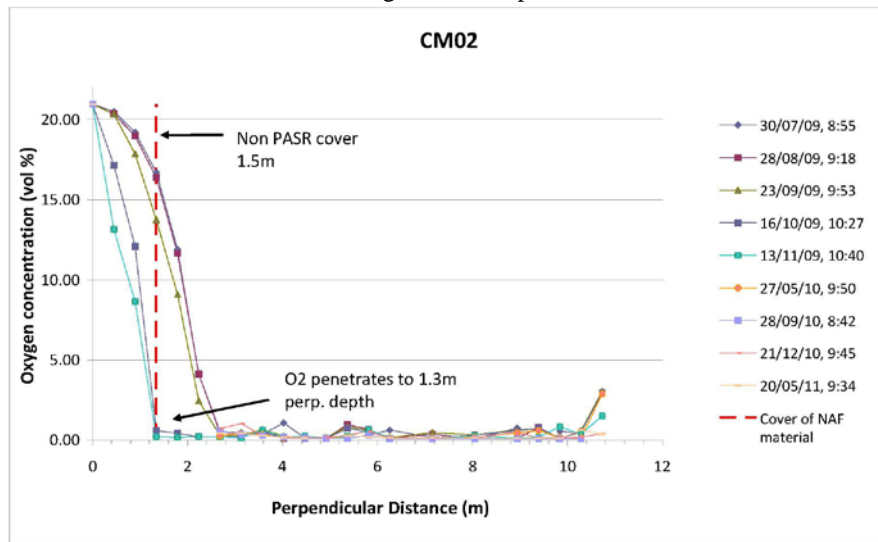


Figure 10: Fill 2 O₂ v perp. depth – reduces to < 1% within non PASR cover

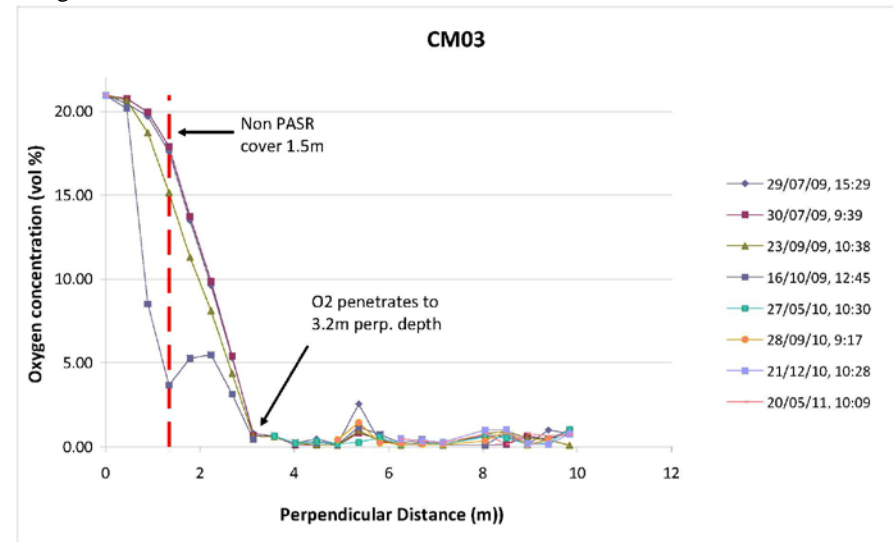


Figure 11: Fill 2 O₂ v perp. depth - O₂ > 1% beyond non PASR cover

by non PASR or PASR treated with a crushed and graded agricultural lime. Encapsulation thicknesses were 1-1.5m (see Table 5 and Figure 9). Herringbone drains were included for the side fill foundations in order to limit lateral seepage into the encapsulated fills. The strategy was that the core PASR would be sufficiently compacted and shielded from the surface that oxygen would be quickly consumed by any oxidation of pyrite, and moisture content would be stable in the core. The encapsulation strategy is a modification from Byerly (1996), with no aglime treatment of the core and lesser (non limestone) underdrainage, but higher standard compaction at 98% and thinner fill lifts at 0.3 m.

The following measures were used to further reduce risks to vulnerable road elements:

- 20 m exclusion zone around RSW blocks and concrete arch (RSW exclusion zone)
- No counting of the ANC for materials in this zone, and separate limits on NAPP and %Scr (see Table 3)
- Drainage behind and beneath RSW blocks, and drainage blankets in cutting floors
- Sulfate resistant cements for bridge foundations and other vulnerable concrete elements
- Non PASR materials for the RSW block and selected zone beneath the pavement.

Owing to the steep and forested nature of the site there was not sufficient room for large sediment ponds. Drainage water from cuttings was therefore treated by small limestone lined basins immediately below culvert outlets for low flows. With higher flows, where dilution of leachates was expected, limestone filled reno mattresses were used to line discharge drains down the boundary between the fill embankments and natural ground. Contingency treatments should drainage and seepage waters be too acidic, were anoxic trench tanks below culvert outlets and interception trench drains below the toes of fill embankments, both filled with crushed limestone. These were not needed, as discharge pH levels from the site during construction remained high.

Cuttings were designed to have mostly steep batters owing to the steep terrain and the need to limit rainfall runoff and aspect of the PASR zones. To ensure geotechnical stability, a significant proportion of the upper weathered sections were soil nailed and shotcreted. To limit exposure to air and rainfall the lower fresher material was treated with an epoxy product (polymer with cement), which RMS has successfully used elsewhere in NSW to stabilise cuttings in fresh basalt and a small trial section of PASR. At Conjola this was not successful with considerable swelling and spalling of the PASR material (possibly connected with surface preparation), and was replaced by shotcrete. Rainfall and seepage in the cuts was channelled along benches and catch drains, as well as water from verge and cut floor drainage layers, to culverts for treatments as for fills.

A Management Plan for Potential Acid Sulfate Rock, developed for the project by RMS and a consultant (Batchelder 2012), included much of the information and measures described above as well as schemes for identification and classification, testing, liming rates, construction monitoring and control, and post construction monitoring and maintenance. The classification scheme (see Table 3) has four materials classes and four classification options reflecting increasing reliability, from rock colour (grey versus brown), through field or laboratory pH_{ox} testing to detailed chemical analysis and ABA. Due to the high risk for RSWs which were up to 18 m high at bridge abutments, the 20 m exclusion zone behind RSW blocks is stricter, with ANC and added agricultural lime (aglime) not counted. In Table 4 material types are matched against aglime dosage requirements, again with varying requirements against level of classification and net acidity, with a FOS of 2 for the ANC and aglime quantity. Aglime was graded from about 5 mm to below 75 microns to provide short and long term capacity. Table 5 shows permitted materials and requirements for the various placement zones, including embankment cores, encapsulation zones and RSW exclusion zone.

Table 3 – Conjola Mountain Realignment - Default Classification Scheme for ASR Material Types

CLASSIFICATION SCHEME OPTION	COLOUR	INDICATIVE CHEMICAL TESTS*		DEFINITIVE CHEMICAL TESTS* (all units kg H ₂ SO ₄ /t equivalent, except %S _{cr})		
		pH _{ox} site	pH _{ox} lab	Net Acidity (ANC FOS 2)	TAA + TRS	TRS (%S _{cr})
A – Non PASR	Brown	≥ 3.5	≥ 3.0	≤ 2.5	-	-
B – Non PASR (RSW excl'n zone)	Brown	≥ 3.5	≥ 3.0	-	≤ 2.5	≤ 0.05
C - PASR	Grey	< 3.5	< 3.0	> 2.5	-	-
D – PASR treated with aglime**	Grey	< 3.5	< 3.0	> 2.5	-	-

* Tests in accordance with QASSIT Acid Sulfate Soils Laboratory Methods Guidelines (V1 – June 2004).

** Test requirements prior to treatment with aglime.

Table 4: Conjola Mountain Realignment - Acid Sulfate Rock Default Liming Rates (kg/t)*

Criterion	Colour	pH _{ox} site, pH _{ox} lab			ABA (kg/t)
Details	Grey rock	>3.5 site, >3.0 lab	>2.5 site, >2.0 lab	≤2.5 site, ≤2.0 lab	2 x Net Acidity
Lime Dosage kg/t	50	30	40	50	2((TRS+TAA)-0.5ANC)

* Agricultural lime (aglime) - Liming rate for min 95% CaCO₃

** Tests in accordance with QASSIT Acid Sulfate Soils Laboratory Methods Guidelines (V1 – June 2004)

Table 5: Conjola Mountain Realignment - Acid Sulfate Rock Details of Placement Zones

Zone No.	Description	Permitted Material Types*	Details
1	Core – of designated fills	C	Encapsulated by zones 2, 3 and 4. Use of aglime, A and D materials in core at discretion of the Principal.
2	Base – of designated fills	A, B, D	Min. 1m thick normal to base, above all fill foundation treatments
3	Batter – of designated fills	A, B, D	Min. 1.5 m thickness normal to batter surface
4	Top of designated fills	A, B	Underside ≥ 1.5 m (0.8 m) below pavement surface (base of select layer)
5	RSW Exclusion Zone	B	Zone ≤ 20m from back and sides of RSW block and arch culvert
6	Other areas	A, B	C or D materials permitted at discretion of the Principal

* Refer Table 3 for details of material types



Figures 12: Monitoring trench PVC tubes for thermistor (right) and O₂ tubes with pink inlets (left).



Figure 13: Thermistor insertion for reading (blue on left) and O₂ tube outlets (right).

8 CONJOLA MOUNTAIN ASR RESEARCH

With the development of a good understanding of the Conjola Mountain site and a PASR Management Plan, the opportunity was taken to research the effectiveness of the encapsulation strategy. Advice from consultant Dr Andrew Garvie of SRK was that the best and most practical indicators of acid rock reaction within the placed PASR materials in embankments would be to monitor oxygen content in the pore air and temperature, because oxidation of pyrite consumes oxygen and produces heat (Garvie, 2008). These techniques are used in management of PASR dumps in mining where temperatures may rise to as much as 70°C (GARDGuide). In mining, oxygen and temperature monitoring strings are often installed in vertical boreholes drilled through the tops of dumps. For the Conjola Mountain road project installation was in horizontal trenches at different stages (heights) of embankment construction, achieved by compaction of 0.3 m thick layers of material as graded earth fill. Such fills have low permeability for air and water in comparison with mine waste dumps, which are generally constructed by end dumping without controlled compaction.

Temperature and oxygen (O₂) monitoring strings were installed in a single trench (about 0.5 m x 0.5 m) at each location at the level of compacted fill material at the time (see Figures 12 and 13). Monitoring points were spaced generally 1 or 2 m apart horizontally from the near the batter surface for a horizontal distance of about 21 m to 27 m across the compacted layer of the embankment (representing about 9 to 13 m depth perpendicular to the batter surface). From March to June 2009 Fill 2 had four monitoring installations (CM01 to CM04) at RLs of 52.8 m to 69.9 m below the ultimate top of the embankment of about RL 73 m. Other trenches were placed at control locations where PASR was to be excluded, and in October 2009 in a PASR dump (CM07), adjacent to the road. Within each trench was placed 2 x 50 mm diameter PVC tubes which housed a temperature thermistor cable in one and 21 air sampling tubes in the other, with air sampling points drilled in the PVC and protected by sand filled geofabric bags. Compacted fill material was

ACID SULFATE ROCK MANAGEMENT IN EARTHWORKS FOR ROADS

CHRIS WALKER

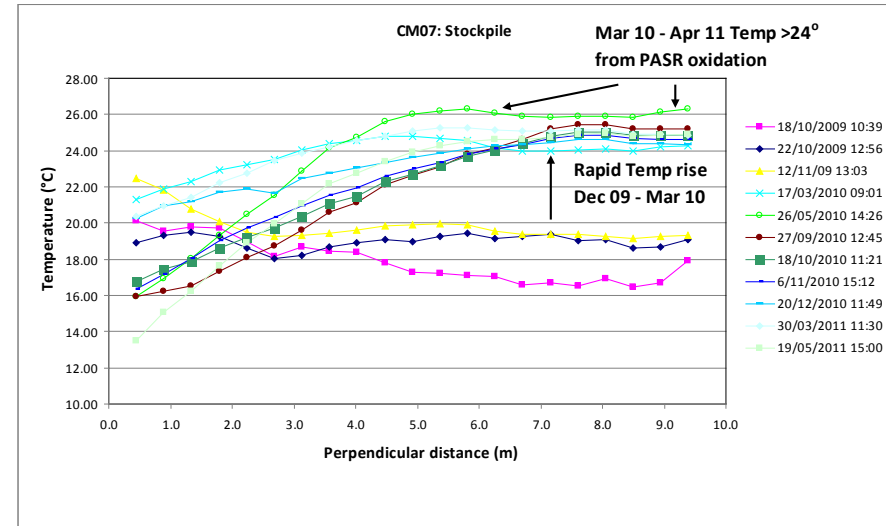
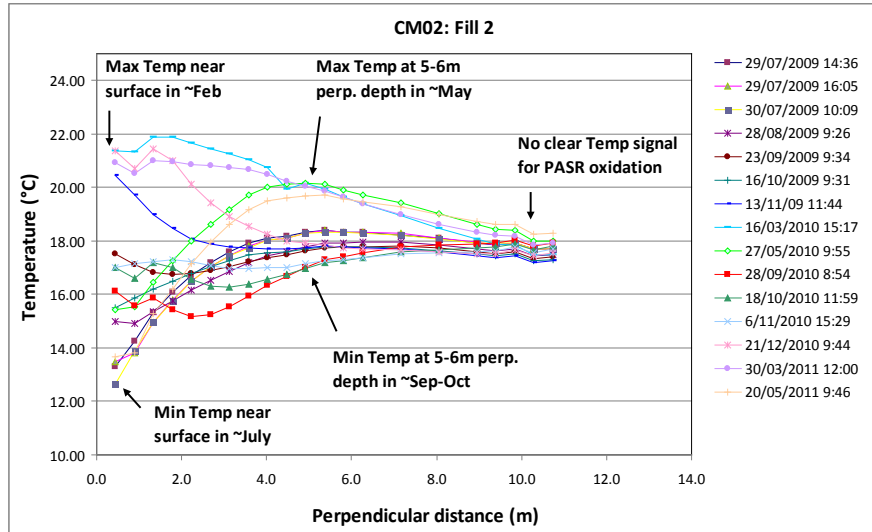


Figure 14: Fill 2 temp. v perp. depth - no clear PASR reaction temperature signal.

Figure 15: PASR dump temp. v perp. depth - clear PASR reaction temp. rise.

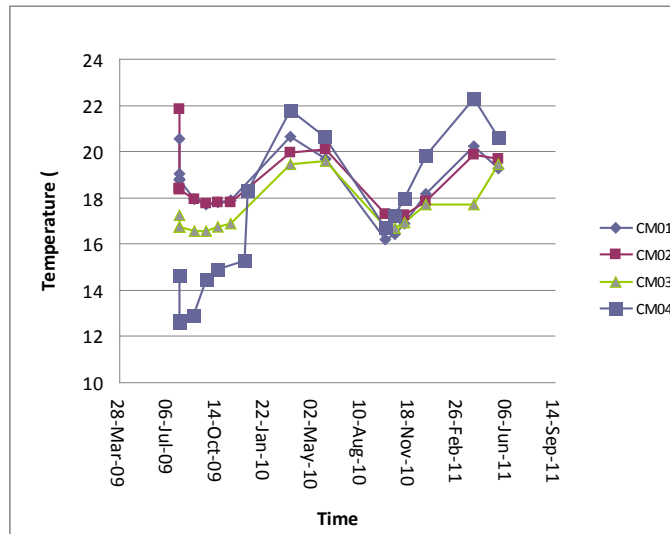


Figure 16: Fill 2 temp. v time for perp. distances of 5.37 m for CM01 to 03 and 5.04 m for CM04 – no clear temp. rise from season to season.

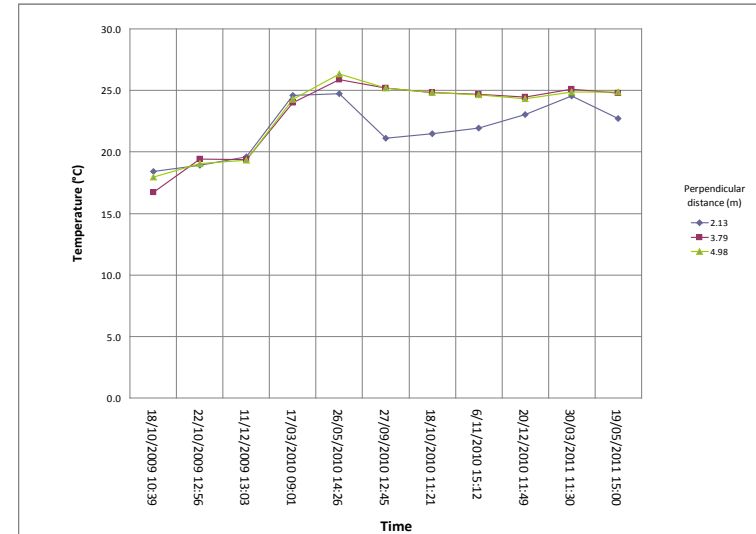


Figure 17: PASR dump temp. v time at perpendicular distances of 2.13 m, 3.79 m & 4.98 m - clear and sustained temp. rise over seasons.

placed into each trench, together with bentonite powder plugs between sampling points to minimise movement of air and water along the backfilled trench.

Temperature was read by an electrical resistance device, and oxygen was measured by a 21 channel oxygen analyser, which pumped air from each tube in turn (thereby sampling the pore air at each point in the embankment string). Data to May 2011 was recorded on a laptop computer. There were uncertainties of materials at control and other sites due to unexpected mixing of PASR and nonPASR within and between fill lifts and the destruction of one monitoring point.

Plots of O₂ against perpendicular distance from the fill batter (depth at 90° to batter) show a reduction from the air average of 20.95% O₂ to less than 1% from the batter surface generally to a perpendicular distance of less than the 1.5m nonPASR cover thickness (see Figure 10). The reduction in O₂ content is rapid and reaches close to a minimum level generally over about 5 to 8 months. Some locations showed rapid reductions to a minimum 10% O₂ over 12 days in one case and to less than 1% at 6 m perpendicular distance after 4 days in another. Overall the reduction in O₂ is not clearly related to the presence or absence of PASR, although at CM03 the deeper penetration of O₂ may be related to diffusion driven by reaction of PASR (see Figure 11), which is present at this location. It is possible that oxygen in the very low permeability compacted fill is consumed by other agents, such as bacteria or organic matter, as well as by reaction of PASR where present. Anomalous data, due to suspected leaks with O₂ at or near 20.95%, was excluded from plots.

Plots of temperature against perpendicular distance are complicated by several factors:

- Temperature of excavated material at the time of emplacement
- Average temperature at a particular time of year affects the near surface zone rapidly
- The temperature signal is conducted inwards from the embankment surface at a rate of about 0.5 m per month
- The temperature signal attenuates as it travels inwards so that at about 10 m distance perpendicular to the batter surface it is close to zero and, without another heat source, the average year round temperature prevails.

Figure 14 shows that the maximum temperatures occur near surface in about February and at 5 m to 6 m perpendicular distance in about May. Figure 16 plots temperature against time for all Fill 2 locations (CM01 to 04) at perpendicular distance of about 5 m to 5.4 m. Overall a clear temperature signal from internal chemical heating cannot be discerned from the seasonal and emplacement temperature trends.

In contrast a clear additional high temperature signal is noted in the PASR spoil dump (see Figures 15 and 17) with steadily rising temperatures from installation in October to December 2009, a rapid rise to March 2010 and then a steady rise to about 26°C in May 2010. Temperatures around 25°C are sustained over the next year to May 2011, except in the outer 2 m to 3m zone of the batter where some seasonal reduction to about 21°C occurred before rising again to near 25°C in March 2011. These high and sustained temperatures are interpreted to be caused by significant exothermic oxidation of pyrite in the PASR, with the pattern of seasonal variation disrupted and average temperatures of about 25°C well above the ambient temperatures and ranges indicated at other locations. At comparable locations in terms of depth below the top of the embankment (CM04 and CM05) the general range is 17 to 22°C over the same one year period from May 2010 to May 2011. Unfortunately at the dump site oxygen measurements were disrupted by the easy infiltration of free water into the uncompacted dump causing flooding of many of the gas sampling points. It is expected that air and oxygen can diffuse (and rainwater infiltrate) more easily into an uncompacted dump than compacted earth fill, thus promoting PASR reactions.

Despite some uncertainties of materials placement, monitoring to May 2011 of temperature and oxygen indicates that oxidation, acid production and chemical release rates have been substantially limited by PASR encapsulation in well compacted fills. Further work is ongoing on reaction rates, oxygen diffusion and sulfate production, which are calculated to be about 5 to 10 times higher in the PASR dump in comparison with the compacted PASR earthfills.

9 DISCUSSION

The following discussion arises out of experience gained from Conjola Mountain and other RMS projects. The presence and significance of ASR should be assessed in the early stages of road projects, and may include screening tests. Later stages, integrated with design development, may concentrate on characterisation, quantification and integration with geological models, ASR sources and placement locations, and treatment and monitoring measures. If significance and risk warrants, these aspects, together with tests and controls on construction, are developed in a PASR management plan, by the principal, contractor or both. Sequencing of earthworks and provision of stockpile and dump areas is important because PASR is often excavated later, in the deeper fresher zones of cuts, but needed earlier for embankment cores. Care is also needed in drainage design so as to adequately handle acid, sulfate salts and dissolved metals in runoff. Low flow basins and high flow rock mattress channels, with limestone rock filling, can appear adequate. However storm events and high sediment runoff can mask the limestone rock, as can plant growth in basins, and rock mattress channels can be bypassed by heavy storm runoff, with erosive results, especially in steep terrain.

For testing of acid sulfate rocks it is important to think carefully about the types of tests. For example if the mineralogy of the rock is well understood, testing for reduced sulfur is likely to be the most relevant for assessing potential acidity. However if samples are suspected of having undergone significant oxidation before testing, then total sulfur may be a better test, provided there is confidence that all of the sulfates have evolved since sampling, and that other forms of sulfur are not present in significant quantities. Reid *et al.* (2005) provide an excellent guide to the fundamentals of sulfur testing, and indeed point to the need for testing of reduced sulfur for backfill materials, in addition to the traditional sulfate tests.

The Conjola Mountain project indicates that encapsulation in compacted zoned road embankments (modified from Byerly, 1996) can effectively isolate excavated PASR from oxygen and water ingress. Instruments indicate rapid decline of oxygen levels across the outer 1.5 m thick non PASR zones to very low levels within the embankment core and no significant temperature signal of ongoing pyrite oxidation, indicating very limited rates of chemical reaction and release. Over time the oxygen front may move into the embankment and ongoing monitoring is needed. Thicker nonPASR outer zones up to 3 to 4 m may be considered, based on the variability and short term of O₂ data. For side fills underdrainage is desirable, preferably as designed rather than as part of the earthworks specification, to prevent seepage water laterally entering the embankment. For under compacted dumps, elevated temperatures indicate ongoing pyrite oxidation, so measures to consider include proper compaction, impermeable covers, aglime treatments and drainage water monitoring and treatment.

For construction, induction of supervisory and contractor personnel into the PASR management plan can establish understanding and commitment to its objectives and is an important component of good identification and control of PASR earthworks. Early stage materials characterisation by definitive (ABA) and other tests can allow indicator test criteria (eg pH_{ox}) to be used for frequent on site classification and control. Vigilance on materials placement and treatment is important, for example PASR in exclusion zones is a risk to durability of steel and concrete elements and can result in expensive remediation and less than ideal solutions. During construction operations nonPASR may be placed in the cores of zoned embankments, and PASR and nonPASR materials may be mixed. It is important to consider such possibilities at the preconstruction stage so that, if necessary, provision is made for these operations to be tightened up in the design and specifications.

One aspect that has been difficult to manage is protection and stabilisation of PASR cutting batters. Steep batters minimise surface runoff but are subject to breakdown, spalling and instability. Shotcrete appears to be the default treatment but is subject to hazards of long term cement leaching and corrosion of reinforcement by acidic waters seeping from behind the batter. Initial attempts at Conjola Mountain with an epoxy treatment were not successful, however there may have been factors of application method or surface preparation. For flatter batters (2H:1V or flatter) approaches include covering with inert fill and topsoil, with neutralising content to encourage plant growth. One aspect needing research and trials is the mechanical durability of PASR materials including test methods and pretreatments, particularly for higher quality materials such as select, verge, upper zone of formation and bridging.

10 CONCLUSIONS

Earthworks involving acid sulfate rocks (ASR) can be successfully managed through combination of investigation and testing, design, construction and monitoring practices, drawing on experiences in the mining, acid sulfate soil and civil engineering areas. Risk, cost and planning are factors affecting outcomes. In the roads industry in NSW awareness and practices have grown over the past one to two decades and focus on both environmental and engineering durability effects. It is important to consider ASR from the earliest stages of road project development and the level of attention and actions should be proportionate with significance of its occurrence and project risks. There is now a reasonable body of experience and research in the civil engineering field and utilisation of expertise from mining and ASS areas. Challenges remain to quantify and improve performance, particularly in the longer term, of bulk ASR earthworks and treatment schemes, to improve treatments for cut batters and to develop tests and specifications limits for assessing durability and performance of ASR in higher quality earthworks and pavement support uses.

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