ABSTRACT

LANG, JOHNSIE RAY. Experimental Investigation of Hydraulic Properties and Sulfate Release of Construction and Demolition (C&D) Waste Fines with the Addition of Lime. (Under the direction of Morton A. Barlaz and Mohammed Gabr).

Construction and demolition (C&D) waste results from construction, renovation, or demolition activities. C&D fines are the soil like materials separated from C&D waste during screening at a recycling facility. Historically, C&D fines have been used as an alternative daily cover at MSW landfills. While the use of C&D fines works well from an operations perspective, the presence of gypsum wallboard ($CaSO_4$) in the C&D fines is problematic. When C&D fines that contain gypsum are buried with waste in a landfill under anaerobic conditions, the sulfate contained in the gypsum is converted to hydrogen sulfide (H_2S). H_2S poses a rotten egg odor, is a threat to human health, and corrodes landfill gas control equipment. In landfills where H_2S production is a problem, operators are forced to install expensive H_2S removal technologies. Preliminary work at laboratory-scale has shown that the addition of lime to C&D fines can raise the pH and inhibit the biological reaction by which gypsum is converted to H_2S. While lime addition shows promise, there is concern about the potential for sulfate to leach from a cover layer containing a C&D fines/lime mixture to an underlying layer of waste in which biological processes are not pH inhibited. The first objective of this work was to assess sulfate release from C&D fines/lime mixtures to determine the effect of lime on sulfate leaching. The work showed significant sulfate leaching as well as increases in the hydraulic conductivity of mixtures of lime and C&D fines with increasing infiltration. Additional work was conducted to evaluate calcium sulfate dissolution and fines settling as explanations for the measured changes in conductivity. The results suggest that both explanations contributed to the measured increases in conductivity.

In addition to the work on sulfate leaching, experiments were conducted to determine whether the moisture in landfill gas could stimulate H_2S production from C&D fines. Results indicate that H_2S production can be initiated from moist landfill gas and that lime has no significant impact on the initiation of H_2S production.

Experimental Investigation of Hydraulic Properties and Sulfate Release of Construction and Demolition (C&D) Waste Fines with the Addition of Lime

by
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Detlef Knappe

DEDICATION

I would like to dedicate this to my son Perry, his father Chris, and my loving parents.

BIOGRAPHY

Johnsie Ray Lang was born and raised in North Carolina (NC). She graduated from high school in Wilmington, NC before attending two years of college at East Carolina University. She later received her Associate of Science degree from Wake Technical Community College. She received a Bachelor's of Science degree from North Carolina State University (NCSU) in Environmental Engineering in 2007. After receiving her bachelor's degree, she worked for two years in consulting engineering. She returned to NCSU in 2010 to pursue her master's degree in environmental engineering.

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CHAPTER 1 - INTRODUCTION

Construction and demolition (C&D) waste is the debris generated during the construction, renovation, or demolition of any type of structure (EPA, 2011). While the disposal of C&D waste in municipal solid waste (MSW) (i.e., Subtitle D) landfills is prohibited in some states, such disposal is standard practice in other states. The Environmental Protection Agency (EPA) estimates that 170 million tons of C&D materials were generated in 2003 from the construction of residential and nonresidential buildings (EPA, 2003). There is heightened interest in the recovery of useful materials from C&D waste and it can be processed at recycling facilities to remove useful materials and divert the fraction that is disposed to landfill. One step in the recycling process is screening to remove soil like particles from the waste stream. C&D fines, the materials separated from C&D waste during screening at a processing facility, have been used as an alternative daily cover at MSW landfills. The use of C&D fines as an alternative daily cover has lead to problems for landfill operators.

An alternative daily cover is any material used instead of soil to cover the working face of a landfill. Landfill owners look for waste materials that can be used instead of soils to reduce operating costs and the landfill storage volume consumed by non-waste materials. The use of C&D fines as alternate daily cover works well from an operational perspective. However, the presence of wallboard in the C&D fines is problematic. Wallboard is largely composed of calcium sulfate, otherwise known as gypsum. When C&D fines are buried with waste in a landfill under anaerobic conditions, the sulfate (SO_4) contained in the gypsum is converted to hydrogen sulfide (H_2S) (Fairweather and Barlaz, 1998). The H_2S is generated by microorganisms that gain energy from the reduction of the sulfate. The mean sulfate concentration in C&D fines from seven C&D processing facilities has been previously documented as 4.3% with a range of 0.17 – 12% (Anderson, 2010).

The formation of hydrogen sulfide is problematic for several reasons. First, it poses a threat to human health because it causes unconsciousness and death when gaseous concentrations exceed 50 parts per million (ppm) (Kilburn and Warshaw, 1995). H_2S is also toxic to the organisms that degrade waste in a landfill. A previous study determined that a dissolved

sulfide concentration of 400 mg S/L severely retarded methane production in a laboratory setting (Shin et. al., 1995). Assuming H_2S is an ideal gas, this concentration of dissolved sulfide corresponds to 556 ppmv of H_2S in the gas phase. Second, H_2S generates a rotten egg odor. Finally, H_2S is corrosive to landfill gas combustion equipment. Depending on the concentration of H_2S in landfill gas, operators may have to install expensive H_2S removal technologies. It can cost anywhere from $0.45 to $0.88 per kilogram (kg) of sulfur removed ($0.20 - $0.40 per lb sulfur) to operate systems that remove large amounts of sulfur (Graubard et. al., 2007).

The overall focus of this research was to identify an acceptable management strategy for controlling H_2S production from C&D fines used as an alternative daily cover in landfills. Preliminary work at laboratory-scale has shown that the addition of lime to a C&D fines mixture (40 pounds (lbs) of lime per ton of C&D fines) can raise the pH and inhibit the biological reaction by which calcium sulfate is converted to H_2S. While lime addition shows promise, there is concern about the potential for sulfate to be released by leaching from a cover layer containing a C&D fines/lime mixture to an underlying layer of waste in which the biological process is not pH inhibited. The first objective of this study was to assess sulfate release from C&D fines/lime mixtures to determine the effect of lime on sulfate leaching.

In previous work, Jang and Townsend (2001) documented that sulfate leaches from C&D fines at concentrations from 890 to 1600 mg /L. In their experiment, 100 mL/min of a sulfuric and nitric acid solution was added once a day for 10 min to columns containing 30 cm layers of C&D fines. The release of sulfate due to acid leaching is not surprising and in fact, sulfate leaching would also be expected from simple water leaching given the solubility of calcium sulfate. The solubility of calcium sulfate hemihydrate ($CaSO_4 - 0.5H_2O$) and gypsum ($CaSO_4 – 2H_2O$) is 2891mg/L and 2592mg/L, respectively (Dean, 1999). This translates to sulfate concentrations of 1446 mg/L and 1296 mg/L, respectively.

The experimentally determined sulfate leaching rates can be correlated to infiltration at actual landfills by determining the porosity of the C&D fines. Infiltration into landfills can be

translated to pore volumes based on the porosity of the waste. Thus, a second objective of this work was to estimate the porosity of C&D fines/lime mixtures.

Initial work to evaluate sulfate release from C&D fines/lime layers resulted in increases in the hydraulic conductivity of the mixtures as the number of pore volumes of water introduced into the system increased. Two theories were evaluated to explain the changes in conductivity. The first theory is that particle mobility within the C&D fines resulted in changes in conductivity because fine particles, with diameters less than 0.075 mm may mobilize and cause the formation of preferential flow channels. The second theory is that the dissolution of calcium sulfate crystals was responsible for increases in conductivity.

While infiltration through a lime/C&D fines layer can be limited by landfill management practices, contact between landfill gas, which is saturated with moisture, and the lime/C&D fines layer is more difficult to control. Thus, the final objective of this study was to evaluate whether the moisture in landfill gas could stimulate H_2S production from C&D fines and the effect of lime on this process.

In summary the objectives of this study are as follows:

i. To assess sulfate release from C&D fines/lime mixtures and to determine the effect of lime on sulfate leaching.
ii. To estimate the porosity of C&D fines/lime mixtures.
iii. To evaluate changes in hydraulic conductivity of the mixtures as the number of pore volumes of water introduced into the system increased and evaluate whether 100% sulfate could be released.
iv. To evaluate whether the moisture in landfill gas could stimulate H_2S production from C&D fines that have been mixed with lime.

CHAPTER 2 - MATERIALS AND METHODS

Experimental Design

Several distinct but related experiments were conducted and each is described sequentially in this section. These included

- validation of an analytical procedure to determine the sulfate concentration in the fines
- column testing to quantify the rate and extent of sulfate release,
- Measurement of the hydraulic conductivity of lime/fines mixtures, and changes due to physical and chemical processes, and
- tracer testing to estimate the porosity of the test samples.

A separate set of columns was also operated to discern the potential of hydrogen sulfide production as a result of moist landfill gas.

To determine the concentration of sulfate in samples of C&D fines, a sulfate extraction method was developed. Testing was conducted on samples of pure gypsum, given its known sulfate concentration, to validate the extraction method. This method was then used to determine the concentration of sulfate in C&D/lime mixtures for several parts of this experiment.

The objective for the first set of columns was to quantify the amount of sulfate released from C&D fines with and without the addition of lime. The effect of lime on sulfate leaching from C&D fines was examined using two sets of columns. In the first set of columns, three treatments were examined in triplicate; no lime, 10 lb of lime per ton of C&D fines, and 40 lb of lime per ton of C&D fines. This set of columns was operated for approximately 30 days or until approximately 35% of the initial sulfate added to each column was leached. During column operation, the flow rate and the concentrations of sulfate, sodium, potassium, and calcium were measured.

Based on results of the first set of columns, a second set of columns was initiated to determine the cause of changes in the hydraulic conductivity that was measured during operation of the initial columns, and to verify that it was possible to leach 100% of the sulfate. As described above, two hypotheses were explored to explain the increase in hydraulic conductivity: fines settlement and sulfate dissolution. The second set of columns were operated for approximately 52 days and 245 days, until approximately 65% or 100% of the initial sulfate added to the column initial was leached, respectively. For this set columns, only the no lime and the 10 lb of lime per ton of C&D fines treatments were examined.

Bromide tracer tests were conducted at several points during the operation of the first and second sets of columns. Using data obtained from the tracer tests, the porosity of the columns was calculated.

The porosity of the C&D fines was also determined by completely saturating quadruplicate columns with deionized (DI) water. Columns were filled from the bottom, allowing the gas filling the voids to escape out of the top of the sample. Prior to adding water, the columns were sparged with carbon dioxide (CO_2). Unlike air, any trapped CO_2 should dissolve in the DI water without affecting the volume. This insures that the volume of water added represents complete saturation. The porosity measured in this manner represents the volume of voids in the column plus the volume of water absorbed by the sample.

As the total mass of sulfate leached reached 65% and 100% of the amount added initially, the columns were destructively sampled to measure the pore size distribution in the columns as a function of depth. The grain size distribution was conducted on samples from the top, middle and bottom of each column to provide information about the mobilization of fine particles in the column.

A third set of columns was constructed to evaluate whether the moisture in landfill gas could stimulate H_2S production from C&D fines. For this set of columns three treatments were tested, gas addition, gas addition + lime, and a control. The control and gas addition + lime treatments consisted of a layer of C&D fines with lime at 40lbs/ton over a layer of MSW.

The gas addition treatment consisted of a layer of C&D fines only over an MSW layer. The MSW layer was a mixture of fresh and actively degrading waste. Saturated gas (50% methane (CH_4)/50% CO_2) was sparged through the gas addition and gas addition + lime treatments while no gas was sparged through the controls. The 50% CH_4/50% CO_2 gas was selected to mimic landfill gas. After 90 days, leachate recirculation was initiated in the control treatment to demonstrate that water flux would stimulate H_2S production. The objective of the gas addition + lime treatment was to evaluate whether lime addition would be sufficient to inhibit H_2S production when saturated gas was passed through the C&D fines/lime layer. The gas addition treatment served as a positive control to demonstrate that H_2S could be produced from C&D fines in the absence of lime when the only source of moisture was saturated landfill gas.

Column Design and filling

The columns used for the experiments were constructed of 3" inside diameter acrylic pipe with polyvinyl chloride (PVC) pipe couplings securing 3" PVC pipe caps to both ends (Figure 1). The acrylic pipe was cut into 12" lengths for each column. The pipe couplings allowed the end caps to be removed for column filling.

Figure 1. Experimental Column

(A) - Top Cap (B) – Column (C) – Bottom Cap

For the first and second sets of columns experiments, a constant head of DI water was supplied by gravity feed from a container placed above the column. Figure 2 illustrates the water supply and sample collection system. A constant water level was maintained in the constant head reservoir (B in Figure 2) by pumping water into the top of this container and allowing excess water to drain back to the water supply container from a port in the side of the constant head reservoir. The top end cap of the column was filled with DI water. Backpressure was also supplied to the column by maintaining a tailwater container (D) connected to the bottom of the column. A constant water level was maintained in the outlet container by a port that allowed water to drain to the waste container (E). The flow rate in the column was adjusted by raising or lowering the level of the outlet container.

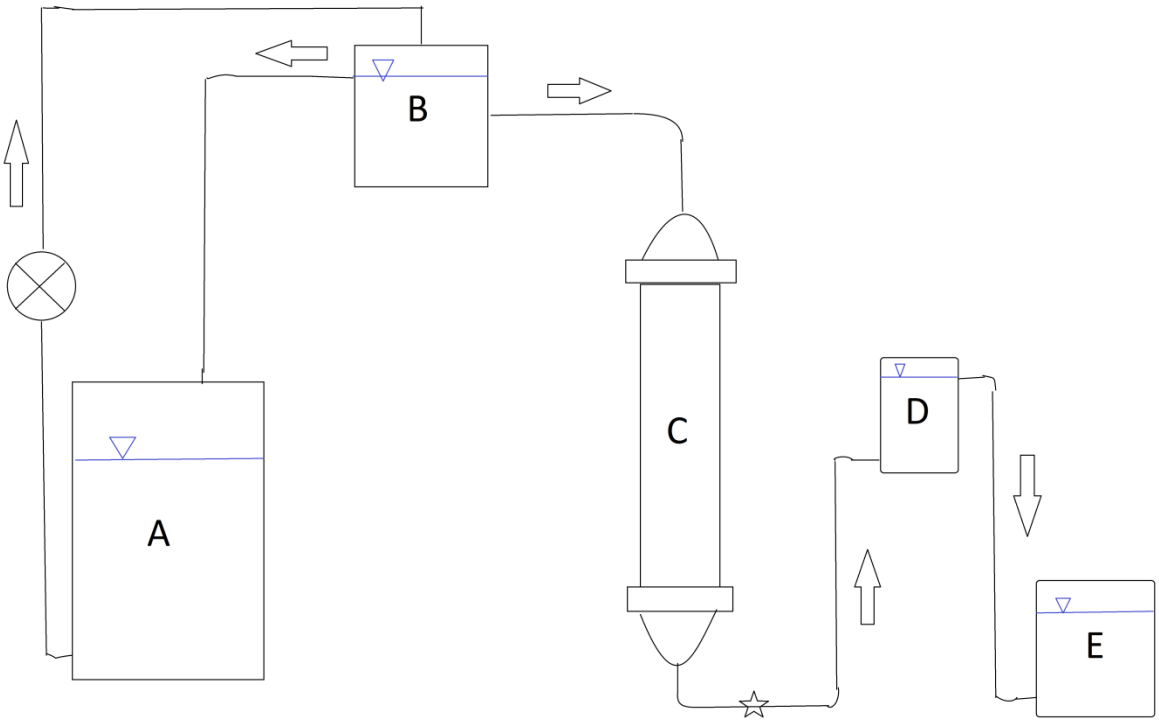

Figure 2. Column Water Supply and Sample Collection System for First and Second Sets of Columns

(A) – Headwater Supply (B) – Constant Head Reservoir (C) – Column (D) – Tailwater Container (E) – Waste Water

A sample of C&D fines received from the Brown Deer Recycling Facility in Wisconsin was used in all experiments. The fines were screened to remove materials greater than about 0.25" that would interfere with column flow and sulfate leaching. Fines were dried at 105°C after screening. Approximately 40% of the C&D fines material was removed during screening.

Prior to filling, a scotch brite pad was placed on the bottom of the column to serve as a barrier to large particles that might clog the outlet port. The C&D fines were added to the bottom cap and the column in approximately 3" layers. Each layer was compacted 40 times with a 2" plastic mallet and 20 times with a 0.5" metal rod. The resulting density was

approximately 1,600 lb per yd^3 (950 kg per m^3). The total volume of each column was determined using the weight of water required to fill the column.

For the third set of columns experiments, the samples were sparged from the bottom with simulated landfill gas (50% CH_4/50% CO_2) that was bubbled through warm water (37°C) to saturate it with moisture. The target flow rate of gas through the sparged columns was 1.17 L/day. This flow rate was calculated by adopting a target gas flux of 100g CH_4/day-m^2 in consideration of the column diameter. This target flow rate was based on reported methane emission rates from landfills which of course vary from relatively low levels in well decomposed refuse to much higher levels in fresh refuse (Chanton et. al., 2011). This target flow rate was selected on the basis of gas flow in the landfill prior to any reduction in flux associated with gas collection and methane oxidation. This value is not comparable to methane emissions at a landfill with gas collection. The actual methane flux within a landfill will vary significantly based on the distance from gas wells. The waste adjacent to a gas well would be expected to experience higher flow rates than waste located away from the wells.

Analytical Methods

The sulfate and bromide concentrations in liquid samples were analyzed using a Dionex ICS-2500 ion chromatograph (IC) with an IonPac AC19 column and an EG40 Eluent Generator. The mobile phase was 20 millimolar (mM) potassium hydroxide. All samples analyzed using the IC were collected using a plastic syringe and filtered using a 0.45 micrometer (µm) syringe filter.

The calcium, potassium, and sodium concentration in liquid samples was analyzed using an Inductively Coupled Plasma - Atomic Emission Spectrophotometer (ICP-AES) Perkin Elmer Model 2000DV (Perkin Elmer Inc., Shelton, CT 06484, USA). All samples analyzed using the IC were collected using a plastic syringe and filtered using a 0.45 micrometer (µm) syringe filter.

The H_2S concentration in gas samples was measured using a Shimadzu GC-2014 with a Restek Rt-XLSulfur packed column and a flame photometric detector. The GC uses helium as a carrier gas with a flow rate of 25 mL/min and a column and injector temperature of 100°C. The flame photometric detector was operated at 250°C.

Measurement of Sulfate in C&D Fines

The sulfate concentration of the C&D fines was determined by performing a "pH 1 extraction" that dissolves calcium sulfate. The pH 1 extraction method was performed by adding 10 to 15 g of sample to a 2 L extraction container. The extraction container was then filled with 2 L of DI water. The pH of the liquid in the container was then lowered to pH 1 using approximately 50 mL of 10 N hydrochloric acid (HCl). The container was placed in a shaker at 100 revolutions per minute (rpm). The total sulfate concentration of each sample was determined by multiplying the dissolved sulfate content by the volume of liquid in each container. As presented later, the optimal time for extraction was shown to be five days.

The procedure used here deviates from that described by Musson et al. (2008) in which 100 g samples were added to 2 L of DI water. Samples were then rotated at 30 rpm for 30 min intervals. After each interval, 1 L samples were removed, settled for 30 min, and filtered, after which the conductivity was measured, and the sulfate concentration was determined using an IC. If the conductivity was greater than 500 µs/cm, the filtrate was returned to the extraction vessel along with 1 L of DI water. This process was repeated until the measured conductivity of the sample was less than 500 µs/cm. After the experiment was terminated, the percent gypsum in each sample was calculated using a summation equation. This method requires more labor and multiple sulfate analyses because of the multiple extraction steps.

A pH of 1 was selected for this method because it is below the equilibrium constant governing the addition of a proton to the sulfate ion creating bisulfate, with a pK of 2 at 25°C

(Snoeyink and Jenkins, 1980). A pH below the equilibrium constant indicates that any dissolved sulfate ions will be protonated, driving the equilibrium of calcium sulfate and sulfate ions towards dissolution.

The pH 1 extraction method developed in this paper was verified using a sample of pure wallboard with the face and back paper removed. The wallboard samples were screened by a No. 4 sieve prior to use. Samples were collected daily and the total sulfate recovery was calculated after each sampling . The optimal time for the extraction was determined to be the time point when 100% recovery was achieved.

Initial C&D fines samples were tested eight times using the pH 1 extraction method and a 15g sample mass. Samples were tested before and after drying to verify that the drying method did not affect sulfate concentration by converting the calcium sulfate from gypsum to the hemihydrate. Five extractions were performed on the sample before drying and three were performed after drying at 105°C. The wet weight of the fines was converted to a dry weight using the moisture content of C&D fines.

Column Testing

Hydraulic Conductivity

The applied hydraulic head and flow rate of the first and second sets of columns were monitored over time and the hydraulic conductivity was calculated using equation 1. The water flow rate through the column was calculated from the volume of leachate collected in the waste container over a known increment of time. The sample height represents the height of the C&D fines/lime mixture in the column and the water pressure is the hydraulic head (in cm), which is the difference in water level between reservoirs B and D in Figure 2. The

hydraulic conductivity was used to determine if changes in the physical properties of the fines were occurring during operation of the columns.

Equation 1: Hydraulic Conductivity of Leaching Columns during Operation

$$\text{Hydraulic Conductivity} = \frac{\text{Flow Rate} * \text{Sample Height}}{\text{Head Difference} * \text{Cross Sectional Area of Column}}$$

Sulfate Leaching

The sulfate concentration at the column outlet for the first and second sets of columns was determined by collecting samples from a port located between the column and the outlet container (Figure 2). While sampling, a valve was closed to the outlet container to allow sampling from the column only. The amount of sulfate leached for each time period was determined by multiplying the sulfate concentration by the volume collected in the waste container. The cumulative mass of leached sulfate was divided by the total mass of sulfate added to the column to determine the percent leached at each time point. The sulfate concentration and the cumulative leaching calculations were used to compare the effect of lime on the amount of sulfate leached.

Bromide Tracer Tests to Determine Porosity

Bromide tracer tests were conducted on the first and second sets of columns at several times during operation to estimate the porosity of the C&D fines/lime layers. The tracer tests were performed by replacing the DI water in the water supply and constant head reservoir containers with a 100 mg/L solution of sodium bromide. After the replacement of the stock solution, the concentration of bromide was monitored at the outlet port approximately hourly

for 18 hr. The time to 50% bromide appearance was used in equation 2 to calculate the seepage velocity in the columns during the tracer tests. The dispersion coefficient was assumed to be 10% of the sample length. Flow rate data were used in equation 3 to determine the Darcy velocity in the column during the tracer tests. The calculated seepage velocity and Darcy's velocity were used in equation 4 to determine the porosity of the columns during operation.

Equation 2: Seepage Velocity

$C = (Co/2) * \text{erfc}((L-v*t)/(2\sqrt{D*t}))$

C = Concentration at time t

Co = Concentration of stock solution

L = Height of sample

t = Time to ~50% bromide appearance

D = Dispersion Coefficient

Equation 3: Darcy's Velocity

$$V_D = \frac{\text{Flow Rate}}{\text{Column Cross Sectional Area}}$$

Equation 4: Porosity of Leaching Columns during Operation

$$\text{Porosity} = \frac{\text{Darcy's Velocity}}{\text{Seepage Velocity}}$$

Hydrogen Sulfide Production

For the third set of columns, the effluent gas was collected in four layer foil gas bags (SKC, 84, PA) and the H_2S concentration was measured weekly. The average weekly flow rate for each column was calculated from the volume of gas in each bag divided by the time between

sampling. Samples analyzed for H_2S concentration were withdrawn from the headspace of the column to eliminate any effect of H_2S gas loss in the bags.

Column Sampling

The sulfate concentrations in the material remaining in the columns from the first set were analyzed after drying and weighing the material. The sulfate concentration was determined by running quadruplicate pH 1 extractions. As columns in the second set of columns were terminated, the columns were cut in half to create three sections, including the bottom cap. The material from each section was dried and weighed separately. Standard method ASTM D 422 was used to determine the particle size distribution of the material in each section of a column.

At the termination of the third set of columns, the moisture content in the C&D fines layer was measured as a function of depth. The moisture contents were measured to verify that moisture had been transferred to the C&D fines/lime layer. Samples were collected from each column at various depths and dried at 105°C.

CHAPTER 3 – RESULTS

Sulfate Concentration

The average percent of sulfate recovered from duplicate gypsum wallboard samples is presented in Figure 3 as a function of time from the beginning of the pH 1 extraction. The recovery represents the percent of total sulfate added that was dissolved at each time point. These results showed that the percentage of sulfate recovery was above 90% after three days. From day five to fourteen, the sulfate concentration stabilized with approximately 100% recovery. Variations in these results after five days demonstrate a small amount of analytical error in the sulfate analysis method. Based on these results, five days was selected as the extraction time for the pH 1 extraction method.

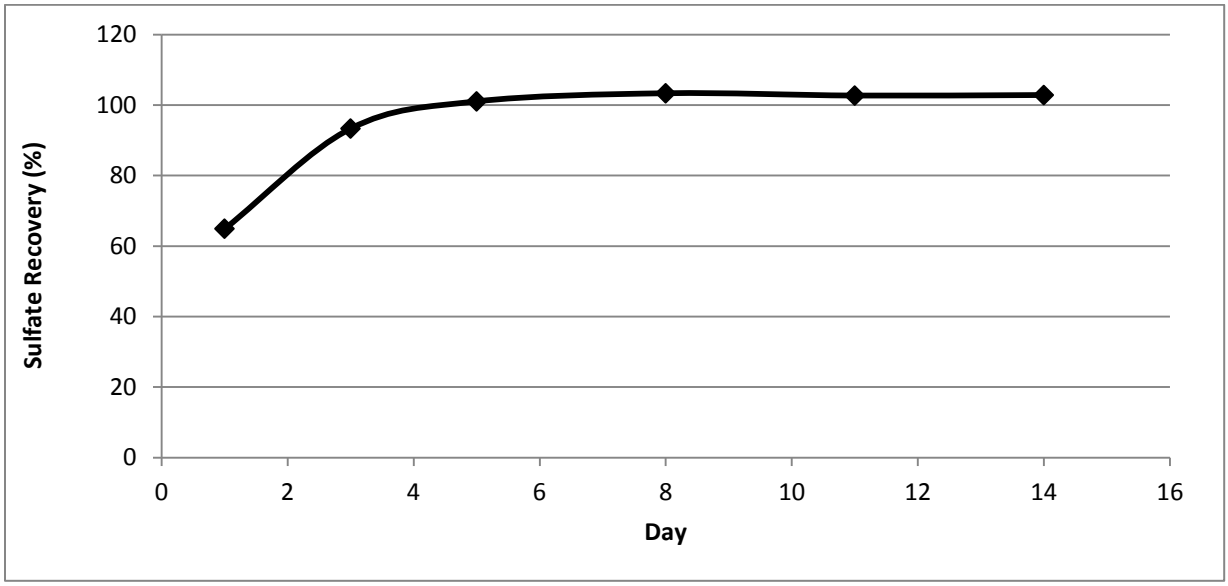

Figure 3. Sulfate Recovery in Samples Prepared for pH 1 Extraction Method Verification

The initial sulfate concentrations in eight replicates of the C&D fines used for all experiments, as measured using the pH 1 extraction method are presented in Figure 4. The results are presented per dry kilogram of screened C&D fines. The average sulfate

concentration in the screened fines was 188.0 g SO_4/kg dry screened fines (standard deviation [sd] = 26.9) or 18.8% SO_4. This value was used as the sulfate concentration of the C&D fines used in this research. Assuming the material removed during the screening process contains no sulfate, the sulfate concentration of the original material can be calculated to be 91.8 g SO_4/kg fines or 9.2% SO_4. This value is higher than the average value previously reported of 4.3% (Anderson, 2010). Variations in sulfate concentrations from different recycling facilities are expected due to the highly heterogeneous nature of C&D waste and differences in the screening processes. The lime used in the experiment was tested to verify that it did not contribute any sulfate to the columns.

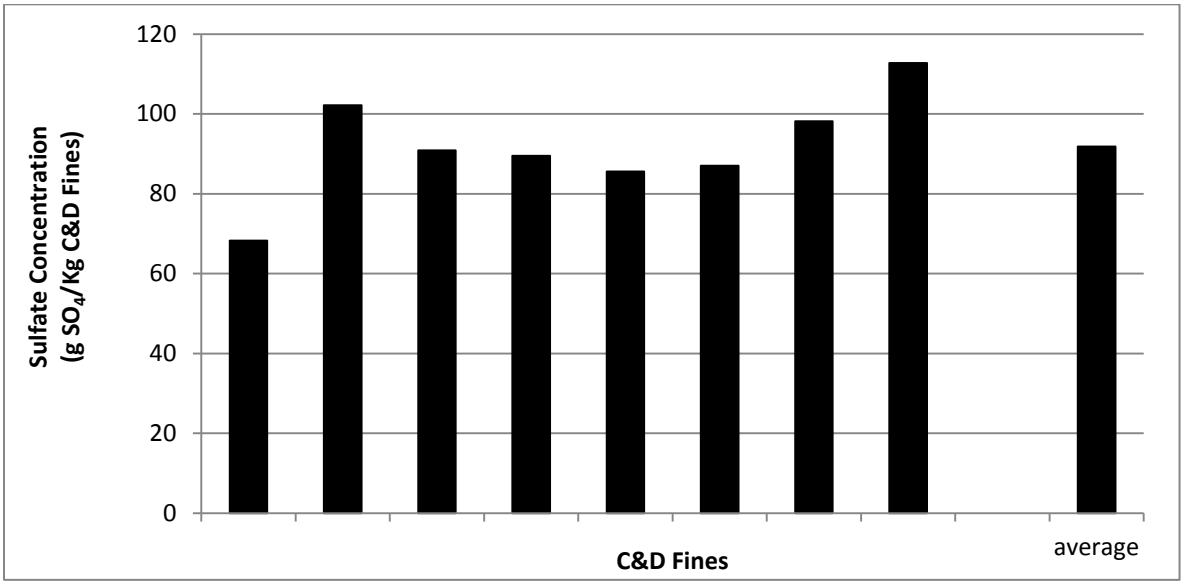

Figure 4. Initial Sulfate Concentrations in C&D Fines Measured Using pH 1 Extraction Method

Porosity of C&D Fines

The results from the bromide tracer tests conducted at various points during the operation of the first and second set of columns are shown in Figure 5. There was no apparent trend in the changes in porosity as a function of the percent of sulfate leached. The porosity of the

material did not increase as sulfate was dissolved. Variations in the columns are random and are most likely due to mobilization of fines through the columns and the creation of preferential flow channels. Based on the approach used to estimate porosity, these numbers are considered an effective porosity in the column. The average porosity for the columns at the beginning of operation was 0.64 (sd = 0.09). The average porosity for all time points was 0.69 (sd = 0.16). The individual tracer curves for each test are shown in Appendix I.

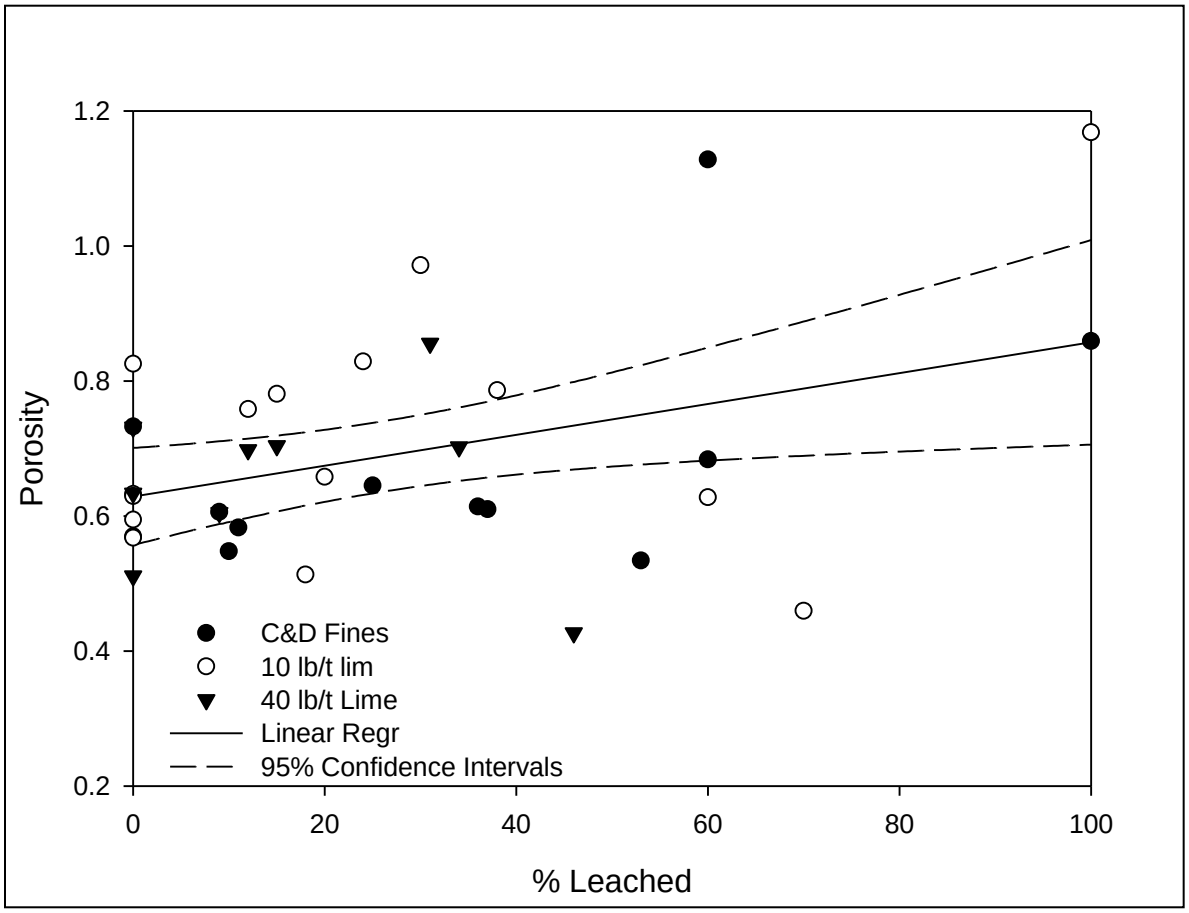

Figure 5. Porosity of the Columns Determined Using the Bromide Tracer Test

The porosities of the C&D fines determined by completely saturating quadruplicate columns with deionized water (DI) are shown in Figure 6. The average porosity determined using this

method was 0.65 (sd = 0.04). This porosity was used as the pore volume for the columns in calculations of the number of pore volumes of water that passed through a column.

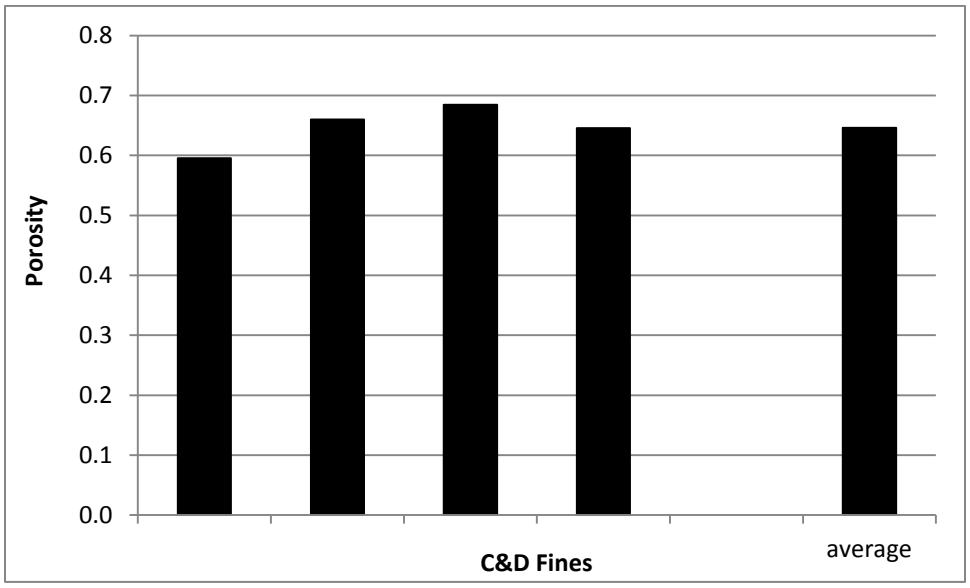

Figure 6. Porosity of Columns Determined Using Saturation Method

The average porosity of the fines determined using the saturation method (Figure 6) was used in Equation 5 to calculate the number of pore volumes per year that would flow through a layer of fines under a specified set of conditions at a landfill. Based on an assumed leachate infiltration rate of 500 gal/acre-day and a 1 m thick layer of fines, leachate flows through the C&D fines layer at a rate of 0.26 pore volumes per year.

Equation 5: Pore Volumes per Year through a 1 m Thick C&D Fines Layer under Assumed Landfill Conditions

$$\text{Pore Volumes} = \frac{\text{Assumed Landfill Infiltration Rate}}{\text{Porosity with Tracer Method} * \text{Volume of C\&D Fines Layer}}$$

$$\text{Pore Volumes} = \frac{(500\text{gal/acre-day})*(365\text{day/yr})*(2.47\text{acre/ha})}{(0.65)*(10000\text{m}^3\text{/ha})*(264.2\text{gal/m}^3)} = 0.26 \text{ pore volumes/year}$$

Column Set One: Sulfate Leaching

The objective of the first set of columns was to measure the effect of lime addition on sulfate leaching. Three sets of columns were operated including triplicate columns loaded with C&D fines that were treated with 0, 10 and 40 lb lime/ton. The average sulfate concentrations at the column outlet and fraction of total sulfate leached are presented in Figure 7. In Figure 7a, sulfate concentrations are presented as a function of time whereas concentrations are presented as a function of pore volumes in Figure 7b. As illustrated, initially there was a surprisingly high release of sulfate in the treatments with no lime and 10 lb lime /ton, but not for the 40 lb lime/ton treatment. Initial concentrations exceeded the solubility of calcium sulfate in the no lime and 10 lb lime/ton treatments. The approximately 7 pore volumes required for the sulfate concentration in the three treatments to equalize corresponds to 27 years in a landfill based on the calculation in Equation 5.

For all three treatments, the steady state sulfate release was between 1300 and 1400 mg/L. To reduce the amount of sulfate leaching to biologically active areas of the landfill, operators should minimize infiltration into C&D fine layers. Because sulfate leaching is a function of infiltration and its solubility, fewer, thicker layers of C&D fines will minimize sulfate leaching as opposed to widespread use as daily cover.

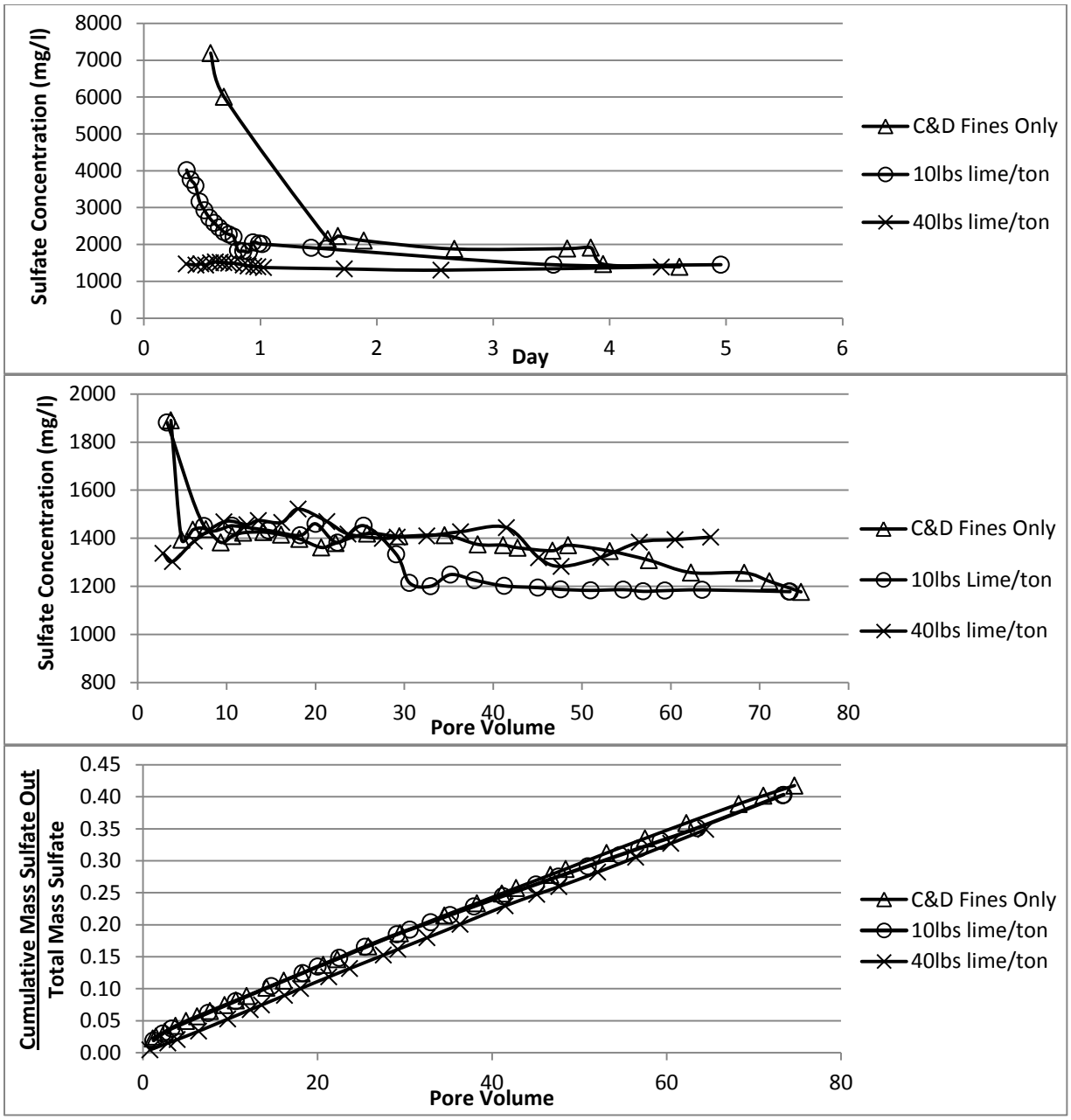

Figure 7. Average Sulfate Concentration in the Column Outlet and Fraction of Total Sulfate Leached for Column Set One

The initial elevated sulfate concentrations in two of the treatments are surprising as the sulfate concentration exceeds the equilibrium concentration associated with gypsum dissolution. The molar concentrations for sulfate, potassium, sodium, and calcium at the

column outlet for one column from each treatment were calculated from the mass concentrations and presented in Figure 8. Sulfate results are only presented for time points where a calcium sample was analyzed. These data indicate that after an initial stabilization period calcium and sulfate were leaching at approximately the same molar concentrations. The approximately equal concentrations of calcium and sulfate indicate that no other forms of sulfate containing compounds were dissolving after the initial values. The initially high value of sulfate compared to calcium in the C&D fines and the 10 lbs lime per ton treatment suggests that another form of sulfate may have been present in the C&D fines.

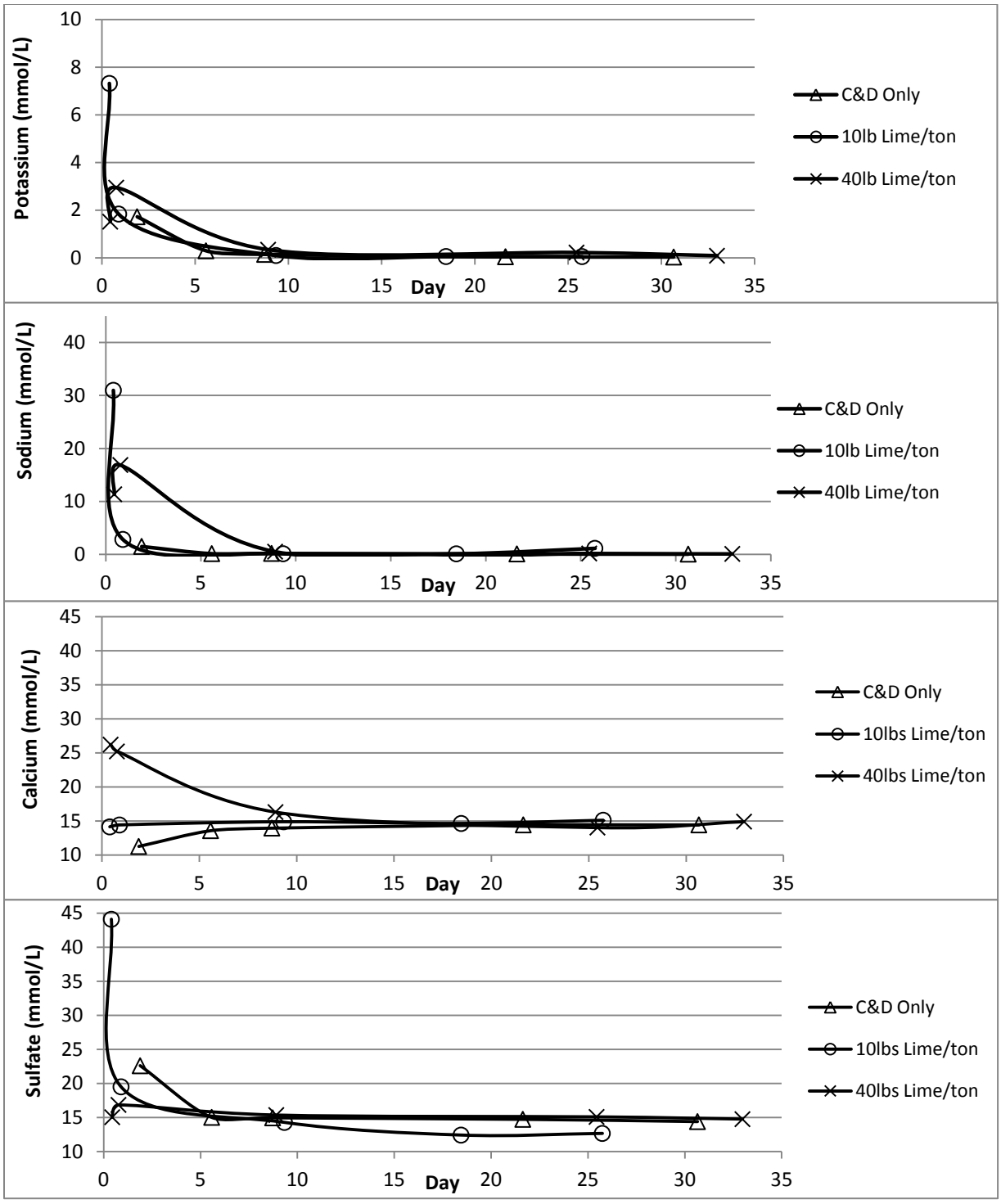

Figure 8. Molar Ion Concentrations in the Column Outlet for Three Columns from Column Set One

The solubility constant for calcium sulfate was calculated for each time point where a sample was a collected for calcium. The results are presented in Figure 9 along with two lines that represent the solubility constants for gypsum ($CaSO_4 – 2H_2O$) and calcium sulfate hemihydrate ($CaSO_4 – 0.5H_20$). The solubility constants for all three columns stabilized at values fairly close to the stability constant for the hemihydrate form of calcium sulfate rather than the gypsum form. These results were surprising because the source of calcium sulfate in C&D fines was gypsum drywall. This indicates that the dying process may have dehydrated the gypsum converting it to the hemihydrate form. This may explain why the sulfate concentration stabilized at a value that is above the solubility of gypsum (1296 mg/L) as the solubility of the hemihydrate is 1446 mg/L (Dean, 1999). Future work could include generating calcium and sulfate samples from columns containing undried C&D fines to determine if calcium sulfate was converted from gypsum to the hemihydrate form during drying.

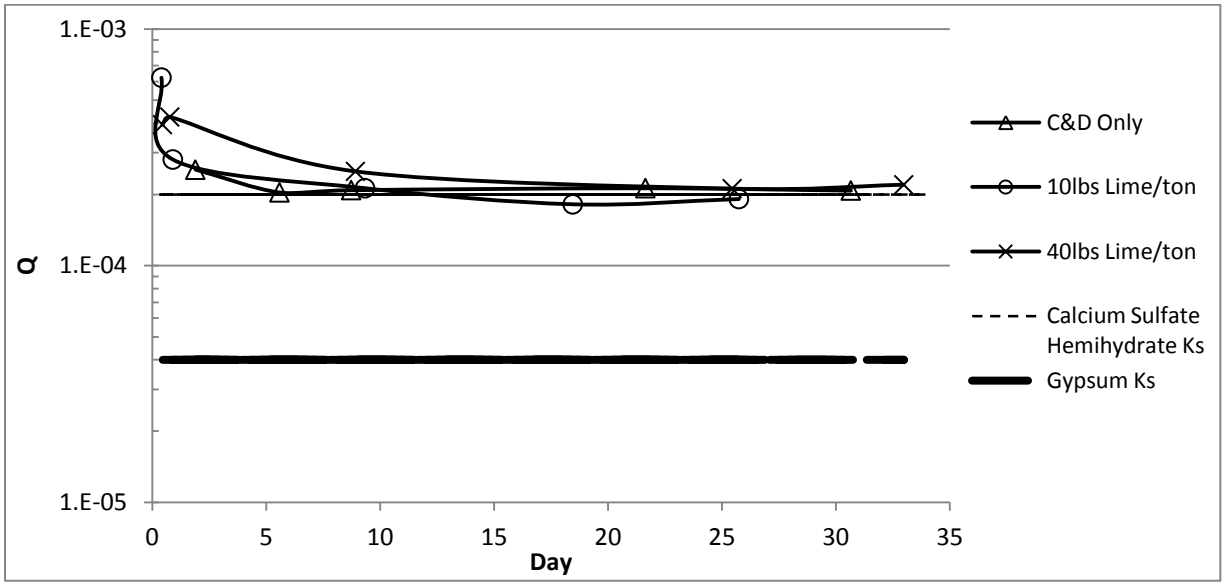

Figure 9. Solubility Constant for Column Set One

Column Hydraulic Conductivity

The flow rate for this set of columns ranged between 900 and 6,600 mL/day. The large range of flow rates can be attributed to rapid changes in conductivity. The hydraulic conductivity increased by one to two orders of magnitude with pore volumes (Figure 10). Random fluctuations in the conductivity can be attributed to the piping and clogging of fine particles in the column and the formation of preferential flow pathways as the sulfate crystals are solublized. Values of conductivity for the column without lime increased significantly less than values for the columns with lime addition. The hydraulic conductivity for the columns in this set never stabilized.

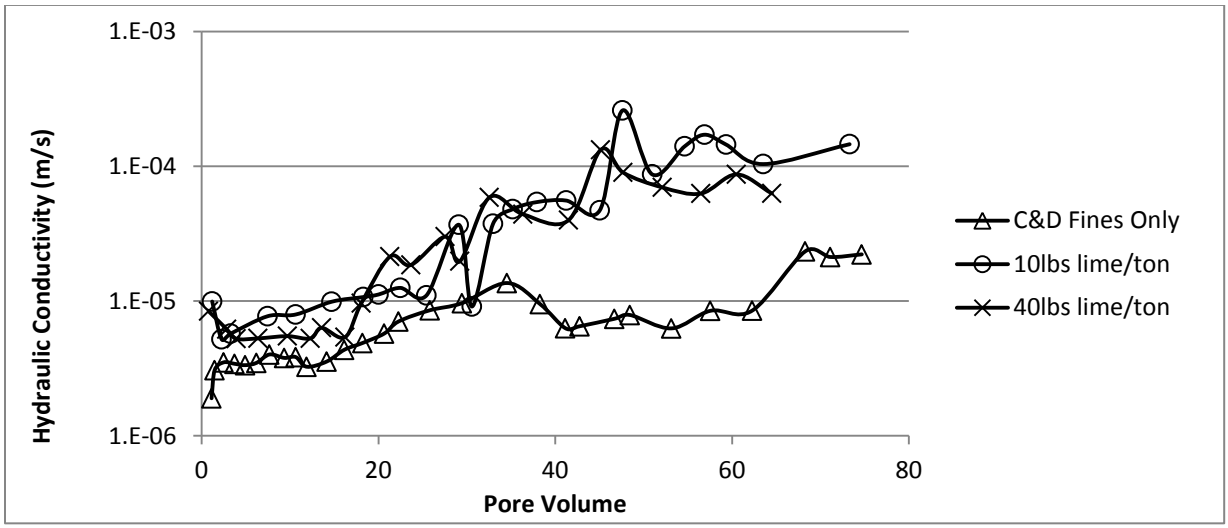

Figure 10. Average Hydraulic Conductivity for Column Set One

The conductivity in the C&D fines only treatment was consistently lower than the treatments with 10 lbs and 40 lbs of lime per ton. One explanation for this is that the lime dissolved with time as water moved through the column and lime dissolution contributed to an increased conductivity. The increase in conductivity is not desirable as increased infiltration leads to additional sulfate transferred to the biologically active portions of the landfill.

Sulfate Balance in the Columns

Table 1 demonstrates the sulfate balance for the columns used for the lime leaching study. The sulfate added to each column was determined by multiplying the sulfate concentration of the C&D fines (18.8% - Figure 4) by the mass of C&D fines added to each column. The cumulative amount of sulfate leached was calculated using the sulfate concentrations for each treatment (Figure 7) and the total volume of water flushed through each column. The sulfate in the remaining solids was determined using pH 1 extractions and the total mass of sample remaining in each column. Between 89.2% and 107.3% of the added sulfate was accounted for in these columns. There are several potential sources of error that could explain the deviation from 100% recovery. Samples were collected for sulfate measurement at discrete time points and variations in the sulfate concentrations between time points were not included in calculations. Errors in the sulfate recovery could also be attributed to the use of an average value for the concentration of sulfate in the added C&D fines, in which the concentration is known to vary.

Table 1. Sulfate Recovery for Column Set One

	Sulfate In (g)	Sulfate Leached (g)	Sulfate in Remaining Solids (g)	Sulfate Recovery
C&D Fines Only				
#1	**328.0**	**118.5**	**219.92**	**103.2%**
#2	**321.0**	**170.6**	**173.79**	**107.3%**
#3	**329.6**	**121.5**	**226.46**	**105.6%**
10lbs Lime/ton				
#1	**333.3**	**101.1**	**208.65**	**92.9%**
#2	**319.6**	**146.4**	**158.77**	**95.5%**
#3	**317.2**	**112.2**	**170.72**	**89.2%**
40lbs Lime/ton				
#1	**330.4**	**153.9**	**189.92**	**104.1%**
#2	**337.1**	**105.6**	**204.99**	**92.1%**
#3	**330.8**	**114.9**	**191.13**	**92.5%**

Column Set Two: Measurement of Particle Size Shifts with Sulfate Dissolution

Based on the results of the first set of columns, a second set of columns was constructed. Duplicate columns were constructed with C&D fines and treated with 0 and 10 lbs/ lime/ton. These columns were operated until about 50% and 100% of the sulfate was leached to explore whether sulfate leaching or fine particle movement could explain the changes in hydraulic conductivity observed for the first set of columns.

The sulfate concentrations at the column outlet and fraction of total sulfate leached are presented in Figure 11. Figure 11 shows that the sulfate concentration, in the two columns operated to 100% sulfate leached, remained below 10 mg/L after approximately 200-250 pore volumes were flushed through the columns. As presented in Figure 11a, the recovered sulfate concentration was calculated as about 115% of the sulfate added in the C&D fines. There are several potential explanations for the recovery of greater than 100% of the added sulfate. First, the concentration of sulfate in the added C&D fines was assumed to be the

average of the measured values presented in Figure 4. Second, samples were collected for sulfate measurement at discrete time points and variations in the sulfate concentrations between time points were not measured. Based on the cumulative sulfate figure, sulfate appeared to leach from the column with lime at a slightly slower rate.

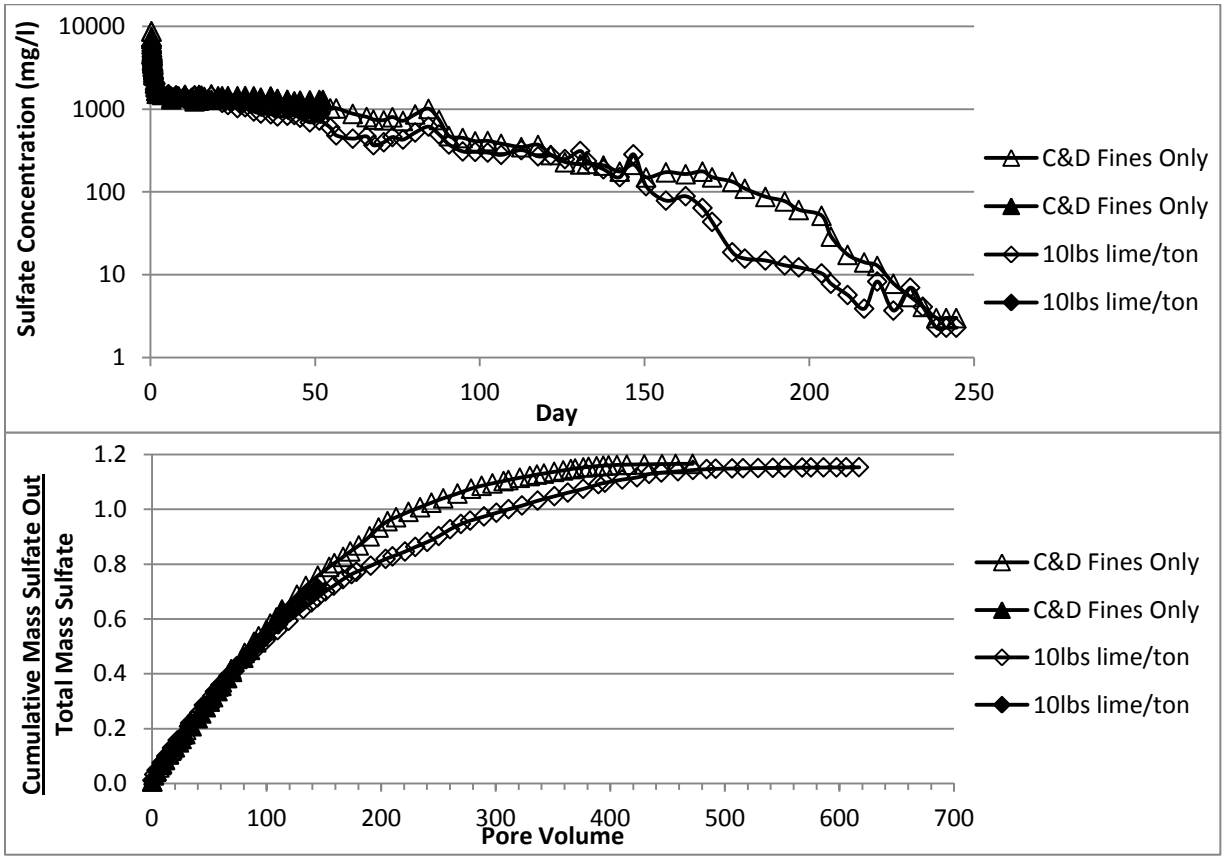

Figure 11. Sulfate Concentration in the Column Outlet and Fraction of Total Sulfate Leached for Column Set Two

The hydraulic conductivity for the columns is shown in Figure 12. For the columns operated until 100% of the sulfate leached, the hydraulic conductivity stabilized after about 100 pore volumes or 50% of the sulfate was leached. The stabilization of the conductivity indicates that the columns reached steady state and the increase in conductivity may be explained by the dissolution of sulfate salt crystals. The average measured hydraulic conductivities for the

columns with and without lime for the period after stabilization (after 100 pore volumes) were 6.9E-5 (sd = 2.7E-5) and 2.1E-4 (sd = 4.1E-5), respectively. Based on these results, the lime appeared to raise the steady state conductivity by a factor of three. In the columns operated until 50% of the sulfate was leached, lime had begun to demonstrate a similar effect on the conductivity just before the columns were shut down. Additional work is needed to replicate the columns to verify this effect of lime on the steady state conductivity.

The effect of lime on the conductivity is important because higher conductivities could lead to higher infiltration rates. As shown in this study, increased infiltration leads to increased sulfate leaching. In order to determine if the difference in conductivity is significant enough to increase infiltration, a comparison of the conductivity in waste to the conductivity in the C&D fines would have to be completed.

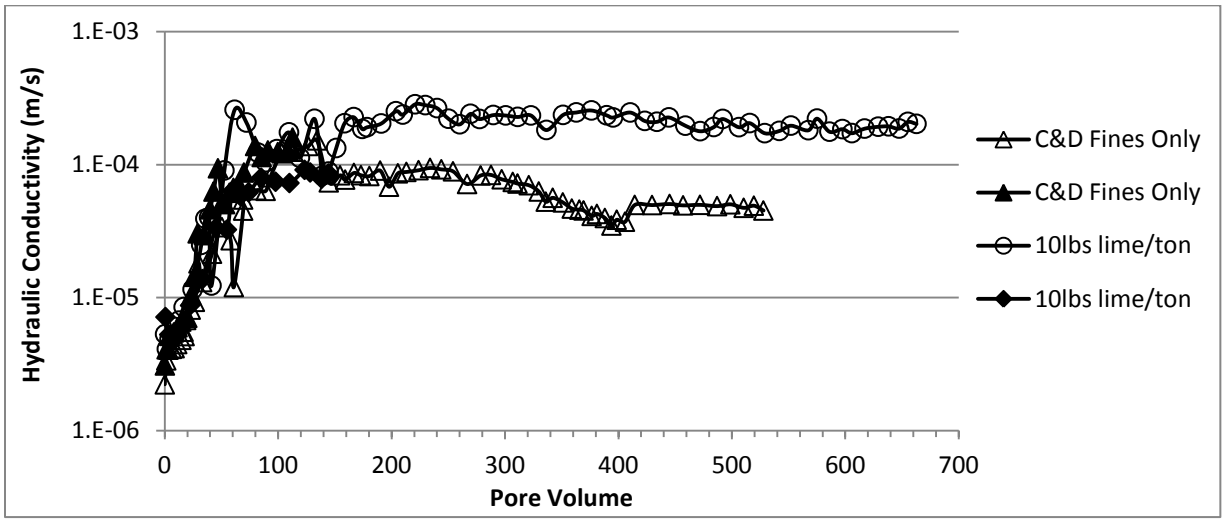

Figure 12. Hydraulic Conductivity for Column Set Two

The mass of sulfate remaining in three sections of the columns at completion of operation is shown in Figure 13. Remaining sulfate was determined by pH 1 extractions of sub-samples of the material in the top, middle and bottom of each column. The top sections of the 50% leached columns demonstrated lower masses of sulfate remaining relative to the middle and

bottom sections, indicating that sulfate near the top of the column was dissolved first. The lower mass of sulfate remaining in the column with lime is due to the higher percent of sulfate leached from this column during operation (Figure 11).

Results for the columns with 100% of the sulfate leached show only a small amount of sulfate remained in the columns at takedown. This confirms the methods used in this experiment by demonstrating that it is possible to leach the entire mass of sulfate from the column. The presence of lime demonstrated no effect on the mass of sulfate remaining in these columns. These results confirm the calculations presented in Figure 11 which showed over 100% sulfate recovery in the column leachate. Possible sources of error that could be the cause of the sulfate recovery above 100% were explained earlier in this section.

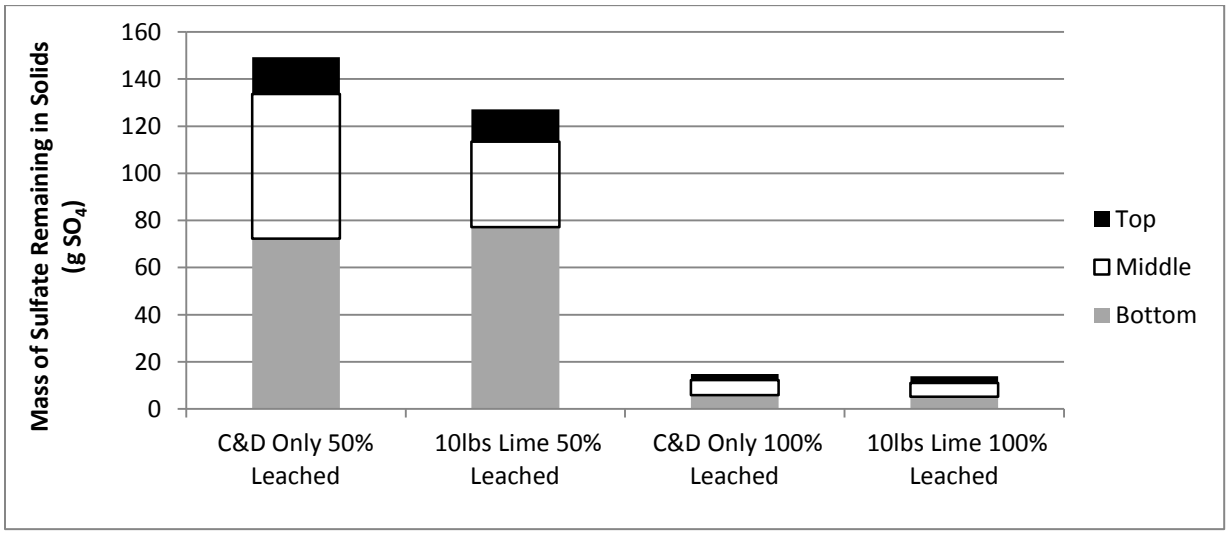

Figure 13. Sulfate Final Recovered on Destructive Sampling of Column Set Two

Table 4 demonstrates the sulfate balance for the second set of columns. Using the results from the pH 1 extraction, the amount of sulfate added to the columns was compared to the amount of sulfate recovered in the column leachate and the residual solids. Between 107.6% and 117.3% of the added sulfate was accounted for in these columns. Sulfate recoveries that

are greater than 100% can be attributed to the same potential sources for the error in the first set of columns (Table 3). Lime did not significantly affect the percent sulfate recovery.

Table 2. Sulfate Recovery for Column Set Two

	Sulfate In (g)	Sulfate Leached (g)	Sulfate in Remaining Solids (g)	Sulfate Recovery
50% SO4 Leached				
C&D Fines Only	**332.7**	**208.58**	**149.35**	**107.6%**
10lbs Lime/ton C&D Fines	**309.9**	**220.72**	**127.18**	**112.3%**
100% SO4 Leached				
C&D Fines Only	**324.9**	**379.03**	**1.98**	**117.3%**
10lbs Lime/ton C&D Fines	**320.7**	**370.09**	**1.86**	**116.0%**

The results for the particle size distribution performed on the second set of columns are shown in Figure 14. The particle size distribution for the starting material prior to water infiltration and sulfate leaching is also presented. The particle size distribution demonstrates an increase in the fine particles in the bottom sections of both treatments with infiltration and increased sulfate leaching. The increase of fine particles in the bottom section was greater in the treatment with lime relative to the treatment with C&D fines only. This indicates that the higher hydraulic conductivities in the columns with lime (Figure 12) may cause fine particles to be mobilized more rapidly.

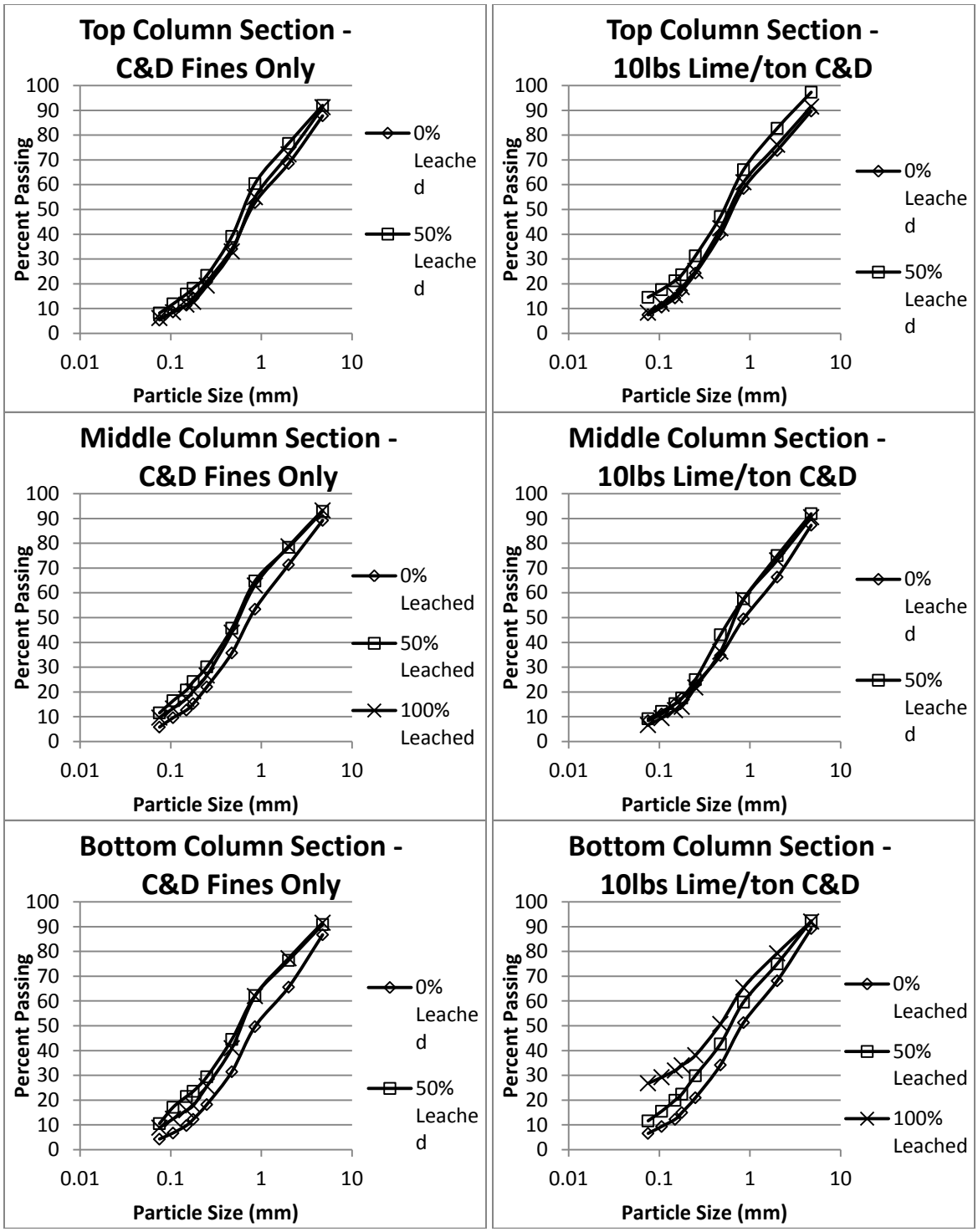

Figure 14. Particle Size Distribution for Column Set Two

Column Set 3: The Effect of Landfill Gas on Lime Inhibition of Sulfate Reduction

A third set of experiments was conducted to evaluate whether the moisture in landfill gas could stimulate H_2S production from C&D fines and if lime addition would be sufficient to inhibit this production. Three treatments were evaluated, each in duplicate columns: gas addition, gas addition + lime at 40lbs/ton, and a control. The control and gas addition + lime treatments consisted of a layer of C&D fines with lime at 40 lbs/ton over a layer of MSW. The gas addition treatment consisted of a layer of C&D fines only over an MSW layer. No gas was fed to the control columns. The MSW added was a mixture of fresh and actively degrading waste.

The average gas flow rate for treatments with gas addition was 1.37 L/day. This flow rate corresponds to an average methane flow rate of 116.8 g CH_4/day-m^2 (Figure 15). This value is slightly higher than the target flow rate of 100 g CH_4/day-m^2. The large variations in the flow rate at the beginning of operation can be attributed to malfunctions in the flow control equipment. These points are considered to be outliers and were not used in the calculation of average methane flow rate. Values for the methane flow rate that are near zero occurred when the gas supply tank ran empty.

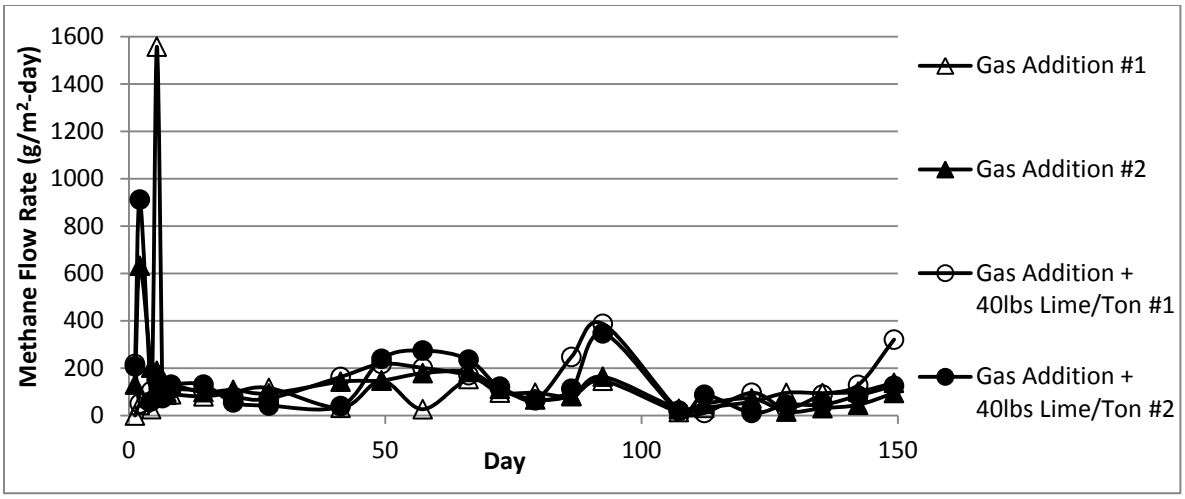

Figure 15. Gas Flow Rates for Columns with Gas Addition

Average H_2S concentrations for each treatment and the H_2S concentration in each column are shown in Figure 16. The average concentration of H_2S in the gas addition only columns remained slightly higher than the concentration in the gas addition + lime columns throughout the experiment. Before leachate recirculation, the H_2S concentrations in control columns were lower than in the columns with gas flow. After leachate recirculation began at 90 days, the H_2S concentration in the control increased sharply as expected, indicating that the addition of moisture to the columns stimulated H_2S production. These results indicate that moisture present in saturated landfill gas can stimulate H_2S production in the laboratory setting and that lime has little effect on this process. There are two mechanisms by which the stimulated landfill gas could initiate H_2S production. First, it is possible that the landfill gas condensate that reached the C&D fines layer was acidic and neutralized the lime. It is also possible that the moisture in the gas leached sulfate from the fines layer back into the pH neutral MSW layer and H_2S production occurred in the MSW layer. In the control columns in which leachate recirculation was initiated, the leachate likely dissolved sulfate from the C&D fines into the pH neutral MSW layer where rapid conversion to H_2S occurred. The H_2S concentrations produced in the all columns after the initiation of leachate recirculation are higher than 556 ppm, the concentration of the sulfide shown to severely retard methane production (Shin et. al., 1995). The high concentrations of this toxic

gas will also have a significant effect on the microorganisms involved in the waste degradation process.

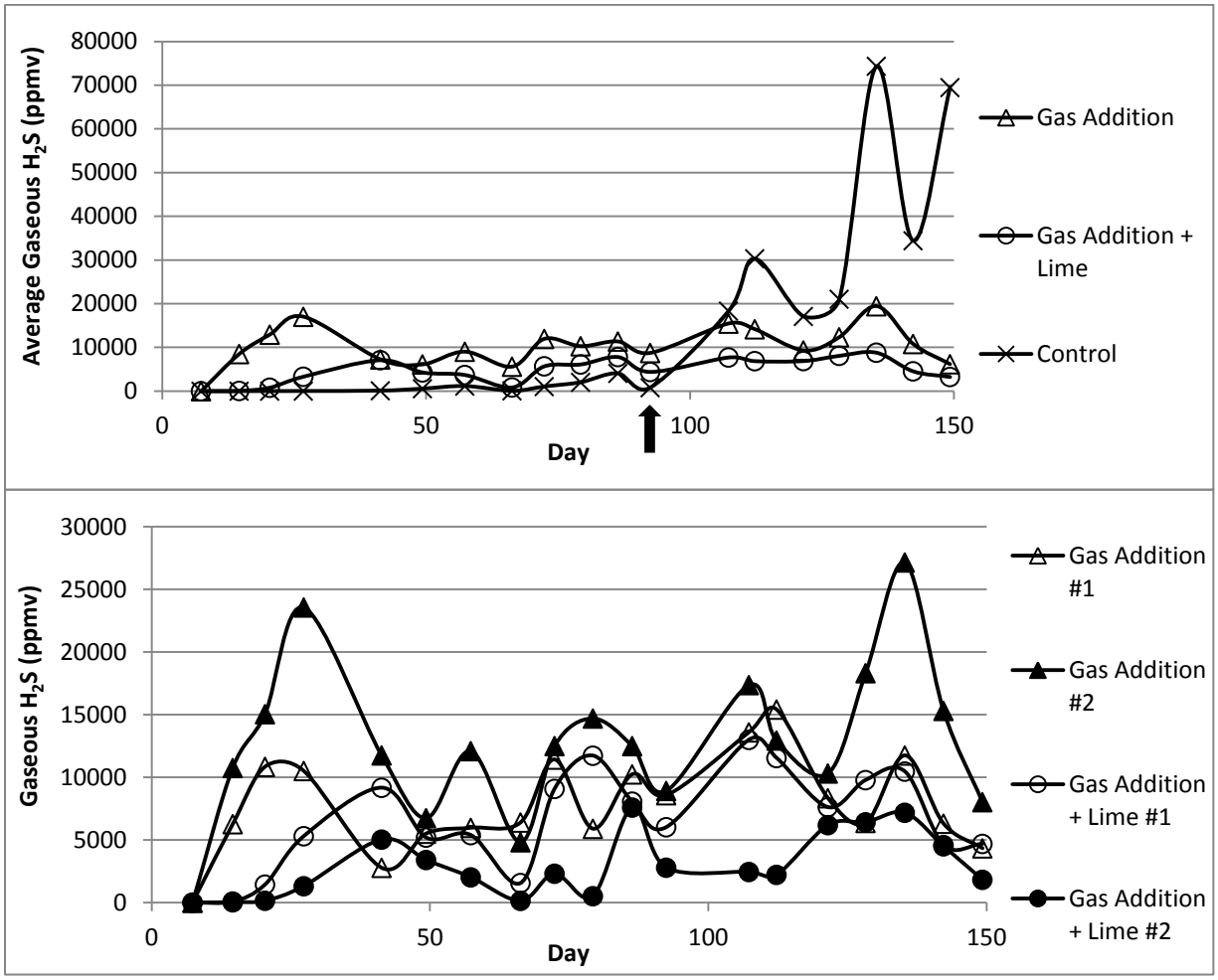

Figure 16. Concentration of H_2S in Column Headspace

(The arrow indicates the start of leachate recirculation in the control columns)

The average H_2S production rate for each treatment and the average cumulative H_2S yield are presented in Figures 17 and 18, respectively. These data indicate that H_2S production could be stimulated from the moisture in landfill gas. H_2S production in the presence of lime treated C&D fines was comparable to that in the C&D fines that were not treated with lime. The lag time prior

to initiation of H_2S production in the columns with lime treated C&D fines suggests that the lime did have an effect for a limited period of time. When considering the rates of gas flux in landfills, this lag was not significant. In landfills the gas flux is greatest near gas collection wells. These results indicate that landfill operators should place sulfate containing materials away from gas wells in order to mitigate the effect of saturated gas on H_2S production. Of course, the collection efficiency of material placed further from gas wells may be lower and a landfill specific strategy is needed.

Both of these treatments in which gas was added resulted in considerably more H_2S than the control with no gas flux. H_2S production in the controls increased sharply with the initiation of leachate recirculation. The leachate likely dissolved sulfate from the C&D fines into the pH neutral MSW layer where rapid conversion to H_2S occurred. However, H_2S production decreased almost as quickly as it increased. The decrease in production could be due to the elevated H_2S concentration (70,000 ppm, Fig. 16) inhibiting further sulfate reduction

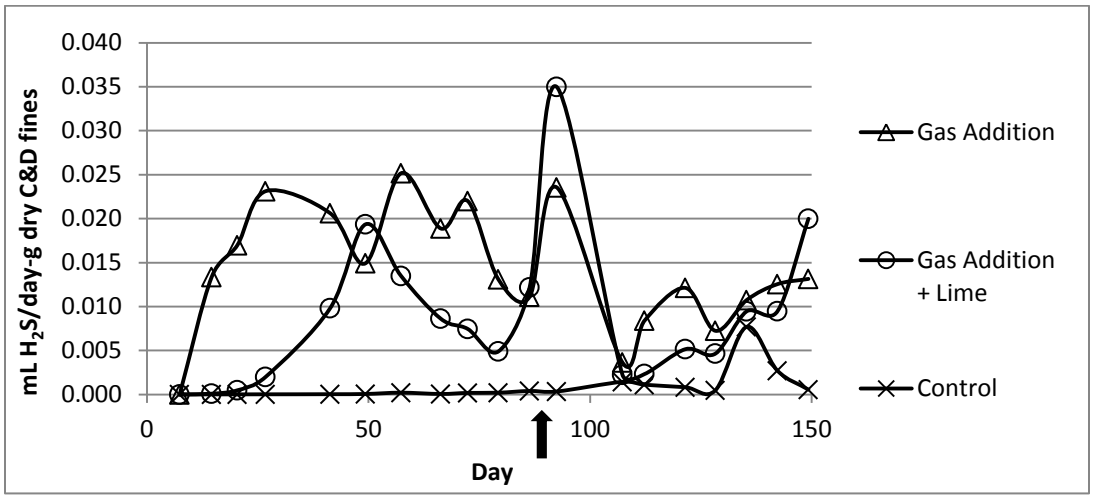

Figure 17. Average H_2S Production Rate

(Arrow Indicates the Start of Leachate Recirculation in the Control Columns)

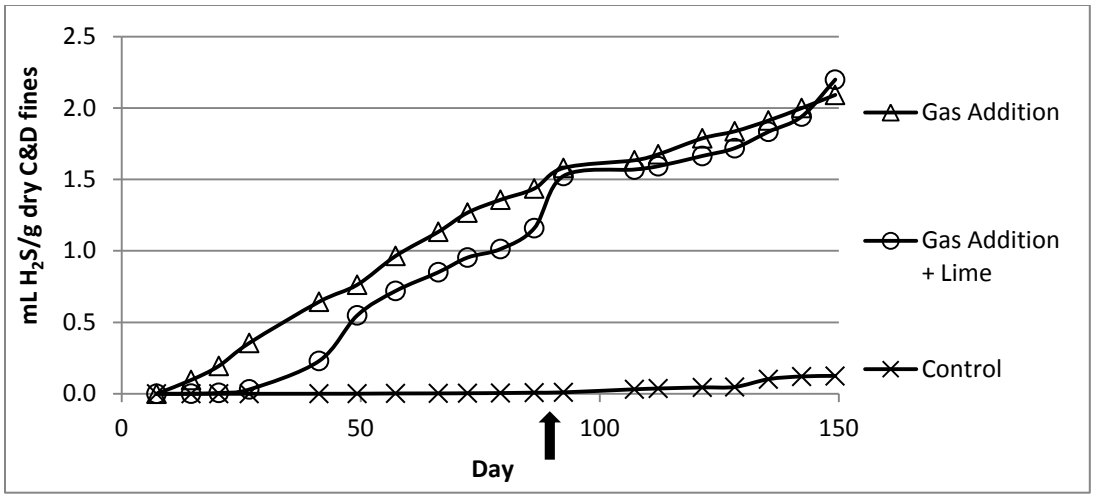

Figure 18. Average Cumulative H_2S Production

(Arrow Indicates the Start of Leachate Recirculation in the Control Columns)

At the termination of the third set of columns, four samples were collected from the C&D fines layer of each column and analyzed for moisture content. Moisture profiles throughout the 8.5" C&D fines layer are presented in Figure 19. Only three samples are presented for Control #1 because the top sample was spilled during drying. The increase in moisture content, from completely dry at the beginning of column operation, indicates that moisture had been transferred to the C&D fines layer in all of the columns. The samples collected from the gas addition columns showed an increase in the moisture content of the samples closer to the MSW layer at the bottom of the column. As gas was added from the bottom of the column, higher moisture near the bottom would be expected. The control columns with leachate recirculation demonstrated higher moisture content than the columns with gas addition as would be expected on the basis of the water added.

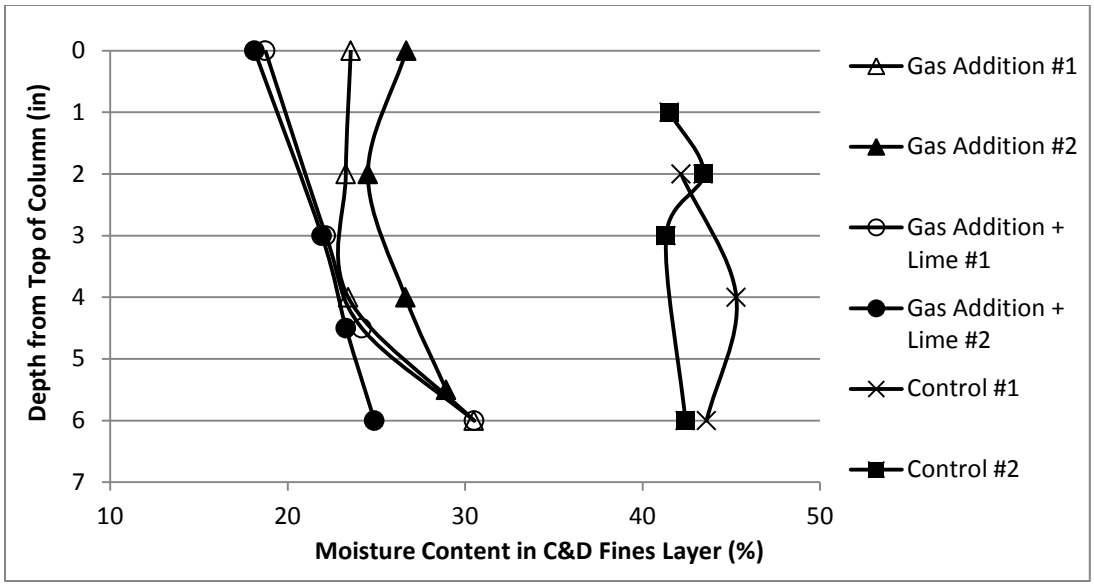

Figure 19. Moisture Content in C&D Fines at the Completion of the Experiment

CHAPTER 4 – CONCLUSIONS

One objective of this work was to assess sulfate release from C&D fines/lime mixtures to determine the effect of lime on sulfate leaching. When lime was added to C&D fines at 40 lbs/ton, it was effective at lowering the concentration of sulfate leached during the first 7 pore volumes. The sulfate results from the first set of columns (Figure 7) demonstrate the initial concentration dropped from approximately 7,000 mg/L with C&D fines only to 1,400 mg/L with 40 lbs lime/ton. The effect of lime and the initially high concentrations of sulfate released from columns without lime are significant because it was estimated that a C&D fines layer in the landfill might only receive ~0.26 pore volumes of liquid per year (Equation 3). Based on these results, lime addition will reduce the mass of sulfate released over the first several pore volumes which will reduce the amount of H_2S formed.

Another important conclusion of this work is that in all treatments, the release of sulfate was rapid and controlled by sulfate solubility. The sulfate results from the first set of columns stabilized to approximately the sulfate solubility after an initial stabilization period. This indicates that landfill operators should minimize infiltration into C&D fines layers. The use of C&D fines as an alternative daily cover is problematic because each layer of fines has the ability to leach equal concentrations of sulfate to underlying waste masses. Landfill operators could reduce the amount of sulfate exposed to biologically active areas by applying C&D fines in fewer, thicker layers.

The second set of columns was operated to determine the cause of the changes in hydraulic conductivity during operation. Two hypotheses were explored to explain the changes in hydraulic conductivity during column operation: fines settlement and sulfate dissolution. The particle size distribution data for these columns (Figure 14) indicates that fine particles were mobilized to the bottom portion of the column during operation. For the bottom portion of the 10 lbs lime/ton treatment, the percent fines increased from 6.6% in the 0% leached column to 26.8% in the 100% leached column. The sulfate concentrations in the columns also suggest that sulfate dissolution played a role the in increases in conductivity during operation.

Lime is considered to be effective at lowering the concentration of sulfate leaching from C&D fine layers for a short period following the addition of the material to landfills. After extensive infiltration, the lime may increase the hydraulic conductivity of the fines layers. For the second set of the columns, the average hydraulic conductivities for the columns with and without lime for the period after stabilization (after 100 pore volumes) were 6.9E-5 (sd = 2.7E-5) and 2.1E-4 (sd = 4.1E-5), respectively. This increase should be considered in the context of the surrounding waste mass to determine if these changes are allowing for additional infiltration. Increased infiltration corresponds to additional sulfate leaching.

A third set of columns was operated to evaluate whether the moisture in landfill gas could stimulate H_2S production from C&D fines that have been mixed with lime. Results indicate that H_2S production can be stimulated by the moisture in landfill gas in C&D fines with or without the presence of lime. Before starting recirculation in the control columns, the columns with gas addition produced approximately 1.5 mL H_2S/g dry C&D fines and the control column produced approximately zero. Concentrations of H_2S produced as a result of the moisture in the simulated landfill gas were higher than levels considered toxic to methanogens which raises the possibility that H_2S production in landfill may result in microbial inhibition, an issue that requires further investigation.

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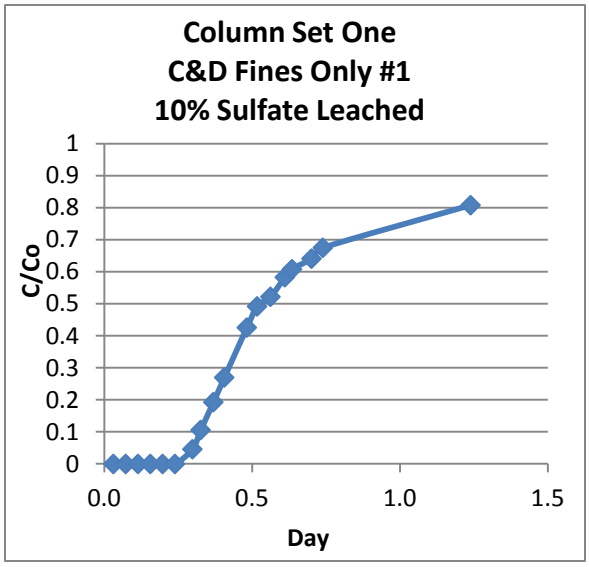
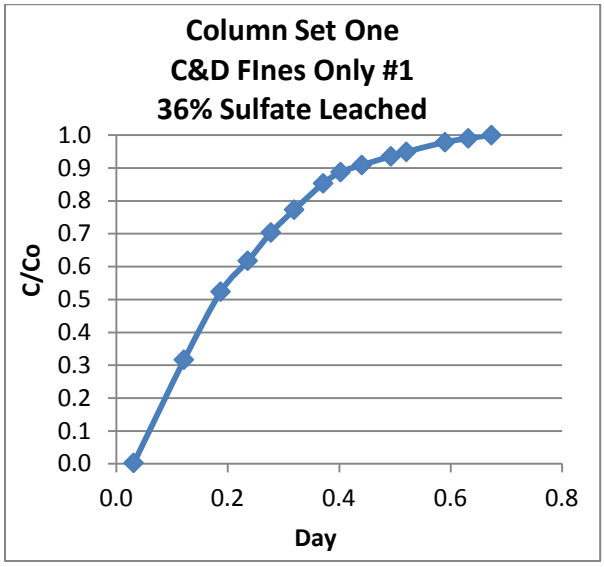
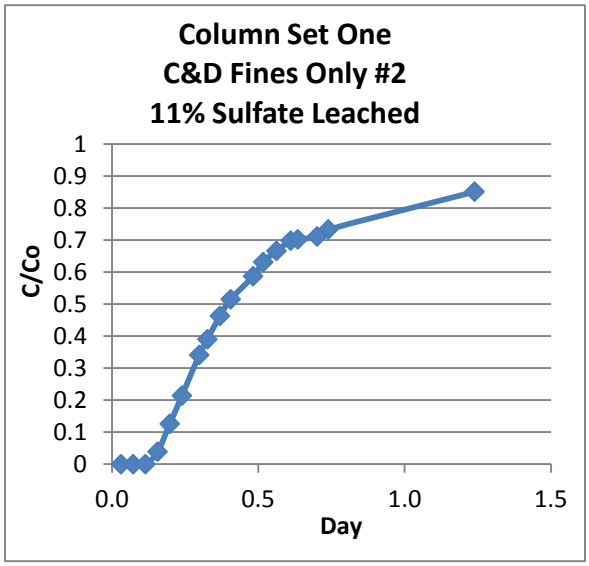
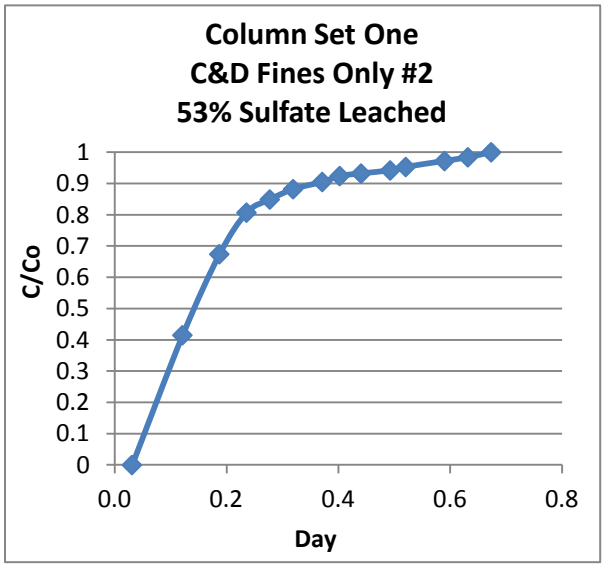
APPENDICES

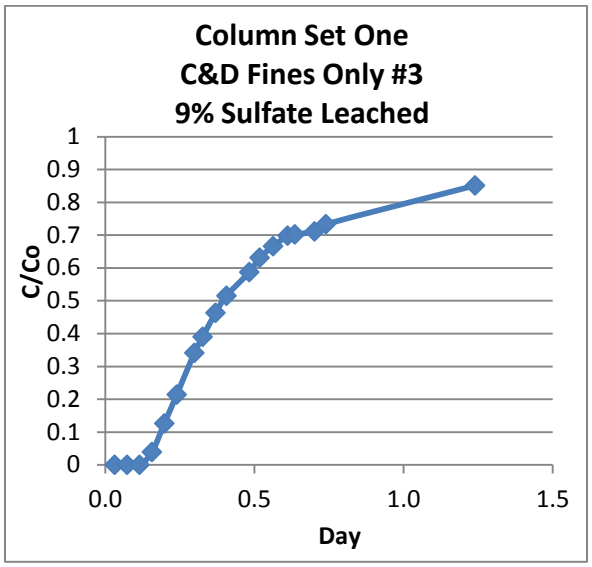
Appendix A – Bromide Tracer Test Curves

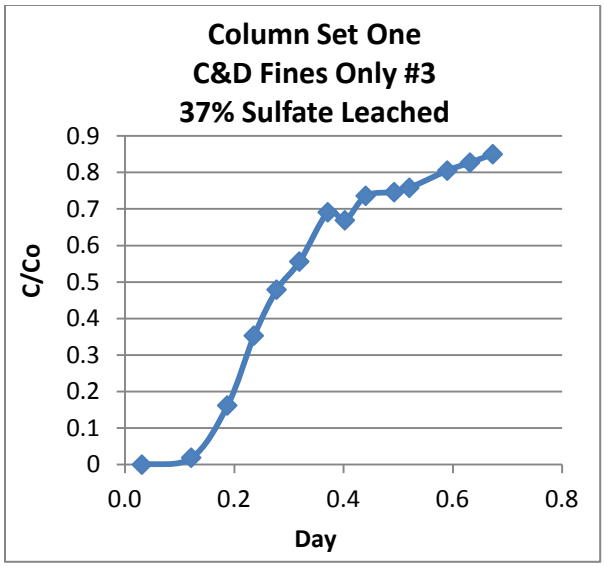


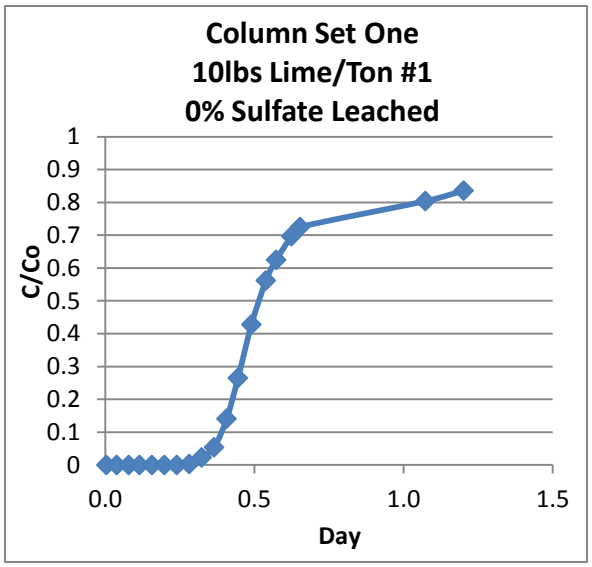


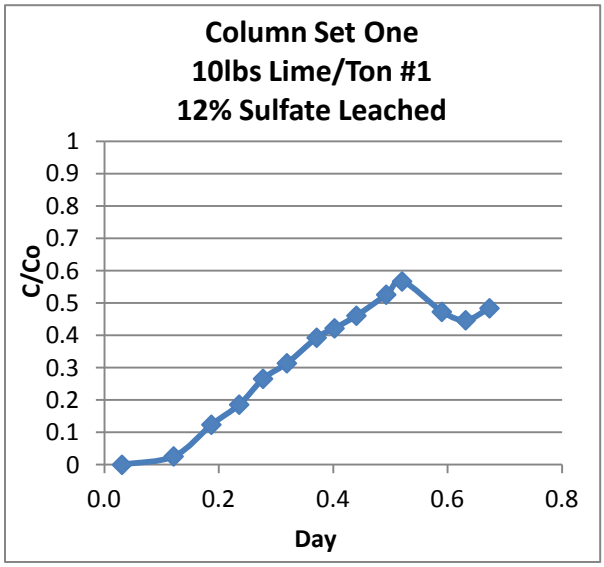


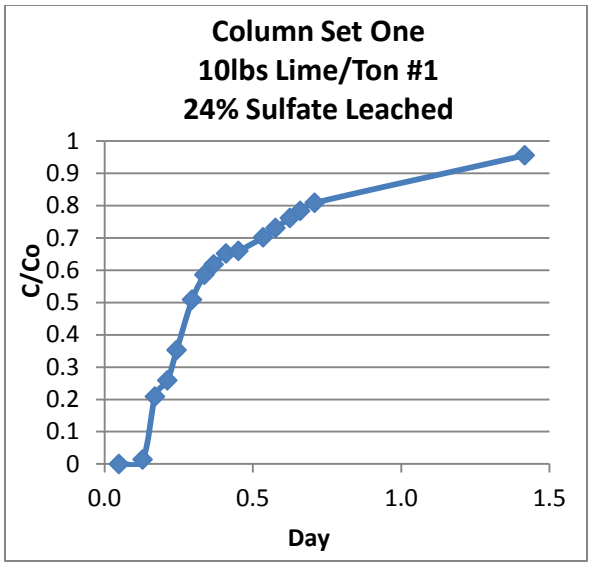


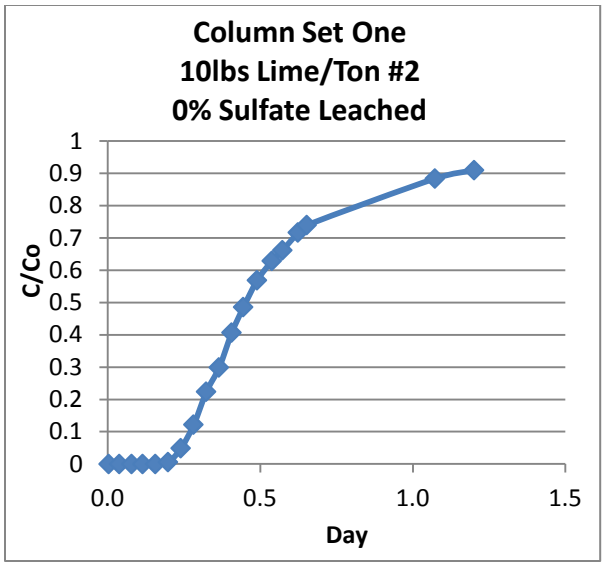

Column Set One
C&D Fines Only #3
9% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

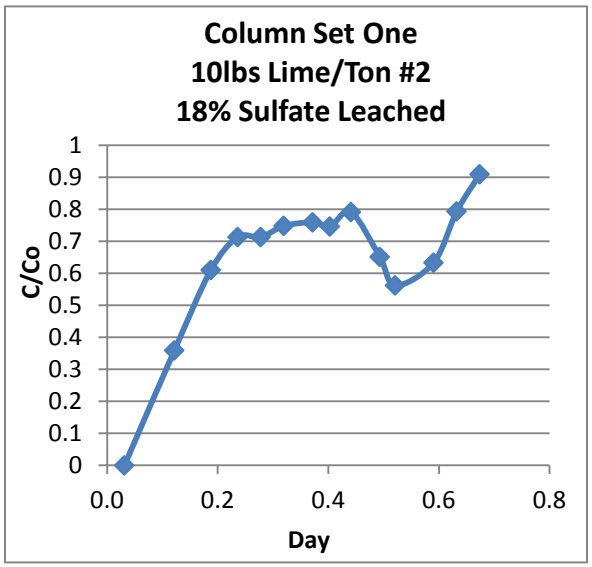

Column Set One
C&D Fines Only #3
37% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.0
0.2
0.4
0.6
0.8

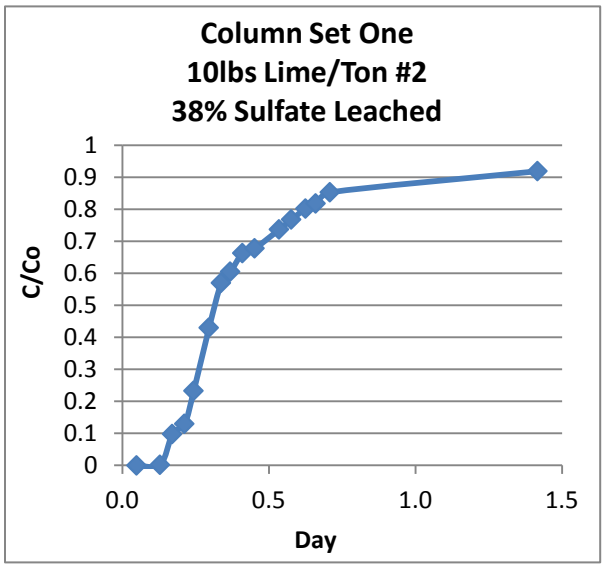

Column Set One
10lbs Lime/Ton #1
0% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

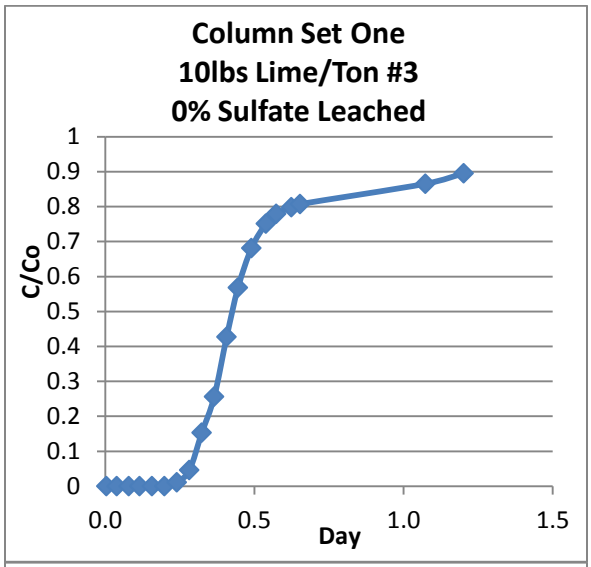

Column Set One
10lbs Lime/Ton #1
12% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.2
0.4
0.6
0.8

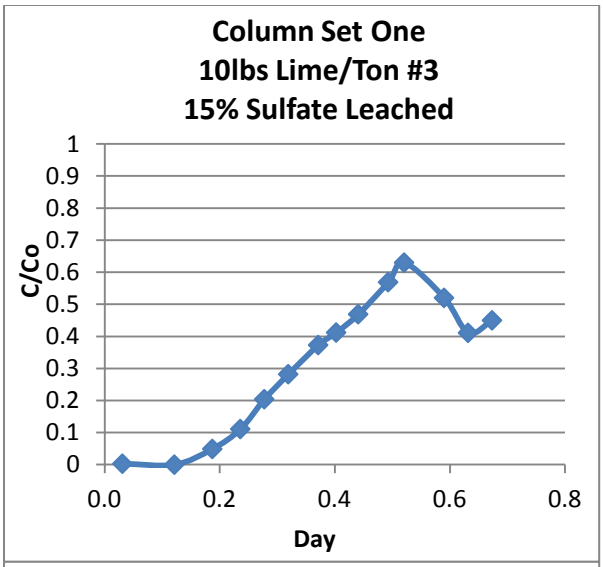

Column Set One
10lbs Lime/Ton #1
24% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

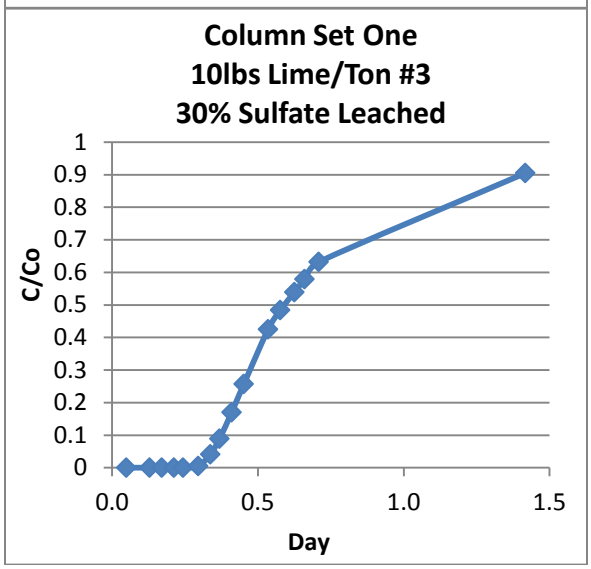

Column Set One
10lbs Lime/Ton #2
0% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

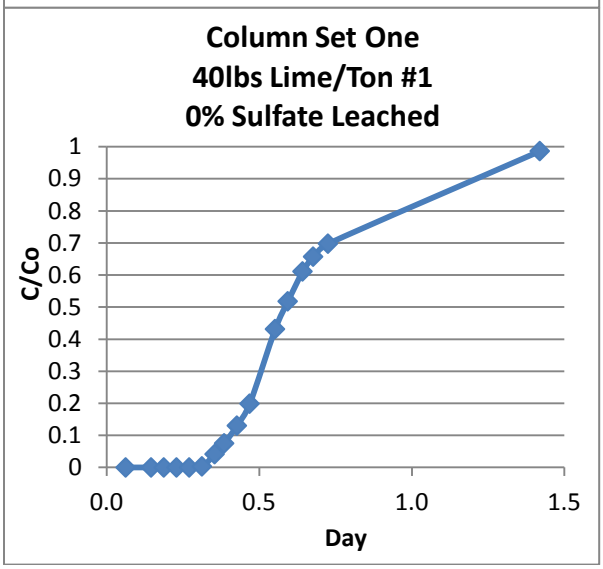

Column Set One
10lbs Lime/Ton #2
18% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.2
0.4
0.6
0.8

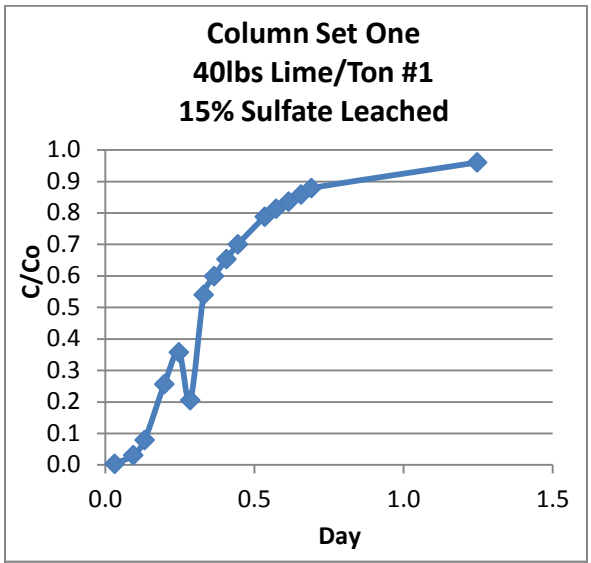

Column Set One
10lbs Lime/Ton #2
38% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

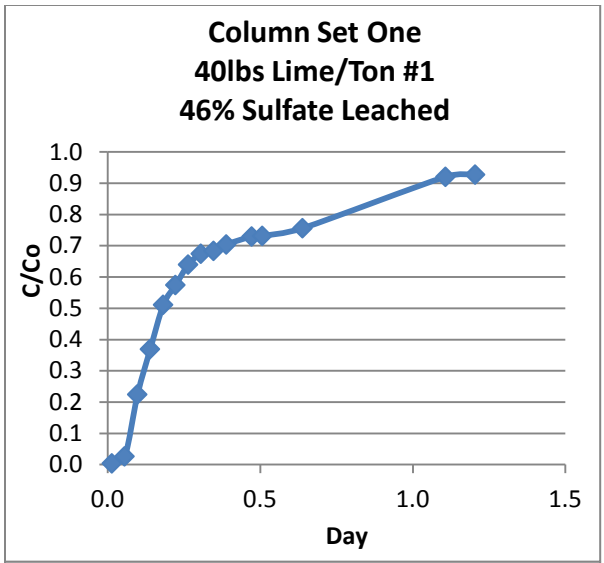

Column Set One
10lbs Lime/Ton #3
0% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

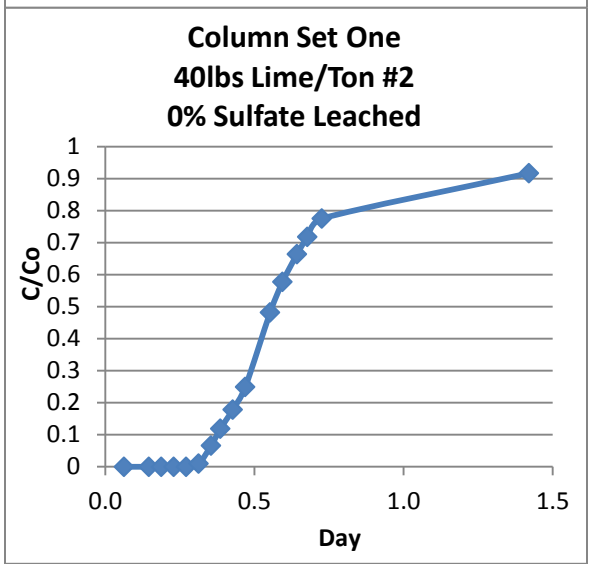

Column Set One
10lbs Lime/Ton #3
15% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.2
0.4
0.6
0.8

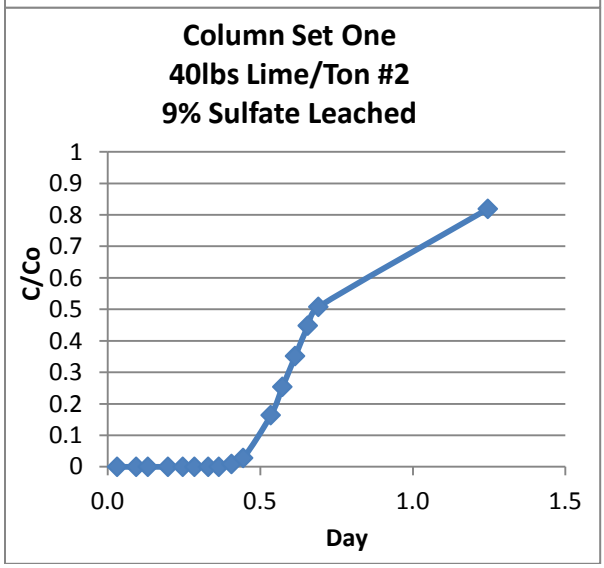

Column Set One
10lbs Lime/Ton #3
30% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

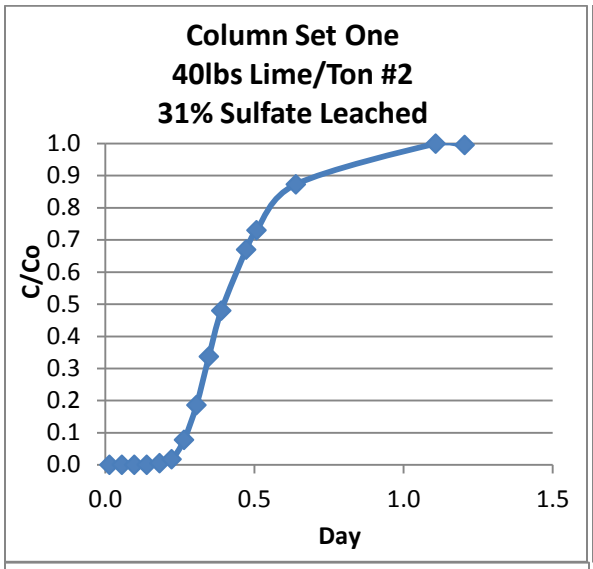

Column Set One
40lbs Lime/Ton #1
0% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

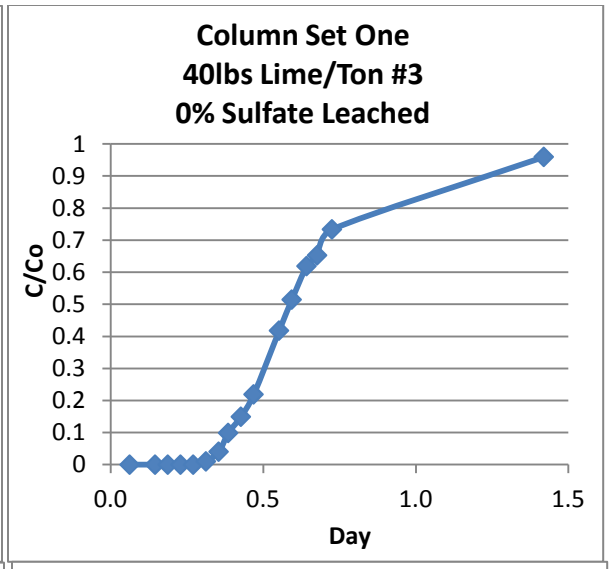

Column Set One
40lbs Lime/Ton #1
15% Sulfate Leached
C/Co
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
Day

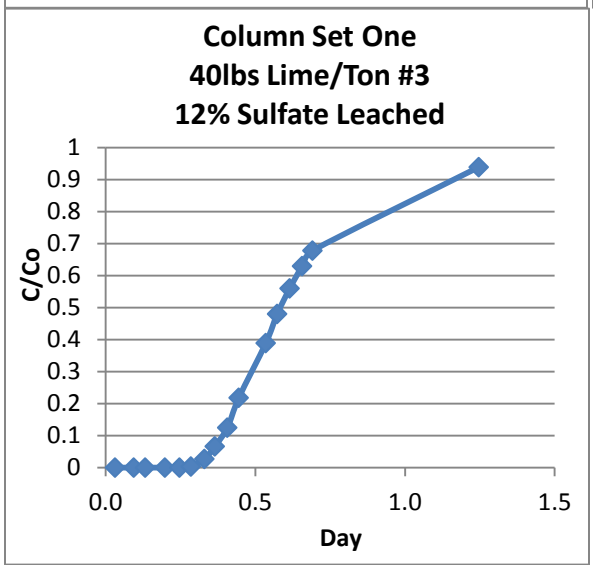

Column Set One
40lbs Lime/Ton #1
46% Sulfate Leached
C/Co
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
Day

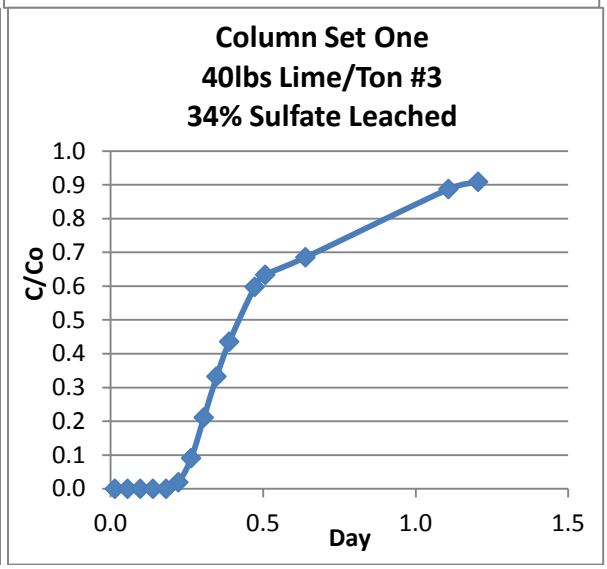

Column Set One
40lbs Lime/Ton #2
0% Sulfate Leached
C/Co
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.0
0.5
1.0
1.5
Day

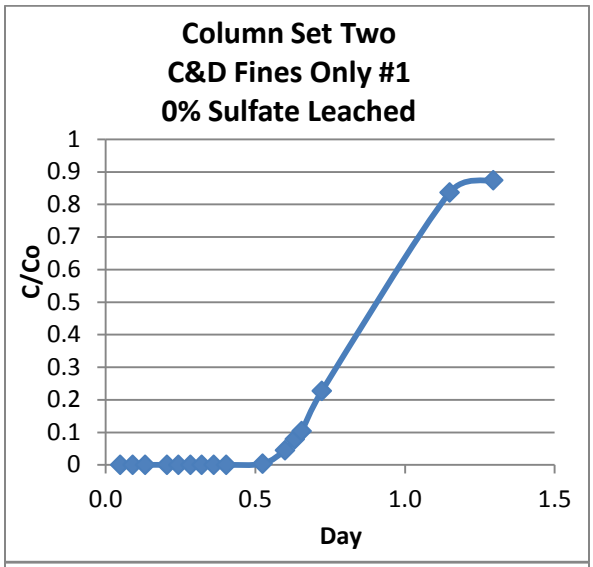

Column Set One
40lbs Lime/Ton #2
9% Sulfate Leached
C/Co
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.0
0.5
1.0
1.5
Day

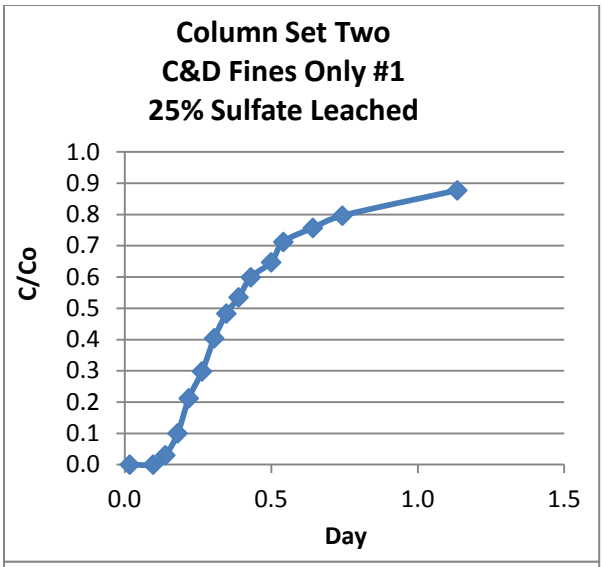

Column Set One
40lbs Lime/Ton #2
31% Sulfate Leached
C/Co
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
Day

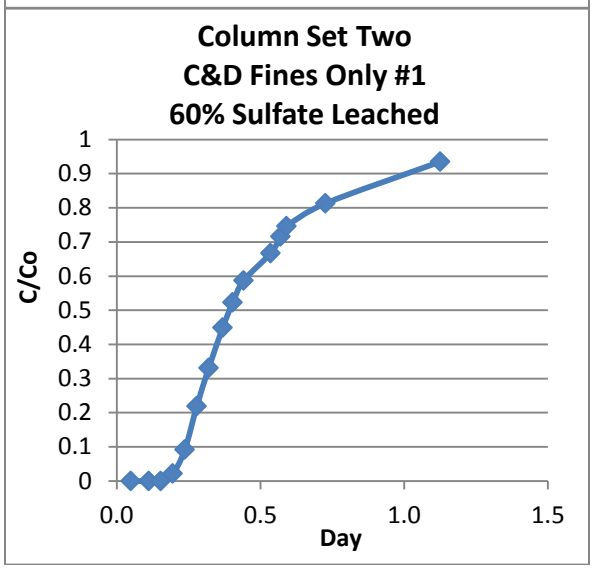

Column Set One
40lbs Lime/Ton #3
0% Sulfate Leached
C/Co
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.0
0.5
1.0
1.5
Day

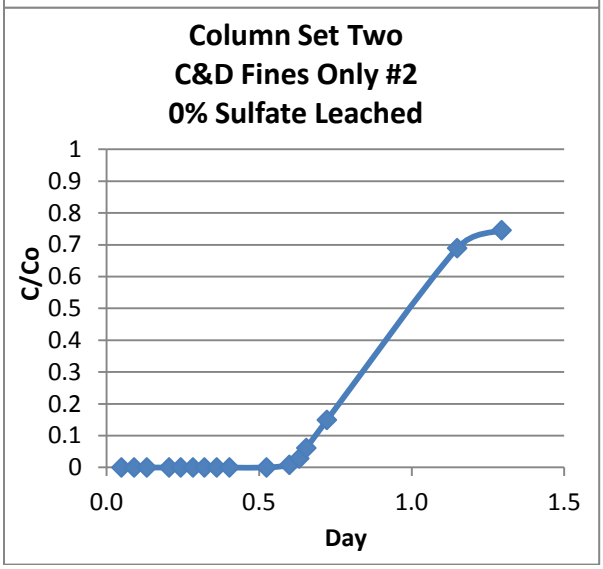

Column Set One
40lbs Lime/Ton #3
12% Sulfate Leached
C/Co
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0.0
0.5
1.0
1.5
Day

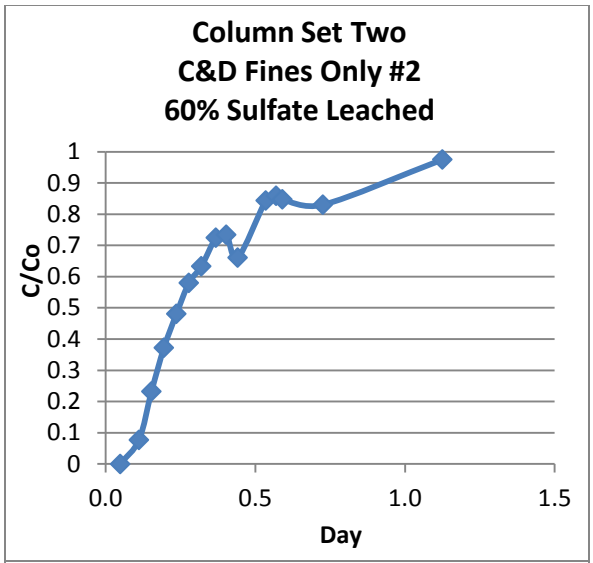

Column Set One
40lbs Lime/Ton #3
34% Sulfate Leached
C/Co
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0.0
0.5
1.0
1.5
Day

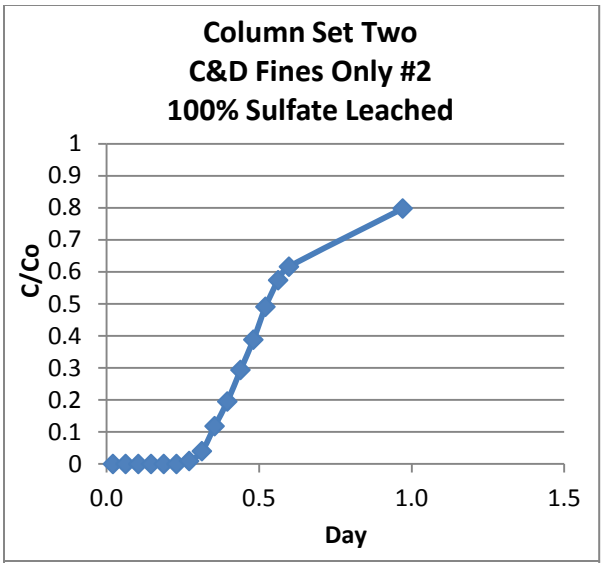

Column Set Two
C&D Fines Only #1
0% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

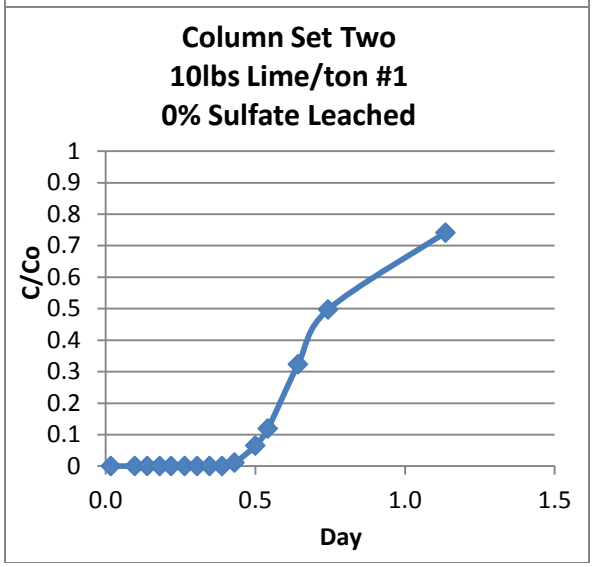

Column Set Two
C&D Fines Only #1
25% Sulfate Leached
C/Co
Day
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1.0
0.0
0.5
1.0
1.5

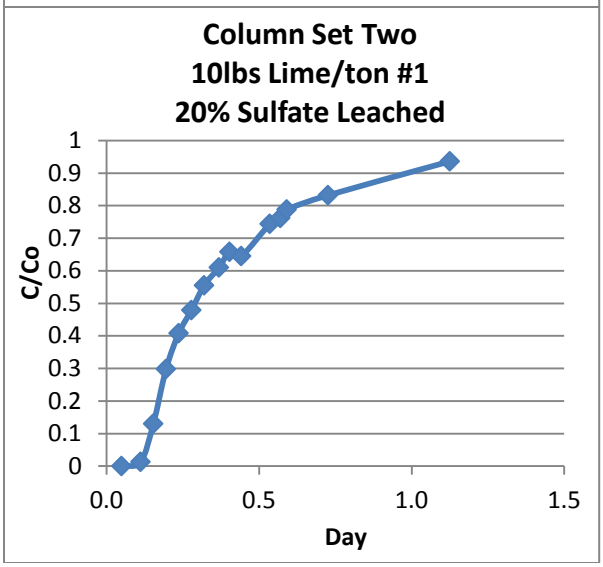

Column Set Two
C&D Fines Only #1
60% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

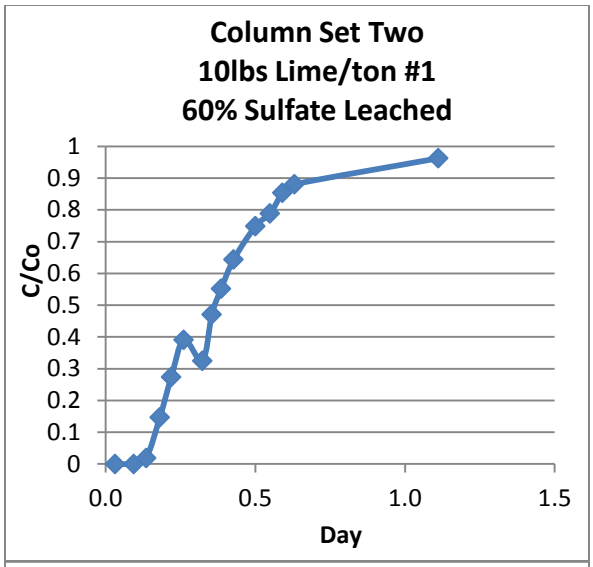

Column Set Two
C&D Fines Only #2
0% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

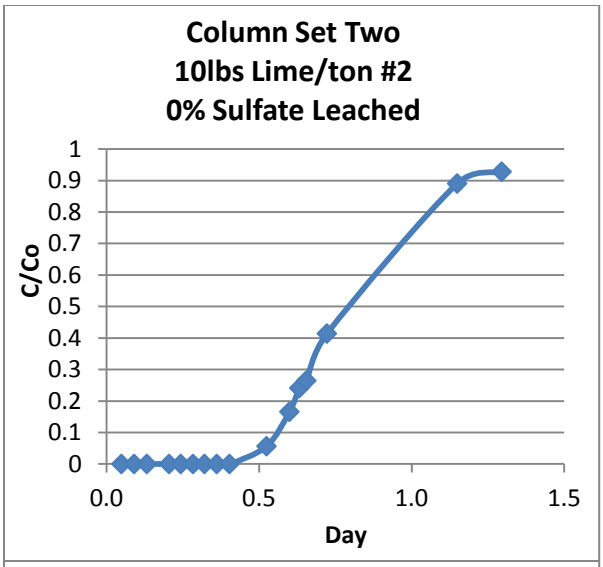

Column Set Two
C&D Fines Only #2
60% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

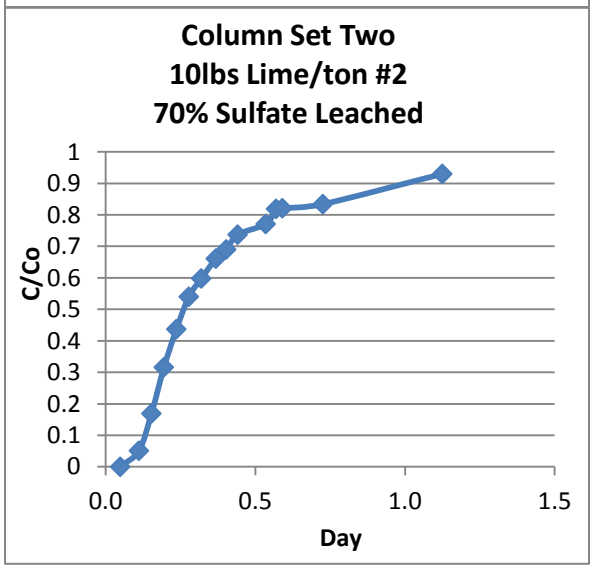

Column Set Two
C&D Fines Only #2
100% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5

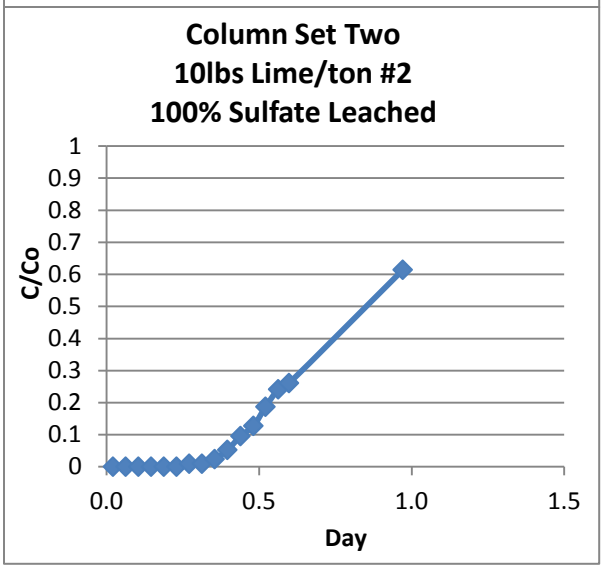

Column Set Two
10lbs Lime/ton #1
0% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5


Column Set Two
10lbs Lime/ton #1
20% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5


Column Set Two
10lbs Lime/ton #1
60% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5


Column Set Two
10lbs Lime/ton #2
0% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5


Column Set Two
10lbs Lime/ton #2
70% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5


Column Set Two
10lbs Lime/ton #2
100% Sulfate Leached
C/Co
Day
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0.0
0.5
1.0
1.5