GAS AND TEMPERATURE VARIATIONS WITHIN ACID-PRODUCING CONSTRUCTION FILL[1]

by

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Abstract. Oxygen, carbon dioxide, and temperature were measured in acid-producing highway fills over a 17 month period to provide in situ evaluation of mitigation designs. All parameters measured showed distinct seasonal trends at all depths with carbon dioxide concentration and temperature highest and oxygen concentration lowest in the summer months. Oxygen concentrations generally increased with depth due to a compacted surface soil layer restricting diffusion from the surface and a well oxygenated basal limestone aggregate layer used for the neutralization of acid drainage. Changes in oxygen and carbon dioxide were correlated throughout the study area. The changes in concentrations could not be related to a single controlling mechanism, rather a combination of organic and inorganic sources indicated by preliminary carbon isotopic analysis. Oxygen is being depleted presumably from both biotic respiration and oxidation reactions. Lesser amounts of carbon dioxide are originating from a combination of neutralization reactions and biotic respiration. Correlations of gas composition with temperature were weak due to the influence of additional variables such as barometric pressure, precipitation, and fill porosity. Temperatures remained conducive to the growth of iron oxidizing bacteria throughout most of the year.

Introduction

The oxidation of pyrite and the production of acid drainage (AD) are important factors in determining water quality in mining regions. In addition, other activities such as road construction may also generate AD (Byerly, 1980). The overall oxidation of pyrite is controlled by 2 reactions. In near-neutral water, pyrite is oxidized by both oxygen and water as follows:

$$FeS_2 + 3.5O_2 + H_2O \longleftrightarrow Fe^{2+} + 2SO_4^{2-} + 2H^+ \qquad (1)$$

A second reaction occurs in which ferric iron acts as an electron acceptor:

$$14Fe^{3+} + FeS_2 + 8H_2O \longleftrightarrow 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad (2)$$

The rate-limiting factor to this reaction is the resupply of ferric iron to the reaction (Singer and Stumm 1970). The ferrous to ferric iron reaction is inhibited by slow oxidation kinetics. Strict chemical oxidation of ferrous iron is extremely slow, with half times on the order of 1000 days, and is incapable of producing observed AD (Nordstrom 1982). Iron oxidizing bacteria, (i.e., *Thiobacillus ferrooxidans*) catalyze this reaction and reduce half times to 20 to 1,000 minutes. This reaction is important because only oxygen sufficient for bacterial activity need be present for the oxidation of pyrite to occur.

Reaction (1) will greatly affect the composition of soil atmosphere. The net result of the reaction is the consumption of 3.5 moles of oxygen and production of 2 moles of acid. In addition, carbonate neutralization

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reactions also affect the soil atmosphere. A simplified AD neutralization reaction would be as follows:

$$2H^+ + CaCO_3 \longleftrightarrow Ca^{2+} + H_2O + CO_2 \quad (3)$$

The source of acidity may be from either reaction (1) or (2).

Biotic respiration and decay of organic matter would also affect the composition of soil atmosphere. Other factors such as barometric pressure, precipitation, soil moisture, and diffusion rates may also play important roles in the composition of soil atmosphere.

Encapsulation Design

The Tellico Plains-Robbinsville Scenic Highway (southeastern Tennessee and southwestern North Carolina), south of the Great Smoky Mountains National Park, utilizes a construction design that incorporates all rock material removed from cutslopes into fill for low-lying areas. This eliminates the need to import/export material, thereby decreasing cost. Previous road construction in this area encountered sulfidic rocks of the Ocoee Supergroup, which upon exposure and weathering, produced AD and severely impacted watersheds. Studies of encapsulation methods by Jago and Byerly (1989) and Byerly (1990) resulted in the present highway design aimed at mitigating AD. The present encapsulation design provides nearly in situ disposal as most rock material is buried close to the excavation site, thereby reducing haul distances and maintaining engineering requirements. Prior to construction, representative rock samples taken from outcrops and drill cores are analyzed for net neutralizing potential (NNP) (Sobek et al 1978). NNP, the net amount of potential acidity produced (AP) upon weathering minus the natural neutralization potential (NP) of the rock, indicates the rock's tendency to produce significant AD upon exposure and weathering. These analytical results determine whether excavated rock from a particular section requires special encapsulation.

Pre-construction slopes and benches were prepared by removing soil and vegetation, and contouring slopes to the construction designs (see Figure 1). Geotechnical filter fabric was laid along the base and a 6 inch layer of limestone aggregate (approximately 1-2 in diameter) was then placed on the filter fabric. An underdrain network consisting of perforated, flexible polyvinyl chloride (PVC) pipe (6 in inside diameter) was placed within the limestone aggregate. The drainage network leads to a single underdrain at the lowest point of the fill base. The aggregate layer was then covered with additional filter fabric which permits percolation of water through the limestone aggregate while retaining the overlying fill material.

Pyritic fill material was spread in 2 ft layers across the fill and compacted to approximately 20% porosity. Actual thickness of individual layers varied from approximately 2 to 5 ft due to large boulders that were occasionally placed in the fill. After completion of each layer, pulverized limestone was spread over the fill at a rate of 500 lb/1,000 ft^2. A 3 ft soil blanket was placed upon the outslope of the fill and compacted to 5% porosity to restrict oxygen diffusion and infiltration of precipitation. The fill was constructed to grade and a base course of low-sulfide metasandstone placed on the surface. Paved ditches and concrete culverts were also utilized to intercept and divert surface runoff. The slopes were treated with a fertilizer/grass seed mixture and covered with straw mulch to prevent erosion until the vegetation was established. Also, brush barriers and silt retention fences were used downslope of constructed fills to provide siltation control until the vegetation was established. The highway will be completed with a paved surface which was not in place during the course of this study.

Methods and Materials

Multi-level Gas Monitoring Wells (GMWs) were installed in 2 highway fills to monitor long-term oxygen, carbon dioxide, and temperature variations to determine gas transport mechanisms and to provide an in situ evaluation of the encapsulation

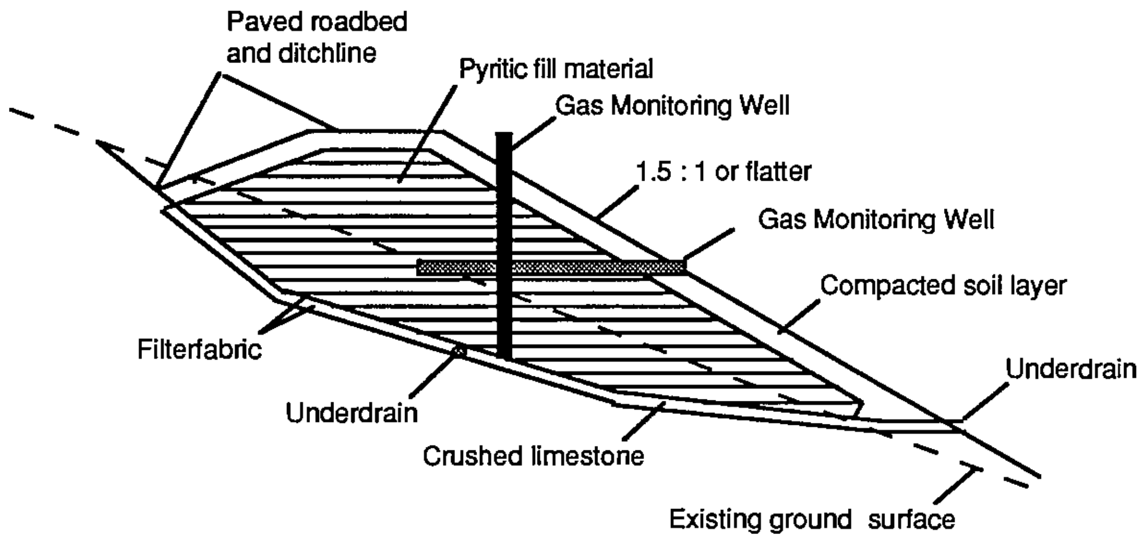

Figure 1. Typical section of embankment design showing gas monitoring wells. Not to scale.

technology. The basic GMW design was adapted from studies by Jaynes et al (1983) and Erickson et al (1985). The GMWs were constructed of 5 ft sections of 4 in inside diameter (ID) schedule-40 PVC casing (see Figure 2). Gas ports were installed in the lower portion of each section by cementing threaded PVC elbows in drilled and tapped 0.5 inch holes. PVC tubing (0.25 in ID) was connected to the elbows and passed through bulkheads to the surface. Air-tight seals around the PVC tubing were obtained with compression seals at the PVC elbows and bulkheads. The bulkheads were used to isolate individual sections and to insure that no atmospheric gas could be transported to the gas ports through ruptures in the GMW wall if damage occurred during installation. Omega type K (24 gauge) thermocouples were installed at each gas port by threading the thermocouple wire through the PVC tubing. The soldered thermocouple tip passed out the gas sampling port and was cemented with PVC epoxy to the exterior of the GMW. In addition, the thermocouple tip was covered with a small piece of PVC to protect it from chemical and physical damage. Each gas port was surrounded by approximately 30-40 pieces of coarse (1-2 in diameter) low-sulfur rock material and filter fabric to provide additional protection and to prevent fine material from clogging the sampling ports. All

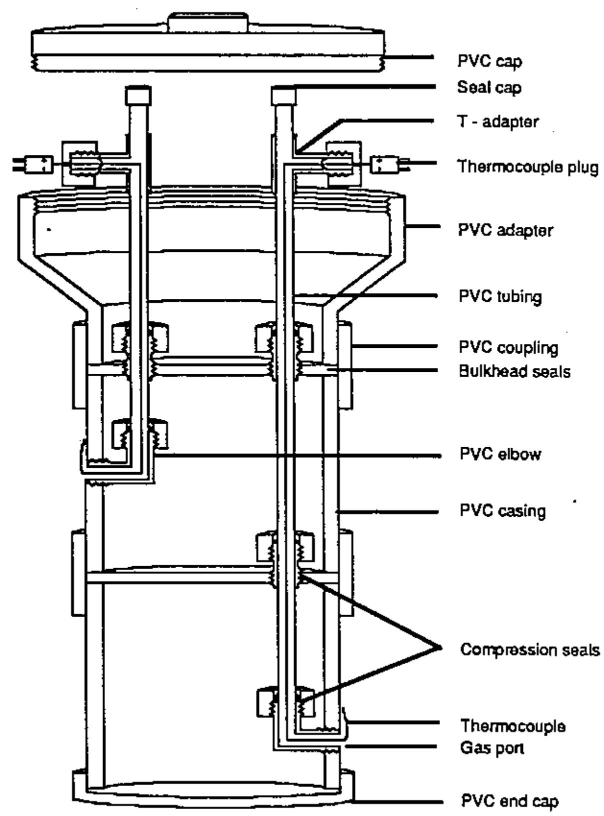

Figure 2. Gas Monitoring Well Cross Section. Not to Scale.

wells were completed by installing screw caps and T-adapters to allow separate access to thermocouples and gas sampling ports, vacuum hose end caps, and thermocouple plug adapters.

Locations of GMWs are based on linear distance (ft) along the survey line of the highway starting from the North Carolina-Tennessee state line. GMWs were installed in 2 separate fills located at stations 383+00 to 387+00 and stations 395+00 to 403+00. Pre-construction slope morphology was significantly different for the 2 fills. From station 383+00 to 387+00, the fill was constructed on and below a steep, rocky slope. The fill from station 395+00 to 403+00 was constructed near the ridgeline and had a gentle slope. Slope morphology affects soil development and runoff with surface flow greater on steep slopes with thin soils. This is important because it may allow for collection and rapid infiltration into the fills along ditchlines. Gentle slopes generally have thicker soils which allow for greater infiltration and percolation through underlying soils rather than through fill material.

Three methods of installation were utilized depending on the method of fill construction and GMW orientation (i.e., vertical or horizontal). All locations in the fills were surveyed prior to installation to insure that the GMWs were placed in the thickest portions of the fill (i.e., at the slope break). At stations 383+00 and 383+50, a single 5 ft section of the GMW was placed on top of the limestone aggregate and a 2 ft layer of fill placed around the base of the well. Following this, successive layers of fill and corresponding pulverized limestone were placed around the GMW and compacted with a backhoe. Approximately 6 in of powdered bentonite was used to provide a seal around each GMW at the midpoint between adjacent gas ports. Additional GMW sections were added as required until the fill was complete. Vertical GMWs at stations 396+00, 397+00 and 401+00 were installed by allowing the construction to proceed until the GMWs' locations were covered by approximately 5-10 ft of fill material. A backhoe was then utilized to excavate a hole down to the limestone aggregate. The GMW was placed in the hole and then backfilled with the excavated soil. Horizontal GMWs (stations 383+25 and 401+12) were installed in shallow trenches. Large rocks were removed and the trench smoothed to prevent damage to the walls of the GMWs. Fully constructed GMWs (total length 25 ft) were placed in the trenches and the end allowed to protrude approximately 1 ft from the fill edge. The GMW design (up to 25 ft length) did not allow for the horizontal GMWs to reach the limestone aggregate. Bentonite seals were positioned at the midpoints between the gas sampling ports and the GMW buried with additional fill material. Actual depths of gas/temperature ports and fill material (soil or pyritic rock) at specific depths are shown in Table 1.

Gas samples were collected and temperature variations were recorded bi-weekly over a 17-month period. Gas sampling consisted of purging 3 times the gas volume of the PVC tubing and estimated annular space surrounding the gas port with a vacuum/pressure pump rated at 20 mm Hg prior to sample collection. The gas samples were then collected in evacuated 1.6 liter Tedlar™ gas sampling bags. Field duplicates were also taken periodically to ensure the integrity of the sampling procedure. Gas samples were analyzed with a Fisher Orsat Gas Analyzer designed to determine carbon dioxide and oxygen concentration. Temperature was measured with an Omega Model HH81 digital thermometer (Type K and T thermocouples) with an operational range of 32°F to 120°F. The digital display was allowed to stabilize (approximately 30 to 60 seconds) prior to recording temperature.

Results

Gas and temperature data, summarized in Table 2, represent samples collected from August 1989 to January 1991. Significant variations in gas and temperature data were observed between stations and with depth. Lowest average temperatures were observed in the near-surface gas ports in the compacted soil bank. Immediately below the soil layer, there was an initial increase in temperature followed by a gradual temperature decrease with depth. Highest

Table 1. GMW Orientations and Sampling Depths.

Station	GMW Orientation	Max. Fill Thickness (ft)	Sampling Depths (ft)	Lithologic Description
383+00	Vertical	18.5	3.5	Soil
			8.5	Fill
			13.5	Fill
			18.5	Fill/Limestone
383+25	Horizontal	N/A	5.0	Soil
			10.0	Fill
			15.0	Fill
			20.0	Fill
			25.0	Fill
383+50	Vertical	19.0	4.0	Soil
			9.0	Fill
			14.0	Fill
			19.0	Fill/Limestone
396+00	Vertical	17.7	2.7	Soil
			7.7	Fill
			12.7	Fill
			17.7	Fill/Limestone
397+00	Vertical	14.0	4.0	Soil
			9.0	Fill
			14.0	Fill/Limestone
401+00	Vertical	10.0	5.0	Soil
			10.0	Fill/Limestone
401+12	Horizontal	N/A	4.0	Soil
			9.0	Fill
			14.0	Fill
			19.0	Fill
			24.0	Fill

oxygen concentrations were observed in the shallow (2-5 ft depth) soil layer in 5 of the 7 GMWs. Mean oxygen concentration in vertical GMWs decreased immediately below the soil layer, but then gradually increased with depth. A similar relationship was also observed in horizontal GMWs (i.e., stations 383+25 and 401+12) with horizontal distance from the soil layer. Oxygen concentration generally was highest in the soil bank. There is a general decrease in oxygen concentration to a minimum at approximately the 10-15 ft gas ports, followed by an increase to the 24 and 25 ft gas ports.

Mean carbon dioxide concentrations in the shallow gas ports however, were lowest in only 3 of the 7 GMWs. Unlike temperature and oxygen, no obvious trends in mean carbon dioxide concentration with depth were observed. Within the separate fills, horizontal GMWs showed consistently lower mean oxygen concentrations and higher mean carbon dioxide concentrations than those for vertical GMWs. This may be the result of greater compaction of fill material around the horizontal GMWs. In addition, the observed carbon dioxide levels in the fill from station 395+00 to 403+00 were approximately twice those observed in the fill from station 383+00 to 387+00. Preliminary carbon isotopic data suggests this may be the result of better vegetative growth along the soil bank from station 395+00 to 403+00 rather than from increased pyrite oxidation and carbonate neutralization.

Table 2. Gas and Temperature Data

Station	Depth (ft)	Carbon Dioxide (percent)			Oxygen (percent)			Temperature (C)		
		mean	max.	min.	mean	max.	min.	mean	max.	min.
383+00	3.5	3.7	9.6	0.3	14.3	18.0	0.7	13.6	25.1	4.3
	8.5	2.9	7.1	0.8	11.2	18.3	0.9	15.5	28.9	7.7
	13.5	3.1	7.5	0.8	11.8	18.5	0.3	14.4	23.1	8.1
	18.5	3.7	8.4	0.9	13.4	19.6	1.1	12.8	19.2	8.0
383+25	5.0	3.5	6.9	1.2	8.9	14.6	2.3	12.2	19.6	2.3
	10.0	4.3	7.8	1.6	2.9	11.2	0.3	13.6	21.1	7.2
	15.0	4.2	7.2	1.5	3.4	9.8	0.3	14.7	21.0	8.8
	20.0	4.3	7.6	1.6	3.7	11.7	0.1	15.0	20.7	9.1
	25.0	4.1	8.0	1.1	2.7	10.2	0.1	14.6	20.5	8.4
383+50	4.0	3.7	7.4	1.3	5.3	16.0	1.1	13.2	20.7	4.4
	9.0	3.8	7.0	1.2	7.8	17.7	0.0	16.1	24.1	9.5
	14.0	3.4	7.1	1.0	10.3	18.4	0.8	15.8	21.5	9.3
	19.0	4.4	7.4	2.2	11.0	17.2	1.0	13.7	18.9	9.0
396+00	2.7	5.6	12.3	2.6	10.6	18.6	0.8	10.9	20.2	1.2
	7.7	8.8	14.9	3.0	6.5	15.1	0.5	12.8	21.8	5.5
	12.7	8.0	16.6	1.5	9.2	19.4	0.6	13.2	20.8	7.5
	17.7	8.4	17.0	1.0	9.1	19.8	0.4	12.9	18.9	8.1
397+00	4.0	5.7	11.0	1.6	10.1	17.8	2.0	12.0	21.9	2.7
	9.0	8.7	13.8	4.2	5.4	14.0	0.2	13.4	22.1	6.5
	14.0	4.8	11.3	0.6	12.4	19.6	0.8	13.2	20.7	8.2
401+00	5.0	9.3	19.0	4.3	7.8	15.3	0.5	12.2	21.8	3.9
	10.0	9.1	18.2	3.8	7.7	15.7	0.8	12.7	22.3	6.1
401+12	4.0	5.2	10.4	2.5	13.5	17.4	5.1	11.5	20.9	1.5
	9.0	10.7	19.6	5.9	7.2	17.6	1.2	12.4	22.0	4.7
	14.0	12.9	19.6	6.8	5.5	12.2	0.9	12.8	21.9	6.6
	19.0	11.7	17.2	6.5	6.4	12.9	0.5	12.9	21.3	7.7
	24.0	9.1	14.0	3.9	8.4	15.6	1.0	12.9	21.3	7.2

Oxygen, carbon dioxide, and temperature trends exhibited large seasonal variations. Oxygen concentrations were greatest during periods of low temperature (winter), while carbon dioxide concentrations were greatest during periods of higher temperature (summer) in all GMWs. Figures 3 and 4 illustrate the seasonal variation as well as differences in gas compositions for the 2 fills.

Table 3 summarizes the results of regression analyses performed on raw data. Correlation between carbon dioxide and oxygen is strong (i.e., $|r|>0.6$) at 24 of 27 sampling depths. Correlation between carbon dioxide and temperature, and oxygen and temperature shows a weaker correlation, with $|r|>0.6$ at only 13 and 7 of 27 sampling depths respectively.

Following periods of heavy precipitation, the basal gas port (19 ft) of station 383+50 GMW consistently yielded large quantities of leachate. This leachate typically had low pH (2.0-2.3) and high conductivity (2,500-5,000 umhos). In addition, leachate from underdrains at both fills was collected. Leachate from the station 383+00 fill had near-neutral pH (6.0-7.0), high conductivity (800-1,000 umhos) and high dissolved sulfate (200 mg/L).

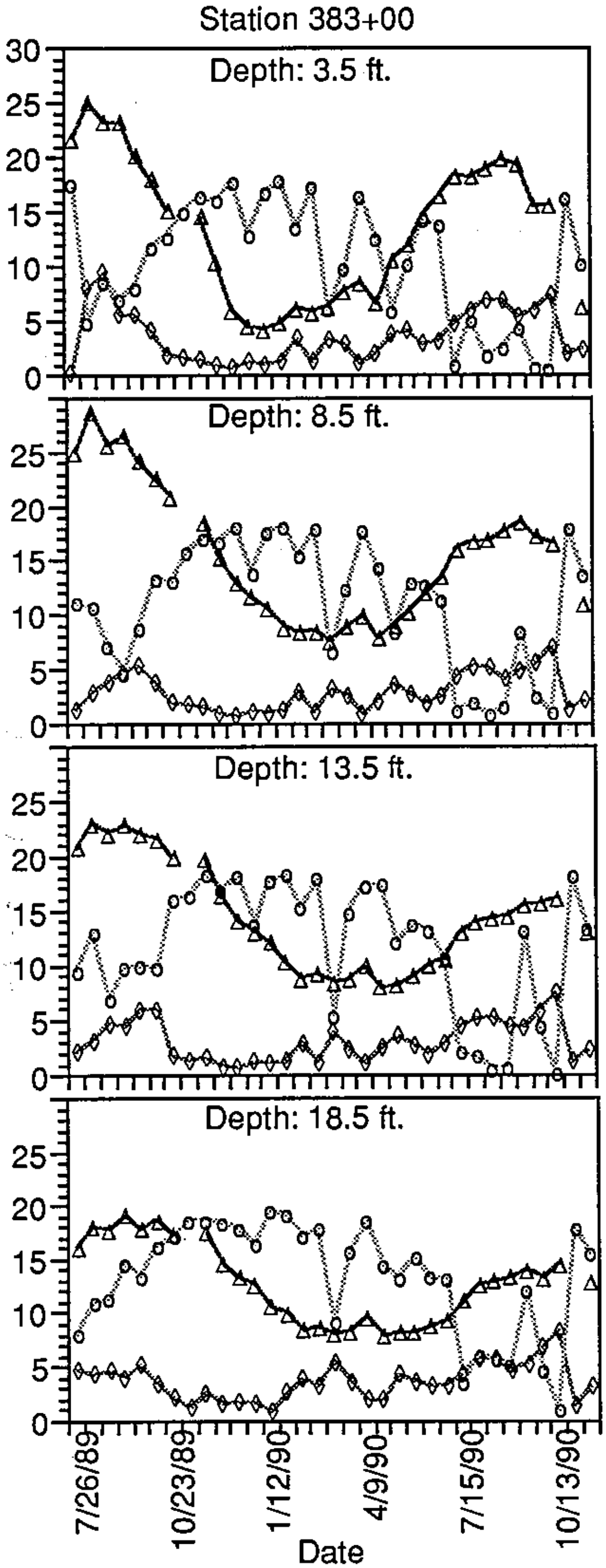

Figure 3. Temperature (C) (Δ) and carbon dioxide (◊) and oxygen (o) concentrations (%) versus time for specified depths in station 383+00 GMW. Note: gaps indicate missing data.

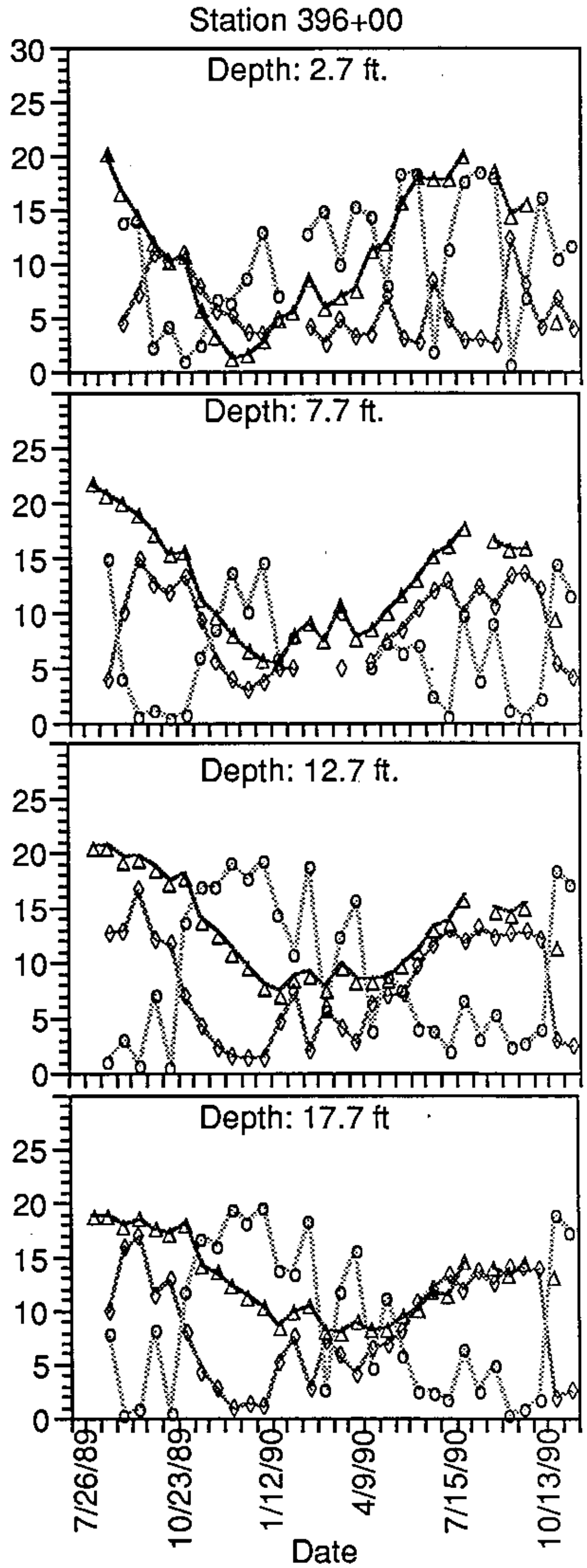

Figure 4. Temperature (C) (Δ) and carbon dioxide (◊) and oxygen (o) concentrations (%) versus time for specified depths in station 396+00 GMW. Note: gaps indicate missing data.

Table 3. Regression Summary.

Station	Depth (ft)	CO2-O2	CO2-T	O2-T
383+00	3.5	-0.83	0.70	-0.51
	8.5	-0.88	0.39	-0.37
	13.5	-0.84	0.35	-0.20
	18.5	-0.86	0.17	-0.10
383+25	5.0	-0.49	0.51	-0.30
	10.0	-0.62	0.64	-0.17
	15.0	-0.78	0.46	-0.32
	20.0	-0.79	0.33	-0.10
	25.0	-0.67	0.24	-0.10
383+50	4.0	-0.40	0.66	-0.63
	9.0	-0.88	0.17	-0.10
	14.0	-0.82	0.04	-0.10
	19.0	-0.44	0.09	-0.33
396+00	2.7	-0.87	0.26	-0.10
	7.7	-0.85	0.68	-0.45
	12.7	-0.92	0.59	-0.40
	17.7	-0.93	0.39	-0.20
397+00	4.0	-0.90	0.91	-0.84
	9.0	-0.90	0.81	-0.78
	14.0	-0.95	0.52	-0.45
401+00	5.0	-0.74	0.81	-0.44
	10.0	-0.83	0.75	-0.45
401+12	4.0	-0.96	0.66	-0.57
	9.0	-0.83	0.75	-0.64
	14.0	-0.87	0.91	-0.78
	19.0	-0.91	0.93	-0.81
	24.0	-0.90	0.82	-0.77

Discussion

Gas and temperature data indicate that the fills remained well oxygenated throughout the year, despite measures to restrict gas diffusion through the surface. The compacted soil layer did restrict gas diffusion from the surface, resulting in relatively low oxygen concentrations immediately below the soil-pyritic rock interface. Increasing oxygen concentrations with depth show that the main source of oxygen is through the limestone aggregate and pipe drainage network.

Strong negative correlations between oxygen and carbon dioxide concentrations were expected, but the values did not indicate a single mechanism for the variations. If biotic respiration was strictly responsible for changes in fill atmosphere, the increase in carbon dioxide should equal the oxygen decrease. Sulfide oxidation/AD neutralization reactions could also provide a similar result with oxygen being consumed in the oxidation process and carbon dioxide produced from carbonate neutralization reactions, provided adequate water is present to transport weathering products through the fill. Preliminary carbon isotope data supports a combination of both organic and inorganic sources of carbon dioxide from biotic respiration and oxidation/neutralization reactions.

The positive correlation between carbon dioxide and temperature is believed due to an increase in biotic activity and an increase in inorganic and organic oxidation reaction rates at higher temperatures. Conversely, negative correlations between oxygen and temperature are the result of decreases in biotic respiration and oxidation/neutralization reaction rates. In addition, the temperature trends at all depths indicate that soil temperatures are dependent on seasonal temperature variations and that heat liberated during sulfide oxidation is relatively insignificant. Temperatures within the fill remain conducive to iron oxidizing bacteria growth throughout most of the year (Buchanan and Gibbons 1974).

Based on low quantities of leachate from fill underdrains, the compacted soil layer appears to effectively restrict infiltration of precipitation. Although infiltration of precipitation is reduced by the compacted soil layer, the presence of significant quantities of leachate in the basal gas port of station 383+50 GMW following heavy precipitation indicates that isolated areas within the limestone aggregate do not drain properly. The steep topography may also influence the volume of water flowing through the fill. This may be the result of depressions in the pre-construction topography or crushed or plugged drainage pipe. The poor water quality indicates a basal weathering zone corresponding to areas of high observed oxygen concentrations. This conclusion is similar to those of Erickson et al (1985) and Good et al (1970). Their studies indicate a thin, near-surface well oxygenated reaction zone. While not at the surface, it is evident that the basal zones have the highest oxygen concentration and thus, greatest potential for the production of AD. These areas represent the greatest concern for potential surface water degradation.

Conclusions

Gas composition and temperature variations have provided important information for the in situ evaluation of highway construction designed to mitigate AD. Results indicate that the fills are well oxygenated with oxygen being supplied through the basal aggregate layer, circumventing the compacted soil layer. The soil layer functions to prevent infiltration of precipitation into the fills. This restricts the transport of weathering products, thereby preventing the development of AD. Observed oxygen concentrations in the deepest portions of the fill may result in a basal zone of sulfide oxidation. During periods of high precipitation, water flowing through the limestone aggregate leaches some of these weathering products. Although the limestone aggregate is presently effective in neutralizing the AD, surface coatings may eventually develop on the limestone and decrease the neutralization ability. It may be beneficial to increase the thickness of the limestone aggregate, particularly in areas of steep, uneven slopes. This would provide addition neutralization potential for AD. In addition, the thicker aggregate layer would facilitate drainage and prevent leaching of weathered material in zones of lower flow within the limestone aggregate.

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