Physical and Chemical Stability of Admixtures in Unpaved Road Soils

by

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Disclaimer

Abstract

Admixtures are placed to control dust and increase strength on unpaved roads. A previous study (Palmer, et al., 1994) has investigated the density and strength changes caused by additives. This project has investigated the performance of the admixtures during and after leaching has occurred.

This report presents information in two main areas of investigation. The first is a soil column study to determine downward, one-dimensional solute transport properties and trends of the admixtures lignin sulfonate, magnesium chloride and calcium chloride. They are applied to stabilize the road soil in a liquid form at about 1/2 gallon per square yard (2.4 L/m^2) or at about 3 percent by weight. The transport properties determined include the retardation factors, the coefficients of hydrodynamic dispersion, the dominant transport mechanism for each additive-soil combination and the effective life of the admixtures in terms of number of pore volumes of water passed through the soil column.

The second area is a rain simulation study to evaluate various physical properties of the road surface related to the addition of the admixtures and/or Kaolinite. These properties include infiltration rates, runoff rates, erosion, and upward leaching of the admixtures into the surface runoff water. These two sections of study allow the effective life (in terms of mm of rain) of the admixtures to be determined. From the effective life, an admixture application schedule is developed.

Additional information studied and researched included: strength increase of the road soil, environmental effects of the leaching admixtures, and a simulation of the solute movement using a computer program.

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Executive Summary

Physical and Chemical Stability of Admixtures in Unpaved Road Soils

Unpaved roads make up a large portion of America's transportation routes. Although these roads are not as smooth and easily traveled as paved roads, they provide a substantial travel route for low volume use such as farm to market roads, forest service roads and haul roads, and can be constructed much more economically than paved roads. Being constructed of local materials, the road surfaces may not have suitable properties for long term stability. They also may have problems with dust generation, washboarding or rutting.

Chemical additives often are applied to the soil surface to reduce dusting. Traditionally, Calcium Chloride and Magnesium Chloride salt solutions have been used, but a third material, Lignin Sulfonate also has become available. Recommended application rates for each of these solutions is 1/2 gallon per square yard (2.4 liters per square meter). This recommendation is made without regard for soil type.

The salts and the lignin solutions have different effects that reduce dusting of the soil. The salts alter the moisture-holding characteristics of the soil that keep the fines moist and attached to the coarser particles through capillary dependent apparent cohesion. Conversely, the lignin acts similar to a sugary coating on the particles holds them together like a cement paste. Because both of these modify the soil structure, they can affect the long term strength of the soil.

The admixtures are all water soluble. Rain will cause them to leach out of the soil, changing the admixture concentration and leaching chemicals into the environment. As the dust-reducing capabilities are diminished, more admixture must be applied to the road surface, increasing the maintenance costs of the road.

A previous study (Palmer, et al., 1995) investigated the strength and density variations caused by different admixture concentrations in three different soils. This study investigates the movement of additives out of the road surface so the effective life of the admixture can be estimated.

Tests Performed

A series of column tests were conducted to determine the transport properties of the admixtures in soil with flowing water. Three soils with differing amounts of clay were mixed with 0 percent, 2 percent, and 4 percent additive by weight, spanning the recommended application rate. The samples were compacted into 180 mm long columns and clear water was trickled through the samples at two or three flow rates. Effluent samples were tested for additive concentrations and the results were plotted as pore volumes of flow against effluent concentration. (One pore volume is the volume of all the air and water in a sample. Two pore volumes of water is the volume of water required to fill the pore space of a sample twice.) The plots show breakthrough conditions, described as the number of pore volumes at which the concentration equals one half of the initial concentration. Based on the advection-dispersion equation for this set of conditions, three factors describing the chemical transport were determined:

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1) the hydrodynamic dispersion coefficient, D_H,
2) the retardation factor, R_d, and
3) the column Peclet number, P_L.

Using these values in the advection-dispersion equation permits estimation of the time required to completely or partially leach the chemicals out of the soils.

After the samples leached to equilibrium conditions, they were extruded out of the columns, trimmed to a 2:1 length to diameter ratio, air dried for seven days, and loaded in uniaxial compression to failure. In addition, selected samples also were strength tested at 0, 1.0 and 1.5 pore volumes of flow.

A rainfall study also was performed. Six selected additive application concentrations and soil types were compacted into runoff pans with dimensions of 1000 by 300 by 50 mm. The pans were sloped at 2 percent as specified by AASHTO for construction of unpaved roads. A 25 mm rainfall was applied for two hours using the University of Wyoming rainfall simulator. Runoff samples were collected to determine runoff sedimentation amounts and admixture losses. Infiltration rates were estimated using compacted samples and surface erosion patterns in the compacted pans were evaluated. Finally, after the sections had a seven-day drying period, vertical additive concentration distributions were determined in sample blocks.

Results of Testing

Several significant findings were determined from the testing procedures. Conclusions based on the column study will be presented first.

1) The Calcium Chloride and Magnesium Chloride behaved similarly in terms of transport properties. They are both conservative solutes which implies they are readily carried from the soil in the aqueous phase regardless of initial additive concentration and that they have no adsorptive properties onto the soil particles.

2) Addition of clay to the initially coarse soil caused the governing transport mechanism to change from advection dominated to diffusive/dispersive dominated. This was indicated by the Peclet numbers which varied from 45 to 6 as clay was added to the soil.

3) Clay retards transport of the additives. With no clay, 80 percent removal of the salts occurs between 0.8 and 1.0 pore volume of flow while 8 percent Kaolinite extends this to 1.8 pore volumes.

4) The time of leaching is related to the infiltration rate of the soil and the rainfall rate. In general, for the range of soil types tested, the salts leached out of the soil to equilibrium conditions in three to nine days, with the total amount of water being about one pore volume.

5) The lignin sulfonate has transport properties similar to the salts. Increasing the clay percentage in the soil has a somewhat greater effect on the retention of lignin than it does in the salts.

6) The dominant transport mechanism for the lignin is diffusion/dispersion. Advection was not found to be significant in the range of soil tested. The lignin significantly decreased the hydraulic conductivity compared to the salts.

7) Eighty percent of the lignin leached out of the soil in 1.3 pore volumes compared to 1.0 or less pore volumes for the salt. Even though the soil may still have some additive in it, by this point, there should be a reapplication of additive.

8) The lignin produced a strength approximately three times greater than the salts. After one pore volume of flow, the lignin samples had higher residual strengths than the salt samples before they were leached.

Significant results from the Rainfall Simulation follow.

1) The lignin combinations had the lowest infiltration rates. A 6 mm crust was formed on the sample surface which blocked the infiltration and prevented the lignin from being leached away. The salts reduced infiltration about midway between the lignin and the untreated soil.

2) Addition of clay lowers the infiltration rate in all cases and extends the life of the admixture.

3) Surface runoff was the highest with the lignin samples and lowest with the untreated soils, i.e., the inverse of the infiltration rates. Similarly, the samples with clay had higher runoffs than those without clay.

4) The salt concentration in the runoff water was low initially and decreased with continuing runoff. The runoff concentration of lignin was significantly higher than for the salts. Apparently the high lignin concentration in the crust provides more opportunity for water to remove the lignin. The lignin loss was significantly lower when it was mixed in the clay-like soils. This has a significant effect on the usable life of the lignin. While there is some effect on the salt-treated soils, it is not nearly as pronounced as with the lignin.

5) The lignin-treated soils showed the smoothest surface after runoff and erosion. The other samples showed more surface disturbance. Raindrop loosening had a considerable effect on the surface roughness.

6) Post rain drying carried the additives back to the surface where they had the greatest effects. In this regard, the admixtures tend to be self healing, which extends the useful life of the additive.

7) There does not appear to be significant lateral movement of the salts or lignin. The water flow apparently is mainly vertical and can be analyzed using a 1-D flow model.

Recommendations

Based on the column study and rainfall study of this project and the density and strength study of the previous project (Palmer, 1994), the following application schedule is recommended.

Base Soil	Addition of Clay	1st Application	Concentration (gal/yd^2)	2nd Application	Concentration (gal/yd^2)
A + Lignin	Yes - 3% Advised	Spring*	0.75	None	0
A + Lignin	No	Spring*	0.75	None**	0
A + $CaCl_2$	No	Spring*	0.75	Late Summer***	0.5
A + $MgCl_2$	No	Spring*	0.75	Late Summer***	0.5

* Following the major spring rainfall.
** Second application would be required following 12" of accumulated rain.
*** Following 3.5" of rain accumulation.

The use of lignin sulfonate is recommended from both Palmer's study and the current one based on the physical properties studied.

Further Studies

Based on the current study, additional studies are recommended. A long term study on the impact to the environment should be developed. It is believed that the lignin has lower impact than the salts on vegetation and also possibly on wildlife. It has been shown that road salts raise the chloride levels in ditches and streams and are detrimental to fish. Lignins will raise the Biological Oxygen Demand (BOD) in surface water which could adversely affect fish and wildlife. These additives should be monitored to determine what if any affect they are having on the environment.

A second study would be an economic evaluation to determine the real economic differences between long term applications of the individual admixtures. This would include the number of applications required, the cost of the additives and the longer term stability of the individual treatments.

CHAPTER 1. INTRODUCTION

Problem Statement

Unpaved roads make up a large portion of America's transportation routes. Although these roads are not as smooth and easily traveled as paved roads, they provide a substantial travel route for low volume use such as farm to market roads, forest service roads and haul roads, and can be constructed much more economically than paved roads.

Following the initial construction of these unpaved roads, a maintenance plan must be devised to increase the stability and hence, the life of the road. The maintenance plan for these roads usually includes application of some type of chemical additive that reduces the amount of dust blown from the road surface. According to Palmer (1994), these additives also can increase the strength of the road soil through stabilization. Application rates for these additives are usually 1/2 gallon per square yard (2.4 liters/m^2) which yields approximately 3 percent of the additive by weight in the top two inches of the road surface (Hansen, 1982). The three most common additives used for this application are Magnesium Chloride, Calcium Chloride and Lignin Sulfonate.

The reapplication interval and hence, the effective life of these additives has not yet been studied. The effective life of the additive in question is most affected by water (usually from rain) leaching the additives out of the soil. Both the salt additives and the lignin sulfonate are readily water soluble, which allows for this leaching process to take place (Langdon and Williamson, 1983). There are two basic problems caused by this leaching process. The first is mechanical; if the additive isn't in the road surface, it can't provide the increased strength to the road surface. The second is environmental. Because these road additives may contain environmentally unacceptable contaminants (e.g. chlorides, heavy metals, BOD increasing organic compounds), potentially harmful conditions could arise if these toxic constituents leach into the ground or surface water (Langdon and Williamson, 1983).

Objectives

The main objective of this project was to model the movement of the road stabilization additives out of the road surface so the effective life of the additives could be determined. The study included a one-dimensional column study, a two-dimensional rain water simulation as well as an attempt to simulate the field conditions using a computer model. Secondary objectives were to test for residual strength in the soil columns following leaching and research the environmental effects these additives may have on vegetation and water sources.

The column study consisted of compacting the base soil from the Fox Park Pit (simulating ASTM standards) with varying concentrations of the three selected road additives. The base soil also was blended with two specified concentrations of clay and additives added. Following compaction, the columns were leached at three constant flow rates until the additive in question was essentially leached from the column. The soil cores were then dried for seven days and strength tests were performed.

The concentration measurements from the column study were then plotted and fit to the advective-dispersive model to determine the coefficient of Hydrodynamic Dispersion (D_H) as well as the Retardation Factors. These parameters are a function of seepage velocity, soil type (clay content), additive concentration and additive type. This part of the study also indicated how easily the solutes were leached from the soil.

The rain simulation study was executed using a rain-simulator, and rain rate (loading) was controlled. This study was done to determine the amount of runoff, infiltration and additive concentration in the runoff water for a given additive, and rain loading and soil type on a sloped 1/4 section of road. The constructed road section also was subjected to an intermittent raining and drying cycle. This was done to determine the additive distribution/accumulation in a soil core following the evaporation process.

The results from these two sections of study allowed a maintenance schedule to be developed based on the amount water infiltrated, amount of runoff, and the amount of water it takes to leach the additive out of the road. In summary, this schedule was a function of soil type, amount of rain, additive type and additive concentration.

The results also were used to simulate this process with a computer model. Finally, the computer model was utilized to simulate different scenarios of admixture movement based on different combinations of additive concentration, additive type, rain loading, and soil type.

CHAPTER 2. LITERATURE REVIEW

Introduction to the Literature Review

The main focus of this study is to model the transport of the road additives through the soil in the aqueous phase. The paralleling study is a rain water simulation, which provides an indication of how much water infiltrates the road surface. This simulation also indicates the concentration of the additive that is carried away in surface runoff.

Solute transport is the primary process acting in the overall study and is therefore the main focus of the literature review. This includes information on all of the solute transport processes and material on one-dimensional column studies. The review also includes a section on the infiltration, runoff, and erosion processes that take place during the two-dimensional rain simulation. This is important information, since both the infiltrated water and the runoff water carry the road additives out of the soil cross-section.

Secondary literature reviewed involves both environmental concerns, soil chemistry, as well as some work in the strength of soils. The environmental aspect is important because the road additives contain some chemical species that may contaminate water, kill vegetation or are regulated by the EPA. Soil chemistry must be investigated, especially for soil with high clay content. Chemicals in soil of this nature have major affects on the soils' structure and permeability and may cause overall reactions with the soil . Following the leaching process the strength of soil will be researched by conducting residual strength tests using the unconfined compression test.

About The Additives

Lignosulfonic acid is a waste product of the sulfite pulping process in the paper industry and is produced in hundreds of thousands of tons yearly. Wood is processed by treating it with sulfuric acid, which breaks down the wood fiber. The waste consists of spent acid and closely related high molecular compounds such as proteins, starch, cellulose, etc. (Brauns, 1952). Following this stage, the "pulp liquor" is usually further processed by neutralizing the acid and reducing the water content. This forms *lignin sulfonate* normally a 50 percent water and 50 percent solid mixture (Langdon and Williamson, 1983).

The primary effects of lignosulfonates on soil are those of cementation and dispersion of clays (Gow et al., 1961). Cementation is derived from the fact that lignosulfonates, being water soluble, act as a glue in the soil. This cementation is due to two physical phenomena: (1) the increase in surface tension in pore water, which results in an increase in apparent cohesion, and (2) reinforcement at the points of particle contact caused by concentration of the clay at those points. Dispersion of the clay fraction benefits stability by plugging voids (decreasing hydraulic conductivity) and consequently increasing water tightness.

Magnesium and Calcium Chloride additives are brines manufactured especially for dust control and soil stabilization. The nearly saturated brine applied is usually 30 to 34 percent salt by weight and has a specific gravity of about 1.30 or a density of about 11 lbs/gallon (Great Salt Lakes Mineral Corp.).

Soil stabilization is achieved due to the hygroscopic and deliquescent properties of these *salt additives* These properties give the soil the ability to resist drying out and maintain the soil at a semi-moist state. Hygroscopicity is the property of absorbing moisture from the air; deliquescence is the property of dissolving in this moisture to form a liquid solution. With both hygroscopic and deliquescent actions acting together, the brine remains in liquid form for longer periods of time and creates a change in pore fluid surface tension.

The vapor pressure of these solutions is much lower than that of pure water at the same temperature. Because evaporation is a direct function of vapor pressure, the evaporation rate is slowed down significantly. Surface tension of salt solutions also is higher than that of pure water - a property that further inhibits evaporation (Sheppard et al., 1990).

The effect of hygroscopicity, deliquescence, lower vapor pressure, and increased surface tension provided by a magnesium or calcium chloride solution in a stabilization project allow the moisture content to be maintained longer - an important factor in obtaining maximum density in the compacted soil and in controlling dust. Additional soil strength also is achieved through particle charge bonding of the fine grained fraction, cationic exchange, crystallization, and possibly chemical reaction with some soil particles (Hansen, 1982).

Solute Transport in the Soil

Many processes are involved in transporting a particular solute or contaminant through the soil. These processes include advection, molecular diffusion, and mechanical dispersion. The basic model to simulate this solute transport dates back to the first part of the twentieth century and is based the *Advective-Dispersive Transport Theory.* The model includes the previously-stated processes and has proven effective in simulating solute transport by such scientists as Ogata and Banks (1961). Also included in this model is the retardation term which is governed by the solute adsorbing on the solid phase of the porous media and consequently, slowing the movement of the solute out of the soil (Ogata, 1970 and Shackelford, 1995b).

Advection

Solutes, or in this case the dissolved road additives, that are carried in groundwater are transported by the process known as *advection* or sometimes termed convection. Advection is defined as the process by which solutes are transported by the bulk motion of the flowing groundwater (Freeze and Cherry, 1979). As paraphrased by Bear (1972), the average linear velocity or the seepage velocity is the flow normal to a unit cross-sectional area divided by the effective porosity (n_e), and is closely related to the advection process. Due to such affects as dead end pores or trapped (occluded) air, not all of the pore space is available for advective transport. Therefore, effective porosity reduces actual porosity in the advection process. The seepage velocity equation is shown below:

$$v_x = \frac{K}{n_e}\frac{dh}{dt} \qquad \textbf{(2.1)}$$

where:

$v_x =$ *seepage velocity (L / T)*
$n_e =$ *effective porosity*
$K =$ *hydraulic conductivity (L / T)*
$\frac{dh}{dl} =$ *hydraulic gradient (L / L)*

Finally, the one-dimensional advective transport equation is shown and is a direct function of the seepage velocity (v_x). The negative sign indicates a downward movement.

$$\frac{\partial C}{\partial t} = -v_x \frac{\partial C}{\partial x} \qquad \textbf{(2.2)}$$

where:

$\frac{\partial C}{\partial t} =$ *Change in concentration with time*
$\frac{\partial C}{\partial x} =$ *Change in concentration with distance*

The characteristic wetting front for the advection process yields a sharp concentration change. Ahead of the front, the solute concentration is quite close to background level. Behind the front, the concentration is nearly the same as the invading water.

Molecular Diffusion

A solute will travel from an area of high concentration to an area of low concentration. The force that causes this solute transport is the concentration gradient. Movement occurs as long as the gradient exists even if the bulk pore fluid isn't moving. The solute movement through water for a given concentration gradient can be expressed in a one-dimensional form using Fick's First Law (Freeze and Cherry, 1979, and Zimmie and Riggs, 1979) and is shown in equation 2.3.

$$F = -D_d \frac{\partial C}{\partial x} \qquad \textbf{(2.3)}$$

where:

$F = mass\ flux$

$D_d =$ *diffusion coefficient* (L^2 / T)

$C =$ *solute concentration* (M / L^3)

$\frac{\partial C}{\partial x} =$ *concentration gradient* $(M / L^3 / L)$

The concentration gradient induced movement also takes place when the concentration is not constant. This process is described in one-dimension using Fick's Second Law and is:

$$\frac{\partial C}{\partial t} = -D_d \frac{\partial^2 C}{\partial x^2} \qquad \textbf{(2.4)}$$

where: $\frac{\partial C}{\partial t} =$ *change in concentration with time.*

Diffusive movement through porous media follows a longer path than through water because the solute must travel around the soil grains. This longer process is accounted for by using the effective diffusion coefficient (D^*) in place of D_d . The effective diffusion coefficient is defined as:

$$D^* = \omega\, D_d \qquad \textbf{(2.5)}$$

where ω is the coefficient that accounts for tortuosity and is always less than one (Bear, 1972). *Tortuosity* measures the effect of shape of flowpath on water flowing through a porous media. Tortuosity (*T*) is defined as L/L_e, where *L* is the straight line path of flow and L_e is the tortuous path the water molecules travel between the grains of soil. The value of ω that accounts for the tortuous path ranges from 0.7 for sandy soils to 0.1 for fine grained soils (Freeze and Cherry, 1979). According to Perkins and Johnston (1963) the value of tortuosity is $\omega = \dfrac{D^*}{D_d} \cong \dfrac{1}{\sqrt{2}} = 0.707$ for a coarse grain soil, since fluid must move on average at about 45° to the net direction of flow as shown in Figure 2.1. Hence, when the fluid has traveled a net distance L, it has actually traveled an average distance of $\sqrt{2}\,L$.

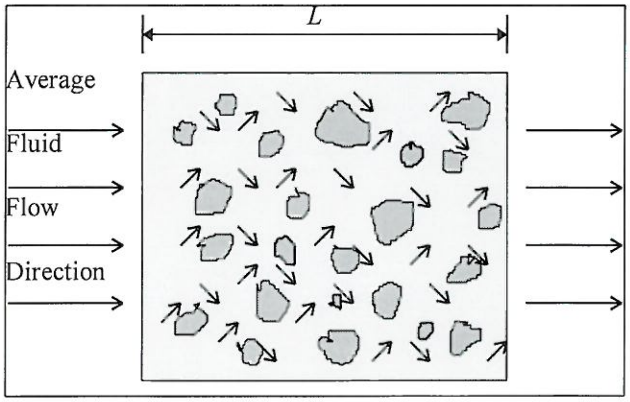

Figure 2.1 Fluid flow at about 45° with respect to average flow direction in a porous medium. Source: Perkins and Johnston (1963).

Mechanical Dispersion

The previous two sections discussed fluid movement that would create an abrupt interface between the connate water and the invading groundwater with respect to solute concentration. Since there is mixing, this abrupt interface is not a realistic description. Therefore, another process must be at work with advection and diffusion. This process, which accounts for the mixing at the displacing water front, is termed *mechanical dispersion*. Considering a domain large enough so effects of individual pores are averaged, there are three basic causes of this phenomenon (Bear, 1972). They are shown in Figures 2.2, 2.3 and stated below:

(2) Path Length - Some fluid particles will travel along longer paths than others.

(2) Pore Size - Some pores are larger than others allowing for different fluid velocities.

(3) Pore Friction - Fluid will move faster in the center of the pore than at the edge.

Two components are involved in the mechanical dispersion process: longitudinal dispersion, governed by the processes shown in Figure 2.2, and lateral dispersion, governed mainly by flowpath as shown in Figure 2.3 (Fetter, 1988). Longitudinal dispersion occurs along the direction of flowpath and is usually dominant over lateral dispersion, which occurs perpendicular to the flowpath (Freeze and Cherry, 1979).

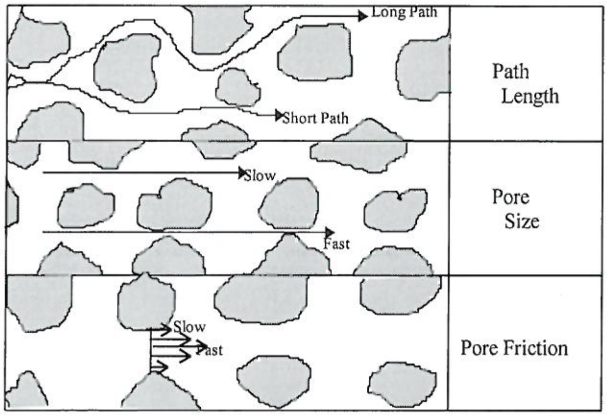

Figure 2.2 Physical features causing longitinal dispersion. Source: Fetter, 1988.

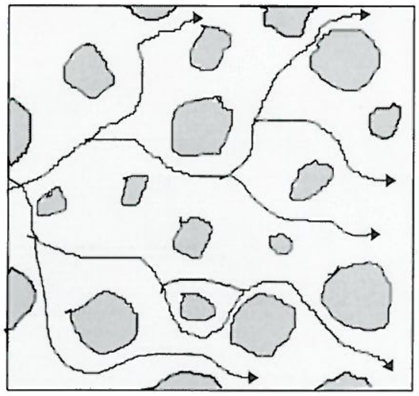

Figure 2.3 Flowpaths causing lateral dispersion. Source: Fetter, 1988.

The coefficient of mechanical dispersion (D_m), as described by Freeze and Cherry (1979), is a function of average linear velocity and is equal to a property of the medium called dynamic dispersivity, α , times the average linear velocity. Since dispersion in the longitudinal direction dominates, then $D_m = \alpha_L v_i$, where i is the principle direction of flow and L is the longitudinal direction.

The Advection-Dispersion Equation

Three mechanisms previously described, as well as processes such as adsorption (retardation), must be included when modeling the transport of a given solute through a porous medium with a mathematical model. The one-dimensional transport model that is used is the well-known advective-dispersion equation (Shackelford, 1995a), or:

$$R_d \frac{\partial c_r}{\partial t} = D_H \frac{\partial^2 c_r}{\partial x^2} - v \frac{\partial c_r}{\partial x} \qquad \textbf{(2.6)}$$

In this equation, c_r is the solute concentration in the pore water of the soil, t is time, x is the macroscopic distance in the direction of transport, v is the average linear or seepage velocity, R_d is the retardation factor and D_H is the coefficient of hydrodynamic dispersion (dispersion/diffusion coefficient).

When applying this form of the advective-dispersive model, there are a few basic, but important assumptions that are made (Shackelford, 1995a, 1994). The assumptions are that seepage velocity, volumetric moisture content, retardation, diffusion/dispersion processes all are constant and the soil is homogenous, isotropic, and nondeformable. The neglected processes include chemical processes (e.g., radioactive decay, precipitation, etc.) and/or biological reactions (e.g., biodegradation).

The *retardation factor* (R_d) accounts for linear, reversible, and instantaneous equilibrium adsorption of reactive solutes. For adsorbing solutes, $R_d>1$ and for non-reacting solutes $R_d=1$, assuming that all pore space is conducting flow (Shackelford and Redmond, 1995b).

The *coefficient of hydrodynamic dispersion* (D_H) both mechanical dispersion and molecular diffusion and can be expressed in terms of the two components (Freeze and Cherry, 1979),

$$\begin{aligned} D_H &= \alpha_l\, v + D^* \\ &= D_m + D^* \end{aligned} \qquad \textbf{(2.7)}$$

where:

D_m = *coefficient of mechanical dispersion*
D^* = *effective diffusion coefficient.*

At low velocity, diffusion is an important contributor to dispersion. Therefore, the coefficient of hydrodynamic dispersion equals the diffusion coefficient ($D_H = D^*$); that is, as $v \to 0$, $D_m \to 0$ and D_H reduces to Fick's second law (Shackelford and Redmond, 1995b). At high velocities the dominant contributor to dispersion is mechanical mixing. Consequently, the coefficient of hydrodynamic dispersion equals the coefficient of mechanical dispersion ($D_H = \alpha_l v = D_m$), (Gershon and Nir, 1969).

Solutions to the Advection-Dispersion Equation

Definition of Terms

The *number of pore volumes* of flow is the cumulative amount of feedwater passed through the column divided by one pore volume of the soil in the column. The column porosity must be determined by standard methods to plot the number of pore volumes versus normalized concentration in the breakthrough curve.

The *normalized concentration* is the actual measured effluent concentration taken periodically at the end of the soil column (@ x=L) divided by the original (initial) concentration of the pore fluid. The normalized concentration is plotted on the y-axis of the solute breakthrough curve.

The *column Peclet number* is a specific number for a given soil type, seepage velocity and column length. It represents the relative effect of advective transport based on seepage velocity to the dispersive/diffusive transport based on the value of D_H (Shackelford, 1994). At high Peclet numbers (e.g., P_L>40) advective transport dominates, and at low Peclet numbers (e.g., P_L<5) diffusive/dispersive transport dominates the process. Additionally, coarse grained materials usually yield higher Peclet numbers and consequently, more advective transport compared to fine grained soils.

The *retardation factor* is a dimensionless factor related to the ability of a given soil to adsorb solutes during the transport. That is, the larger the retardation factor, the greater the adsorption capacity of the soil for that particular solute. Solutes with reactive properties have $R_d>1$, while nonreactive solutes have $R_d=1$. The retardation factor only represents attenuation due to reversible equilibrium exchange reactions. During actual testing it may be difficult to distinguish reversible equilibrium exchange reactions from nonreversible reactions such as precipitation (Shackelford, 1994).

There are two mathematical definitions for the retardation factor. The first is determined from results of batch equilibrium tests using (Shackelford and Redmond 1995b):

$$R_d = 1 + \frac{\rho_d}{n} K_d \qquad \textbf{(2.8)}$$

where ρ_d is the dry density of the soil, n is the porosity and K_d is the slope of the adsorption curve known as the "distribution coefficient". The retardation also can be defined as the ratio of the average flow rate of a nonreactive solute to that of a reactive solute (Freeze and Cherry, 1979), or:

$$R_d = \frac{v_n}{v_r} = \frac{v_n t_c}{L} \qquad \textbf{(2.9)}$$

where v_n is the average linear velocity of a nonreactive solute, v_r is the rate of movement for a reactive solute, and t_c = the time required for the center of mass to reach the end of a column of length, L. This is the definition for determining the retardation factor from column studies. According to Shackelford (1994), the method based on column studies is the best method to determine R_d, since the porosity and soil density are more similar to field conditions than batch tests which represent static slurry suspensions. The column tests also represent a transient system in which there is flowing chemical solution.

The values of R_d can vary with soil type and solute in the pore water. Although this is true, research has found that for coarse-grained material with nonreactive solutes (R_d=1), a relative effluent concentration of 0.5 is reached when one pore volume (T) has passed the column. This corresponds to purely advective transport. However, some studies indicate breakthrough can occur much earlier ($T < 1$). These studies involve soils and seepage velocities which impart dispersive/diffusive transport (Shackelford, 1994). From this statement, it can be concluded that R_d can be less than a value of one. It has been found that other factors can cause the retardation factor to be less than one. These factors are discussed further in the conclusion.

Introduction to Column Testing

The advection-dispersion equation has many different solutions depending on the initial and boundary conditions. These different solutions are usually applied to "soil column tests" to obtain the parameters R_d and D_H. This is achieved by fitting the analytical solution to the measured effluent data from the laboratory column tests in the form of "breakthrough curves". These "solute breakthrough curves" are plots of *normalized concentration* of effluent out of the soil column versus *number of pore volumes* of displacing water passed through the column.

In the first and most common solution, the soil is free of the solute, and water, with a known concentration of the solute, is passed through the soil section (case one). The concentration of the solute leaving the soil section is measured periodically. The soil section is a soil column of known length and cross-sectional area. This test data has a typical "S" shaped breakthrough curve that is shown in Figure 2.4.

Another solution to the advection-dispersion equation fits the conditions for this project. This solution is not very common, but seems realistic for many applications. Initially, the soil in this scenario has a known concentration of the solute in the soil (case two). The feedwater displacing the soil solution is free of any solutes and the effluent leaving the soil column is measured for the concentration of the solute. A typical breakthrough curve for these conditions is shown in Figure 2.5.

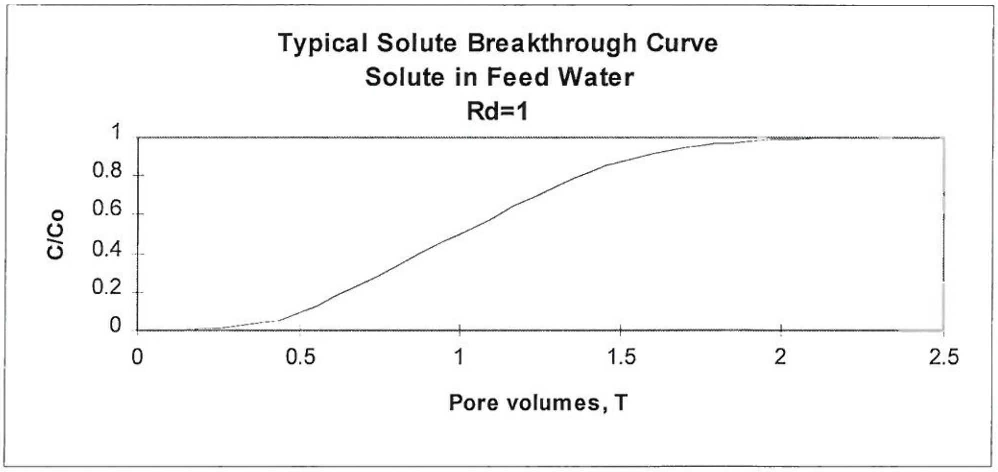

Figure 2.4 Typical solute breakthrough curve with solute in feedwater.

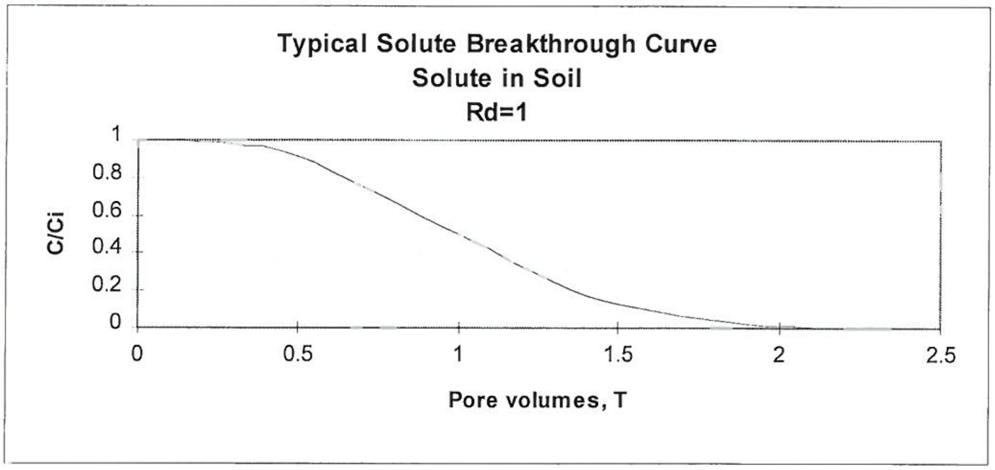

Figure 2.5 Solute breakthrough curve with solute initially in the soil.

Two solute concentrations must be considered based on the assumed column length of the soil (Fig. 2.6). If the column is assumed to be infinite in length, the solute concentration at location x = L is the resident concentration, c_r (Shackelford, 1994).

The second type of concentration that is discussed is the effluent concentration, c_e. This concentration is used in a finite column analysis of length *L*, and is the flux averaged concentration of solute in water leaving the column. The difference between these two types of concentrations is shown in Figure 2.6. The effluent concentration will be used in this project.

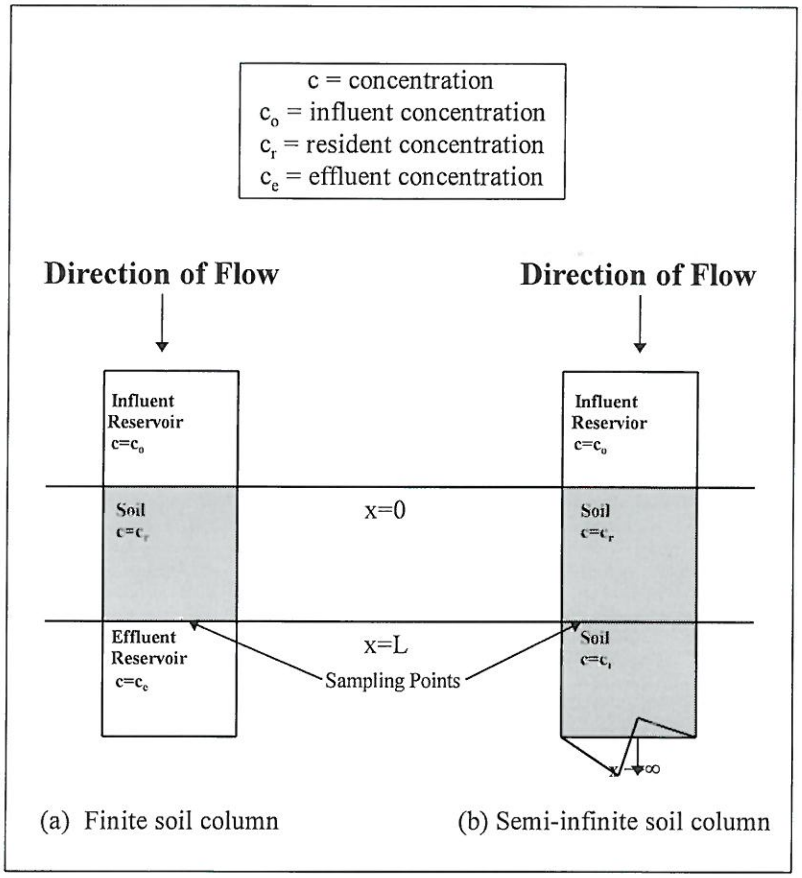

Figure 2.6 Difference between resident and effluent concentration. Source: Shackelford, 1994.

Solutions

Solute Flow into Initially Clear Soil - The solution to case one is now investigated. Before solving this case, the initial and boundary conditions must be stated. Since a finite column analysis is used, the boundary conditions and the solution are in terms of effluent or flux-averaged concentration. The initial and boundary conditions are as follows (Lapidus and Amundson 1952; Ogata and Banks 1961; Shackelford 1994):

$$c_e(x,\ 0) = c_i = 0; \quad c_r(0,\ t) = c_o; \quad \frac{\partial c_e(\infty,\ t)}{\partial x} = 0 \quad \textbf{(2.10)}$$

which results in the following solution:

$$\frac{c_e(L, t) - c_i}{c_o - c_i} = \frac{c_e}{c_o} = \frac{1}{2}\left[erfc(\xi_1) + exp(\xi_2)erfc(\xi_3)\right] \quad \textbf{(2.11)}$$

The dimensionless arguments for the analytical solution (2.11) are as follows:

$$\xi_1 = \frac{1 - T_R}{2\sqrt{\frac{T_R}{P_L}}};\ \xi_2 = P_L;\ \xi_3 = \frac{1 + T_R}{2\sqrt{\frac{T_R}{P_L}}} \quad \textbf{(2.12)}$$

where:

$$T_R = \frac{vt}{R_d L} = \frac{T}{R_d},\ and\ P_L = \frac{vL}{D_H} \quad \textbf{(2.13)}$$

Clear Water Flow into Initially Solute Filled Soil - The solution to case two, which has the solute initially incorporated in the soil matrix, is now stated (van Genuchten and Alves, 1982). The initial and boundary conditions are:

$$c_e(x, 0) = c_i;\quad c_r(0, t) = c_o = 0;\quad \frac{\partial c_e}{\partial x}(\infty, t) = 0 \quad \textbf{(2.14)}$$

which yields the following solution:

$$\frac{c_e(L, t)}{c_i} = \frac{c_e}{c_i} = 1 - \frac{1}{2}\left[erfc(\xi_1) + exp(\xi_2)erfc(\xi_3)\right. \quad \textbf{(2.15)}$$

where the arguments are the same as previously stated for case one.

In both solutions, *T* is a dimensionless time factor representing the number of pore volumes of flow passed through the column, P_L is the column *Peclet number, v* is the average linear velocity, R_d is the retardation factor, *L* is the length of the column and D_H is the coefficient of hydrodynamic dispersion.

Applying Advective-Dispersive Equation Solution

Values of retardation factor and Peclet number are the two main properties determined in a column study. They are found by fitting the applicable solution of the advective-dispersive equation to soil column experiment data (breakthrough curve). The values of P_L and R_d are varied until the best fit is achieved. Following this procedure, the value of D_H can be calculated based on the column length, the fitted Peclet number, and the known seepage velocity,

$$D_H = \frac{vL}{P_L}, \textit{ with appropriate units} \qquad \textbf{(2.16)}$$

Once these properties are determined, valuable information concerning the solute transport for a particular soil type is known. This information includes:

1. the transport mechanism for the solute,
2. the reactive properties of the solute,
3. the effects of different soil types on transport mechanism,
4. the effects of different soil types on reactive properties of the solute,
5. the effects of different seepage velocities the on transport mechanism,
6. the effects of different seepage velocities the on reactive properties of the solute, and
7. the speed at which different solutes leave the soil matrix as related to both time and number of pore volumes of feedwater passed through the soil column.

Soil Chemistry

Clay particles are colloidals usually having a net negative charge. The net negative charge causes the clay component to give soil many unique properties. These properties are activated when the soil comes in contact with water, especially when the water contains a significant electrolyte concentration, or some other organic or inorganic component. Since most soils contain some amount of clay as a component, it is necessary to investigate the properties, chemical reactions, and structural effects the clay component has on the soil under these conditions.

Definitions

Several important definitions used in soil chemistry follow (Mitchell, 1993 and Lambe, 1958).

Isomorphous Substitution - Accepting of one ion in a crystal structure for another ion (usually of different size and valence) without changing crystal form. Although the crystal form doesn't change, the net charge can change.

Electrical Potential - The work necessary to bring a unit charge from an infinite distance to a particular point.

Colloid - A particle that has a surface to mass ratio large enough to cause electrical forces to dominate mass forces and is in the size range of 1 micron to 1 millimicron (10A).

Electrolyte - Charged ions in water solution (e.g., Ca^{2+}, Na^{+}).

Soil Fabric - The arrangement of soil particles, particle groups, and pore spaces in a soil. The fabric has a large affect on soil strength.

Double Layer/Gouy-Chapman Theory

Clay particles are colloidal particles in a soil matrix that normally carry a net negative charge caused primarily by isomorphous substitution that is balanced by exchangeable cations. Clay, in the dry state, has the cations clustered around the clay surfaces to neutralize the charge. When the clay fraction of soil is exposed to a water environment, the cations, plus a small number of anions, swarm around the particle (Figures 2-7a and 2-7b). The swarm is termed the *double layer* and the colloid plus the ions is called the *micelle*. The double layer ends at a point where electrical potential (Ψ) is zero. The cations are sometimes called "exchangeable" since they can be replaced by other cations in the soil water solution (Lambe, 1958).

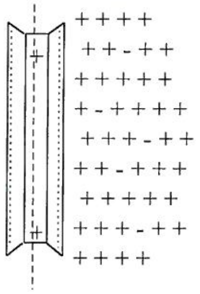

Figure 2-7a
The Clay Micelle.
Source: Lambe, 1958.

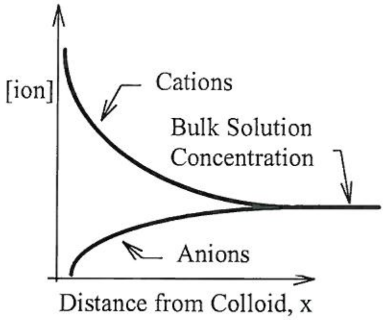

Figure 2-7b
Ion Concentration Distribution.

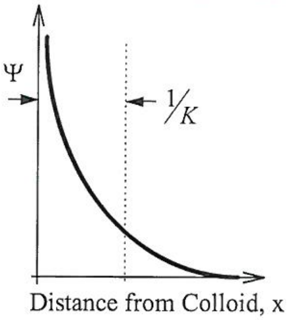

Figure 2-7c
Electrical Potential (Ψ) versus distance, *x*.

The Gouy-Chapman theory models the double layer and defines a double layer thickness (*1/K*) shown in Figure 2-7c (Mitchell, 1993). It balances the electro-static attraction acting on a cation with the repulsive forces caused by concentration gradient diffusion. The factors in the theory include electrolyte concentration (n_o), ion valence (v), dielectric constant (D), static permittivity of a vacuum (ε_o=8.85 x 10 -12 $C^2J^{-1}m^{-1}$), electronic charge in coulombs (e), Boltzman constant (k=138 x 10^{-23} J°K^{-1}) and temperature (T). Other factors that effect the double layer include size of hydrated radius, and pH (Lambe, 1958). The following equation governs the Gouy-Chapman theory:

$$\frac{1}{K} = \left(\frac{\varepsilon_o D k T}{2\eta_o e^2 v^2} \right)^{\frac{1}{2}} \qquad \textbf{(2.17)}$$

The double layer thickness is increased by:

1. Increasing the dielectric constant.
2. Decreasing the ion valence.
3. Decreasing the electrolyte concentration.
4. Decreasing the temperature.

Similarly, decreasing the hydrated radius of the cation will decrease the thickness since the ion can approach the colloidal surface more closely. High pH encourages dissociation of cations and increases the net charge, thus expanding the double layer (Lambe, 1958 and Mitchell, 1993).

Effect of Double Layer on Clay Structure

The two main structures in a clay are *dispersed* and *flocculated* (Lambe, 1958). Flocculation is the edge-to-face orientation caused as clay particles try to move closer together. The flocculated structure yields a soil with a comparatively high permeability and a random soil fabric. Dispersion is the side-to-side orientation of the clay plates when the particles try to move apart. This structure yields a soil with a more stable soil fabric and a much lower permeability. These orientations are shown in Figure 2.8. The structure of clay is mainly influenced by attractive and repulsive forces (Rosenqvist, 1959). The attractive forces are due to fluctuating dipoles, or van der Waals forces and are sensitive to electrolyte concentration, valence and other factors discussed above. The repulsive forces are due to repulsion between adjacent negatively charged faces and are essentially constant. This information leads to the following conclusions:

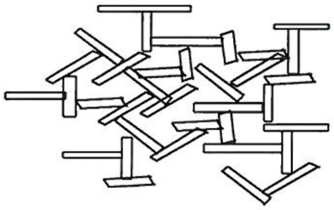

Figure 2.8a Flocculated clay structure
Source: Lambe, 1958.

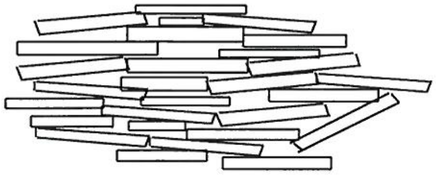

Figure 2.8b Dispersed clay structure

1. If the double layer thickness is decreased (e.g., Increase in electrolyte concentration from salts) the repulsive force acts over a shorter distance.

This allows the colloids to move closer together so the edge of one particle can be attracted to the face of another, giving a flocculated structure.

2. If the double layer thickness is increased (e.g., increased pH from organic chemical) the edge attraction is masked. Particles move further apart which prevents edge to face attraction, resulting in a dispersed structure (Mitchell, 1993 and Lambe, 1958).

Cation Exchange

Since clay colloids carry a negative charge, cations are attracted to the clay particles. These ions are held electrostatically on the surface and most are free to distribute through the liquid phase. These cations are termed adsorbed cations (Tan, 1982). Exchange reactions involve replacement of these ions with a group of different ions which may have the same or a different charge or size. This exchange may not affect the overall clay structure (Mitchell, 1993).

Three sources of exchange capacity in clays have been found (Taylor, 1959):

1. Isomorphous substitution. e.g. Al^{+3} for Si^{+4} in the silica sheet with balancing cations attracted to cleavage surface.
2. Broken bonds.
3. Replacement of hydrogen of an exposed hydroxyl.

The cation replacement occurs when a cation of one type is replaced for another (e.g., replace Ca^{+2} with Mg^{+2}). The ease with which an ion is replaced depends on valence, relative abundance of exchanging ion, and ion size. Ordinarily cation exchange follows the *lyotropic series* shown below (Mitchell, 1993).

$$Na^{+} < Li^{+} < K^{+} < Rb^{+} < Cs^{+} < Mg^{+2} < Ca^{+2} < Ba^{+2} < Cu^{+2} < Al^{+3} < Fe^{+3} < Th^{+4}$$

It is possible to displace a cation of high replacing power with one of lower power by mass action where the concentration of the replacing cation is very high compared to that of the other more powerful ions. Cation exchange capacities (CEC) of various clays are show in Table 2.1 (Taylor, 1959).

CLAY MINERAL	CEC MEQ/100 GRAMS SOIL
KAOLIN	3 - 8
ILLITIC CLAYS	40
MONTMORILLONITES	80
VERMICULITES	110 - 120

Table 2.1 CEC of various clays. Source: Taylor, 1959

Erosion, Infiltration, Runoff, and Evaporation Processes

A rainstorm can cause many processes to act simultaneously on the soil. These processes include erosion, infiltration, and runoff, all which are dependent on the magnitude of the rainfall event, as well as on each process separately (e.g. erosion depends on runoff rate which depends on infiltration rate). Since all of these processes are interconnected, they must be addressed together.

Soil erosion is the end result of two physical processes: the detachment of soil particles from the soil mass and the transport of these particles away from the soil mass. The detachment process generally results from two separate conditions (Young, 1984). The first occurs in small channels (rills) and is the result of the shearing forces caused by the flowing water, while detachment in the nearly level areas (interrill) is caused by the raindrop impact.

The detachment in the small channels is termed *rill erosion* and is often evaluated as wash erosion. The detachment in the areas between the channels is designated *interrill erosion* and is often evaluated as splash erosion. These two processes occur simultaneously, while transforming interrill areas to rill areas. This transformation is the change from high detachment-low transport (interrill-dominated) to low detachment-high transport (rill-dominated) system (Moore and Singer, 1990).

There are three basic stages of runoff and infiltration used to evaluate soil erosion (Moore et al., 1990). The first stage is from the first rainfall to the first point of runoff. The second stage is from initial runoff to steady-state runoff and infiltration. The final stage occurs when there is steady-state infiltration and runoff. The occurrence of the stages is a direct function of the particle size distribution, organic matter, mineral makeup, clay content, etc. The general trend in tests performed by Moore and Singer (1990) with three different soil shows splash erosion to be at a peak during stage II and gradually decreased during stage III. Wash erosion increased throughout their 90 minute tests, unlike runoff rates which attained a constant level. This trend suggests that rill erosion is still increasing throughout the test.

A major contributor to soil erosion (sedimentation rate) and infiltration rate is soil seal or *crust formation.* As suggested previously, the infiltration rate shows a rapid decrease until a constant runoff level is achieved. This rapid drop is due to the crust formation in stages I and II. These soil crusts are usually very thin layers (<2-3mm) and are characterized by greater density, finer pores, and lower conductivity than underlying soils (Smith et al., 1990).

Crust formation in soils exposed to the beating action of falling drops is due to two complementary mechanisms: (1) physical disintegration and slaking caused by water drop impact and water accumulation on the soil surface, and (2) chemical dispersion and movement of soil clays which can clog the pores immediately beneath the surface (Stern et al., 1991). The first is controlled mainly by the kinetic energy of the drops while the second is controlled by concentration and composition of cations in the soil (Smith et al., 1990).

These two mechanisms form three basic types of soil seals: structural crusts, depositional crusts, and chemical dispersion. Crusts primarily due to raindrop impact are referred to as structural crusts. Those formed due to transport and deposition of fine particles are labeled depositional crusts. The final category are those formed due change in chemical structure (dispersion). Combinations of the three crusts can be formed when these processes act together (Remley and Bradford, 1989).

The clay mineralogy, exchangeable ions, and electrolyte concentration in the soil solution are the primary factors that affect chemical dispersion, or the formation of the third soil crust type. When a high electrolyte concentration is provided, chemical dispersion is prevented and a seal with a higher permeability is formed by mechanical means. Recent studies (Stern et al. 1991) of soil erosion and infiltration on highly weathered kaolinitic soils of south eastern U.S. have shown that these soils rapidly form impermeable surface seals due to the chemical dispersion process. Smectite and illite clay are known to be more dispersive and would form lower conductivity seals than kaolinite clay.

Infiltration during a rainfall event is affected by soil texture, physical properties of the soil, surface condition, rainfall characteristics, and initial moisture content (Kim and Chung, 1994). Water that has infiltrated the crust into the soil can be modeled using the well known *Green-Ampt Infiltration Model.* This model simulates the water front moving through the soil while considering many of the soil properties. The Green and Ampt (1911) infiltration is:

$$f(t) = \frac{dF}{dt} = K_{av}\left(1 + \frac{S_{av} \cdot M}{F}\right) \qquad \textbf{(2.18)}$$

where:

$f = \textit{infiltration rate (cm / hr)}$
$\mathrm{K_{av}} = \textit{average hydralic conductivity (cm / hr)}$
$\mathrm{S_{av}} = \textit{average capillary pressure head at the wetting front (cm)}$
$\mathrm{M} = \textit{initial moisture deficit}\ (cm^3 / cm^3)$
$F = \textit{cummulative infiltration}\ (cm^3)$
$t = \textit{time (hr)}$

Throughout the year the porosity, capillary pressure, and the conductivity of the soil change. Eventually these properties stabilize as the effects of compaction, traffic and rainfall fully compact the soil (Kim and Chung, 1994). This is the condition that the rainfall simulation will attempt to simulate.

Evaporation of the precipitation from the soil is the process which begins following the rainfall event. This process draws the soil water from the soil. It is influential in carrying a fraction of the additive back to the surface of the road following the vertical (downward) one-dimensional transport process (Salama et al., 1992). This fraction is the amount that is dissolved in the soil solution. This process causes a soil profile to be formed which may concentrate the additive at the surface of the road until the next rainfall event.

Another process that takes place is the movement by concentration gradient. Following leaching, the additive is more concentrated deeper in the road surface and moves toward the surface (area of low concentration) once downward groundwater flow stops.

Soil Strength

"The ability of a soil deposit to support an imposing loading or for a soil volume to support itself is governed by the shear strength of the soil" (McCarthy, 1993). The shear strength is governed by two separate processes. They are the cohesion and the internal friction given by the following equation (Mitchell, 1993):

$$\tau = \bar{c} + \bar{\sigma}\, tan\bar{\phi} \qquad \textbf{(2.19)}$$

where:

$\tau =$ *shear strength*
$\bar{c} =$ *cohesion*
$\bar{\sigma} =$ *effective stress, and*
$\bar{\phi} =$ *angle of internal friction.*

Inspection of this equation shows that a cohesionless soil obtains strength only from the angle of internal friction. This angle depends on certain factors: soil type, angularity, density and particle interlocking, and a factor of particle crushing.

The strength testing procedure used in this project is the unconfined compression test, a triaxial test where the confining pressure (σ_3) is zero. The axial stress to fail the soil specimen is designated q_u. The results, based on a total stress analysis, can be plotted on τ versus σ coordinates as shown in Figure 2.9. The shear strength or cohesion is one half the unconfined axial stress and is designated as (McCarthy, 1993):

$$c = \tau = \frac{1}{2} q_u \qquad \textbf{(2.20)}$$

where:

$c = \tau$, *the shear strength*

q_u = *the ultimate axial stress at failure and is a function of* $\bar{c}, \bar{\sigma}, \bar{\phi}$ *and* $\phi = 0$.

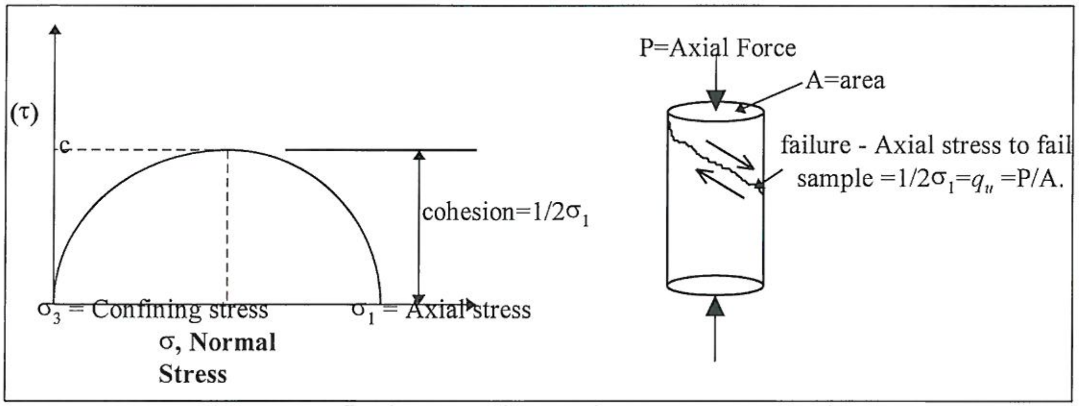

Figure 2.9 Unconfined compression test data. Source: McCarthy, 1993.

Environmental Concerns

Road additives applied to the unpaved road surface do not stay in the road surface forever. They must be continually reapplied to keep the concentration in the road at a level needed to stabilize the roads. These additives become solutes in water introduced to the road system. The water is introduced, as previously discussed, through precipitation (rain or snow) which dissolves the additives. The precipitation then infiltrates through the road surface into the groundwater or it flows off the road surface into drainages, streams and eventually lakes. Either of these "pathways" will carry a portion of the additive away into the soil or water supplies. If the concentrations are too high, this may have some significant effects on plant and animal life.

Salt Additives

In recent years there has been little research on contamination with stabilization salts. There has, however, been extensive research in pollution with de-icing salts and therefore much of this literature is used. This is feasible since the salts used for stabilization and de-icing are the same, except for the application process. De-icing salts are applied to paved roads in the solid form and the stabilization additives are applied to unpaved roads in liquid form. The main differences that can be noted from intuition are that de-icing salts runoff the paved road and then infiltrate or runoff at the shoulder, while stabilization salts infiltrate the road surface or runoff immediately.

One of the main concerns with the use of road salts is the contamination of water supplies. The main contaminate associated with salt ($MgCl_2$ or $CaCl_2$) is the chloride concentration, since chloride concentration is controlled by the EPA's drinking water standards and has been shown to be toxic. The chloride source is shown by the following dissociation (Adams, 1973):

$$CaCl_2 + water \xrightarrow{ionization} Ca^{2+} + 2Cl^- \qquad \mathbf{(2.21)}$$

Some of the precipitation will runoff to surface waters and some percolates down with the groundwater, which in general, ultimately discharges into surface streams

(Weigle, 1967). The concentration of chloride in the groundwater or surface water depends on: (1) rate of application, (2) soil type, (3) type, intensity and amount of precipitation, and (4) the drainage of the road system (Pollock and Toler, 1973). Additionally, the concentration in the surface waters also depends on amount of dilution or stream size the runoff water flows into (Demers and Sage, 1989).

A study on the groundwater in Massachusetts showed significant increases in the chloride concentration due to these salts. The background concentration in the water is 5 to 15 mg/L, based on an analysis of public water supplies by the Massachusetts Department of Public Health. Chloride concentration in groundwater from wells along a salted highway shows a significant increase over the standard background levels. The concentrations observed in 1971 were nearly 400 mg/L, although this concentration would depend on the amount of precipitation (Pollock et al., 1973). These results show that there is reason for concern.

Another study involving surface water concentrations in four streams located near a salted highway was conducted. The background level was about 2 mg/L upstream of the highway. In all the streams analyzed, the chloride concentration increased significantly to a maximum of about 35 mg/L. This study shows these higher concentrations throughout the year, indicating that the source is available yearly and not just during applications. Although these concentrations are not above the maximum contaminant level (MCL) set by the EPA, the long term effect of this exposure is not known (Demers and Sage, 1989).

Salt injury to vegetation usually develops as a general growth reduction followed by leaf scorch, curling, leaf drop, stem dieback, and gradual decline resulting in death of the plant (Zelazny and Blaser, 1970). Salt interferes with normal photosynthesis and plant respiration and at acute levels kills the leaves directly. The most susceptible plants are the aspen, white pine hemlock, and maples. Mature spruce trees seem to be most resistant (Minsk, 1973 ; Piatt and Krause,1974). It has also been noted in a study by Zelazny (1970) that the silver maple died from chloride poisoning and osmotic effect of salt in the soil solution.

Animals and fish are very resistant to the salt poisoning compared to vegetation. It is reported by Hanes et al. (1970) that chloride concentrations of 400 mg/L are harmful to trout, which is the main concern in Wyoming, while Bass can handle up to 4000 mg/L. This shows that trout easily could be affected if high chloride concentration of groundwater reached a surface stream or if a stream is located near a treated road such as in the Fox Park area.

Animals seem to be little affected if they drink from a contaminated stream. Water supplies in Montana containing salt concentrations of 2500 mg/L are designated as acceptable for stock. In Australia, cattle and sheep have been sustained on water containing 25,000 mg/L, while lethal doses of salt for dogs, pigs and cows are 30 to 60 g, 130 g and 3 kg respectively (Hanes et al., 1970). However, a problem has been noted with wild animals such as deer. Animals that require salt to live are attracted to the unnatural salt lick and can be hit by vehicles, injuring both the driver and the animal (Minsk, 1973).

Lignin Sulfonate

The pollution due to the Lignin additive is measured in terms of Biochemical Oxygen Demand (BOD). The BOD is the weight of oxygen (usually in mg/L) required to degrade and stabilize the organics that infiltrate the surface water. An example of this degradation is shown by the following chemical equation (Lapinskas, 1989):

$$C_nH_{2n+2} + \underline{\underline{O_2}} \xrightarrow{bacteria, H_2O, Nutrients} Protein + water + CO_2 \quad \mathbf{(2.22)}$$

The importance of this measurement can be seen by the comparison of human and industrial discharges. While an estimated 0.17 pounds of oxygen is required by bacteria to decompose a daily human discharge of waste, nearly 1,000 pounds are required to decompose one ton of bleached sulfite pulp. If the level of BOD is too high, it adversely affects the complicated chain of life from bacteria to plankton to fish life (Allen, 1972) in natural waters. This shows a need to monitor BOD in the mountain streams adjacent to lignin treated roads.

Conclusion to Literature Review

The literature review shows that there are many complicated and interactive processes taking place in the transport of stabilization additives out of the road section. There must be studies conducted that include the complicated one-dimensional solute transport as well as a two-dimensional study to find the effects of erosion, infiltration and runoff on the road surface.

To obtain relevant and useful results, these tests must incorporate many different conditions and combinations. The column and rain simulation studies must have different variations of linear velocity (rain rates), additive type and concentration, as well as different soil types ranging from a granular non-plastic type to a plastic soil with a higher clay content. The additive types, concentrations and the soil type must be varied to allow soil chemistry changes to take place in the soil. These changes reflect differences in many parameters including infiltration, erosion, retardation, and the governing transport mechanism.

The results are used to define an efficient application schedule for the stabilization additive. The schedule depends on results form both studies, mainly infiltration and solute breakthrough time. This schedule gives a basic structure to be followed confidently and efficiently when applying the additives.

CHAPTER 3. TESTING METHODS AND PROCEDURES

Introduction

The study, as previously stated, involves two separate but related scenarios: the one-dimensional solute transport study and the two dimensional rain study. The first is executed using soil columns with various additive concentrations and constant rain loadings (seepage velocities) to obtain solute transport characteristics. The second is executed using a rainfall simulator at a constant rain loading to determine erosion, runoff, infiltration, and additive runoff characteristics. The design of both sections were carefully thought out to give as complete and accurate results as possible.

To obtain accurate results, the soil preparation procedures must be consistent and carefully executed. These procedures must simulate ASTM standards and include sieving, compaction, and blending of the soil with the additives and clay. The column study involves compaction of soil columns while the rain study involves construction of small road sections.

Other aspects also need specific attention. The first is the control of a constant rain loading on the columns. Constant rain rates are needed so the advective-dispersive solute transport model can be fit to the effluent data. The other section of the study that needs careful consideration is the measurement of the additive concentration in the column effluent and the runoff water.

Soil Choice

The main soil, labeled "Soil A," is one which is currently used for unpaved road construction by the U. S. Department of Agriculture Forest Service in the Fox Park area. This soil also was the main soil used in the strength study by Palmer (1994). It is a nonplastic soil and is obtained from the Fox Park Pit, south of Wyoming Highway 230.

According to AASHTO M 147-65 (1993), the road surface soil specimens should meet road construction standards. These standards include gradation specifications and plasticity requirements. Following sieve, Atterburg and soil classification procedures, the soil met the gradation specifications but did not meet the plasticity requirement where the plasticity index (PI) must be between 4 and 9. This resulted in the decision to introduce "Soil B," which also parallels Palmer's (1994) study. This soil is Soil A blended with 8.5 percent kaolinite which yields a PI of about 5 and falls within AASHTO standards. Finally, an intermediate soil was introduced and designated as "Soil C." This is Soil A blended with 3 percent kaolinite and has intermediate properties of A and B, but does not meet plasticity requirements. The combination of these three soils yields information on both plastic and nonplastic soils.

Additive Concentration

Additives were blended to the soil at concentrations of 0, 2, and 4 percent by weight of dry soil. These concentrations covered the range of application in road surface maintenance.

Common application amounts of the stabilization additives is about 1/2 gallon per each square yard in the top two inches of the road surface (Hansen, 1982). This computes to a volume of about 1.5 ft^3 of soil affected by the 1/2 gallon of the additive. The dry density of the compacted soil is about 130 pcf while the specific gravity of the salt additives is 1.30. This results in an additive concentration of about 2.78 percent by weight as shown below.

$$\%conc. = \frac{\tfrac{1}{2}gallon}{1.5ft^3} x \frac{ft^3}{130lb} x 8.34 \frac{lb}{gallon} x 1.30 = 2.78\% \qquad \textbf{(3.1)}$$

One-Dimensional Column Study

The column study was performed using a two-inch diameter soil column six inches long to simulate the road surface. The three soil types with three concentrations of the three additives are leached at three rain loadings. The leachate is tested for concentration of the additive used and solute breakthrough curves are plotted to obtain the transport properties.

Definitions

Absorbence - When light is passed through a sample of water or some other liquid mixture, a fraction of the light does not pass through the sample. This is the fraction of the light absorbed. The absorbance is usually related to the color of the liquid and depends on the wavelength.

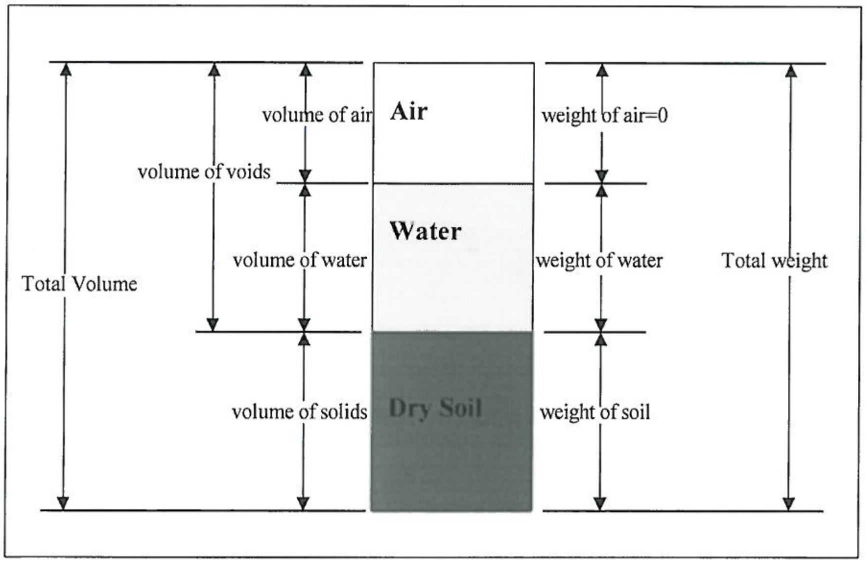

Figure 3.1 Phase diagram of soil sample to explain defined soil properties.

The *water content* of soil is the weight of water divided by the weight of dry soil, represented as a percentage.

Soil porosity is the volume of the voids in a soil sample divided by the total volume of that soil sample.

The *percent saturation* is the volume of water divided by the volume of the voids expressed as a percent. A completely saturated sample has a saturation of 100 percent. See Figure 3.1 for clarification of these soil properties.

Column Design

The columns are designed to simulate the top six inches of the road surface, since that depth is where the additives are applied. The columns are constructed of two-inch PVC pipe with a funnel attached at the bottom to collect the leachate. They are seven inches in length to allow for the six-inch soil section with one inch allowing for attachment of the water feed with a number 11 rubber stopper. This length-to-width ratio is also greater than 2.5, which is a requirement for short column studies as stated by van Genuchten and Parker (1984). The design is shown in Figure 3.2.

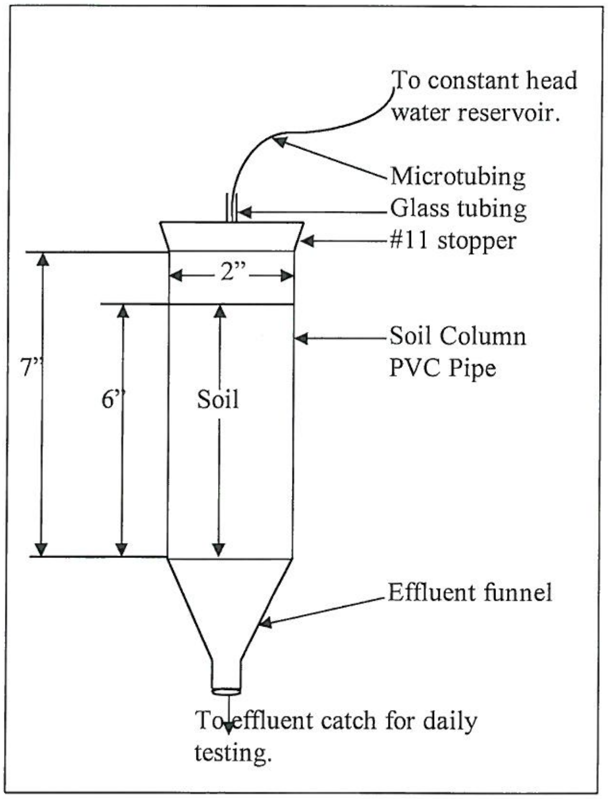

Figure 3.2 Column Design

Moisture-Density Relationship

Prior to the soil column preparation, the moisture content at which the maximum density occurs must be determined. This is found using the standard moisture-density test designated as ASTM D 698. The soil is compacted in a standard moisture-density mold according to the following: 12,375 pound-ft of energy (*E*) must be used to compact one cubic foot of minus 4.75 mm soil. The calculation of this is shown in Equation 3.2. Using a 5.5 pound compaction hammer with a one-foot drop and three layers of minus

4.75 mm soil requires 25 blows per layer to impart the required energy into the soil in the 0.03333 ft^3 standard proctor mold.

$$E = \frac{\left(25\, {}^{Blows}\!/_{Layer}\right)\left(3\, Layers\right)\left(5.5\, \frac{pounds}{blow}\right)\left(1\, Foot\right)}{0.03333\, ft^3} \qquad \textbf{(3.2)}$$

$$E = 12{,}375 \frac{pound - ft}{ft^3}$$

This procedure is performed at increasing water contents until the maximum density is achieved at a particular water content. The water content which corresponds to this maximum dry density is termed the *optimum water content.*

This is the water content around which roads are constructed and therefore all soil column compaction is carried out at this water content. All three soils had optimum water contents between 8 and 9 percent, so the compaction procedures are done at 8.5 percent. Since the columns are not the same volume and dimensions as the standard proctor mold, the compaction procedure is modified so that the correct amount of energy is applied to the soil in the columns. This is shown in equation 3.3 which is a rearranged form of 3.2. Another modification is using five layers instead of three since the column is much more slender than the standard mold.

$$\frac{Blows}{Layer} = \frac{12{,}375 \frac{pound - ft}{ft^3}\left(0.01091 ft^3\right)}{\left(5 layers\right)\left(5.5\, {}^{pounds}\!/_{blow}\right)\left(1 ft\right)} \qquad \textbf{(3.3)}$$

$$\frac{Blows}{Layer} = 4.9095 \cong 5$$

Rain Loading Control

Since the advective-dispersive equation used to model the solute transport requires a constant seepage velocity, a method must be determined to maintain the three designated flow rates while simulating reasonable amounts of water infiltration the roads could see on a particular day.

The method used to achieve the constant flow is the use of microtubing. When a suction is applied on a particular length of tubing attached to a constant head reservoir, the flow will be constant. The length of tubing and, consequently, the tubing friction is then varied to obtain different flowrates of water. A curve was developed for the tubing used and is shown in Figure 3.3.

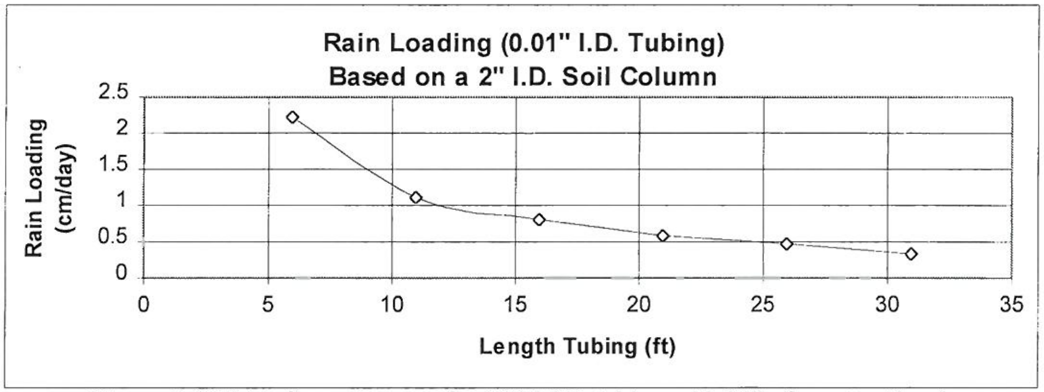

Figure 3.3 Water flowrate curve for 0.01" I.D. tubing with 18" of constant head.

The tubing curve allows three different lengths of tubing to be selected that correspond to the desired water loading for the column study. The three lengths selected are six feet, 11 feet and 20 feet, which correspond to the following rain loadings as shown in Table 3.1.

TUBING LENGTH (FT)	RAIN LOADING (CM/DAY)	FLOWRATE (CM^3/DAY)
6	1.53	31
11	0.84	17
20	0.50	10

Table 3.1 Selected lengths and corresponding rain loadings.

Pre-testing

Prior to the actual column study, selected soils were compacted to the previously described standards. The columns were then run at the various flowrates. This procedure was executed for about two weeks to determine that the method would work smoothly. Following this operation, the porosity and percent saturation were determined. The porosity is needed prior to the column study so breakthrough curves can be plotted versus *number of pore volumes*. This form of the curve is needed so advective-dispersive equation can be fit to the plot. The *percent saturation* is needed to determine if the advective-dispersive equation applies. This equation models solute transport in a saturated condition, so the columns must be effectively saturated. The tests showed saturations ranging from 93 to 98 percent. It was concluded that the model could be applied with a small error.

Leachate Solute Concentration Measurements

The solute breakthrough curves necessitate the measurement of solute concentration in the column effluent on a periodic schedule. At the designated flowrates, daily measurements give enough data points to plot the curves.

Since there are so many combinations of soil type, additive type, flowrate and additive concentration there are a large number of measurements. These measurements demand an accurate and time-efficient method so the daily measurements can be completed. After researching a number of methods including titrations, the method chosen for the salt additives ($MgCl_2$, $CaCl_2$) is the use of ion sensitive probes. These give accurate and quick results.

The principle behind the use of these probes is a correlation of millivolts (mV) read on a standard pH meter to the concentration of the solute in the effluent, since the ions are charged particles and have an associated voltage. The ion sensitive probe is used in place of the pH probe. The probe is placed in the liquid and the mV reading is noted. This reading then corresponds to a concentration given on plot of mV versus concentration that is developed with standards of the solute in question.

The method chosen to measure the concentration of lignin is the use of a spectrophotometer. The spectrophotometer measures the amount of light (visible or UV) absorbed into a specific water solution at a specific wavelength of light. The amount of light absorbed varies with concentration of lignin.

The procedure involves two calibration steps. The *absorbance* of a lignin sample is measured at various wavelengths of light to determine a “peak or plateau” absorbance, which gives a sensitive point to measure. Once this plateau is determined, a calibration curve is developed by measuring absorbances at known concentrations of lignin and at the plateau wavelength. Once this curve is established the effluent absorbance can be measured and the complimentary concentration can be taken from the calibration curve. The plateau and the calibration curves are shown in Figures 3.4 and 3.5.

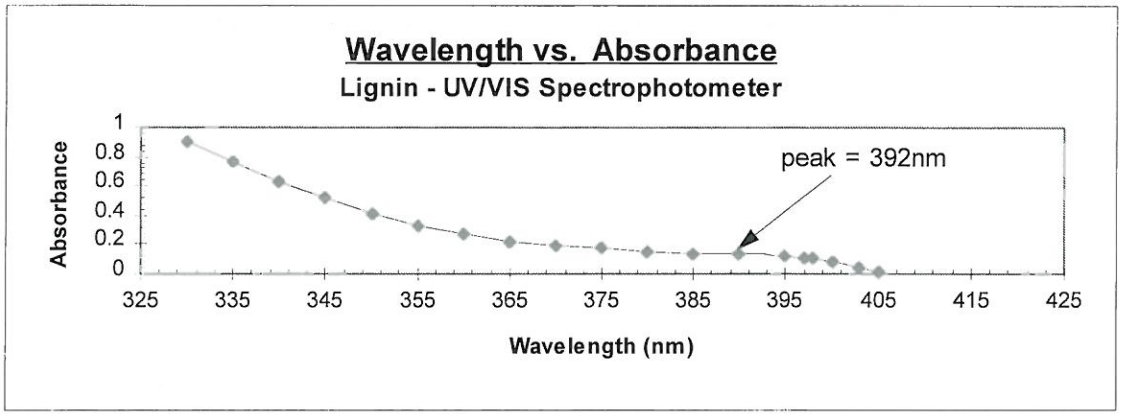

Figure 3.4 Plateau absorbance for lignin.

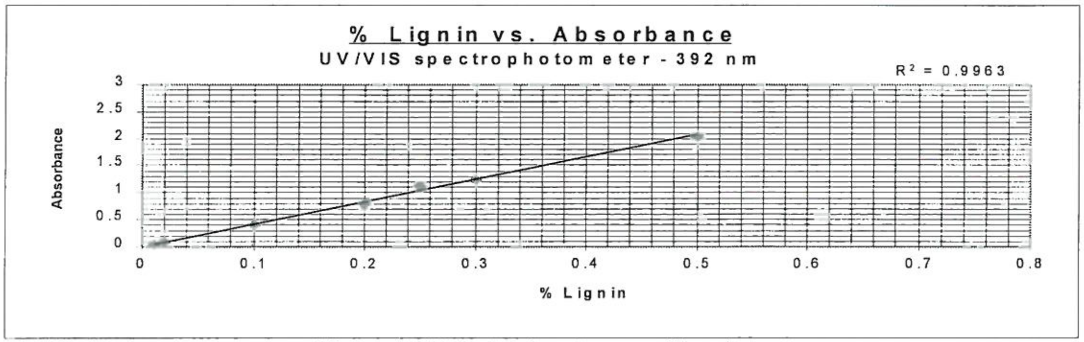

Figure 3.5 Lignin absorbance calibration.

Rain Study

The rain study is used to determine surface runoff properties of the soil including erosion, runoff rates, and solute concentrations, as well as infiltration to correlate the infiltrated groundwater to the column studies. The simulation was done with various combinations of the soils and additives under one constant rainfall event which simulates an average Wyoming mountain storm in the Fox Park area. To simulate an initial dry road condition, these soil specimens are allowed to come to an equilibrium water content with the atmosphere prior to the study.

Test Design

The concept behind the design of the rain simulation is to incorporate all the parameters including erosion, runoff, and infiltration during the rain, and the evaporation processes following a rain event into one test sequence. This is performed so all the samples are exposed to the same controlled conditions to obtain consistent results as well as conserve on time.

Six road sections were built that measured 39" X 11.5" X 2" and have the properties shown in Table 3.2. These dimensions were used because they equal the size of the compaction trays accompanying U.W.'s rain simulator. These six road sections had varying additives and clay contents and were sloped at 2 percent as designated by AASHTO (1993) for construction of unpaved roads. These sections previously were weighed and initial water content was determined. Following the rain event, a representative soil sample was taken to determine the final water content.

TRAY NUMBER	SOIL TYPE	ADDITIVE TYPE	ADDITIVE CONCENTRATION (%)	SLOPE OF SECTION (%)
1	A	NONE	0	2
2	A	$CACL_2$*	4	2
3	A	LIGNIN	4	2
4	C	NONE	0	2
5	C	$CACL_2$*	4	2
6	C	LIGNIN	4	2

*$CaCl_2$ is the only salt used, since both salts have essentially the same transport characteristics

Table 3.2 Properties of road sections.

The erosion, runoff rates, and additive runoff characteristics are determined from this section of the rain simulation. All of the cumulative runoff volumes are collected at selected times. Samples for solute concentration and sedimentation in the runoff are also collected at this time. With the known cumulative volumes collected at selected time intervals, the runoff flowrates can be computed to find the steady state runoff rates for the soil-additive combinations. This section also shows the time intervals to the three stages of runoff talked about in the literature review (all infiltration, increasing runoff, and steady-state runoff)

The concentrations of the solutes in the runoff samples are measured in the same way as the effluent samples in the column study. These concentrations are plotted versus cumulative runoff volume and the fraction of the road additive carried away in the surface runoff is determined. At this point the percent of additive left in the soil for downward groundwater transport is known.

The samples collected to measure solute concentration were saved following solute measurement and were filtered using an apparatus similar to that in Figure 3.6. The filtering procedure follows test 2540D in Standard Methods for the Examination of Water and Wastewater (Greenburg et al., 1992). The soil filtered out is oven dried and weighed. Knowing the weight of soil and the sample size gives sedimentation rates in g/liter of runoff throughout the experiment. This can be plotted versus the cumulative runoff (liters). The area under the curve is the total weight of sedimentation for the six different sections.

Infiltration rate determination is the final part of the rainfall study. The samples prepared are in the same additive-soil combinations as the road section, only they are compacted in a standard proctor mold which is a four-inch-diameter cylinder. The idea behind this is simple. The mold and soil are weighed before testing. Immediately after the rainfall, the samples are weighed again. The difference between these two weights is the amount of water that has infiltrated that particular sample at the given equilibrium water content.

The completion of the rainfall initiates the beginning of the last process. This process is evaporation and is allowed to take place with the smaller infiltration study sections. The samples are allowed to dry until they achieve an equilibrium water content with the atmosphere (approximately seven days). They are then extruded from the molds and an additive concentration profile is found in the soil. It is expected that the evaporation process will carry the additives toward the surface in the evaporating groundwater, thus giving a profile that decreases in concentration (mg additive per kg of dry soil) as depth into the soil increases.

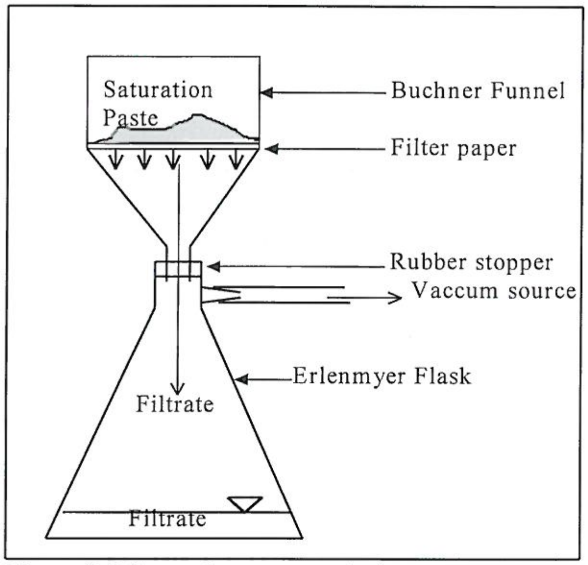

Figure 3.6 Saturation paste analysis.

The concentration profile is determined using a saturation extract method as described in Methods of Soil Analysis (Black, 1965). The extruded samples are sliced into approximately one-inch slices. The slices are then prepared in the following steps. First, the soil sample of known water content is transferred to a dish with a cover and weighed. The slice is then saturated with distilled water and mixed to a consistent mixture. The weight of dry soil can be calculated knowing the weight of "wet soil" and the water content. The samples were allowed to stand for four hours to allow the additives to dissolve into solution. The saturation paste is transferred to a "Buchner " filter funnel fitted with a low ash filter paper. Vacuum is applied to suck the filtrate from the paste as shown in Figure 3.6. The concentration of solute is measured in the filtrate by methods previously described. Knowing the volume of filtrate and the weight of the soil sample tested, the number of milligrams of the solute per kilogram of soil is calculated. The results of each slice is now plotted in the form of concentration versus depth.

Rain Simulator Design

The rain simulator used is one that is already designed and fabricated by the civil engineering department at the University of Wyoming. It has been used extensively in the field and the laboratory at the University of Wyoming, and has been proven to be an effective device to simulate rainfalls of various intensities and durations.

The simulator consists of three rotating sprinkler nozzles above the soil samples. The rotation speed is controlled by a motor, while the rain intensity is controlled by the number of nozzles in use and the amount the water feed valve is opened. The amount the feed valve is opened corresponds to a pressure reading so the same pressure and, consequently, the same intensity can be applied upon demand. The rain simulator is shown in Figure 3.7.

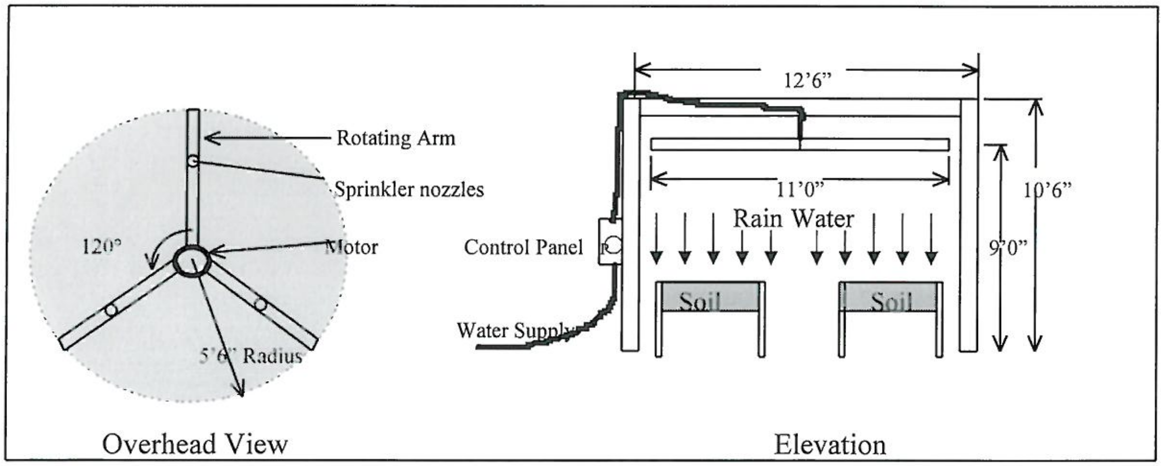

Figure 3.7 Rain Simulator (Not to Scale).

Compaction Procedures

The compaction for the rain study must also simulate road construction, therefore modifications of the standard proctor energy equation is again utilized to achieve a standard compaction close to the maximum dry density. The soils were again compacted between 8 and 9 percent to be within 1/2 of a percent of optimum moisture content.

The infiltration molds are actual proctor molds, therefore the standard procedure can be used. This is to compact three separate layers with 25 blows per layer with the standard 5.5 pound hammer. The road sections require modification because of the large size. They are compacted in two layers with the standard hammer pounding about 600 blows per layer to apply the necessary 12,375 pound-ft per cubic foot of energy. The large number of blows are required due to the large volume of soil.

Rain Rate

The rain loading for the rainfall simulator is determined by looking at past hydrologic records for the Fox Park area. Looking at the records and talking with Hasfurther (1995), a University of Wyoming hydrologist, indicate that there are fairly intense storms in the mountain areas with intensities of around three inches per hour during a large spring storm. The study objective is to model a fairly large storm to be conservative in terms of additive application. The storm that is simulated is to allow a one-inch (2.54 cm) rain event to occur over a two-hour period. This rain rate corresponds using only one nozzle on the rain simulator.

Residual Strength Study

This section determines if any additional strength is left in the soil following the removal of the additive after the leaching process. The first part of this evaluation involves removal of the soil columns from the PVC pipe for testing. The samples are trimmed to a two-to-one length ratio as specified for the unconfined compression (UCC) test designated ASTM D 2166-85. The soil specimens are air dried for one week prior to testing in the UCC device. Once the specimens are tested and compared to compacted samples with no road additives, the determination of residual strength is made.

The final part of the strength testing procedure is finding the curve of strength versus amount of water passed through the soil columns. As water passes through the columns the additives are removed thus decreasing the additive concentration as an increasing amount of water passes through. This test is done by testing the soil columns for their strength at specified intervals of leaching rather than testing when all of the additive is leached from the soil. To determine this strength curve, the intervals are used when zero, 0.5, one and 1.5 pore volumes have passed through the soil columns.

Computer Model

Once the column and rain study were completed, it was found that the solute transport was mainly a one dimensional downward transport process. This allowed a spreadsheet program that evaluates the advective-dispersive equation to adequately model the movement of the road additives and a two dimensional program is not needed. This program is a function of the soil type and additive type where the retardation factor and the coefficient of hydrodynamic dispersion are varied to output a representative solute breakthrough curve for the appropriate additive-soil combination. The program is given in Appendix A.

CHAPTER 4. RESULTS

Introduction

The results of this study are divided into two main sections as was the previous chapter. The two main areas include the one-dimensional soil column study and the two-dimensional rain simulation. All areas of investigation are explained and the results are summarized or displayed in representative graphs and tables of quantitative data. There also are some qualitative results which are derived from observation. This is especially true in the rain water study.

There are two more sections of results that are secondary and are not included in the main objectives of this study. These include a residual strength study following the leaching process, and the modeling of the downward solute transport in a one-dimensional computer model. The computer model, examples of all calculations and figures showing all the data are given in the appendices.

Classification of Main Soil

The main soil (Soil A) used in this study, as well as in the construction of the unpaved roads in the Fox Park area, was collected from the Fox Park pit south of Wyoming Highway 230. It is a nonplastic soil which meets AASHTO's gradation requirements, but not the plasticity requirements, where the plastic index (PI) must fall in the range of 4 to 9 (AASHTO, 1993). Its AASHTO classification is A-1-b (PI=0).

Soil B uses a blend of Soil A and 8.5 percent kaolinite. This is done so a soil with both AASHTO gradation requirements as well as plastic requirements is used. It had similar gradation as soil A, with a PI of six. The final soil is Soil C which is Soil A blended with 3 percent kaolinite. It has intermediate plastic properties.

Soil Analysis

An analysis of selected cations and anions in the Soils A and B was conducted. This was done to see if there are any concentrations of the ions high enough to substantially affect soil-solute interactions or cation exchange. The results of this analysis is shown below.

Ion Available (mg/Kg soil)	Soil A	Soil B
Ca^{++}	129	135
Mg^{++}	23	22
Na^{++}	6	9
K^{+}	<10	<10
Cd^{++}	<.02	<.02
Pb^{++}	0.4	0.8
Cu^{++}	0.56	0.62
Fe^{+++}	4.6	6.6
SO_4^{-2}	2.0	1.5
Cl^{-}	21	15

Table 4.1 Ion analysis of selected soil types without additives. (Dept. of Plant, Soil and Insect Science, Soil Testing Laboratory, UW)

Column Study

The column study yields information related to the downward transport of the dissolved additives (solutes) in the groundwater. The retardation factor and Peclet number are determined by fitting the effluent concentration data to the solution of the Advection-Dispersion equation, Eq. 2.15. The coefficient of hydrodynamic dispersion is then found using Eq. 2.16. These results are functions of the soil types, seepage velocities, additive types and additive concentrations.

Salt Additives - Breakthrough Curves, D_H, P_L and Transport Trends

The column testing of the combinations of salt additives ($CaCl_2$, $MgCl_2$) with the three soil types and the three selected seepage velocities, yield that both salts travel through the soil at about the same rate and with the same properties. This is shown in Figures 4.1, 4.2 and 4.3. For this reason, both salt additives are considered in the same section.

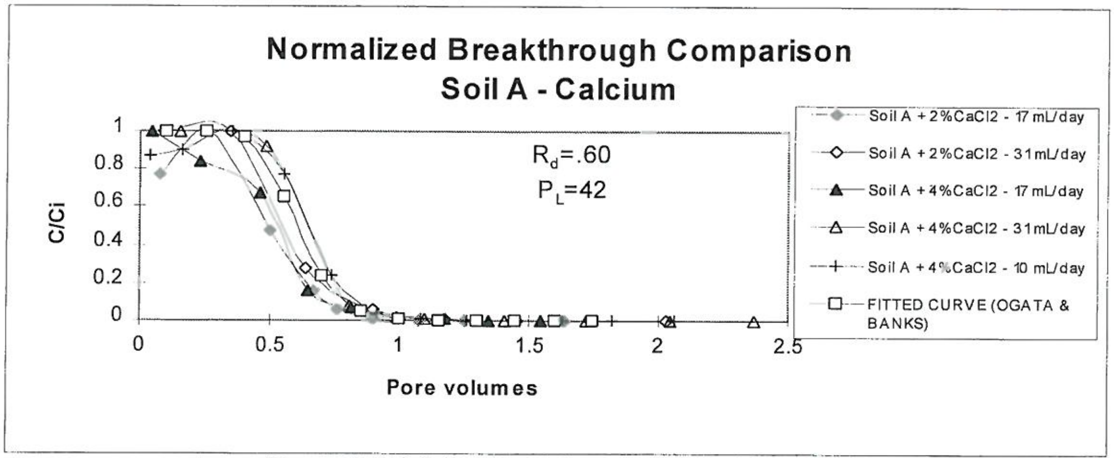

Figure 4.1 Calcium Breakthrough Curve with Soil A.

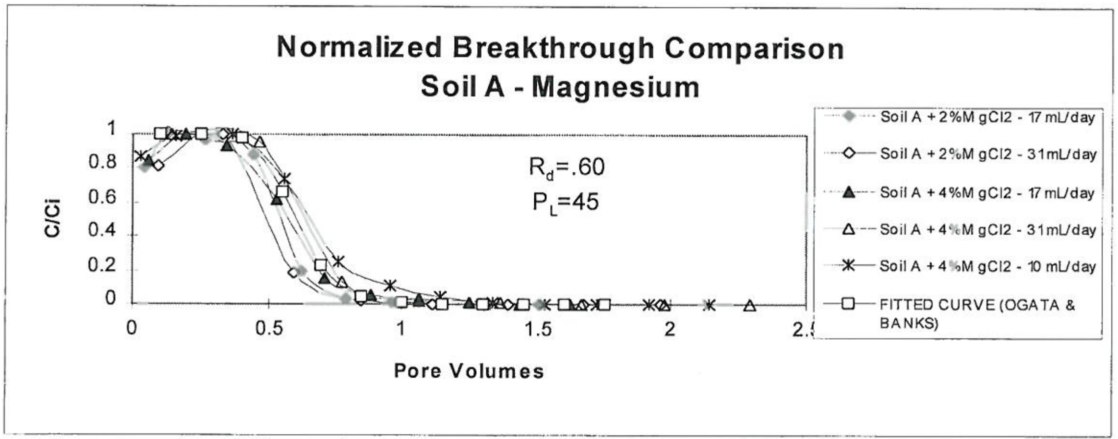

Figure 4.2 Magnesium Breakthrough Curve with Soil A.

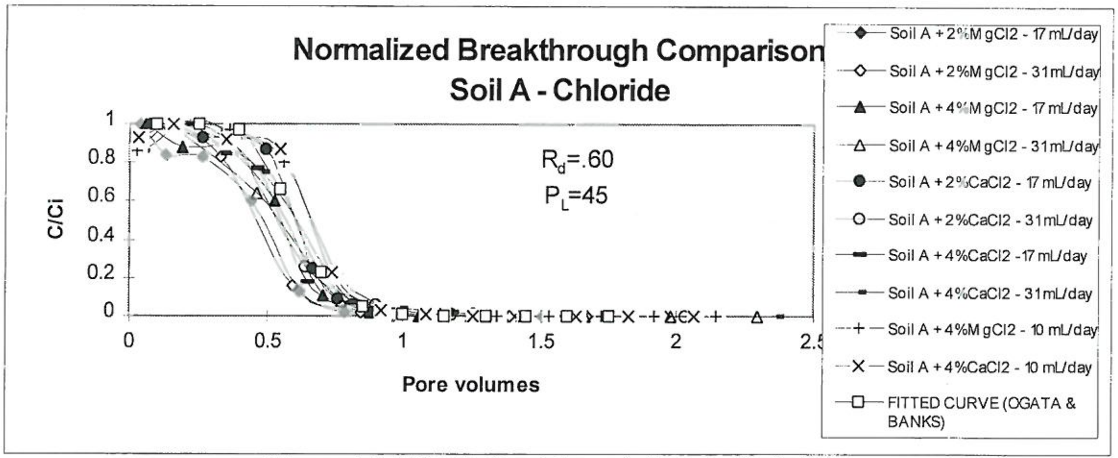

Figure 4.3 Chloride Breakthrough Curve with Soil A.

The salt transport properties remain constant for all the concentrations and seepage velocities, but the transport properties vary as the soil type changes. As clay is added to the base soil, the transport goes from advective (groundwater flow) dominated transport (P_L = 45) to diffusive (concentration gradient) dominated transport (P_L = 6) as shown in Figure 4.4 and 4.5. Shackelford, et al. (1995a) indicates that diffusion dominates for fine-grained soils such as kaolinite. The Peclet numbers found from the column study allow coefficients of hydrodynamic dispersion to be calculated and plotted versus percent clay added as shown in Figure 4.6. A summary of these properties is shown in Table 4.2.

ADDITIVE SOLUTE	SOIL TYPE	PECLET NUMBER
CA^{++}	A	42
CA^{++}	B	6
CA^{++}	C	16
MG^{++}	A	45
MG^{++}	B	---
MG^{++}	C	16
CL^{-}	A	45
CL^{-}	B	5
CL^{-}	C	15

Table 4.2 Salt additive solute with associated Peclet numbers.

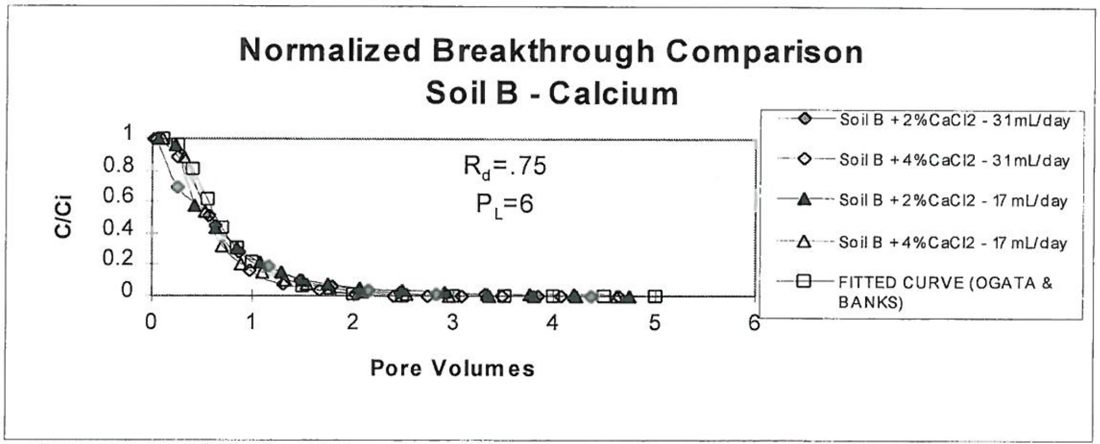

Figure 4.4 Calcium Breakthrough Curving, showing diffusion dominates when clay is added.

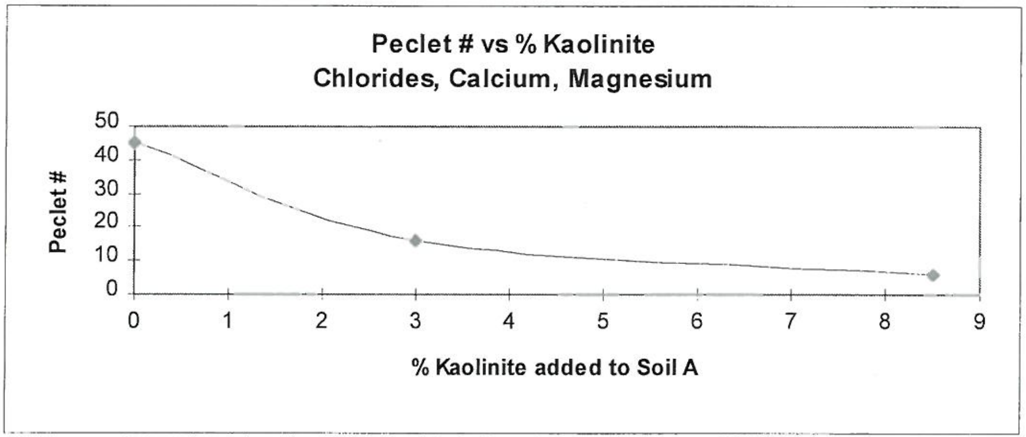

Figure 4.5 Advection dominates with Soil A, but translates to diffusion as clay is added.

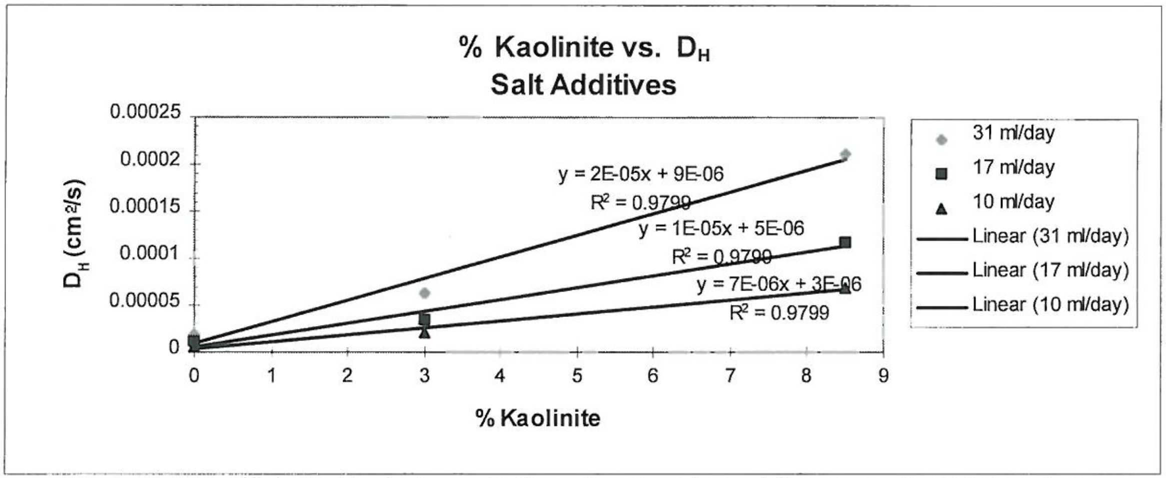

Figure 4.6 Coefficient of hydrodynamic dispersion plots derived from theoretical fits to column breakthrough curves.

Another important piece of information derived from Figures 4.1 through 4.4 is that the salt additives have effectively been transported out of the soil in one pore volume of groundwater. This property is independent of the soil type and additive concentration. This indicates that additive application rate is mainly dependent on the amount of precipitation, since the water is what leaches the salts out of the soil. Eight-and-a-half percent kaolinite does retard the additive slightly, giving a longer, low concentration residual in the soil.

The time relation between additives for different soil types and seepage velocities also can be explored. It can easily be seen that for slower seepage velocities (smaller rain events) the salt additives remain in the road for a much longer period of time (Figure 4.7). The effect of soil type on the effective life also can be shown. The addition of clay slows the transport of additives, but it is not as dramatic as the affects of seepage velocity (Figure 4.8).

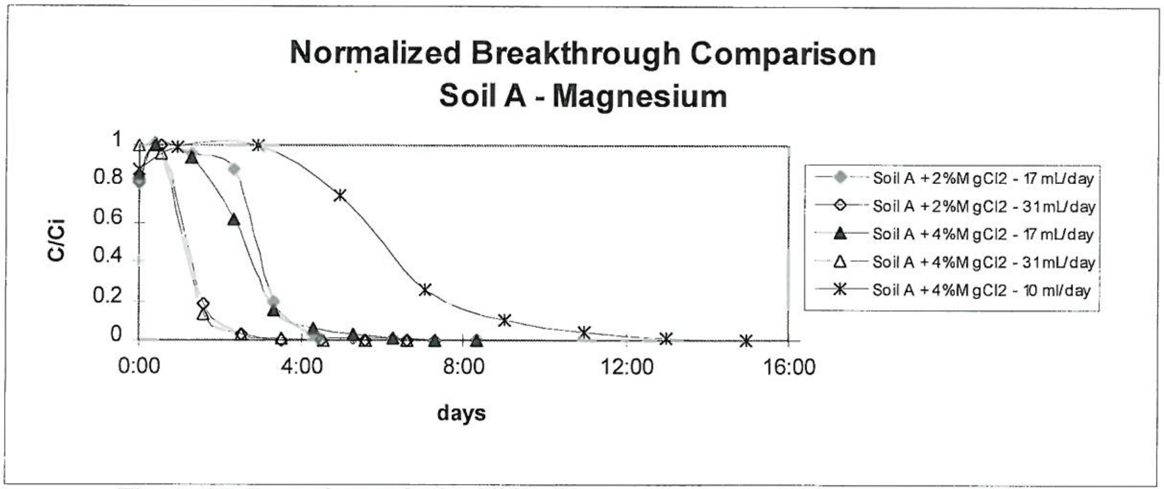

Figure 4.7 Dependence of salt additive life on seepage velocity for constant soil type.

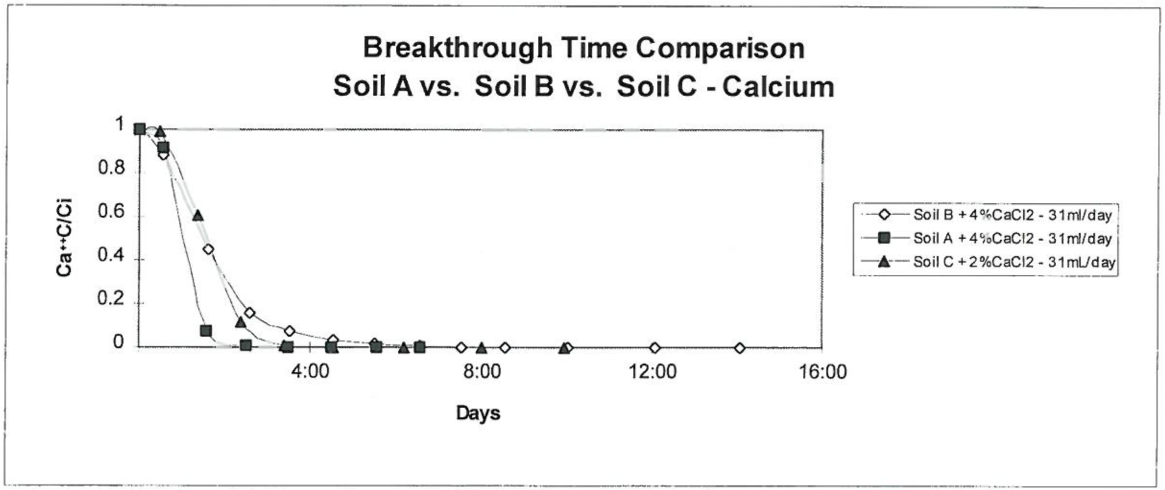

Figure 4.8 Dependence of additive life on soil type for constant seepage velocity.

Salt Additives - Retardation Factors

It can be seen from the previous breakthrough curves that the additives in the groundwater system are conservative solutes. That is, they do not have adsorptive properties and are transported out of the soil columns in about one pore volume regardless of soil type. When the advective-dispersive equation is fit to the salt breakthrough data for all soil types, the retardation factors that fit the data are all less that one (Table 4.3), but increase as the percent kaolinite is increased (kaolinite slightly retards transport).

Additive Solute	Soil Type A	Soil Type B	Soil Type C
Ca^{++}	0.6	0.75	0.65
Mg^{++}	0.6	0.80	-----
Cl^{-}	0.6	0.75	0.65

Table 4.3 Retardation factors for additives in different soil types.

This refutes the idea that conservative solutes (non-reactive) have R_d values of one. Two possible reasons for this phenomena were found during the literature review.

The first is derived from the definition of the retardation factor as stated by Shackelford et al. (1995b). This definition is stated below:

$$R_d = 1 + \frac{\rho_d}{n} K_d \qquad \textbf{(4.1)}$$

where R_d is the retardation factor, ρ_d is the density of the soil, n is the porosity, and K_d is the distribution coefficient and is the slope of the "adsorption curve." An example of an adsorption curve is illustrated in Figure 4.9.

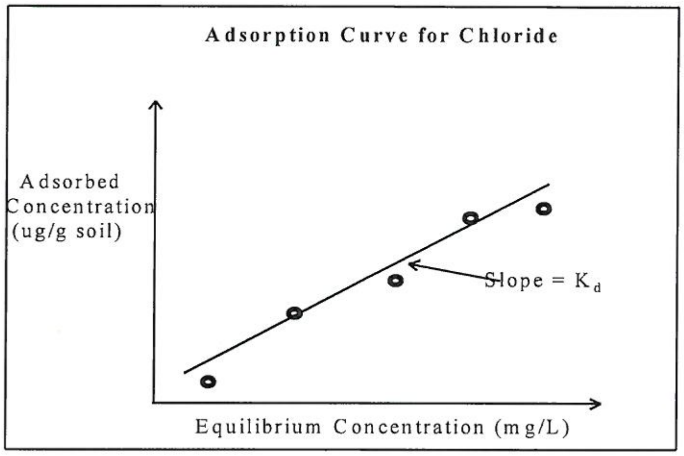

Figure 4.9 Example of Adsorption Curve

Since the additive is in the soil column before the test and the soil is allowed to dry for one week, the salt comes out of solution and crystallizes on the soil particles. Once water is added, the solutes "desorb" thus giving the slope of the adsorption curve a negative value which yields a value less than one for R_d by definition.

The next reason that R_d could be less than one is that the retardation factor of one for a conservative solute is based on the idea that all pore space is conducting flow (Shackelford et al., 1995b). According to Shackelford (1994), the breakthrough (c_e/c_o=0.5) of non-reactive solute such as chloride (R_d=1), should occur at one (1) pore volume of flow (T=1) and therefore T=R_d. Similarly, a reactive solute may have R_d of two, and breakthrough (c_e/c_o=0.5) for this case would occur at two (2) pore volumes.

This data is related to the effective porosity of the soil. The ratio of effective porosity to total porosity is given as follows:

$$T_e \frac{n^e}{n} = T = R_d \qquad \textbf{(4.2)}$$

where T is the actual pore volumes measured based on the total porosity, n, and T_e is the actual (effective) number of pore volumes based on the effective porosity, n_e.

Since the solute is initially in the soil in very high concentrations and is allowed to dry (crystallize) on the soil particles, the salts take up some pore space. As the test is run, the salt dissolves and the effective porosity approaches total porosity by the end of the test. Although the effective porosity approaches the total porosity, it is always less. Examining equation 4.2, it is easily observed for non-reactive solutes that the retardation is less than one for these conditions. This is especially true when solutes are in such a high concentration they take up a large percent of the total porosity when they dry and crystallize on the soil particles. An example of this is shown in the results where the R_d for chloride, a non-reactive solute, in Soil A is equal to a value of about 0.65

Effects of Salts on Soil Properties

Another result found from the column study is the effect of the salts on the conductivity of the soil, especially those which contain clay. The columns containing clay and the salt additives were leached at the selected seepage velocities. During these tests, the soil accepted the water readily. Testing continued until the salts were effectively leached from the soil, at which time the water ponded and overflowed out of the column. A column with no salt additives was then run and also would not accept water.

This phenomena is due to the salts leaching out which causes the clay to disperse and thus dramatically decrease the hydraulic conductivity of the soil. The flocculated structure developed under high concentrations is a more random, stronger structure with higher conductivity than the dispersed structure discussed in chapter two.

Lignin - Breakthrough Curves, D_H, P_L and Transport Trends

The lignin columns also were tested with the same concentrations, soil types, and seepage velocities as the salt additives. These column studies yield similar information as for the salt columns. The main difference is that the dominating transport process for lignin with all three soil types and seepage velocities is diffusion since Peclet numbers are small (Figures 4.10 - 4.12). All three curves have the same characteristic shape for diffusive transport while the salts range from the characteristic steep advective curve to the more gradual diffusive curve.

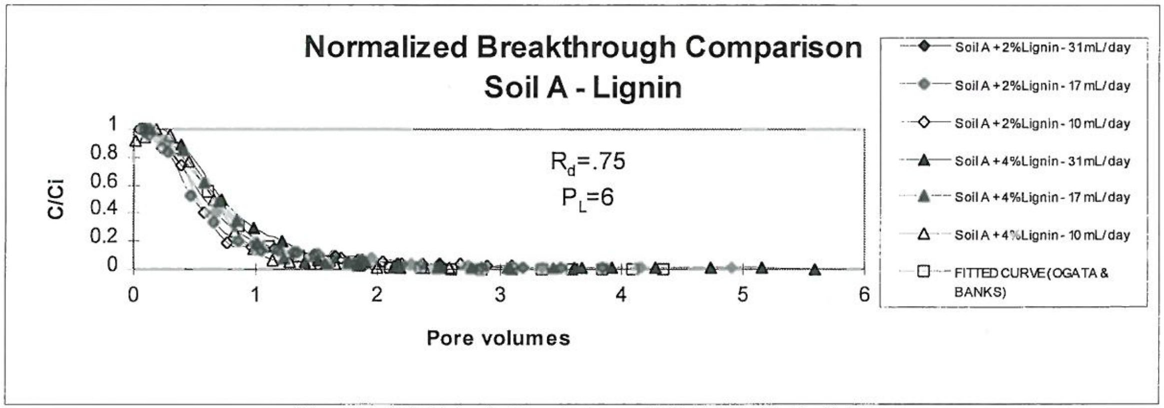

Figure 4.10 Lignin Breakthrough Curve with Soil A.

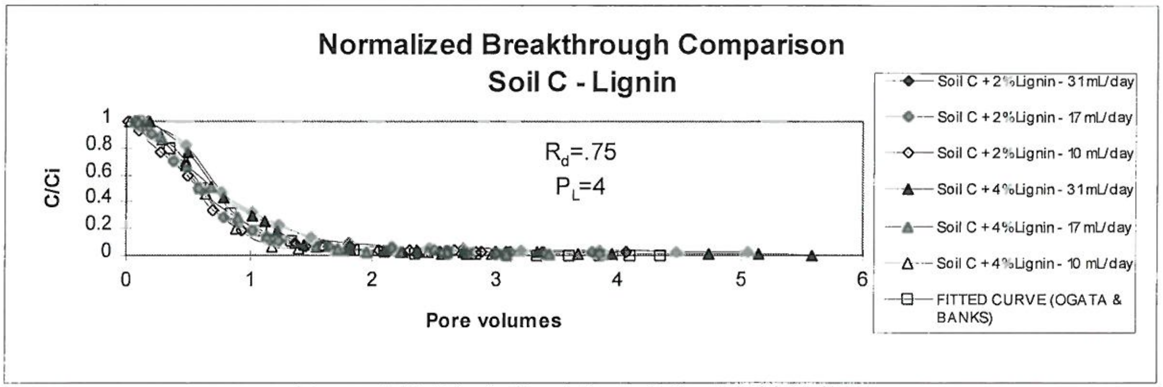

Figure 4.11 Lignin Breakthrough Curve with Soil C.

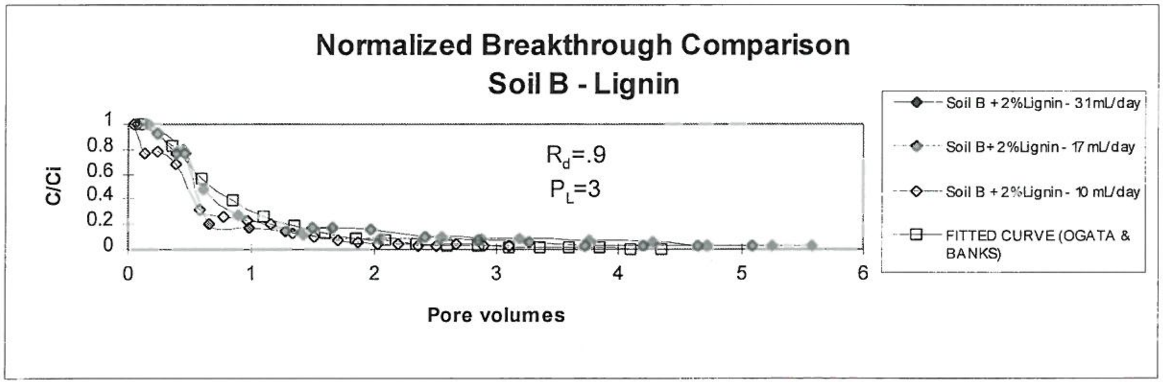

Figure 4.12 Lignin Breakthrough Curve with Soil B.

Although diffusion dominates the lignin transport, the transport becomes even more diffusive dominated and Peclet numbers become even smaller as clay is added (Figure 4.13), but they are independent of seepage velocity. This parallels the behavior of the salts, only the process is not as obvious. Coefficients of hydrodynamic dispersion also are calculated and plotted versus percent kaolinite added (Figure 4.14). A summary of the Peclet numbers is shown (Table 4.4).

Additive	Soil Type (%clay)	Peclet Number
Lignin	A (0)	6
Lignin	B (8.5)	3
Lignin	C (3.0)	4

Table 4.4 Lignin with associated soil type and Peclet numbers.

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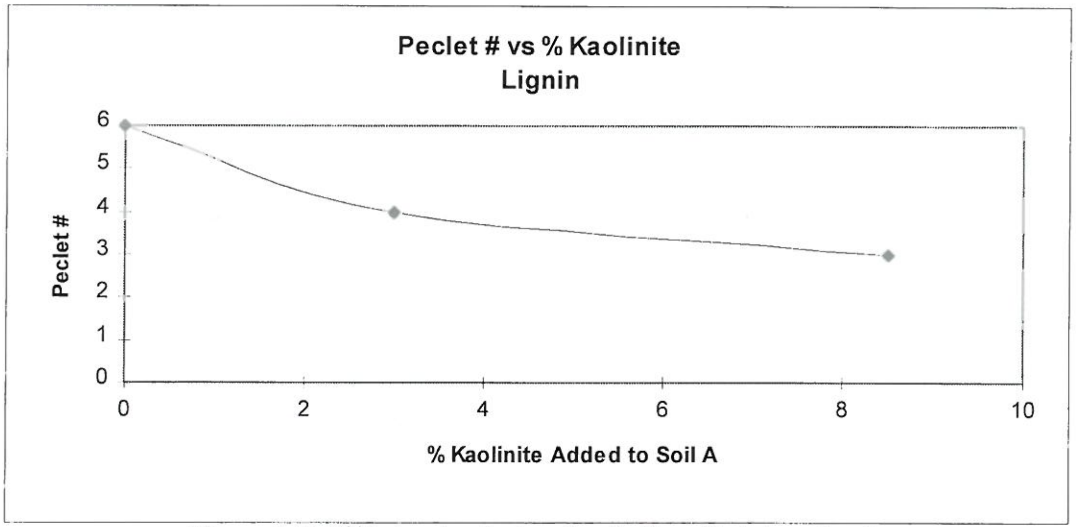

Figure 4.13 Diffusion dominates all soils (Low Peclet numbers).

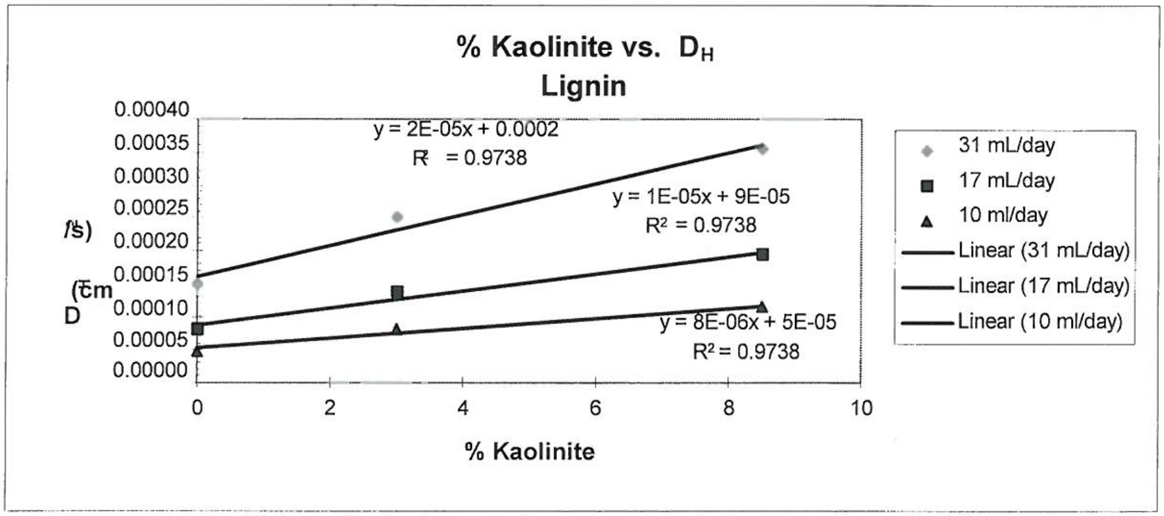

Figure 4.14 Coefficient of hydrodynamic dispersion plots derived from theoretical fits to column breakthrough curves.

As with the salts, the rate at which the lignin leaves the soil is dependent on the seepage velocity and hence, the amount of precipitation or storm size. Large storms leach the lignin much faster than the smaller storms studied (Figure 4.15). This is true for all combinations except this next, unique, case. At a concentration of 4 percent lignin and 8.5 percent kaolinite, the combination of the lignin dispersing and plugging the soil, and the larger amount of kaolinite decreased in the conductivity of the soil dramatically. This prevents water infiltration and leaves the lignin in the soil much longer than any other soil-additive combination studied for any rain event (Figure 4.16). It is shown from this Figure that with 2 percent lignin, the additive is still readily leached from the same soil for all seepage velocities.

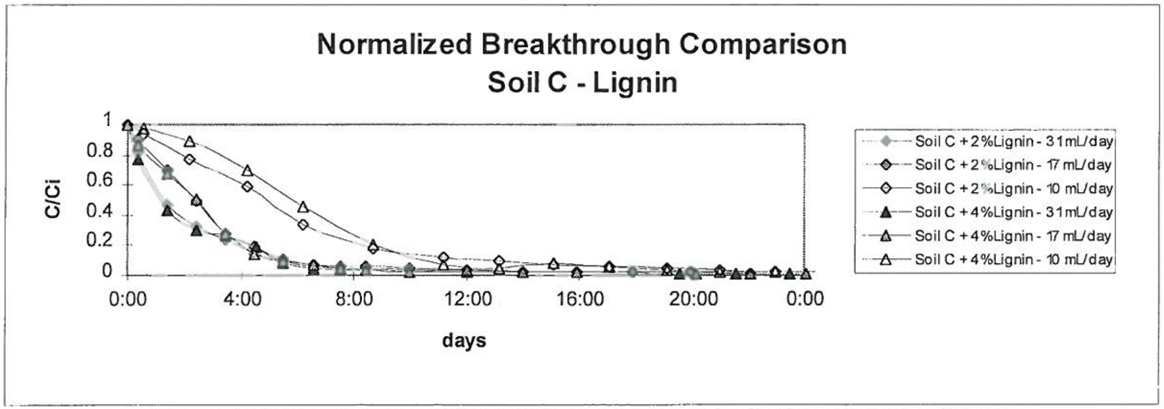

Figure 4.15 Dependence of lignin life on seepage velocity for constant soil type.

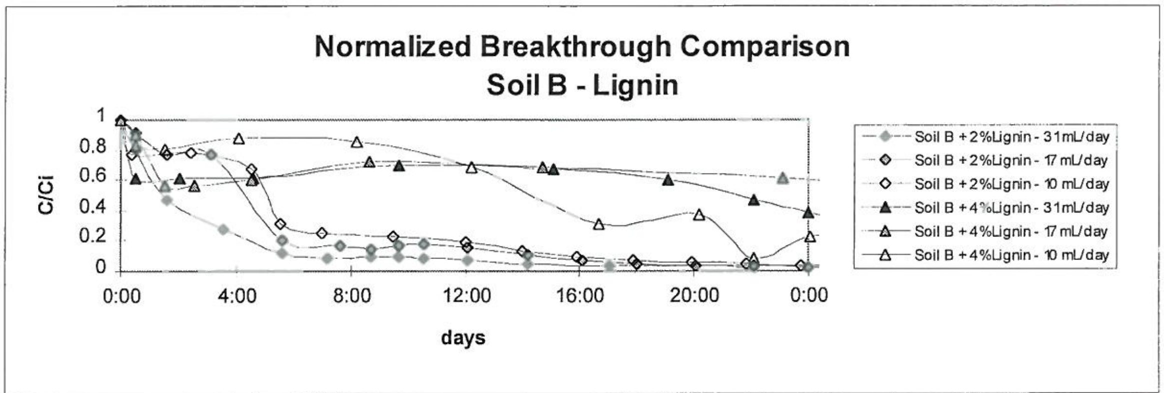

Figure 4.16 Lignin life increases dramatically at 4% with addition of 8.5% clay.

The effective life of lignin is lengthened as clay is added to Soil A. This parallels the salt additives and does not slow down the movement significantly until the concentration of lignin is increased to at least 4 percent. The main increase in life is found only in the time that a small, residual concentration remains in the soil. A comparison of soil type affects is shown for 2 percent lignin at constant seepage velocity (Figure 4.17).

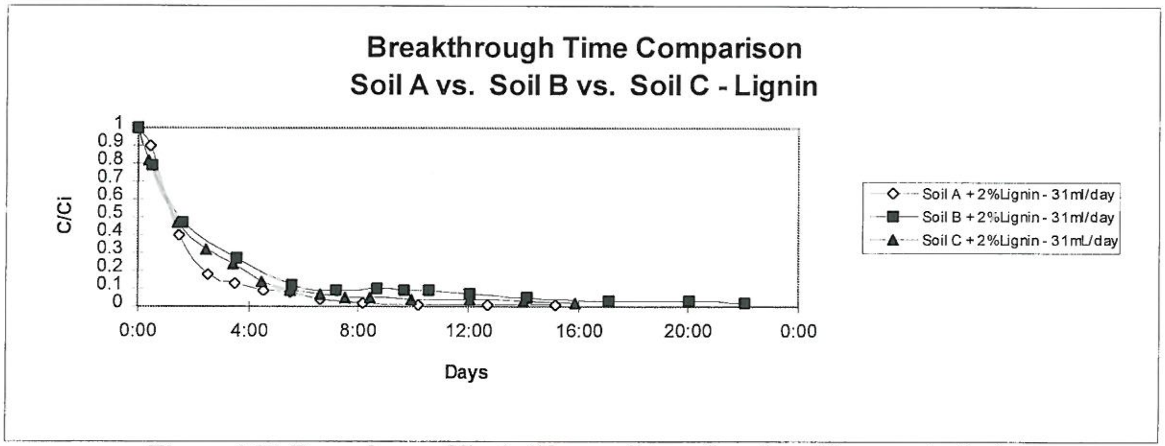

Figure 4.17 Dependence of lignin life on soil type (less than 4% concentration).

Lignin - Retardation Factors

It is shown from the collected data that lignin also is readily transported from the soil. Looking at the breakthrough curves indicate that the c/c_i value of 0.5 also occurs at less than one pore volume for all soil types as with the salts. This gives retardation factors of less than one for all combinations when the advective-dispersive model is fit to the breakthrough curves as shown in Table 4.5. Explanation for this phenomena is the same as that for the salt additives in section 4-3-2. The values of R_d also increase as clay is increased, thus, slowing the transport.

Additive	Soil A	Soil B	Soil C
Lignin	0.75	0.90	0.75

Table 4.5 Retardation factors for lignin with the three soil types.

Effects of Lignin on Soil Properties

As stated in the literature review, lignin will increase the water tightness of the soil. This may be due to several factors. Dispersing the clay fraction decreases permeability and may be due in part to increasing of the Dielectric constant from the addition of an organic acid to the groundwater. These dispersing clays also may provide support at the contact points of the larger particles after the water content decreases. This will be discussed further in the strength results section.

The main affect that lignin has on the soil is plugging the voids. The lignin is very viscous and contains about 30 percent solids. Once this is added to the soil and is allowed to dry, the void space is lowered and plugged, thus increasing water tightness. This is very evident when lignin is applied at a concentration of at least 4 percent with the smaller void ratio provided when kaolinite is added at 8.5 percent.

Rain Simulation Study

The rain simulation resulted in some useful data and results. Although only one rain event was simulated there are results on erosion, runoff, infiltration, additive concentration, and evaporation for six combinations of additives, additive concentration, and soil type. This data is presented in the following five sections and representative graphs and tables are displayed to allow for easier interpretation of the results.

Infiltration Properties

The prepared infiltration specimens were allowed to achieve an equilibrium water content which took about one week. Following the two-hour rain storm, the following infiltration rates and associated water contents were found (Table 4.6).

Infiltration Rates and associated water contents								
1"/Hr storm with a 2-Hr Duration								
Soil Type	Additive	Dry Density (pcf)	Compaction water Content (%)	Initial Water Content (%)	Final Water Content (%)	Weight Water Infiltrated (g)	Ave. Infiltration Rate (in/hr)	Ave. Infiltration Rate (cm/hr)
A	None	132.5	8.96	1.61	7.5	116.1	0.254	0.64516
A	4% $CaCl_2$	135.47	8.11	4.75	6.96	45.4	0.0993	0.252222
A	4% Lignin	138.55	7.6	3.51	4.59	22.54	0.0491	0.124714
C	None	135.98	7.91	1.3	4.97	75.5	0.165	0.4191
C	4% $CaCl_2$	139.3	7.74	4.5	6	32.6	0.0713	0.181102
C	4% Lignin	140.25	8.49	3.98	4.31	7.2	0.0157	0.039878

Table 4.6 Infiltration rates and associated water contents.

It is observed from these results, that lignin-soil combinations had the lowest infiltration rates, while the soil with no additives had the highest infiltration. The salt combinations had intermediate rates of infiltration.

The low lignin infiltration is due to a hard crust formed on the road section during the drying process (Figure 4.18). This crust becomes more developed during the rain storm because of the beating action of the rain drops. This action causes physical disintegration of the soil clods leading to deposition of fines in the pores. There also is the dispersion of the surface layers, increasing water tightness, which is more evident in Soil C since it has a higher clay content and thus lower infiltration.

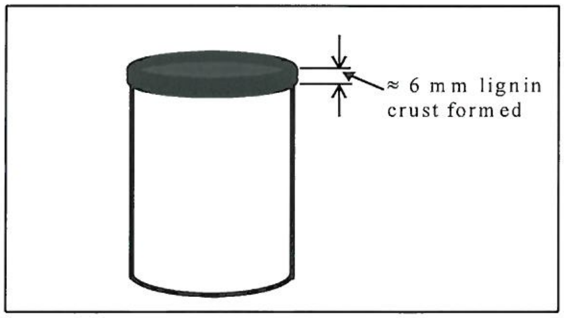

Figure 4.18 Lignin crust formed during drying and thickened during rain storm.

Runoff Rates

The low infiltration of the lignin should yield the highest runoff since water that isn't infiltrated must runoff. Likewise, the salt samples should produce intermediate runoffs and the plain soils should give the lowest runoffs. Additionally the clay soil should produce comparatively higher runoffs .

The runoff data found from the two percent sloped road sections gave reasonably good results, but they don't coincide exactly with the comments above. The curves showed the three characteristic runoff stages until equilibrium runoffs were achieved (Figure 4.19). The main problem with this testing is that some water leaked down the sides of the road sections, resulting in lower runoffs, since only the runoff and not all of the losses were measured.

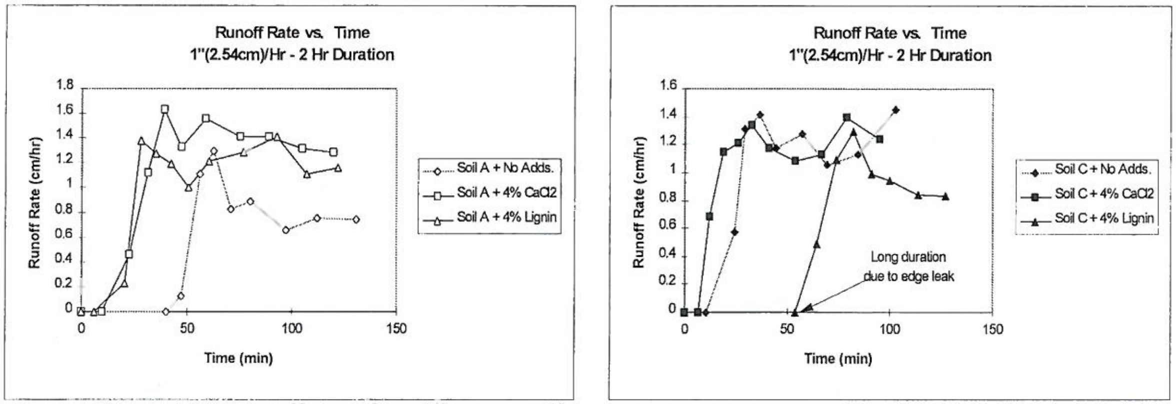

Figure 4.19 Runoff rates found from runoff water measurements on sloped road sections.

Comparing the runoff rates to the relative values that should have occurred, it is observed that edge leaks affected the runoff measurements. These leaks were caused by the soil drying and shrinking away from the edges of the pan during the drying period.

The equilibrium runoff values for the lignin should have been much higher than any of the others, while the plain soil should have had the lowest runoff rates. The salt-soil combinations seemed to give fairly good values because of their hygroscopic and deliquescent properties. These properties did not allow the soil to shrink as much since the salts draw water out of the air. This minimized edge leaks.

Although these curves don't follow theory exactly, they do give general curve shapes and reasonable values. When one thinks of an actual road, the edge leaks could simulate cracks which would lower surface runoff. A comparison of the equilibrium runoff rates to those calculated from the infiltration specimens based on a 2.5 cm storm is shown in Table 4.7. This is done by calculating the amount of the storm infiltrated from the measured water contents in the soil. This amount is then subtracted from 2.5 cm to obtain the calculated surface runoff. The calculated runoff rates would simulate the actual runoff of a well-constructed unpaved road and the measured values are low, especially for the lignin, but may simulate a poor road with cracks present.

SOIL TYPE + ADDITIVE	MEASURED RUNOFF RATE (cm/hr)	CALCULATED RUNOFF RATE (cm/hr)
A	0.85	1.85
A+4% LIGNIN	1.4	2.38
A+4% $CACL_2$	1.5	2.25
C	1.3	2.08
C+4% LIGNIN	1.0	2.46
C+4%$CACL_2$	1.3	2.32

Table 4.7 Comparison of measured runoffs to those calculated from infiltration specimens.

For purposes of evaluation, the calculated runoffs are closer to real values and will be used to base conclusions on. This is justified because the final water contents for the sloped road sections didn't correspond to the infiltration values, proving there were leaks, but did correspond to the infiltration sections (Table 4.8). This further proves that the calculated rates are good numbers, since both water contents for the six combinations are very close.

SOIL TYPE + ADDITIVE	ROAD SECTION FINAL WATER CONTENT (%)	INFILTRATION SPECIMEN FINAL WATER CONTENT
A	8.385	7.50
A+4% LIGNIN	4.420	4.59
A+4% $CACL_2$	7.165	6.96
C	6.005	4.97
C+4% LIGNIN	5.150	4.31
C+4% $CACL_2$	5.540	6.00

Table 4.8 Comparison of final water contents for Road sections and Infiltration specimens.

Additive Concentration in Runoff

The runoff water carries a fraction of the soil's additive away in the surface water. The amount of the additive carried away is determined to see if there is a substantial

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additive concentration decrease in the soil. The residual in the soil can then be determined to see what fraction is still in the soil for downward transport.

The salt additives had a small fraction carried away in the runoff. Following the analysis for calcium and chloride in the runoff water, the curves in Figures 4.20 and 4.21 were produced.

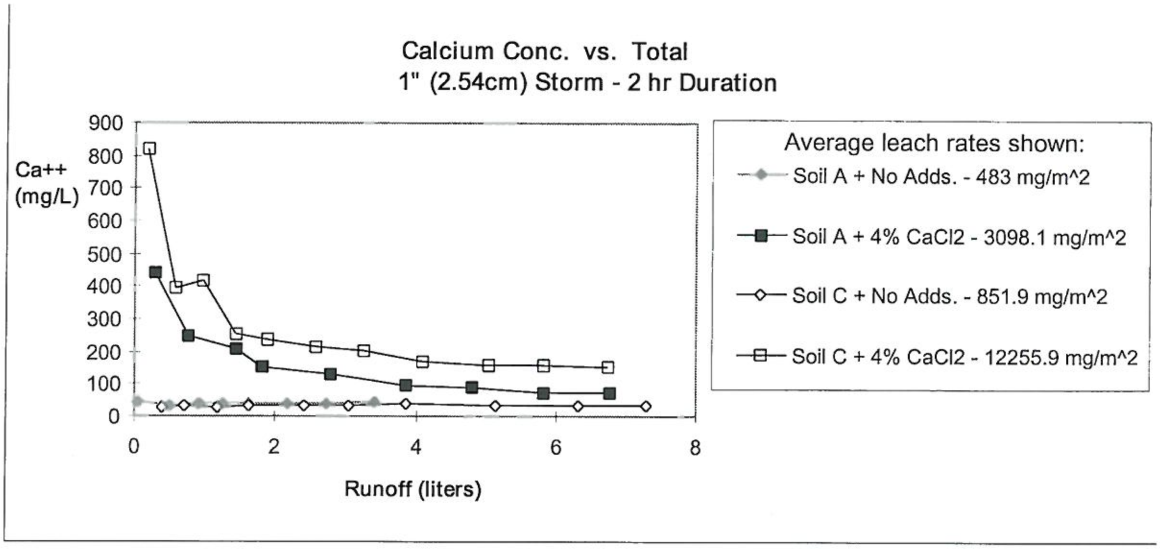


Figure 4.20 Calcium concentration in runoff water.

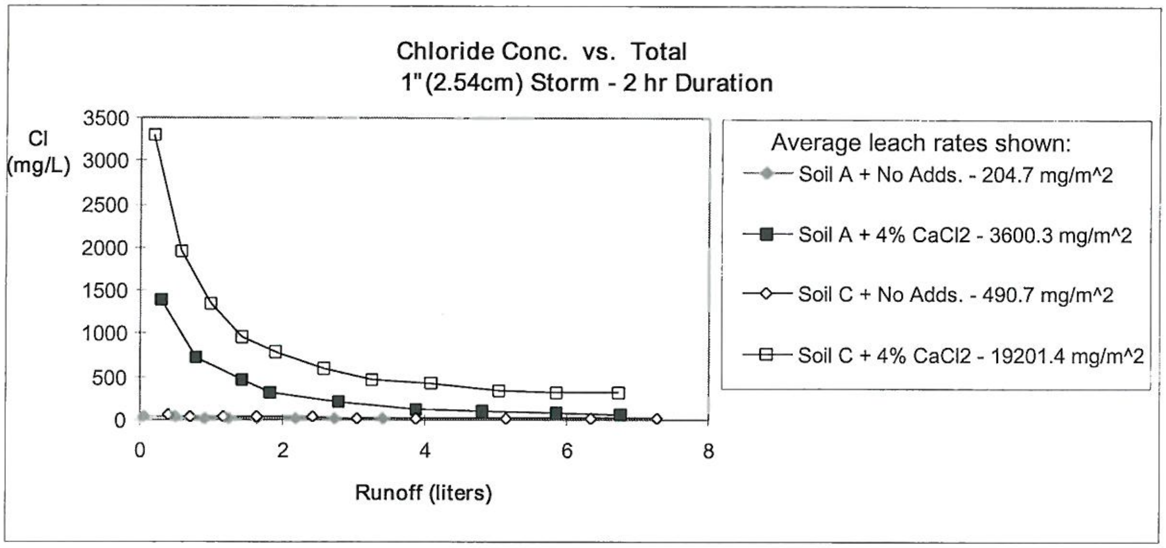


Figure 4.21 Chloride concentration in runoff water

The areas under these curves are determined to find the amount (g/m^2) of the solute carried away in the 2.5 cm storm over the two-hour period. These values are then compared to the concentration in the soil in mg/m^2. This comparison is shown in Table 4.9.

Soil Type	Cl$^-$(g/m^2)	Ca^{++}(g/m^2)	% Decrease From Original (B*) Conc.
A+4% CaCl$_2$ - B*	807.2 (in soil)	454.1 (in soil)	---
A+4%CaCl$_2$ - A*	3.6 (in water)	3.1 (in water)	Cl$^-$ = 0.46 % Ca^{++} = 0.68%
C+4%CaCl$_2$ - B*	807.2 (in soil)	454.1 (in soil)	---
C+4%CaCl$_2$ - A*	19.2 (in water)	12.3 (in water)	Cl$^-$ = 2.4% Ca^{++} = 2.7%

*B-Before storm, A-After two hour storm

Table 4.9 Comparison of solutes in runoff water to the additive in the soil.

From this table, it can be observed that most of the CaCl$_2$ remains in the soil. The soil with the clay loses about four times as much as Soil A. This is probably due to the lower infiltration rate (higher runoff) of the soil with the clay. Although Soil C has the larger loss, neither is a substantial amount for the volume of rain to which the samples were exposed.

The lignin-soil combinations have similar curves, but a larger percentage of the original concentration was lost. This is because of the accumulation of the lignin at the surface of the road during the drying process as shown in Figure 4.18. Since there is a large concentration at the surface initially, there is more available to be carried off in the surface water. The developed runoff concentration curves are shown in Figure 4.22.

The areas under these curves are determined to find the amount in L/m^2 of the lignin that is carried away in the 2.5 cm storm over the two-hour period. These values are then compared to the concentration in the soil in L/m^2. This comparison is shown in Table 4.10. It is observed that Soil C (A + 3% Kaolinite) holds the lignin in the soil substantially better than Soil A under the same conditions.

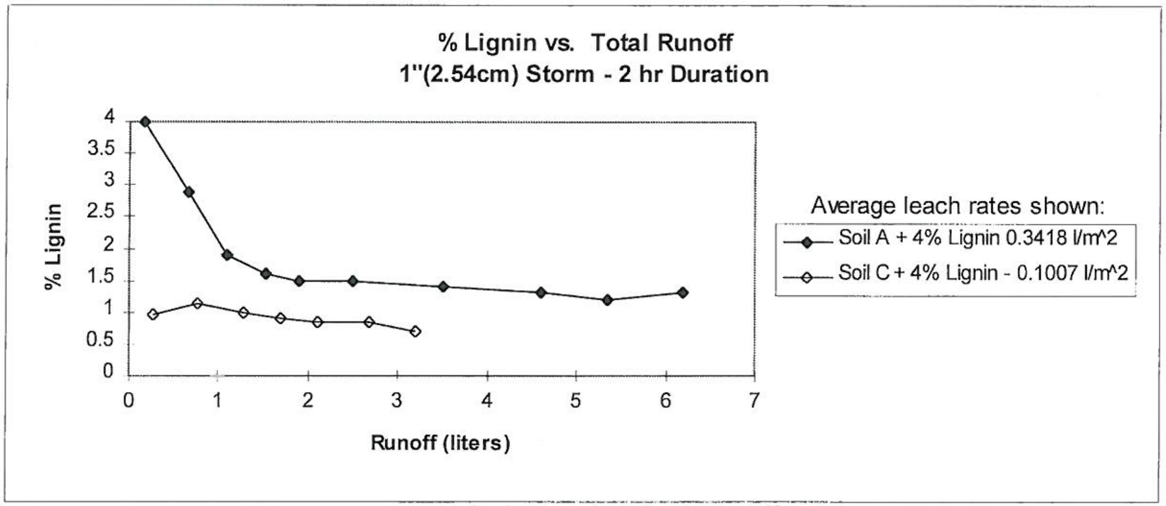


Figure 4.22 Lignin concentration in runoff water.

Soil Type	Lignin (L/m^2)	% Decrease from Original (B*) Concentration
A+4% Lignin (B*)	1.45 (in soil)	---
A+4% Lignin (A*)	0.34 (in water)	23.5%
C+4% Lignin (B*)	1.45 (in soil)	---
C+4% Lignin (A*)	0.10 (in water)	6.9%

*B-Before storm, A-After two-hour storm

Table 4.10 Comparison of solutes in runoff water to the additive in the soil.

Erosion

Erosion is an important parameter to be determined because erosion degrades the unpaved road surface and causes need for repair. The soil-additive combinations with the lowest erosion rates are most desired. The erosion rates can be misleading. Samples with the highest runoff rates (and lowest infiltration) have the fastest velocity and therefore can carry sediment away more readily. The samples with the highest infiltration rates were observed to have a very large splash erosion, but the runoff was not fast enough to carry as much sediment. This may cause the worst erosion case (Soil A with no Adds.) not to seem as drastic because the wash erosion is low, but the splash erosion is most severe. Figure 4.23 shows sedimentation rates for the six combinations.

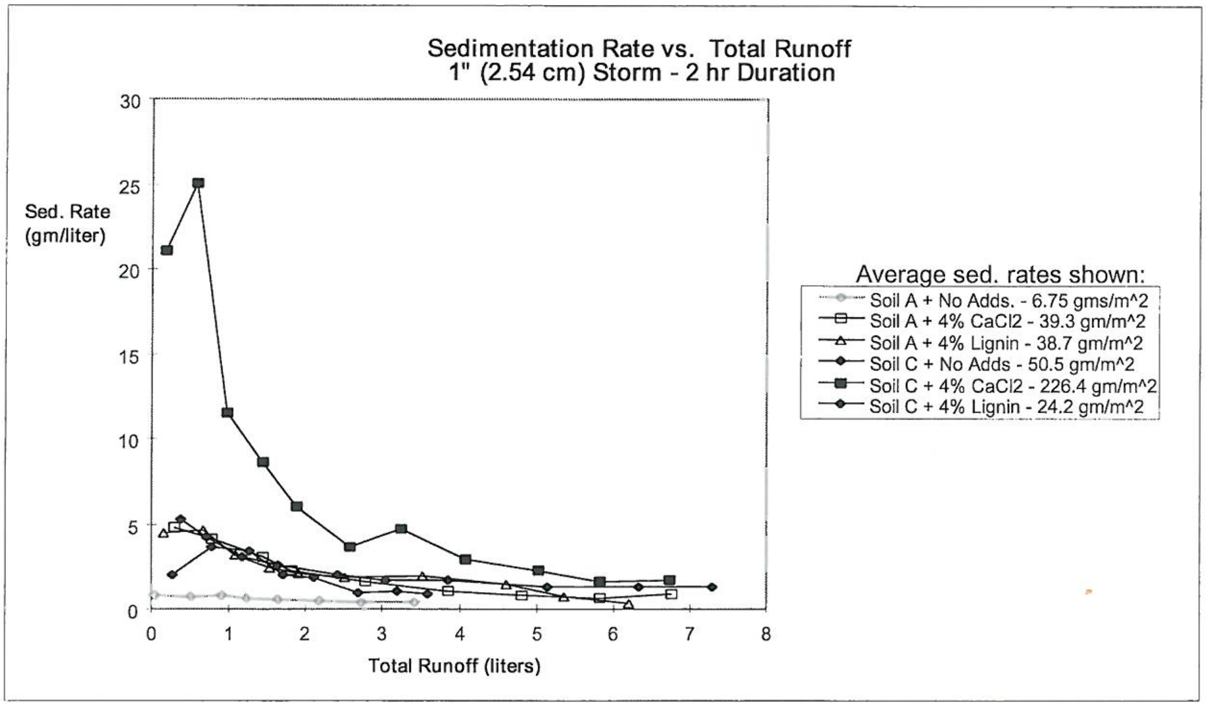


Figure 4.23 Sedimentation rates for the six tested simulations.

Soil C with $CaCl_2$ yielded the highest sedimentation. This combination showed a comparatively large sedimentation from the others, which were very similar. Soil A shows a very low erosion, due to the high infiltration rate. The low runoff of Soil A could not carry the eroded soil from the rain drop impact. There are similar results for other samples. For these reasons the sedimentation rates determined from the laboratory analysis are not as important as the qualitative (observed) results (Table 4.11).

SOIL-ADDITIVE COMBINATION	SEDIMENTATION RATE (g/m^2)	OBSERVED EROSION*
A	6.75	XXX
A+4% $CACL_2$	39.3	XX
A+4% LIGNIN	38.7	X
C	50.5	XXX
C+4% $CACL_2$	226.3	XX
C+4% LIGNIN	24.2	X

*xxx-High, xx-Intermediate, x-Low.

Table 4.11 Observed erosion compared to average sedimentation.

The above table shows that all measured sedimentation rates are fairly low. This is due to the good compaction, low slope and low runoff velocity. The soils with no additives had the highest observed erosions due to the splash erosion component. The impact of the rain drops loosened the soil at the road surface. These samples had very rough surfaces following the storm events, but much of the disturbed soil was not carried down the road slope. The salts had similar results.

The soil-lignin combinations had the lowest observed erosions. The surfaces following the rain event were still very smooth and had little disturbed soil on them. This is due to the hard, smooth crust that is formed during the drying process of the road section, as well as the cementation properties of lignin. Another general trend of the study is that addition of clay increases the erosion. This is due to the increase in the amount of fines (- #200) in the road surface. These fines are more easily carried away because of their small size.

Evaporation

Following a rain storm the ground begins to dry. This carries moisture to the surface from the soil. The water that is carried up brings solutes with it which are left in the soil as the moisture evaporates. This process also acts when the road surface dries, bringing the additives to the surface in higher concentration. An analysis of additive concentration in the soil was performed following the drying process to determine these distributions with depth. They are shown below.

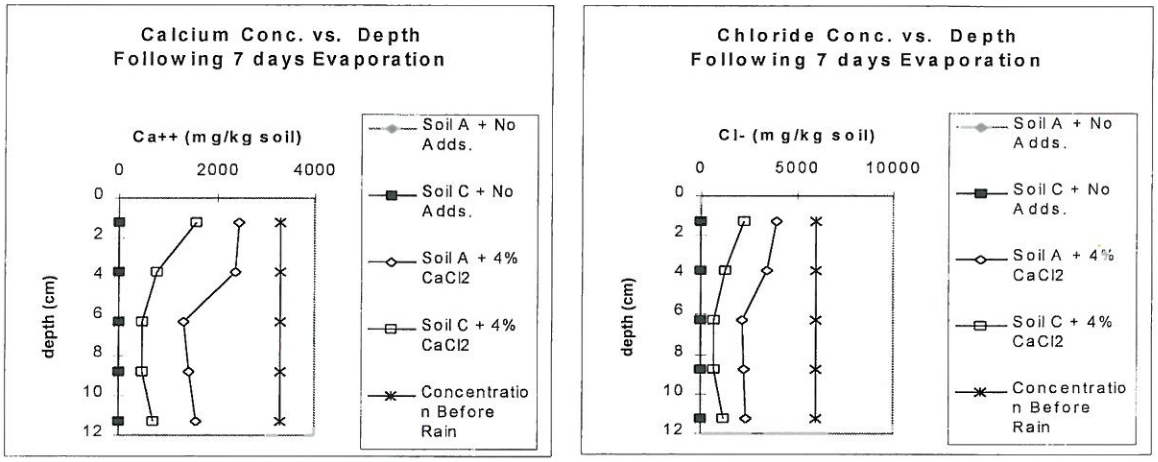


Figure 4.24 Concentration profiles of calcium and chloride following evaporation.

These profiles show the accumulation of the salts at the surface of the soil and are quite a bit lower than the original concentration as shown. This is because of the saturation paste method used for the analysis. There will always be some of the solute left in the soil following the filtering process. This, combined with the fraction that was carried away on surface runoff are the reasons for the difference in the concentrations.

The average concentration of salts in the clay soil is quite a bit lower than the nonplastic soil following the drying process. This occurs because the clay loses more of the additives in the surface runoff during a storm as was shown in section 4-4-3.

The lignin evaporation results yielded the same shape curves as did the salts. They had the same high concentration at the surface, but lower concentrations than the soil-lignin combination before the rainstorm. The concentration profile is shown in Figure 4.25. This figure shows much lower concentrations than the original at depths below the surface, also due to the method. The saturation paste method uses a filtration process which leaves a lot of the lignin in the soil and also filters some of the lignin solids out. This results in the lower concentrations, but does give the general trends and curve shape. The curves show that the clay soil has slightly higher concentrations. This parallels the fact that the clay soil didn't lose as much of the lignin in the surface runoff.

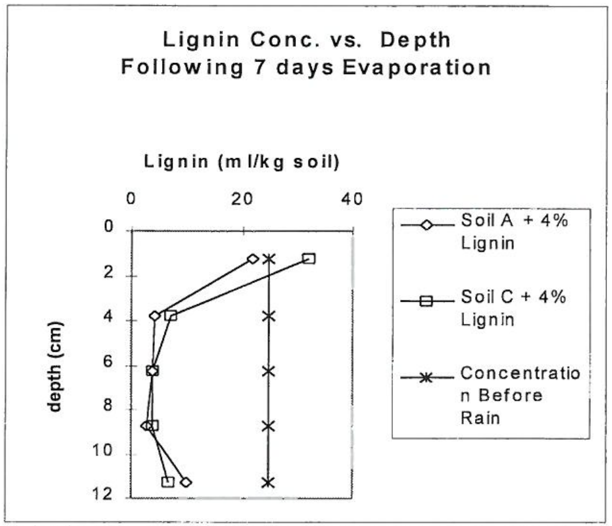


Figure 4.25 Lignin concentration versus depth following evaporation processes.

Residual Strength

Once the additives are completely removed from the road surface by downward transport or from surface runoff (i.e., after more than five pore volumes of water has leached through the soil), there is a need to determine if the additives leave any residual strength increase. The general trend is that they don't leave much, if any, residual strength.

Once the lignin is completely gone (greater than five pore volumes), the pore space is increased, since the lignin which occupied some fraction of the pore space is gone. Combined with the loss of the cementation properties. this results in the weak strength of the soil following the leaching process. This compares with the strength of the soils with no additives prior to testing (Table 4.12).

RESIDUAL STRENGTH OF SOIL AFTER LEACHING CYCLE

Soil Type	Additive	Add. Concentation	Leach rate	Max. Stress	Max. Stress
		%	mL/day	KPa	psf
Soil A	no adds	0	31	425	20415
Soil A	$MgCl_2$	2	31	477	22912
Soil A	$MgCl_2$	2	17	363	17403
Soil A	$MgCl_2$	4	17	451	21651
Soil A	$MgCl_2$	4	10	462	22180
Soil A	$CaCl_2$	2	31	431	20681
Soil A	$CaCl_2$	2	17	413	19802
Soil A	$CaCl_2$	4	31	561	26908
Soil A	$CaCl_2$	4	17	507	24348
Soil A	$CaCl_2$	4	10	436	20910
Soil A	Lignin	2	31	276	13233
Soil A	Lignin	2	17	268	12888
Soil A	Lignin	2	10	330	15840
Soil A	Lignin	4	31	296	14198
Soil A	Lignin	4	17	331	15881
Soil A	Lignin	4	10	341	16375
Soil B	no adds	0	0	379	18189
Soil B	$MgCl_2$	2	31	398	19095
Soil B	$MgCl_2$	2	17	326	15661
Soil B	$MgCl_2$	4	31	406	19505
Soil B	$MgCl_2$	4	17	369	17708
Soil B	$CaCl_2$	2	31	401	19229
Soil B	$CaCl_2$	2	17	612	29395
Soil B	$CaCl_2$	4	31	362	17374
Soil B	$CaCl_2$	4	17	520	24958
Soil B	Lignin	2	31	431	20691
Soil B	Lignin	2	17	440	21142
Soil B	Lignin	2	10	382	18354
Soil B	Lignin	4	31	432	20723
Soil B	Lignin	4	17	438	21015
Soil B	Lignin	4	10	332	15923
Soil C	$CaCl_2$	4	31	239	11465
Soil C	$CaCl_2$	4	17	232	11118
Soil C	Lignin	2	31	310	14862
Soil C	Lignin	2	17	271	12996
Soil C	Lignin	2	10	286	13726
Soil C	Lignin	4	31	296	14186
Soil C	Lignin	4	17	395	18973
Soil C	Lignin	4	10	254	12206

Table 4.12 Residual strengths following leaching.

The salt additives had similar results. They showed little residual strength following the additive removal (after five pore volumes). The main strength increase with the salt additives results from the crystallization of the salt between the soil particles. There also is some increase in strength due to the flocculated (stronger) structure of the clay fraction from the high electrolyte concentration.

A relationship between additives and number of pore volumes passed through the samples (Soil C) also was developed (Figure 4.26). It showed that the lignin had very high initial strengths almost three times that with the calcium chloride. At about one pore volume the strength leveled off at nearly half its initial strength, while the salts, at a strength one-half that of the lignin columns, started to show a slight increase from the change in the soil structure.

Following leaching one pore volume in the salts, the strength decreases because there isn't much salt to crystallize in the still flocculated structure. After all of the salt is completely washed from the soil there is some strength increase. Once the salt is completely removed the structure becomes more dispersed. This dispersion accounts for the strength increase because the clay gathers at the contact points of the large particles (Figure 4.26, and Table 4.12).

The low infiltration rate of Soil C with lignin would make this combination last a long time. This combination would require about 100 cm (40 inches) of rain to achieve one pore volume passing the soil and would require only about two applications per a year.

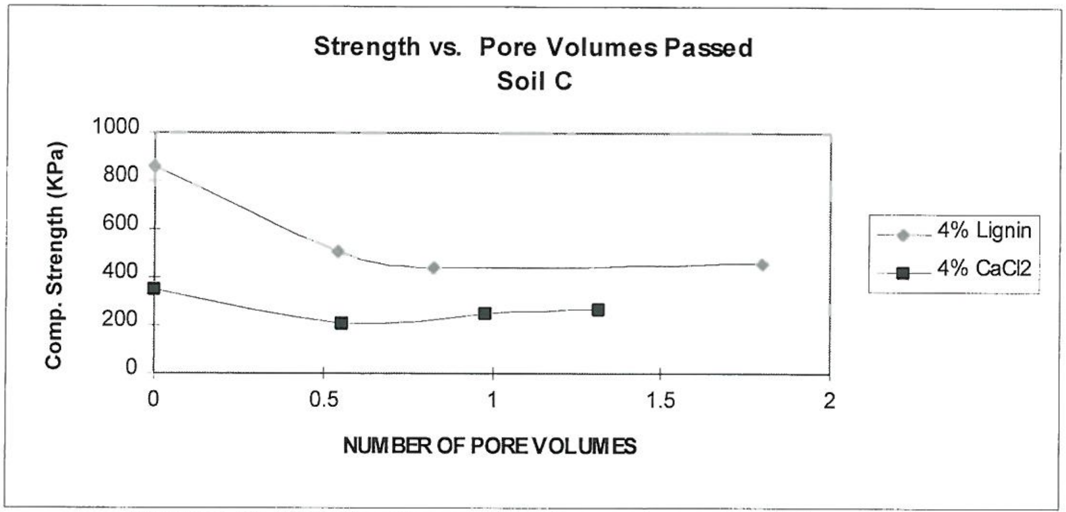


Figure 4.26 Strength versus number of pore volumes passed through soil.

The initial strengths of the soils in Figure 4.26 can be used for comparison of the strength before leaching (at zero pore volumes) to those residual values in Table 4.12. It can be seen that the lignin approximately doubles the soil strength, while the salt additives add little additional strength.

A final result from this section of study is the affect of clay addition on the residual strength. This had little affect on the salts, but as clay was added to the lignin samples there was an increase in the residual strength. This is probably due to the decrease in porosity resulting in a more dense, stronger structure.

Computer Modeling

The computer model was executed for the three soils with the salt and lignin additives. There are six representative curves that are found for the soil-additives combinations. They are shown with the complementary Peclet number and retardation factor in Figures 4.27 through 4.29.

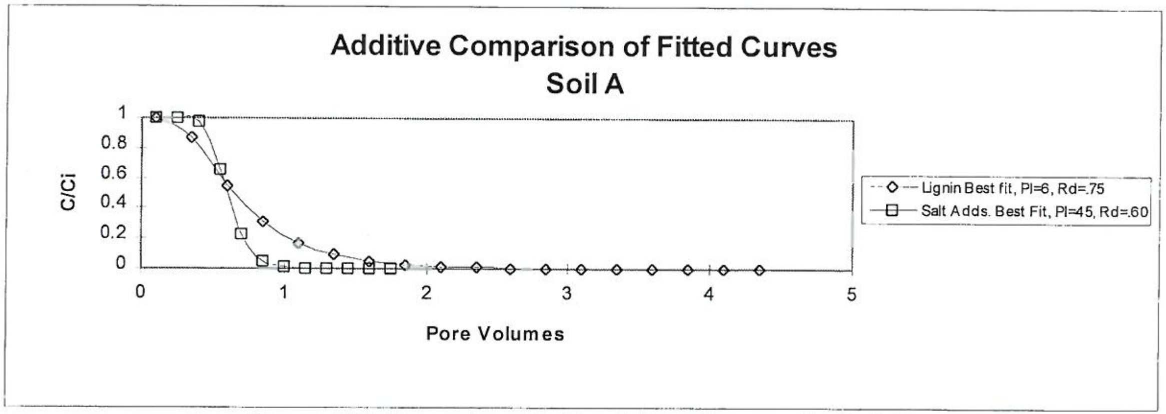


Figure 4.27 Computer output breakthrough curves for Soil A.

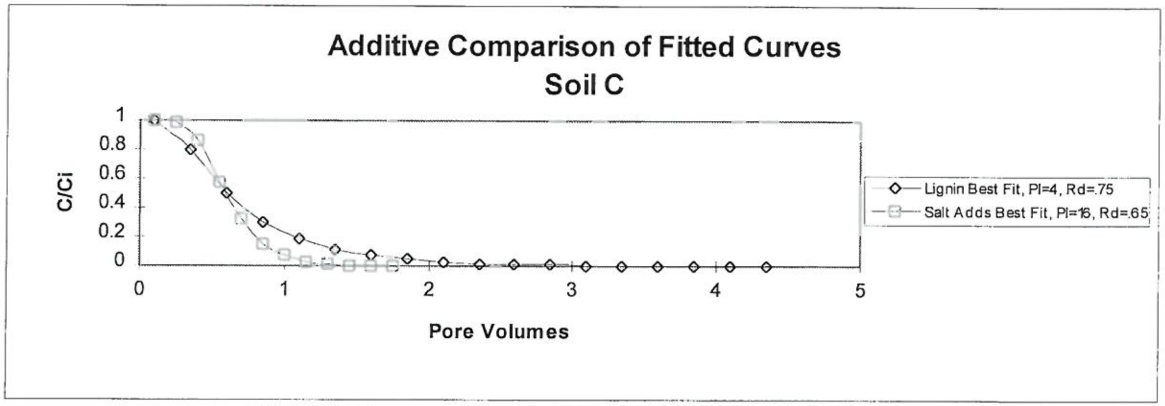


Figure 4.28 Computer output breakthrough curves for Soil C.

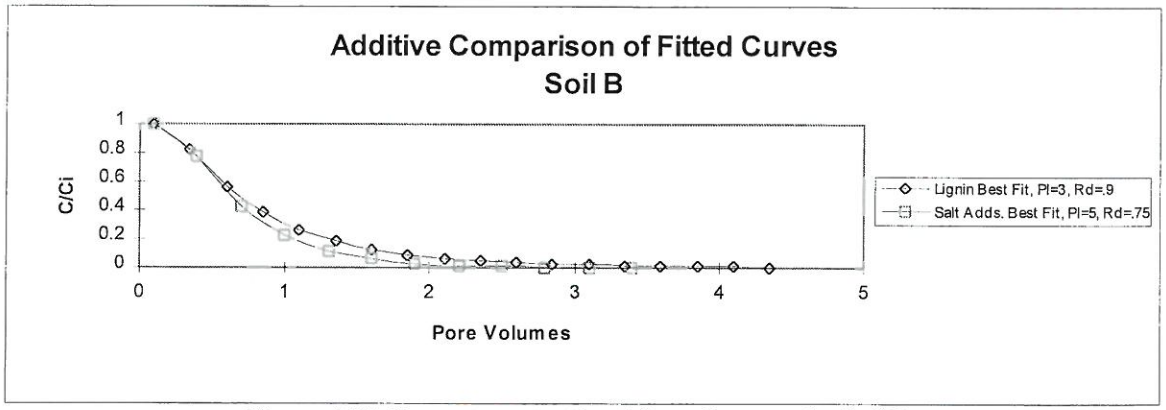


Figure 4.29 Computer output breakthrough curves for Soil B.

CHAPTER 5. CONCLUSIONS

Introduction

The results in Chapter 4 were found from the column study and the rain simulation with the various soil-additive combinations in the three specified additives. They are lignin sulfonate, calcium chloride and magnesium chloride. From these results, conclusions can be drawn about the downward solute transport, surface water solute transport, erosion, infiltration rates, runoff rates and effective life of the additives. The effective life is determined by results from both the column study and the rain simulation. Conclusions on the dominating type of transport, as well as how accurately the advective-dispersive model fit the solute breakthrough data, also are made.

Finally, conclusions on the best performing additive-soil combination can be drawn with respect to soil strength during the leaching process. The strength decreases as more water is leached through the columns, but some combinations performed better than others. The performance of the computer model also will be discussed.

Soil Column Study

Conclusions drawn from the column study include dissolved additive transport properties and trends. They encompass the effects of clay addition, seepage velocity and additive concentration. Some of the properties include reactive properties that effect retardation, breakthrough times and diffusion coefficients that govern the dominating transport process.

Salt Additives

From the column breakthrough data, the first conclusion that can be made is that both magnesium chloride and calcium chloride travel with the same transport properties and for this reason are grouped together in the "salt additives" category. The salt additives are both conservative solutes. That is, they are readily carried from the soil in the aqueous phase regardless of additive concentration and have no adsorptive properties. This is shown because the breakthrough ($c/c_i = 0.5$) occurs at less than one pore volume of groundwater flow and the additive is effectively gone ($c/c_i \cong 0.0$) from the soil at about one pore volume (Figures 4.1 to 4.3).

The addition of clay to Soil A (the base, nonplastic soil) gradually changes the governing transport mechanism from advective-dominated to diffusive/dispersive-dominated (Figure 4.4). Advection dominates when no clay is added, while both processes (advection and diffusion/dispersion) occur at 3 percent kaolinite addition. Full diffusion/dispersion-dominated transport occurs when kaolinite is at 8.5 percent. This is shown in the results section where Peclet numbers vary from 45 to six as clay is added.

The addition of clay also slightly retards the transport of the additives. With no clay, total removal of the additives occurs at about one pore volume of flow, but with 8.5 percent kaolinite, there is a longer, low concentration residual. Total removal occurs at about 1.8 pore volumes of flow. All three soils still promote conservative solute transport since breakthrough ($c/c_i=0.5$)occurs at less than one pore volume.

This information concludes that both salt additives, regardless of concentration, leach rate, and soil type have an effective life that lasts until about one pore volume of flow has passed the soil. Since the total porosity of the three soils only varies from 0.301 to 0.260, the total pore volume of all the soils is about the same for evaluation purposes.

As is expected, the rate at which the additives leave the soil depends on the storm size. At 31 ml/day (1.53 cm/day) of continuous exposure to influent (rain) the salt additives last about three days. The 17 ml/day (0.84 cm/day) loading required about five days for total removal and the 10 ml/day (0.50 cm/day) rate removed all of the additive in about nine days (Figure 4.7). These durations were slightly increased when 8.5 percent clay is added, but not significantly except at very low concentrations.

Lignin Sulfonate

The lignin sulfonate also is a conservative solute and is readily transported from the soils. The breakthrough ($c/c_i = 0.5$) occurs at less than one pore volume for all three soil types. As clay (kaolinite) is added to the base soil the transport is retarded little more than with the salt. The values for R_d for lignin ranged from 0.75 to 0.90 while those for the salts ranged from 0.60 to 0.75.

The dominating transport mechanism for all three soil types using lignon is diffusion/dispersion. This is evident because of the low Peclet numbers required to fit the advective-dispersive equation to the breakthrough data for the lignin-soil columns (Figures 4.9 to 4.11). As clay is added, the dominate process favors diffusion/dispersion even more. The Peclet numbers range from six for Soil A to three for Soil B (A+8.5% Kaolinite). This proves that clay has much less affect on the transport of lignin since there is a Peclet number range of only three (6→3), while there is a range of 39 (45→6) for the salt additives.

The addition of kaolinite does retard the transport of the lignin as clay is added in the higher concentration. The value for R_d at zero and 3.5 percent kaolinite is 0.75, while it is a value of 0.90 when clay is at 8.5 percent. Although the retardation is evident as clay is added, this only increases the time at which the low concentration ($c/c_i \cong 0.15$ or 15% of the original concentration) of lignin remains in the soil. Lignin is completely removed from Soil A at about 1.9 pore volumes, from Soil C at about 2.0 pore volumes and from Soil B at about 3.0 pore volumes.

Although these numbers are larger than those for the salts, the effective life for all soil-lignin combinations is about 1.3 pore volumes (Soil B may be about 1.75 pore volumes). After 1.3 pore volumes of flow, the residual concentration (c/c_i) is less than or equal to 0.2 for Soils A and C and equal to about 0.25 for Soil B. This isn't a substantial concentration for stabilization purposes and reapplication is needed at this point.

As is expected, the rate at which the lignin leaves the soil depends on the storm size. At 31 ml/day (1.53 cm/day) of continuous exposure to influent (rain) the lignin lasts about eight days. The 17 ml/day (0.84 cm/day) loading required about 12 days for total removal and the 10 ml/day (0.50 cm/day) rate removed all of the additive in about 16 days (Figure 4.15). These durations were slightly increased when clay is added, but not significantly, except at very low concentrations.

This is true for all cases except for the combination of Soil B with 4 percent lignin, as this combination which reduced the soil conductivity so much that it accepted water very slowly no matter what leach rate (Figure 4.16). This kept the additive in the soil for a very long time since the amount of water that carries the lignin from the soil was greatly reduced. The lignin remained in the soil at c/c_i of 0.70 (70 percent of original concentration) for almost 24 days of continuous exposure to all three leach rates. This is contrasted to the Soil B with 2 percent lignin which is completely gone form the soil in 24 days.

Fit of the Advective-Dispersive Equation

The solution of the advective-dispersive equation requires a saturated soil condition. This was tested before the actual column study was conducted and the columns met the condition. Once the breakthrough data was collected and the model was fit, the results were satisfactory. The solution to the advective-dispersive equation (case 2) fit the data almost perfectly for both additive types and for all transport mechanisms (Figure 5.1 and 5.2).

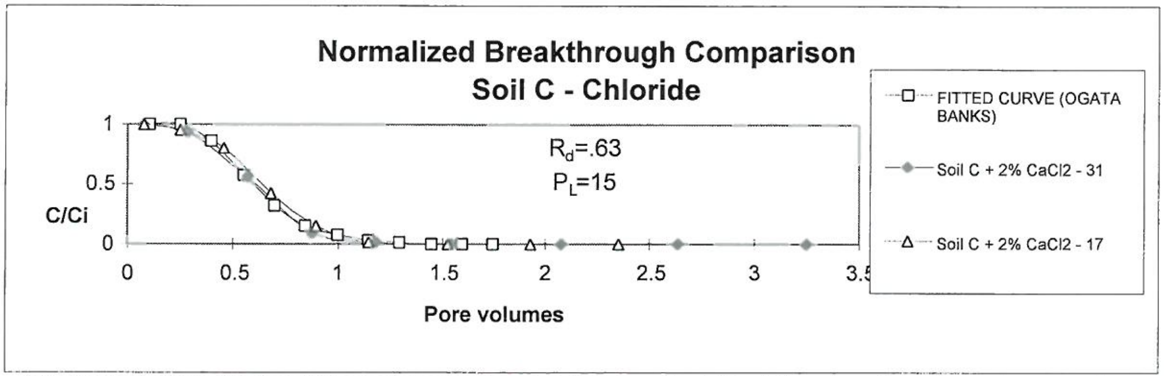


Figure 5.1 Chloride breakthrough curve showing the excellent fit of the advective-dispersive equation when both advection and diffusion/dispersion are acting.

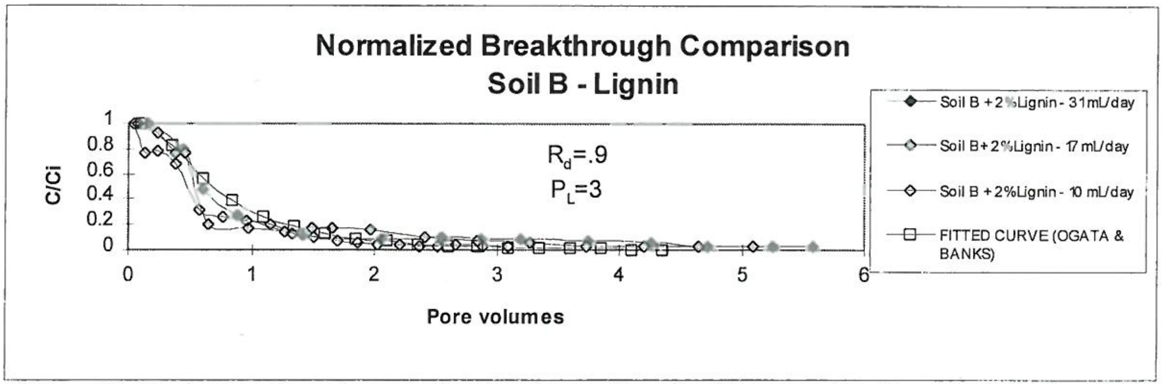


Figure 5.2 Lignin breakthrough curve showing the excellent fit of the advective-dispersive equation when mainly diffusion/dispersion is the dominate transport process.

It is observed that the lignin is always transported through diffusion/dispersion (low Peclet numbers), while the salt additives range from advective-dominated transport (Peclet number of 45) to diffusive/dispersive-dominated transport (Peclet number of six). The curves for both additive types flatten out as the clay is added, which is characteristic of the diffusive/dispersive transport.

Rain Simulation

The conclusions of the rain simulation are based on the results in Chapter 4. The conclusions are divided into five sections, as were the results. These sections include infiltration, runoff rate, additive concentration in the runoff, erosion and evaporation processes. The conclusions include the affects of additive type and clay addition on the stated processes.

Infiltration Processes

The lignin-soil combinations had the lowest infiltration rates of any other combinations. This is due to the hard crust that is formed during the drying process before the rain simulation. This crust is about six millimeters thick and is very impermeable to water. Crust formation during the rain storm, as was stated in Chapter 2, also decreases the infiltration.

The low infiltration of the lignin road sections is also due to lignin increasing water tightness of the soil. Water tightness is from the decrease in pore volume by addition of solids in the lignin, as well as from the lignin dispersing the clay fraction of the soil, decreasing the permeability of the soil. The exceptionally low infiltration keeps the water out of the road section. This keeps the lignin in the road longer since the water is what dissolves and carries the lignin out of the soil in downward transport.

The salts had intermediate infiltration rates. The main reason for this probably is because the salt-soil combinations started with the highest initial water contents because of the salt's ability to draw water out of the atmosphere and hold it in the soil. This high initial water content leaves less pore volume for the water to infiltrate. The depositional crust formation during the rain storm also decreases the infiltration through the storm.

The soils with no additives have the largest initial infiltrations. This to be expected because these specimens had the largest water deficit, since they start the process with the lowest initial water contents. This low initial water content is due to the fact that they have no salt or initial crust to hold the moisture in. The absence of a tight crust also allows more water to permeate the soil surface.

As would be expected, the addition of clay decreases the infiltration in all cases as shown in Table 4.6. The decrease in the permeability of the soil by addition of clay is the main reason for the lower infiltration. The crust formation of a clay soil also is more readily achieved due to formation of a chemical crust (Chapter 2) which disperses the clay, thus increasing the water tightness.

It can be concluded that the addition of clay will increase the life of additives by the fact that clay decreases the amount of water that infiltrates the soil. This allows for less of the additive to dissolve and be carried downward in the groundwater.

Runoff Rates

As stated in the results, the conclusions are based on the calculated runoff rates. These runoff rates are a subtraction of the infiltration from the 2.5 cm storm, and using these values as average rates. The lignin had the highest rates, the salts had intermediate values and the soils, with no additives, had the lowest rates. The addition of clay to Soil A also increased the runoff rates when compared to Soil A. The reasons for these conclusions are the same those for the infiltration processes, since the water that doesn't infiltrate must runoff.

A final conclusion based on the actual runoff curves involves the time of the three stages of runoff (Chapter 2). These stages include time to first runoff, time for increasing runoff, and the time to equilibrium runoff. These times are generalizations based on soil type. Exact values can't be found because of the edge leaks discussed in the results.

Soil A had the longest time to first runoff (about 40 minutes). This is because of the high infiltration of this soil. Soil A, with both salt and lignin, had runoff times of about 10 and six minutes respectively because of the much lower infiltration rates. All of the Soil C combinations had about the same times (six to 10 minutes) to first runoff. The increasing runoff stage lasted about five to seven minutes for all combinations, and equilibrium rates are achieved until the end of the storm following the increasing stage.

Additive Concentration in Runoff

The salt concentration in the runoff water from the salt-soil combinations was minimal compared to what was left in the soil. The results indicate approximately a 0.5 percent decrease in the additive in the Soil A combination and about a 2.5 percent decrease in the salt in Soil C. This shows that there is minimal additive loss in the surface water. The plots (Figures 4.20 and 4.21) also show that as the storm goes on, the concentration of the salt in the runoff water dramatically decreases in the first half hour of the storm. This indicates that durations from an hour to much longer storms (six to eight hours) would cause this same insignificant loss the salt additive.

he addition of clay to the soil slightly increases the amount of salt lost in the runoff. A possible reason for this is that the infiltration is lower for the Soil C. This would give a higher runoff which would carry more solute, since the total runoff volume is greater. Although the addition of clay slightly increases the additive loss, the amount for both soils is not a concern when considering the concentration that is still left in the soil (97.5 to 99.5 percent of the original) for dust control and stabilization.

The loss of lignin in the surface water is quite a bit greater. This is likely due to the thick crust that is formed (Figure 4.17) on the road surface during the drying process prior to the rain simulation. This thick crust is almost all lignin and leaves a large amount of lignin exposed to the rain during a typical storm which allows the surface water to dissolve and carry the lignin away. The results show a 6.94 percent loss of the lignin from Soil C and a 23.5 percent loss from Soil A during the two-hour storm.

The plot (Figure 4.22) indicates a fairly constant equilibrium concentration of lignin in the runoff water (1 percent for Soil C and 1.5 percent for Soil A). This is different from the salts where there is large initial drop in concentration and would indicate a continual increase in cumulative lignin loss as duration of the storm increases. The values are about 3 percent per hour for Soil C and about 5 percent loss per hour for Soil A (for a 2.5 cm/hour storm). This statement indicates that it is advisable to add some clay to the road to decrease loss through surface water, thus leaving the lignin in the road for stabilization.

The clay ties the lignin up so the loss is lower than the soil without clay. Possible explanation for this could be a crust formation with a lower lignin concentration. The initial water contents of the infiltration specimens (Table 4.6) are as follows. Soil A with lignin had a water content of 3.51 percent and Soil C with lignin had an initial water content of 4 percent. This indicates that Soil C has less evaporation taking place which would carry less lignin to the surface. This would cause a less concentrated lignin crust to be formed and consequently, the loss in the surface water would be lower.

Following the accumulation of the soil column, additive concentration, infiltration and runoff data, a table can be formed indicating the life of the additives with respect to the amount of precipitation. This is based on soil type, additive type and infiltration rates. This is for Soil A and C since these are the only two soils tested in the rain simulation. Soil B would perform even better than Soil C for lignin since the clay fraction is higher, thus tying up the lignin more effectively and giving a lower infiltration rate. This is an exceptionally high fraction of clay (8.5 percent) and may it not be practical to add to the road surface because of cost or constructability.

Table 5.1 consolidates these conclusions to develop design and application guidelines for the combinations of soils and additives. Calculations use the infiltration rates determined from the rain simulation for the 2.5 cm/hr storm and find the depth of rain water needed to expose the soil to the number of pore volumes required to remove 80 percent of the additive in the road surface (i.e. The higher the infiltration rate, the less rain required to expose the soil to one pore volume of water assuming constant porosity). The number of pore volumes required for 80 percent removal (c/c_i=0.20) is determined from the column study breakthrough curves. This is calculated for the top two inches and the top four inches of the road. It is concluded from Table 5.1 that just 3 percent kaolinite dramatically increases the effective life of the lignin. The low infiltration rate of this soil

Soil Type	Add. Type	Infiltration Rate (cm/hr)	Effective Life in Pore Volumes ($c/c_i=0.2$)	Total Porosity	Effective Life (Based on cm of Rain exposure)*	Effective Life (Based on cm of Rain exposure)**
A	Salt	0.252	0.75	0.301	5.78 cm (2.3")	11.56 cm (4.62")
A	Lignin	0.125	1.0	0.301	15.05 cm (6.02")	31.09 cm (12.44")
C	Salt	0.181	0.80	0.269	7.70 cm (3.08")	15.40 cm (6.16")
C	Lignin	0.040	1.3	0.269	56.55 cm (22.27")	113.1 cm (45.24")

* Top two inches (5 cm) of road, **Top four inches (10 cm)of road.

Table 5.1 Effective life of soil-additive combinations.

in combination with lignin requires 113 cm of rain to achieve a relative concentration (c/c_i) of 0.2, which has been designated as the effective life when reapplication is needed. This combination would require only one application per year. Soil A with lignin also performs well, requiring an application after 31 cm of rain which also is adequate, since the summers are very dry in Wyoming (usually less than 31 cm).

The salts are leached more quickly, mainly because of their higher infiltration rates. The effective life with Soil A is about 11.5 cm of rain, while the effective life with Soil C is at about 15.4 cm of rain. Both of these additives would probably require two applications per year depending on the amount of moisture precipitated. Since the clay doesn't decrease the application that much but does cause more salt to be carried away in the surface water, it is probably not justified to add it.

Erosion

All of the erosion rates are fairly low due to good, controlled compaction techniques at or near optimum water content and the low slope. Soil C with additives showed comparatively higher erosion rates than Soil A. This is caused by the larger fraction of fines which are lighter and more readily carried off the road from the runoff water. It is concluded that the addition of clay doesn't help the erosion problem.

As was stated in the results, some of the lower erosion rates are not accurate. Some of the road sections with the highest infiltration rates showed low sedi-mentation rates, but had the highest observed erosion as noted in Table 4.11. The surfaces were very rough and loosened following the precipitation, but showed low erosion rates following lab analysis. This is because the splash erosion from the rain impact was large, but the runoff rate was too low to carry the loose soil off of the road. Examples of this are Soil A and C with no additives.

The observed (qualitative) results are the best to draw conclusions from. The lignin combinations showed the smoothest and least disturbed surfaces due to the hard lignin crust initially in place. These road sections had sufficiently large runoffs to carry most of the loose soil off the road. The other four all had fairly rough surfaces and are hard to distinguish between because the rain drop impact loosened the soil. This soil was not always carried off the surface, which would account for the lower sedimentation rates determined in the results. The lignin out-performed the salts again.

Evaporation

As is expected, the evaporation process following the rain carried the additives back to the surface in a noticeably higher concentration. This is a good property because the additives are returned to the surface of the road where they are needed for stabilization. This also returns them upward following the downward solute transport processes so they, in effect, are not carried away as readily. Because the lignin was initially concentrated in the crust, it had a much higher increase in concentration at the surface compared to the salts.

Strength Study

It is concluded that following the complete removal of the additives, there is little residual strength. These tests were conducted when five to eight pore volumes had passed the soil columns and the additives were completely removed.

The strength versus number of pore volumes curve (Figure 4.25) showed a strength decrease as water was passed through the soil. The lignin out-performed the salts by a factor of about three and had a higher residual strength at one pore volume than the calcium chloride strength before it was leached. This shows the lignin is superior as a strength additive.

Computer Modeling

The computer-generated breakthrough curves fit the data for the six additive-soil combinations very well, showing the change from advective transport to diffusive/dispersive transport as the soil changes from the nonplastic Soil A to the plastic

Soil B. The generated curves also show the strong trend of mainly diffusive/dispersive transport for lignin regardless of the soil type.

A breakthrough curve can be generated for any soil by simply changing the Peclet number (based on soil type) and the retardation factor for the soil type and the additive used (salt or lignin). These values come from the retardation factor tables and plots of Peclet number versus percent clay found in the results chapter. The Peclet number and retardation factor are changed in the input section of the computer model found Appendix A.

CHAPTER 6. RECOMMENDATIONS

Introduction

Recommendations are given for application intervals, addition of clay to the Soil A to increase additive life and additional studies that could be conducted. The recommended additive also will be discussed, based on effective life, erosion and increased soil strength.

Recommended Application Schedule

The application of all three additives would be conducted in the normal fashion as recommended by Palmer (1994) following the spring rain season. The lignin would only require one application per year while the salts would likely require two applications per year, the second at late summer, depending on the rainfall volume.

The addition of 3 percent clay with the lignin is recommended since it dramatically decreases the infiltration rate, which increases the additive life. It also ties the lignin up which keeps it from running off as a solute in the surface water. The addition of clay doesn't significantly improve any of the studied properties when used with the salts. The infiltration is decreased some, but two applications are still required with either soil type. The soil with the clay also loses more of the salt in the surface runoff and has a much higher erosion rate. These findings prove that it is not advisable to use clay with the salt additives. The following application schedule is recommended based on the results and conclusions of the column and rain simulation study.

Base Soil	Addition of Clay	1st Application	Concen- tration (gal/yd^2)	2nd Application	Concen- tration (gal/yd^2)
A + Lignin	Yes - 3% Advised	Spring*	0.75	None	0
A + Lignin	No	Spring*	0.75	None**	0
A + $CaCl_2$	No	Spring*	0.75	Late Summer***	0.5
A + $MgCl_2$	No	Spring*	0.75	Late Summer***	0.5

*Following the major spring rainfall. **Second application would be required following 12" of accumulated rain. ***Following 3.5" of rain accumulation.

Table 6.1 Recommended additive application schedule.

Recommended Additive

The additive of choice is definitely the lignin sulfonate. It out-performed the salts in all categories. The effective life is much longer since it has the lowest infiltration rate and the slowest downward transport. The observed erosion of the lignin also was the best and still had a hard smooth surface following the two hour rain. The road surface was rough when the salts were used.

Another reason that lignin is recommended is that it causes a significant increase in soil strength in both cohesive and cohesionless soils. The strength achieved with the lignin was almost three times that obtained with the salts.

One of the main advantages with the use of salts is dust control, since salt keeps the soil moist by drawing water out of the atmosphere. The hard crust formation obtained when using lignin also would control dust through its cementing properties and keep the moisture in the soil by isolating it from the atmosphere.

Based on all these advantages found when using lignin, it is obvious that lignin is the best additive. The economics need to be studied, but to maintain similar road quality, lignin requires only one application while salts need two. This would probably result in higher cost for salts, not only for the materials, but also for labor, time and equipment.

Computer Modeling

The recommended use of the computer model is for determining the additive life as related to the number of pore volumes of water that have passed through the soil. This is already found for Soils A, B and C. The program is useful if a soil with a different percent of clay is used. A breakthrough curve could then be generated based on the Peclet number and retardation factor (found from the retardation factor tables and Peclet number graphs in chapter 4) for that soil and additive used. Although a breakthrough curve can be generated, the life of the additive could also be found from interpolation since graphs have already been generated for the three soils. These include Soil A with effectively no clay, Soil C with three percent clay and Soil B with 8.5 percent clay.

Additional Studies

Additional research is required in many areas to fully understand the stabilization additives. A study on the impact on the environment is recommended. It has been proven that the road salts raise the chloride levels in the streams. This can be detrimental to fish. The lignin will increase the BOD of surface water, which results in oxygen depletion and can kill micro-organisms, insects and fish. These additives should be monitored for concentration in the nearby surface waters to determine what, if any, affect they are having on the water ecosystem.

Salts also kill plant-life and attract large animals to the road, increasing car-animal collisions. A study could be done to determine the increase in collisions, as well as the magnitude of plant kill near the roads.

The rain simulation in this study used only one concentration, two additives, two soil types, one storm duration, one storm intensity and one road slope. A recommended area of research is to significantly vary all these properties to determine more additive-rainfall relationships. This may change the effective life of the additives.

A final area of research that would be helpful is a economic study to determine the application cost of each additive. This would be a function of the number of applications required, additive type, labor, time, and equipment costs. This would help determine the best additive to use based on cost.

Appendix A - The Advection/Dispersion Model

The Advection/Dispersion model described in Section 2-5-3 of the text was programmed using Excel. The visable screen and the graphical output is shown below. The actual model is given on the next page.

Input Section

Rd =	0.6
Pl =	2

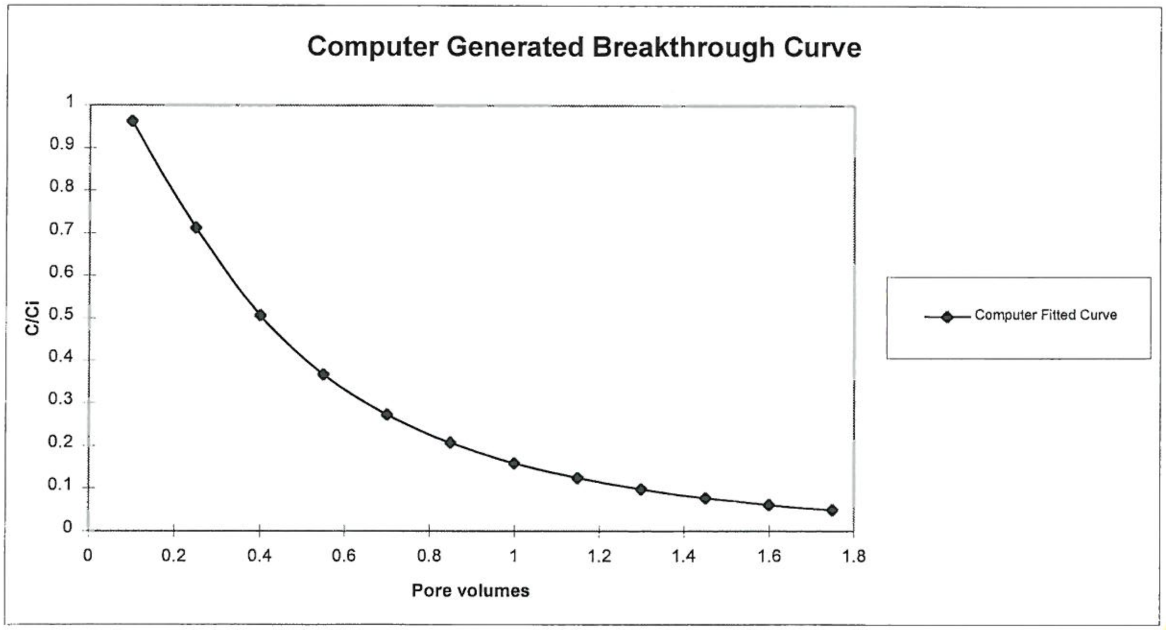
User input Retardation
User input Peclet No.

T	Tr	eps1	eps2	eps3	C/Ci
0.1	0.16667	1.44338	2	2.02073	0.96362
0.25	0.41667	0.63901	2	1.55188	0.71279
0.4	0.66667	0.28868	2	1.44338	0.50614
0.55	0.91667	0.06155	2	1.41555	0.36733
0.7	1.16667	-0.1091	2	1.41842	0.27294
0.85	1.41667	-0.2475	2	1.43571	0.20681
1	1.66667	-0.3651	2	1.46059	0.15919
1.15	1.91667	-0.4682	2	1.4897	0.12412
1.3	2.16667	-0.5604	2	1.52122	0.09781
1.45	2.41667	-0.6444	2	1.5541	0.07777
1.6	2.66667	-0.7217	2	1.58771	0.0623
1.75	2.91667	-0.7936	2	1.62165	0.05023

T = No. of Pore Vols.

eps1, eps2, eps3 = Equation 2.12

C/Ci = Equation 2.15



Input Section

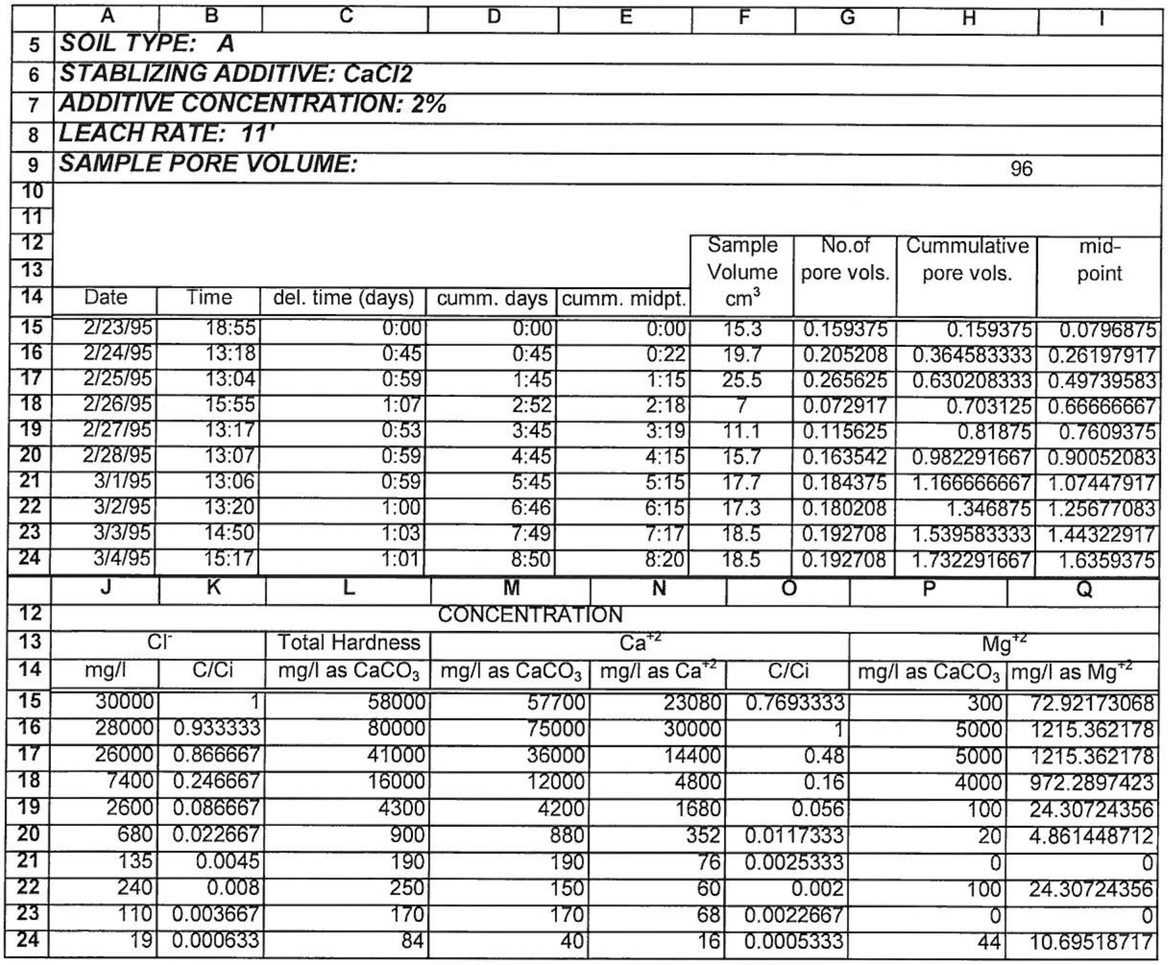
Rd =	0.6
PI =	2

T	Tr	eps1	eps2	eps3	C/Ci
0.1	=A7/$D$3	=(1-B7)/(2*SQRT(B7/$D$4))	=$D$4	=(1+B7)/(2*SQRT(B7/$D$4))	=IF(C7>0,1-0.5*(ERFC(C7)+EXP(D7)*ERFC(E7)),1-0.5*((1+ERF(-C7))+EXP(D7)*ERFC(E7)))
=A7+0.15	=A8/$D$3	=(1-B8)/(2*SQRT(B8/$D$4))	=$D$4	=(1+B8)/(2*SQRT(B8/$D$4))	=IF(C8>0,1-0.5*(ERFC(C8)+EXP(D8)*ERFC(E8)),1-0.5*((1+ERF(-C8))+EXP(D8)*ERFC(E8)))
=A8+0.15	=A9/$D$3	=(1-B9)/(2*SQRT(B9/$D$4))	=$D$4	=(1+B9)/(2*SQRT(B9/$D$4))	=IF(C9>0,1-0.5*(ERFC(C9)+EXP(D9)*ERFC(E9)),1-0.5*((1+ERF(-C9))+EXP(D9)*ERFC(E9)))
=A9+0.15	=A10/$D$3	=(1-B10)/(2*SQRT(B10/$D$4))	=$D$4	=(1+B10)/(2*SQRT(B10/$D$4))	=IF(C10>0,1-0.5*(ERFC(C10)+EXP(D10)*ERFC(E10)),1-0.5*((1+ERF(-C10))+EXP(D10)*ERFC(E10)))
=A10+0.15	=A11/$D$3	=(1-B11)/(2*SQRT(B11/$D$4))	=$D$4	=(1+B11)/(2*SQRT(B11/$D$4))	=IF(C11>0,1-0.5*(ERFC(C11)+EXP(D11)*ERFC(E11)),1-0.5*((1+ERF(-C11))+EXP(D11)*ERFC(E11)))
=A11+0.15	=A12/$D$3	=(1-B12)/(2*SQRT(B12/$D$4))	=$D$4	=(1+B12)/(2*SQRT(B12/$D$4))	=IF(C12>0,1-0.5*(ERFC(C12)+EXP(D12)*ERFC(E12)),1-0.5*((1+ERF(-C12))+EXP(D12)*ERFC(E12)))
=A12+0.15	=A13/$D$3	=(1-B13)/(2*SQRT(B13/$D$4))	=$D$4	=(1+B13)/(2*SQRT(B13/$D$4))	=IF(C13>0,1-0.5*(ERFC(C13)+EXP(D13)*ERFC(E13)),1-0.5*((1+ERF(-C13))+EXP(D13)*ERFC(E13)))
=A13+0.15	=A14/$D$3	=(1-B14)/(2*SQRT(B14/$D$4))	=$D$4	=(1+B14)/(2*SQRT(B14/$D$4))	=IF(C14>0,1-0.5*(ERFC(C14)+EXP(D14)*ERFC(E14)),1-0.5*((1+ERF(-C14))+EXP(D14)*ERFC(E14)))
=A14+0.15	=A15/$D$3	=(1-B15)/(2*SQRT(B15/$D$4))	=$D$4	=(1+B15)/(2*SQRT(B15/$D$4))	=IF(C15>0,1-0.5*(ERFC(C15)+EXP(D15)*ERFC(E15)),1-0.5*((1+ERF(-C15))+EXP(D15)*ERFC(E15)))
=A15+0.15	=A16/$D$3	=(1-B16)/(2*SQRT(B16/$D$4))	=$D$4	=(1+B16)/(2*SQRT(B16/$D$4))	=IF(C16>0,1-0.5*(ERFC(C16)+EXP(D16)*ERFC(E16)),1-0.5*((1+ERF(-C16))+EXP(D16)*ERFC(E16)))
=A16+0.15	=A17/$D$3	=(1-B17)/(2*SQRT(B17/$D$4))	=$D$4	=(1+B17)/(2*SQRT(B17/$D$4))	=IF(C17>0,1-0.5*(ERFC(C17)+EXP(D17)*ERFC(E17)),1-0.5*((1+ERF(-C17))+EXP(D17)*ERFC(E17)))
=A17+0.15	=A18/$D$3	=(1-B18)/(2*SQRT(B18/$D$4))	=$D$4	=(1+B18)/(2*SQRT(B18/$D$4))	=IF(C18>0,1-0.5*(ERFC(C18)+EXP(D18)*ERFC(E18)),1-0.5*((1+ERF(-C18))+EXP(D18)*ERFC(E18)))

Appendix B - Representative Column Breakthrough Data Sheet

This appendix includes a representative column breakthrough data sheet.

Representative Column Breakthrough Data Sheet:

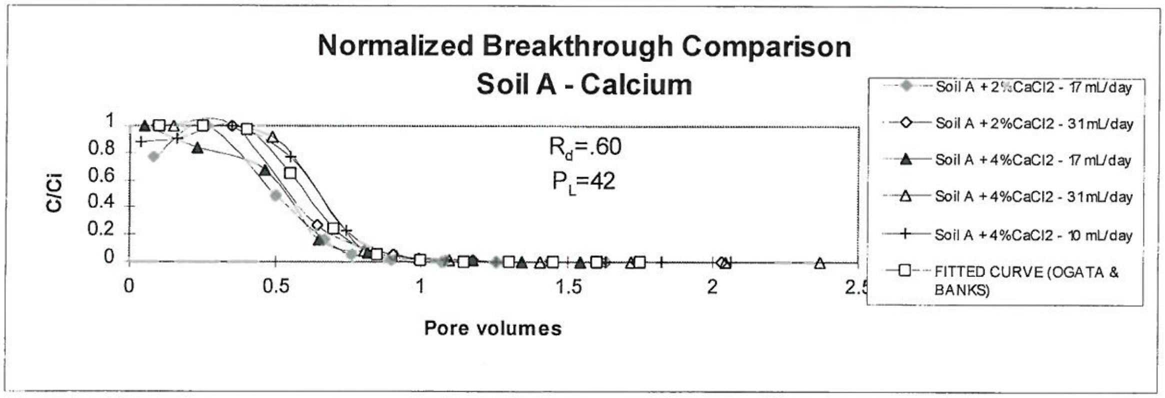


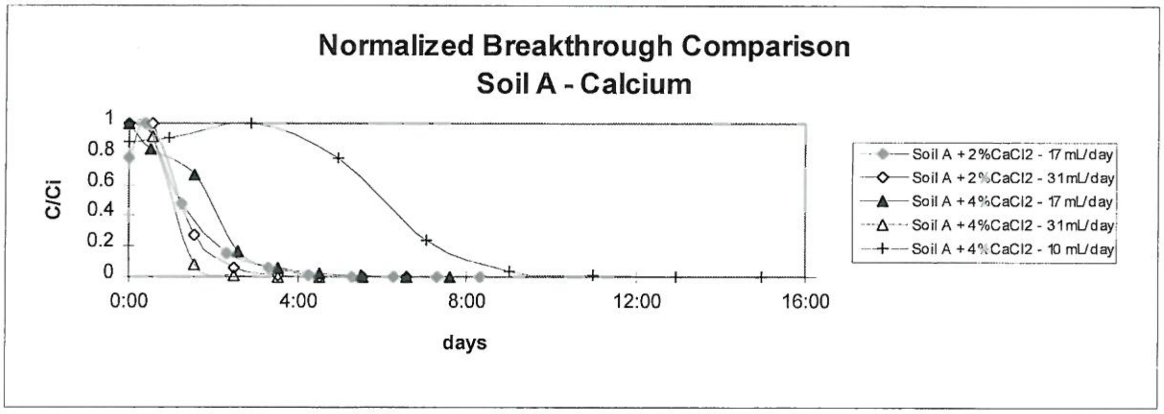
	A	B	C	D	E	F	G	H	I
5	*SOIL TYPE: A*								
6	*STABLIZING ADDITIVE: CaCl2*								
7	*ADDITIVE CONCENTRATION: 2%*								
8	*LEACH RATE: 11'*								
9	*SAMPLE PORE VOLUME:*							96	
10									
11									
12						Sample Volume cm^3	No.of pore vols.	Cummulative pore vols.	mid-point
13									
14	Date	Time	del. time (days)	cumm. days	cumm. midpt.				
15	2/23/95	18:55	0:00	0:00	0:00	15.3	0.159375	0.159375	0.0796875
16	2/24/95	13:18	0:45	0:45	0:22	19.7	0.205208	0.364583333	0.26197917
17	2/25/95	13:04	0:59	1:45	1:15	25.5	0.265625	0.630208333	0.49739583
18	2/26/95	15:55	1:07	2:52	2:18	7	0.072917	0.703125	0.66666667
19	2/27/95	13:17	0:53	3:45	3:19	11.1	0.115625	0.81875	0.7609375
20	2/28/95	13:07	0:59	4:45	4:15	15.7	0.163542	0.982291667	0.90052083
21	3/1/95	13:06	0:59	5:45	5:15	17.7	0.184375	1.166666667	1.07447917
22	3/2/95	13:20	1:00	6:46	6:15	17.3	0.180208	1.346875	1.25677083
23	3/3/95	14:50	1:03	7:49	7:17	18.5	0.192708	1.539583333	1.44322917
24	3/4/95	15:17	1:01	8:50	8:20	18.5	0.192708	1.732291667	1.6359375

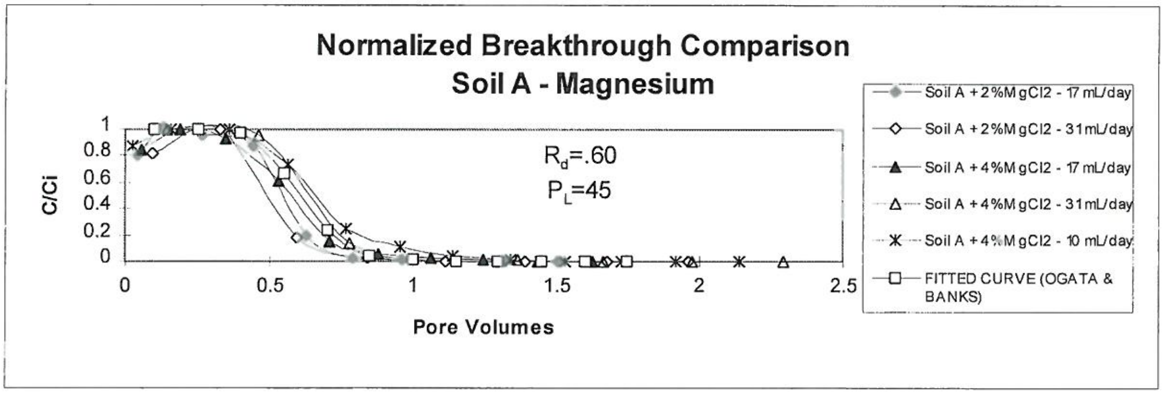
	J	K	L	M	N	O	P	Q
12	CONCENTRATION							
13	Cl$^-$		Total Hardness	Ca^{+2}			Mg^{+2}	
14	mg/l	C/Ci	mg/l as CaCO$_3$	mg/l as CaCO$_3$	mg/l as Ca^{+2}	C/Ci	mg/l as CaCO$_3$	mg/l as Mg^{+2}
15	30000	1	58000	57700	23080	0.7693333	300	72.92173068
16	28000	0.933333	80000	75000	30000	1	5000	1215.362178
17	26000	0.866667	41000	36000	14400	0.48	5000	1215.362178
18	7400	0.246667	16000	12000	4800	0.16	4000	972.2897423
19	2600	0.086667	4300	4200	1680	0.056	100	24.30724356
20	680	0.022667	900	880	352	0.0117333	20	4.861448712
21	135	0.0045	190	190	76	0.0025333	0	0
22	240	0.008	250	150	60	0.002	100	24.30724356
23	110	0.003667	170	170	68	0.0022667	0	0
24	19	0.000633	84	40	16	0.0005333	44	10.69518717

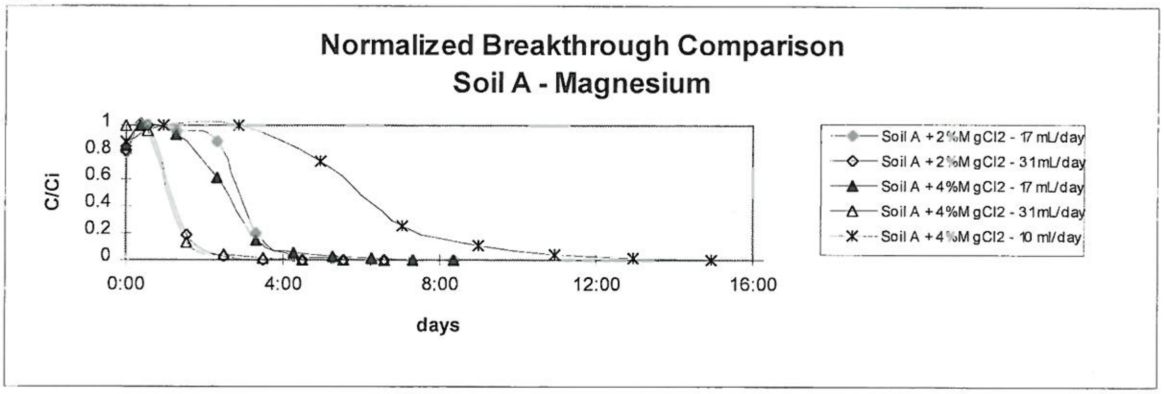
Appendix C - The Normalized Breakthrough Curves for All Soils

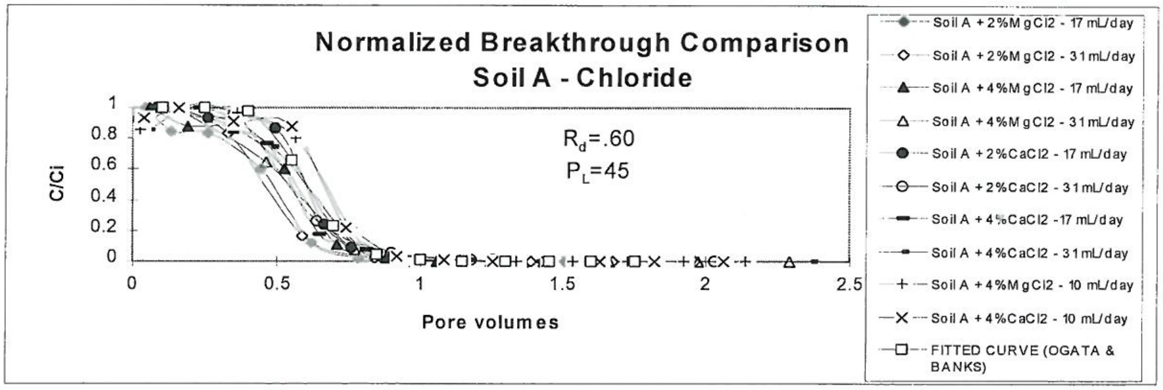
This appendix includes the normalized breakthrough curves for all soil-additive combinations at all the selected flowrates in the column study.

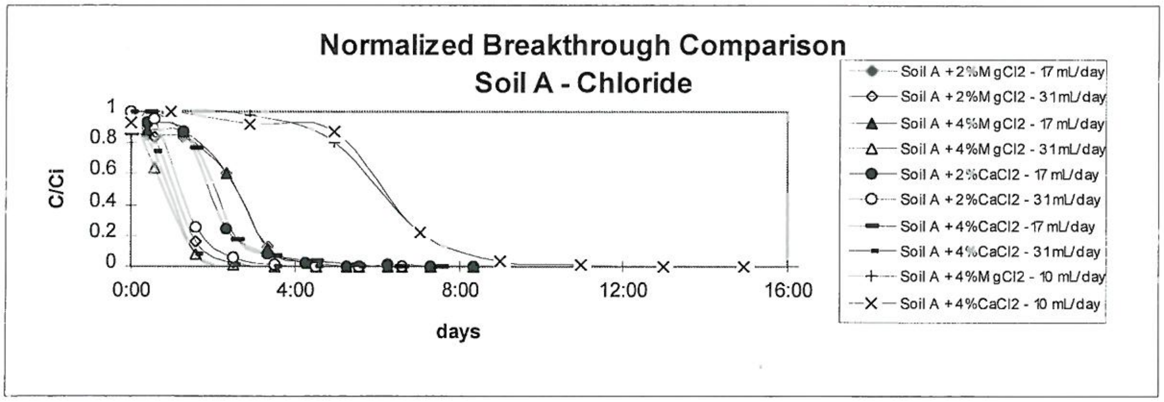


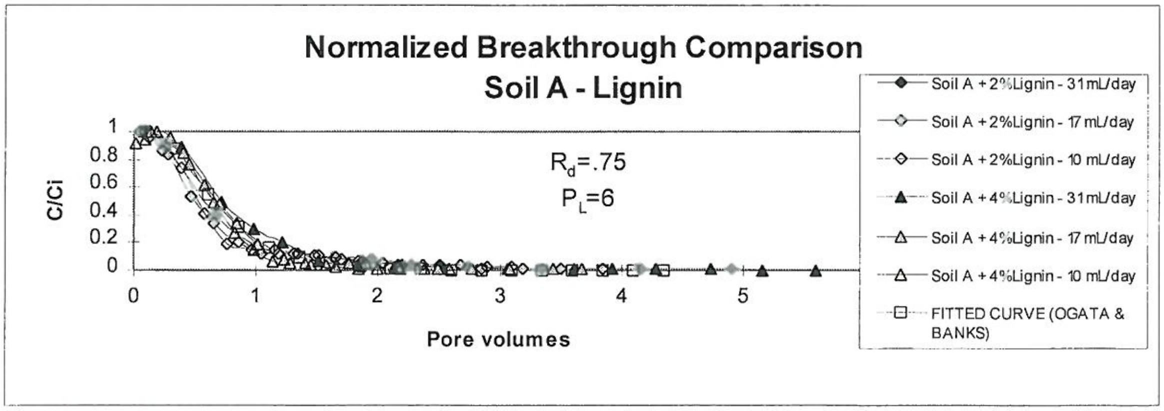


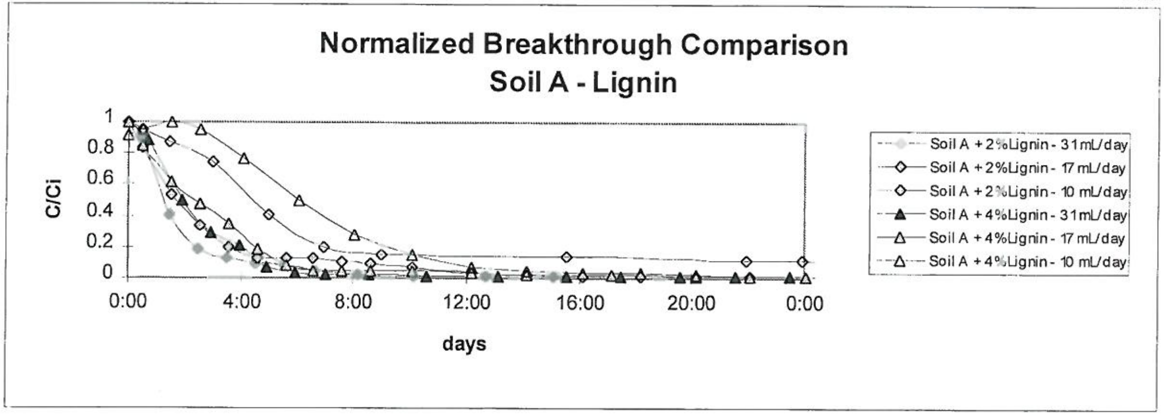


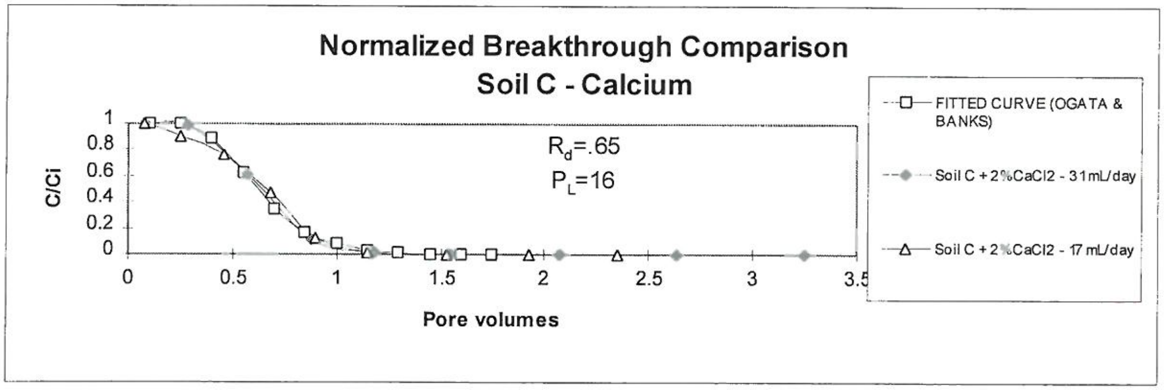

Normalized Breakthrough Comparison
Soil A - Magnesium
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
days
Soil A +2%MgCl2 - 17 mL/day
Soil A +2%MgCl2 - 31mL/day
Soil A +4%MgCl2 - 17 mL/day
Soil A +4%MgCl2 - 31mL/day
Soil A +4%MgCl2 - 10 ml/day

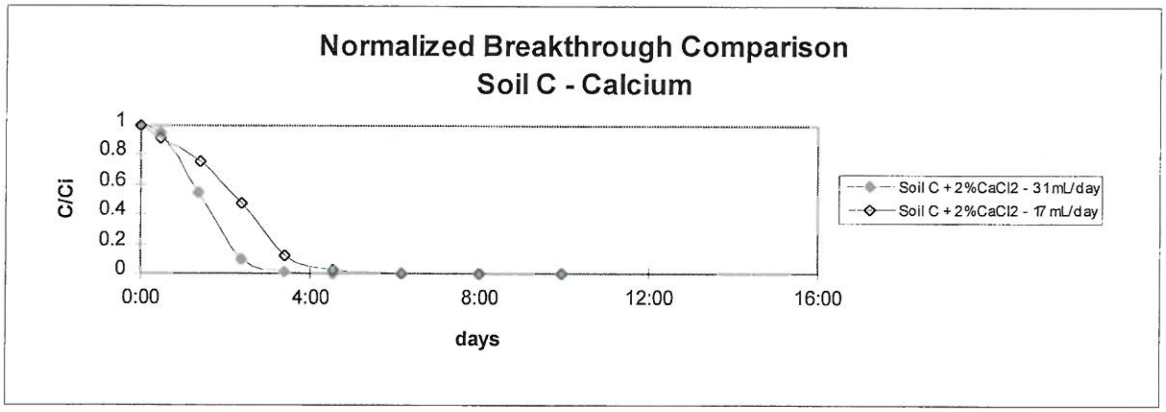

Normalized Breakthrough Comparison
Soil A - Chloride
R_d=.60
P_L=45
C/Ci
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
Pore volumes
Soil A +2%MgCl2 - 17 mL/day
Soil A +2%MgCl2 - 31mL/day
Soil A +4%MgCl2 - 17 mL/day
Soil A +4%MgCl2 - 31mL/day
Soil A +2%CaCl2 - 17 mL/day
Soil A +2%CaCl2 - 31mL/day
Soil A +4%CaCl2 -17 mL/day
Soil A +4%CaCl2 - 31mL/day
Soil A +4%MgCl2 - 10 mL/day
Soil A +4%CaCl2 - 10 mL/day
FITTED CURVE (OGATA & BANKS)

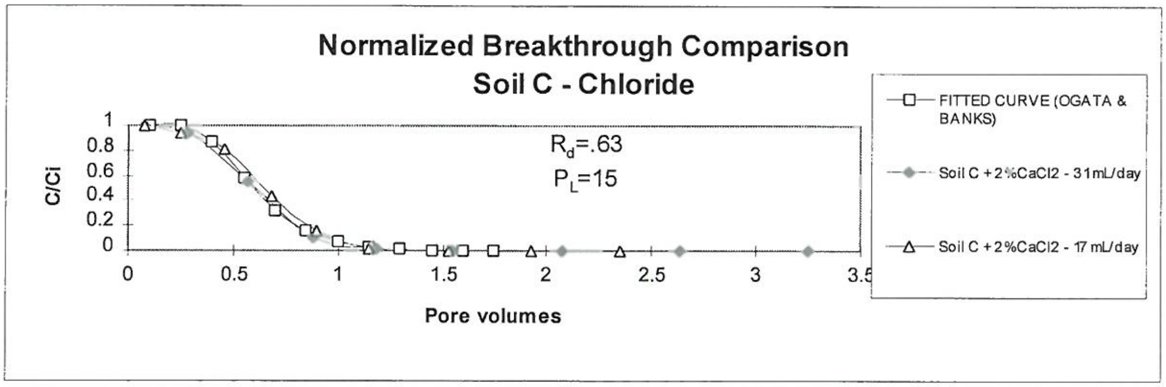

Normalized Breakthrough Comparison
Soil A - Chloride
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
days
Soil A +2%MgCl2 - 17 mL/day
Soil A +2%MgCl2 - 31mL/day
Soil A +4%MgCl2 - 17 mL/day
Soil A +4%MgCl2 - 31mL/day
Soil A +2%CaCl2 - 17 mL/day
Soil A +2%CaCl2 - 31mL/day
Soil A +4%CaCl2 -17 mL/day
Soil A +4%CaCl2 - 31mL/day
Soil A +4%MgCl2 - 10 mL/day
Soil A +4%CaCl2 - 10 mL/day

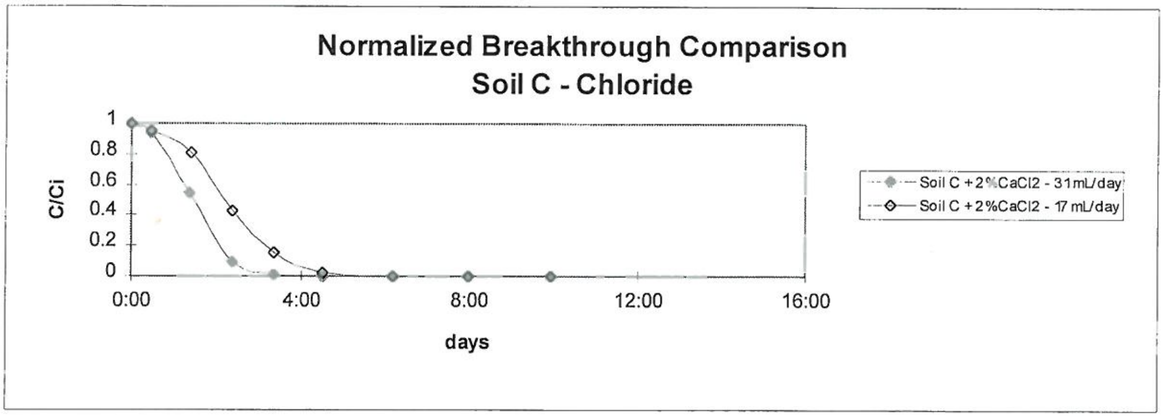

Normalized Breakthrough Comparison
Soil A - Lignin
R_d=.75
P_L=6
C/Ci
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
Pore volumes
Soil A +2%Lignin - 31mL/day
Soil A +2%Lignin - 17 mL/day
Soil A +2%Lignin - 10 mL/day
Soil A +4%Lignin - 31mL/day
Soil A +4%Lignin - 17 mL/day
Soil A +4%Lignin - 10 mL/day
FITTED CURVE (OGATA & BANKS)

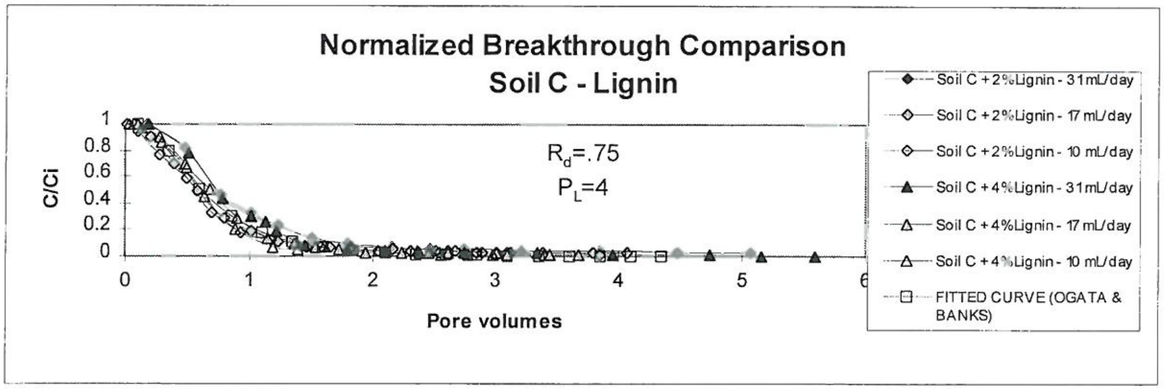

Normalized Breakthrough Comparison
Soil A - Lignin
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
20:00
0:00
days
Soil A + 2%Lignin - 31mL/day
Soil A + 2%Lignin - 17 mL/day
Soil A + 2%Lignin - 10 mL/day
Soil A + 4%Lignin - 31mL/day
Soil A + 4%Lignin - 17 mL/day
Soil A + 4%Lignin - 10 mL/day

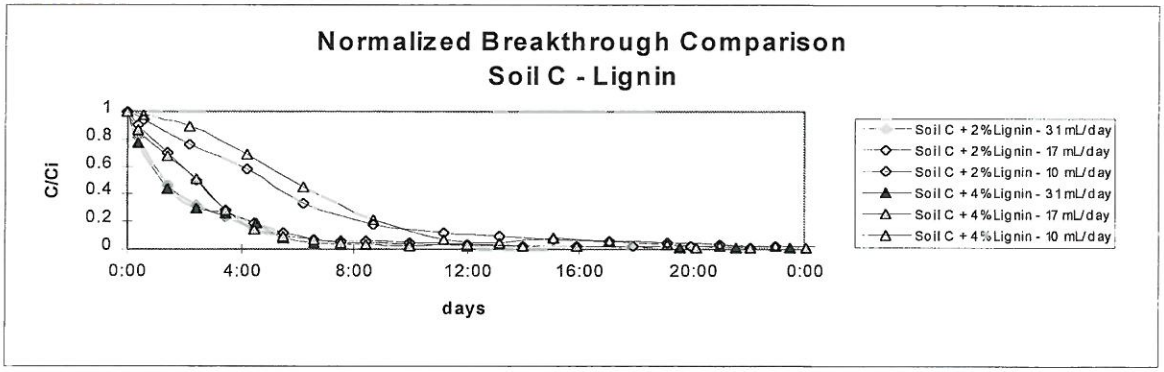

Normalized Breakthrough Comparison
Soil C - Calcium
C/Ci
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
Pore volumes
R_d=.65
P_L=16
FITTED CURVE (OGATA & BANKS)
Soil C + 2%CaCl2 - 31mL/day
Soil C + 2%CaCl2 - 17 mL/day

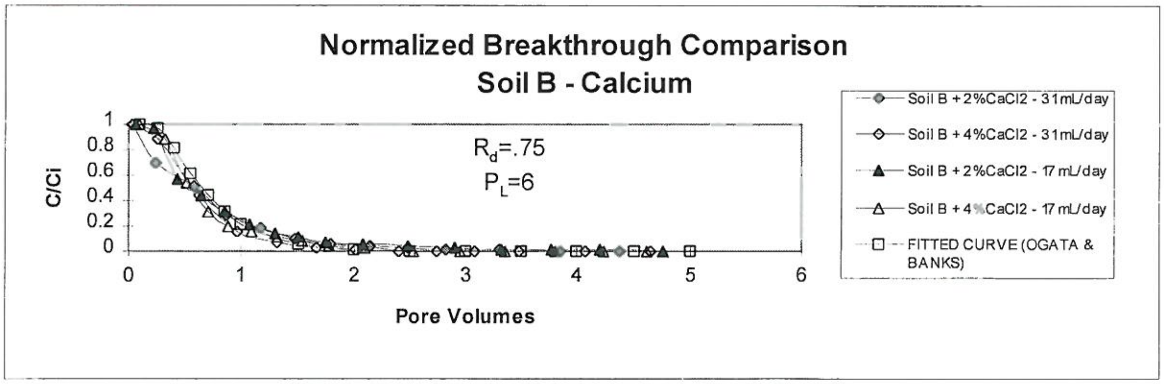

Normalized Breakthrough Comparison
Soil C - Calcium
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
days
Soil C + 2%CaCl2 - 31mL/day
Soil C + 2%CaCl2 - 17 mL/day

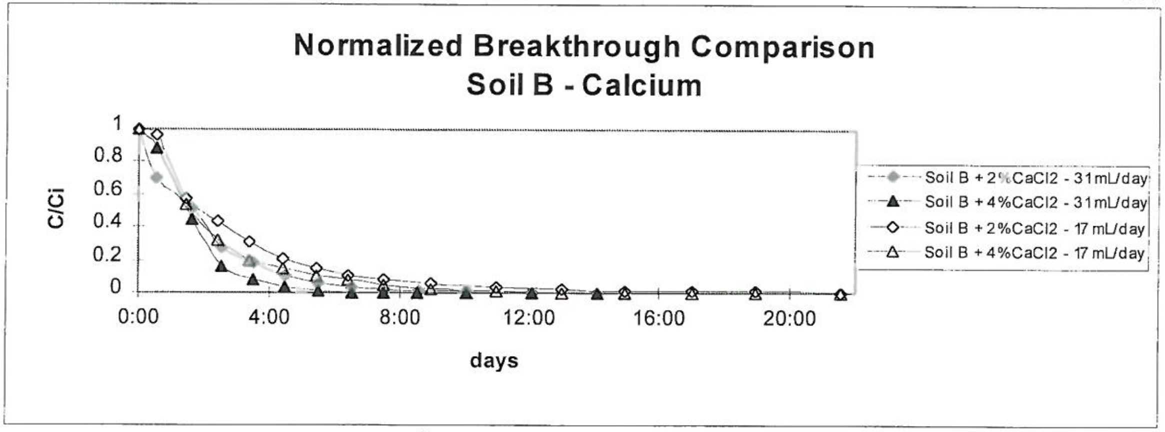

Normalized Breakthrough Comparison
Soil C - Chloride
C/Ci
1
0.8
0.6
0.4
0.2
0
0
0.5
1
1.5
2
2.5
3
3.5
Pore volumes
R_d=.63
P_L=15
FITTED CURVE (OGATA & BANKS)
Soil C + 2%CaCl2 - 31mL/day
Soil C + 2%CaCl2 - 17 mL/day

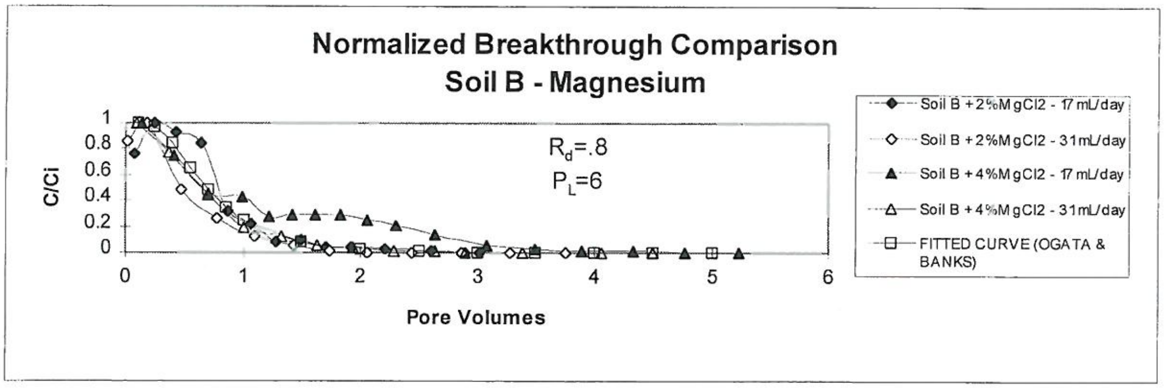

Normalized Breakthrough Comparison
Soil C - Chloride
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
days
Soil C +2%CaCl2 - 31mL/day
Soil C +2%CaCl2 - 17 mL/day

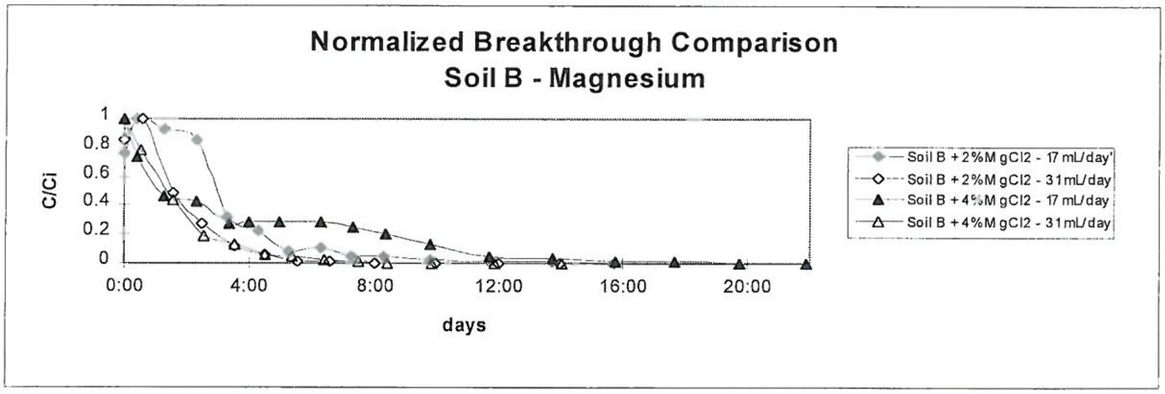

Normalized Breakthrough Comparison
Soil C - Lignin
R_d=.75
P_L=4
C/Ci
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
Pore volumes
Soil C +2%Lignin - 31mL/day
Soil C +2%Lignin - 17 mL/day
Soil C +2%Lignin - 10 mL/day
Soil C +4%Lignin - 31mL/day
Soil C +4%Lignin - 17 mL/day
Soil C +4%Lignin - 10 mL/day
FITTED CURVE (OGATA & BANKS)

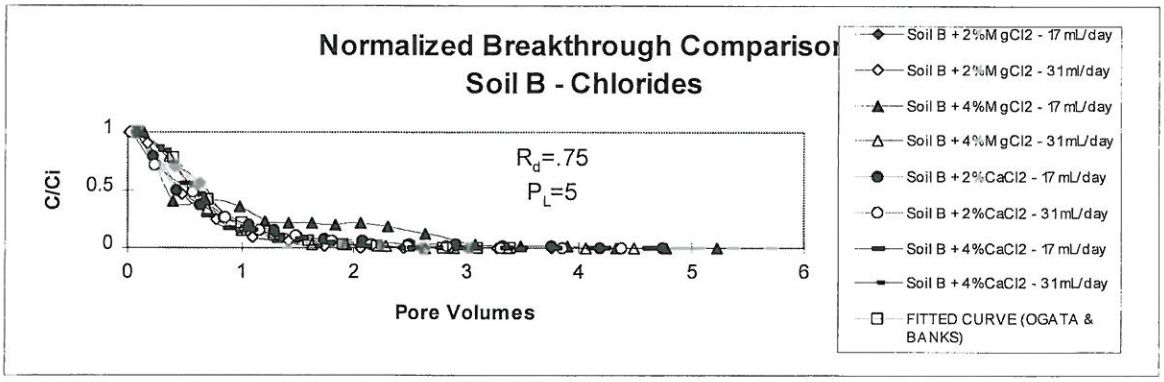

Normalized Breakthrough Comparison
Soil C - Lignin
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
20:00
0:00
days
Soil C +2%Lignin - 31mL/day
Soil C +2%Lignin - 17 mL/day
Soil C +2%Lignin - 10 mL/day
Soil C +4%Lignin - 31mL/day
Soil C +4%Lignin - 17 mL/day
Soil C +4%Lignin - 10 mL/day

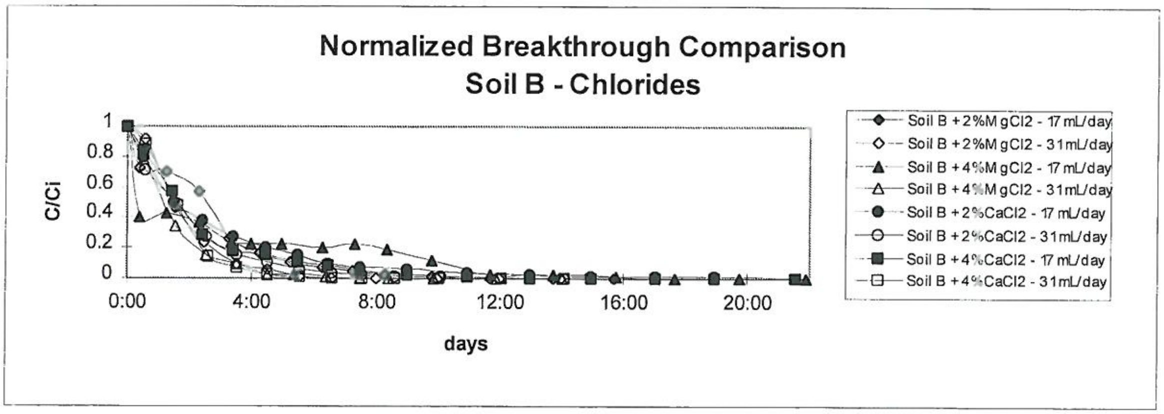

Normalized Breakthrough Comparison
Soil B - Calcium
R_d=.75
P_L=6
C/Ci
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
Pore Volumes
Soil B +2%CaCl2 - 31mL/day
Soil B +4%CaCl2 - 31mL/day
Soil B +2%CaCl2 - 17 mL/day
Soil B +4%CaCl2 - 17 mL/day
FITTED CURVE (OGATA & BANKS)

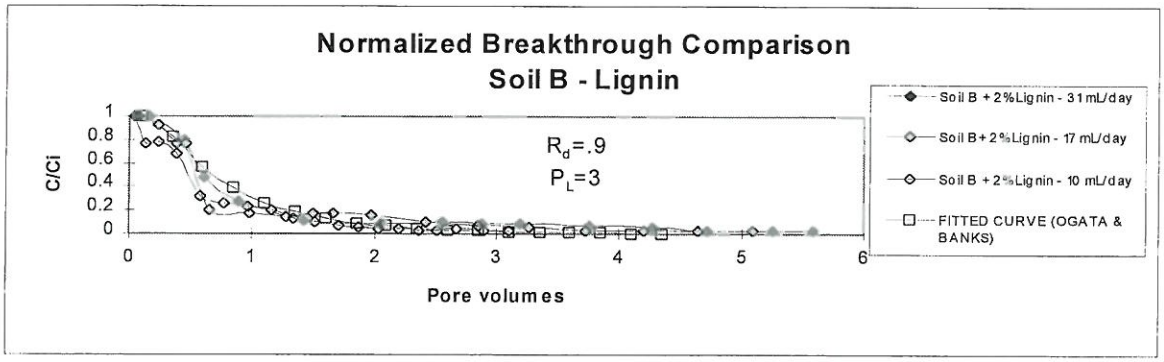

Normalized Breakthrough Comparison
Soil B - Calcium
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
20:00
days
Soil B + 2%CaCl2 - 31mL/day
Soil B + 4%CaCl2 - 31mL/day
Soil B + 2%CaCl2 - 17 mL/day
Soil B + 4%CaCl2 - 17 mL/day

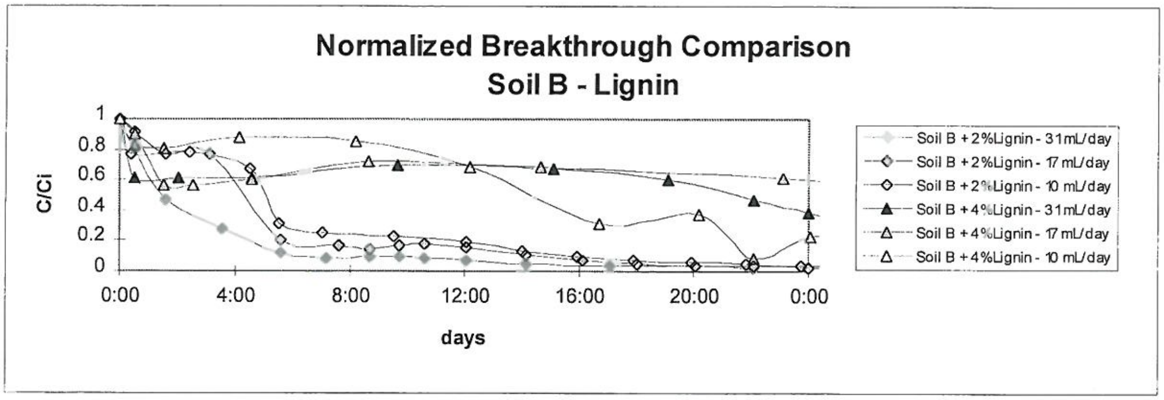

Normalized Breakthrough Comparison
Soil B - Magnesium
R_d=.8
P_L=6
C/Ci
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
6
Pore Volumes
Soil B + 2%MgCl2 - 17 mL/day
Soil B + 2%MgCl2 - 31mL/day
Soil B + 4%MgCl2 - 17 mL/day
Soil B + 4%MgCl2 - 31mL/day
FITTED CURVE (OGATA & BANKS)


Normalized Breakthrough Comparison
Soil B - Magnesium
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
20:00
days
Soil B + 2%MgCl2 - 17 mL/day
Soil B + 2%MgCl2 - 31mL/day
Soil B + 4%MgCl2 - 17 mL/day
Soil B + 4%MgCl2 - 31mL/day


Normalized Breakthrough Comparison
Soil B - Chlorides
R_d=.75
P_L=5
C/Ci
1
0.5
0
0
1
2
3
4
5
6
Pore Volumes
Soil B + 2%MgCl2 - 17 mL/day
Soil B + 2%MgCl2 - 31ml/day
Soil B + 4%MgCl2 - 17 mL/day
Soil B + 4%MgCl2 - 31mL/day
Soil B + 2%CaCl2 - 17 mL/day
Soil B + 2%CaCl2 - 31mL/day
Soil B + 4%CaCl2 - 17 mL/day
Soil B + 4%CaCl2 - 31mL/day
FITTED CURVE (OGATA & BANKS)

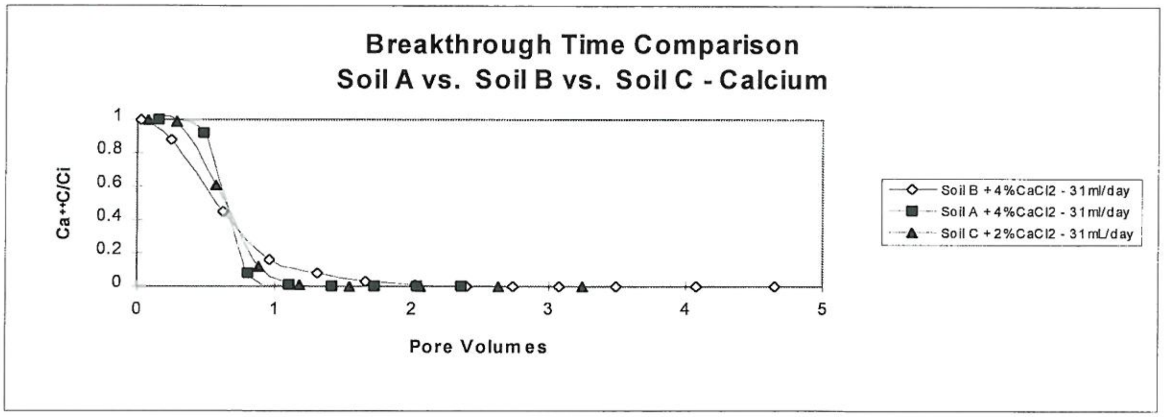

Normalized Breakthrough Comparison
Soil B - Chlorides
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
20:00
days
Soil B +2%MgCl2 - 17 mL/day
Soil B +2%MgCl2 - 31 mL/day
Soil B +4%MgCl2 - 17 mL/day
Soil B +4%MgCl2 - 31 mL/day
Soil B +2%CaCl2 - 17 mL/day
Soil B +2%CaCl2 - 31 mL/day
Soil B +4%CaCl2 - 17 mL/day
Soil B +4%CaCl2 - 31 mL/day

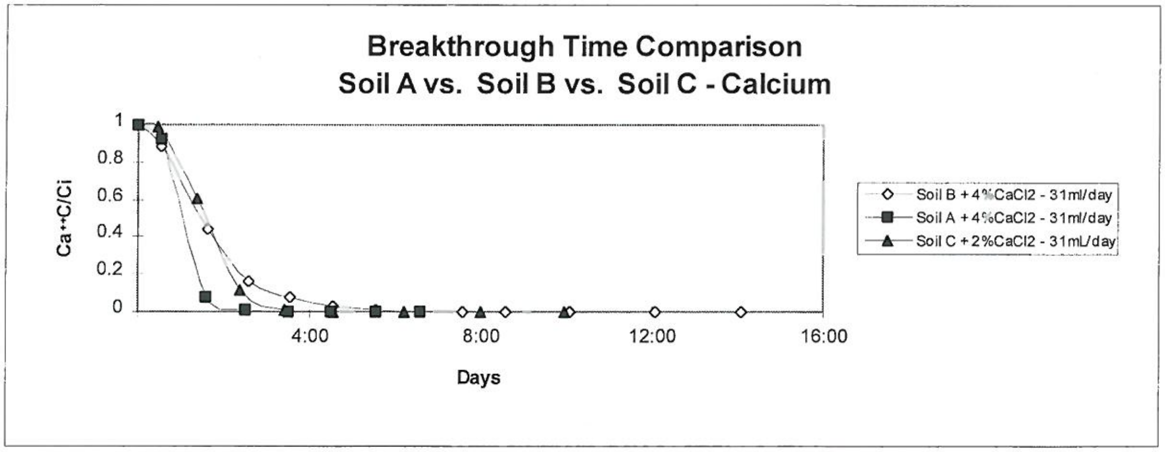

Normalized Breakthrough Comparison
Soil B - Lignin
C/Ci
1
0.8
0.6
0.4
0.2
0
R_d=.9
P_L=3
0
1
2
3
4
5
6
Pore volumes
Soil B +2%Lignin - 31 mL/day
Soil B+2%Lignin - 17 mL/day
Soil B +2%Lignin - 10 mL/day
FITTED CURVE (OGATA & BANKS)

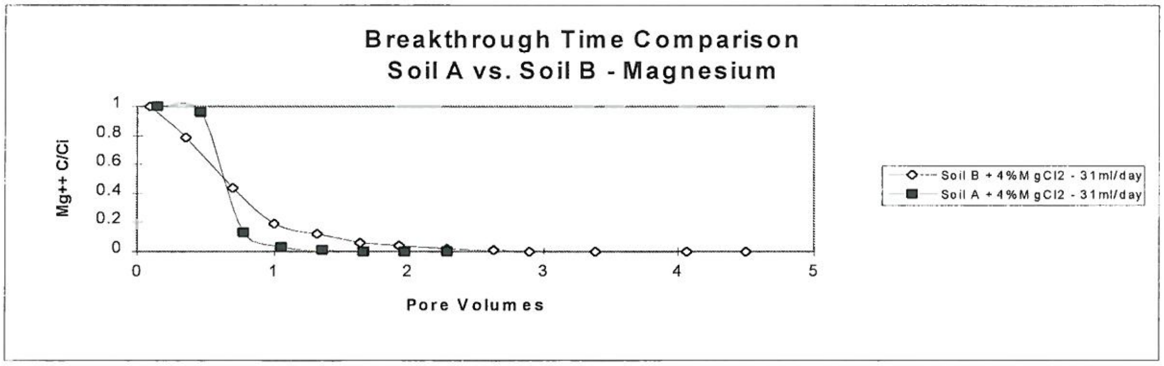

Normalized Breakthrough Comparison
Soil B - Lignin
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
20:00
0:00
days
Soil B +2%Lignin - 31mL/day
Soil B +2%Lignin - 17 mL/day
Soil B +2%Lignin - 10 mL/day
Soil B +4%Lignin - 31mL/day
Soil B +4%Lignin - 17 mL/day
Soil B +4%Lignin - 10 mL/day

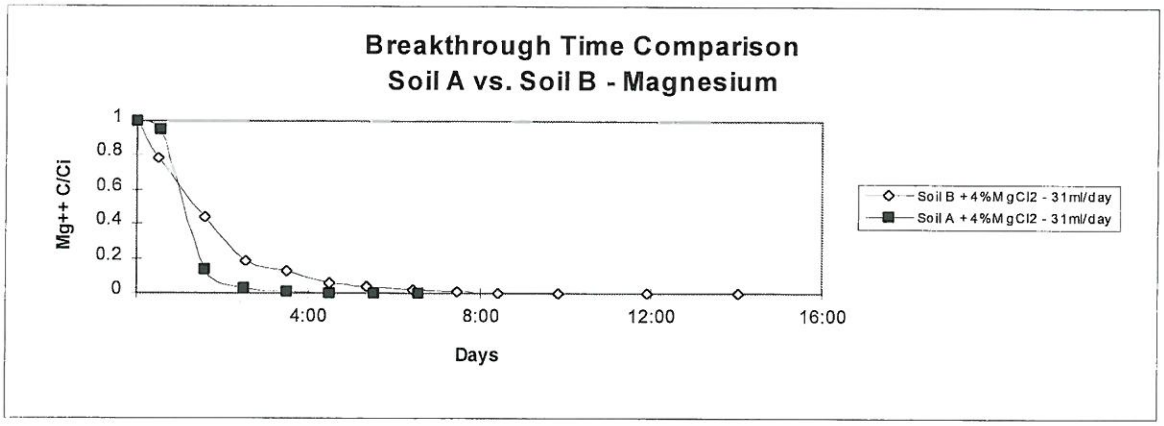
Appendix D - Comparison of Breakthrough Curves by Additives

This appendix compares breakthrough curves by additive for the three soil types at constant seepage velocity.

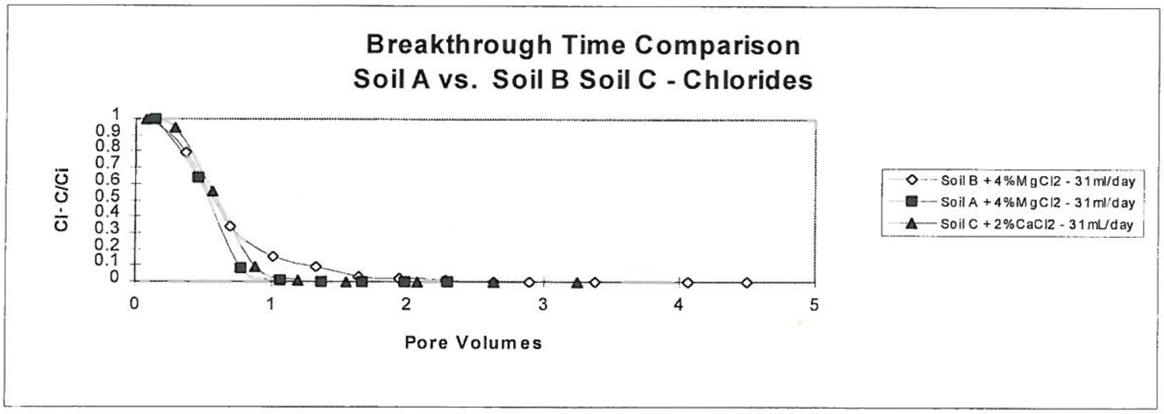




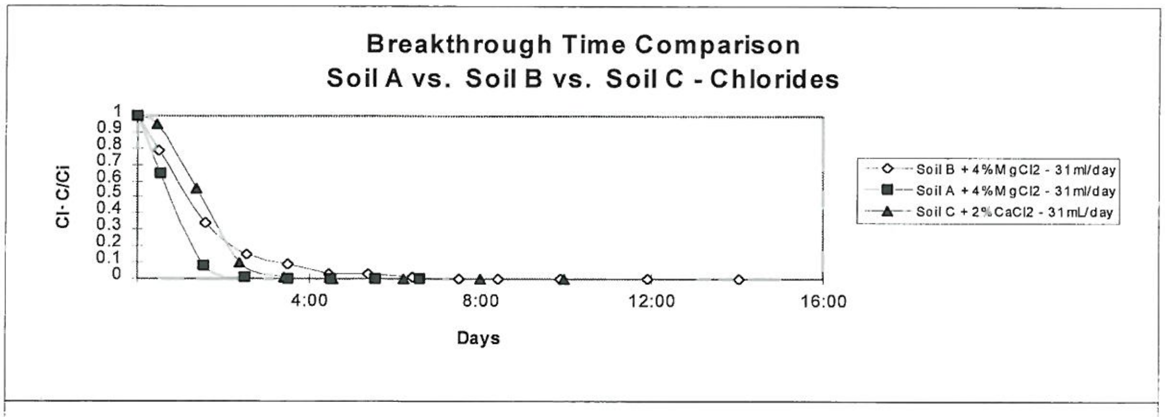




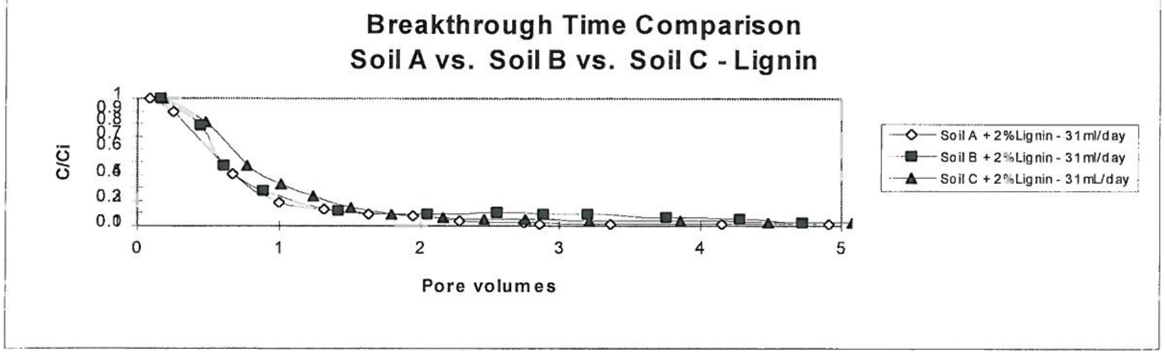
Breakthrough Time Comparison
Soil A vs. Soil B - Magnesium



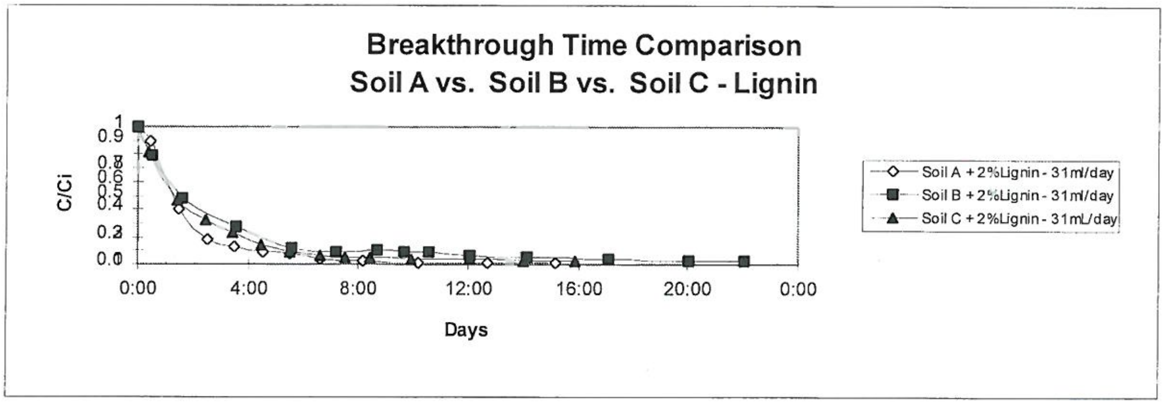
Breakthrough Time Comparison
Soil A vs. Soil B Soil C - Chlorides



Breakthrough Time Comparison
Soil A vs. Soil B vs. Soil C - Chlorides

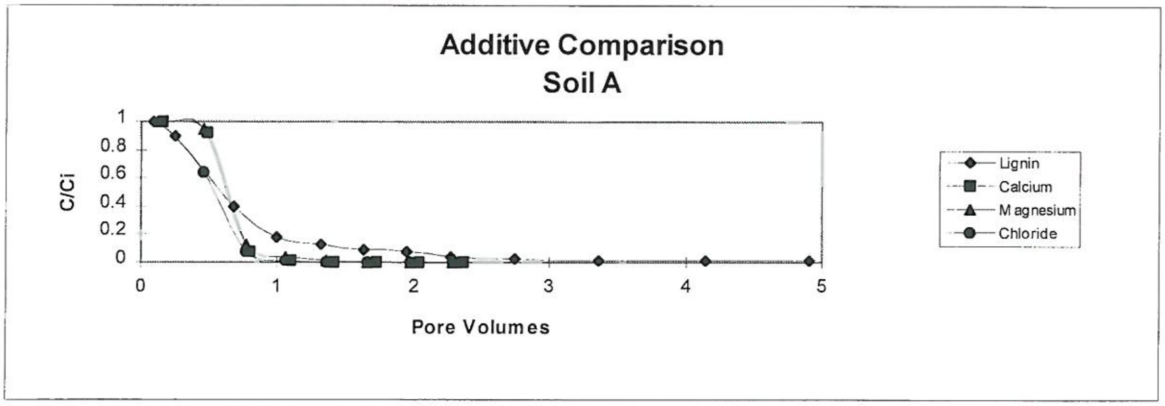


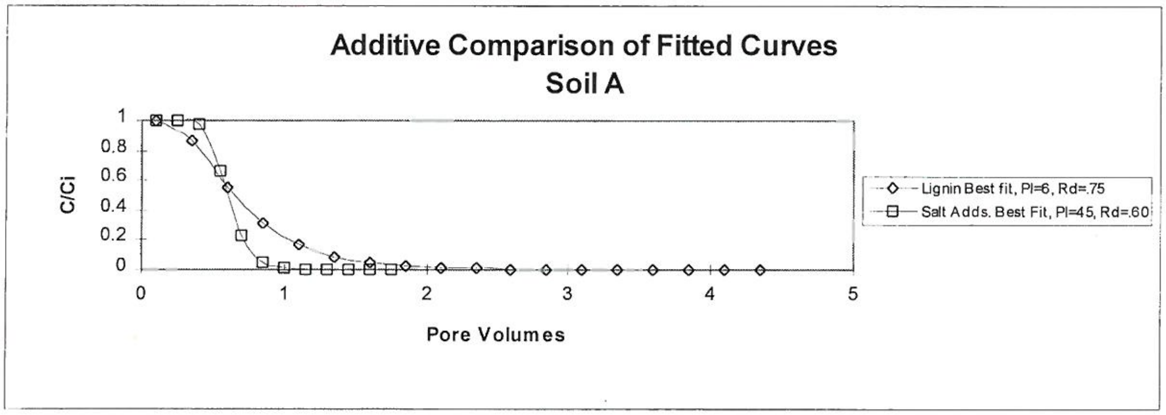
Breakthrough Time Comparison
Soil A vs. Soil B vs. Soil C - Lignin

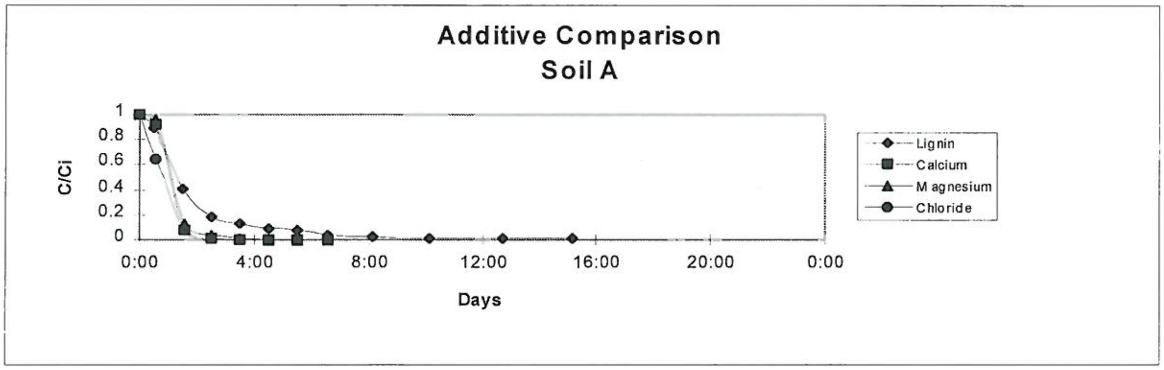

Breakthrough Time Comparison
Soil A vs. Soil B vs. Soil C - Lignin
C/Ci
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0
0:00
4:00
8:00
12:00
16:00
20:00
0:00
Days
Soil A + 2%Lignin - 31ml/day
Soil B + 2%Lignin - 31ml/day
Soil C + 2%Lignin - 31mL/day

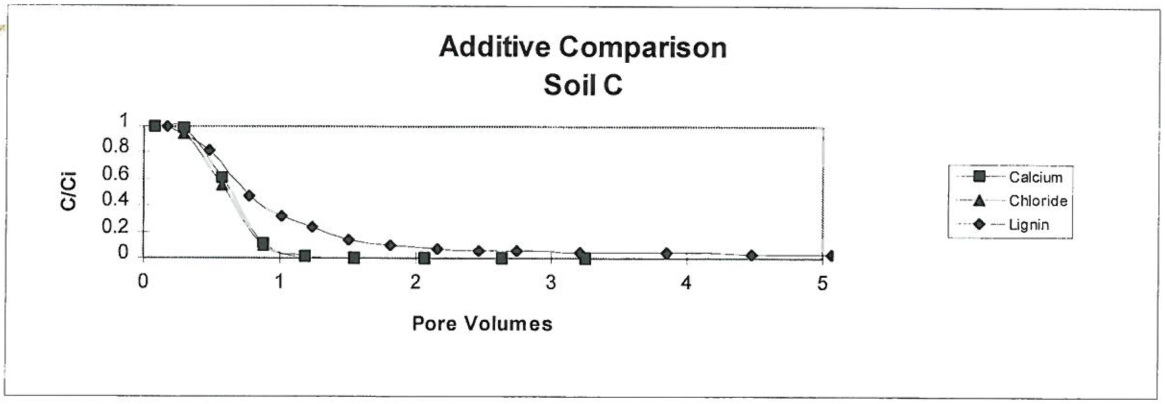
Appendix E - Comparison Breakthrough Curves by Soil Type

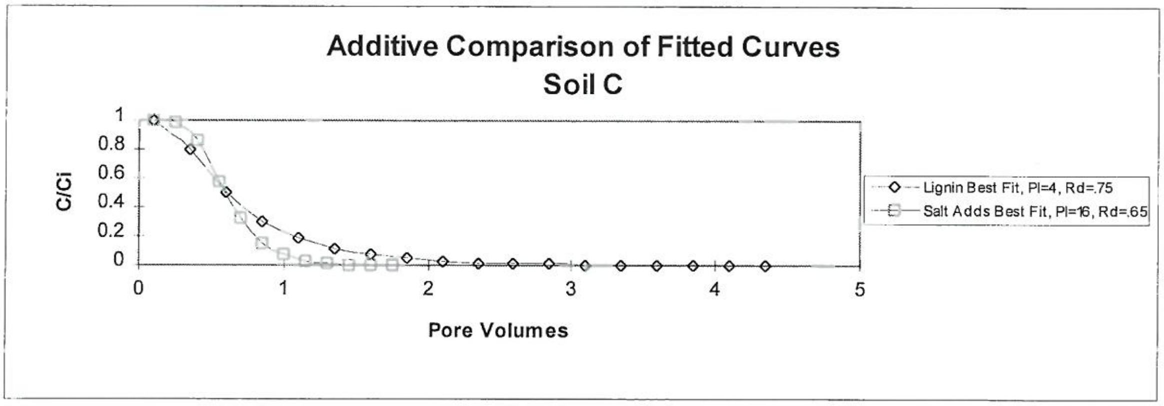
This appendix compares breakthrough curves by soil type for all the additives at a constant seepage velocity.

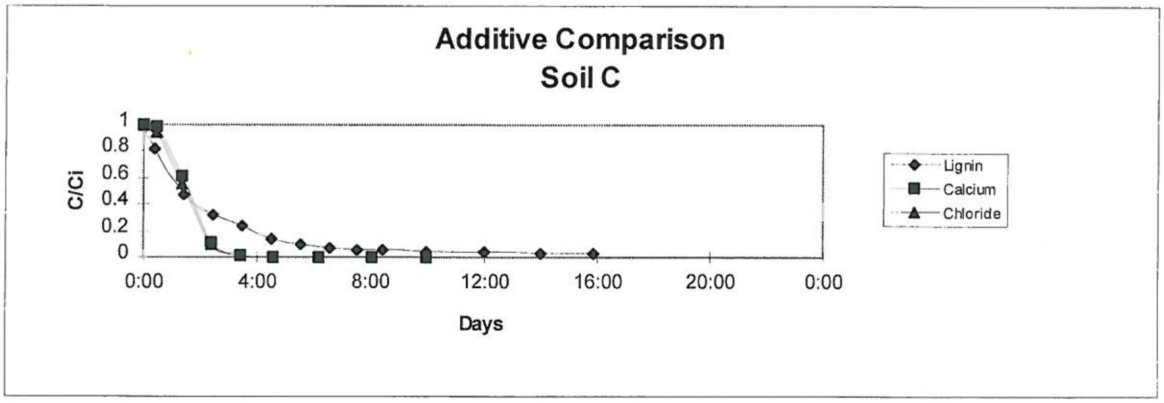


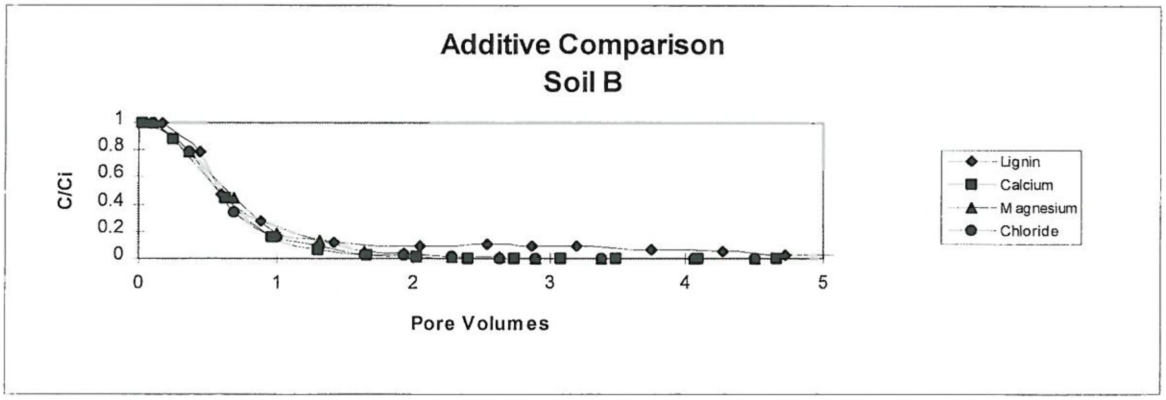


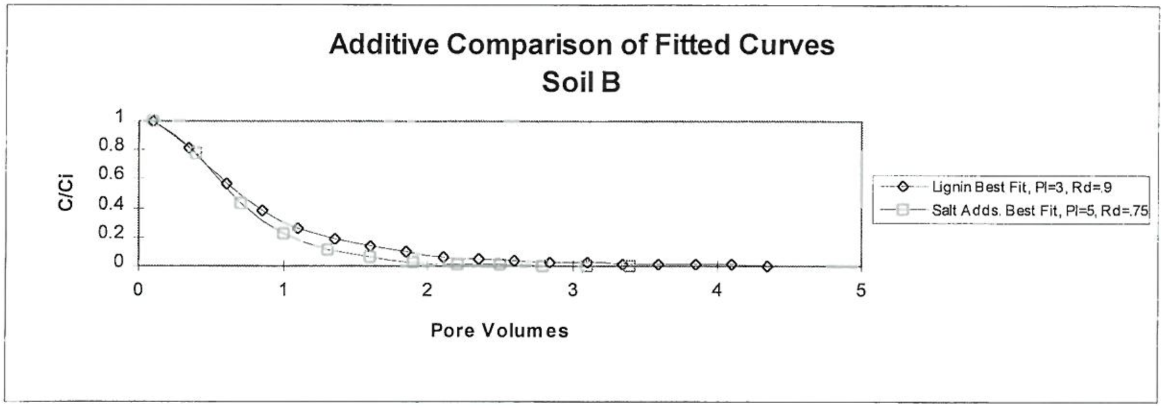


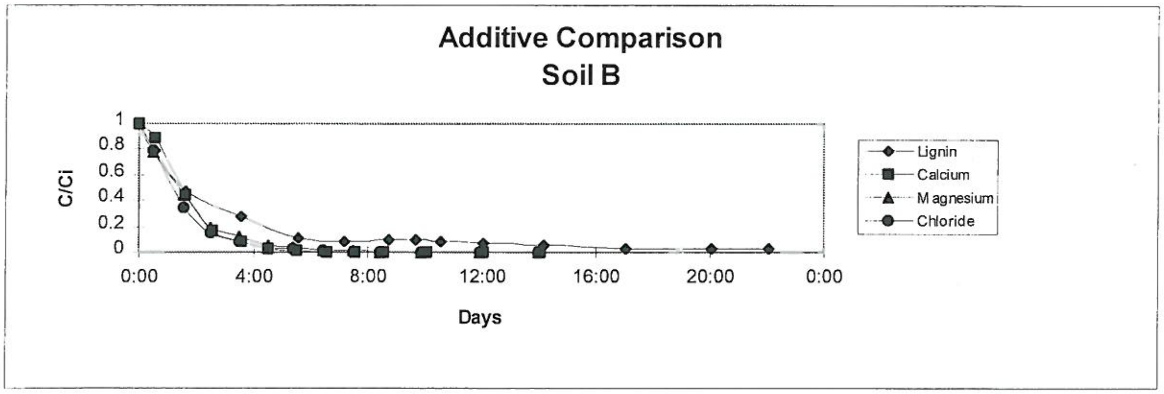

Additive Comparison
Soil C
C/Ci
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
Pore Volumes
Calcium
Chloride
Lignin


Additive Comparison of Fitted Curves
Soil C
C/Ci
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
Pore Volumes
Lignin Best Fit, Pl=4, Rd=.75
Salt Adds Best Fit, Pl=16, Rd=.65


Additive Comparison
Soil C
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
20:00
0:00
Days
Lignin
Calcium
Chloride


Additive Comparison
Soil B
C/Ci
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
Pore Volumes
Lignin
Calcium
Magnesium
Chloride


Additive Comparison of Fitted Curves
Soil B
C/Ci
1
0.8
0.6
0.4
0.2
0
0
1
2
3
4
5
Pore Volumes
Lignin Best Fit, Pl=3, Rd=.9
Salt Adds. Best Fit, Pl=5, Rd=.75


Additive Comparison
Soil B
C/Ci
1
0.8
0.6
0.4
0.2
0
0:00
4:00
8:00
12:00
16:00
20:00
0:00
Days
Lignin
Calcium
Magnesium
Chloride

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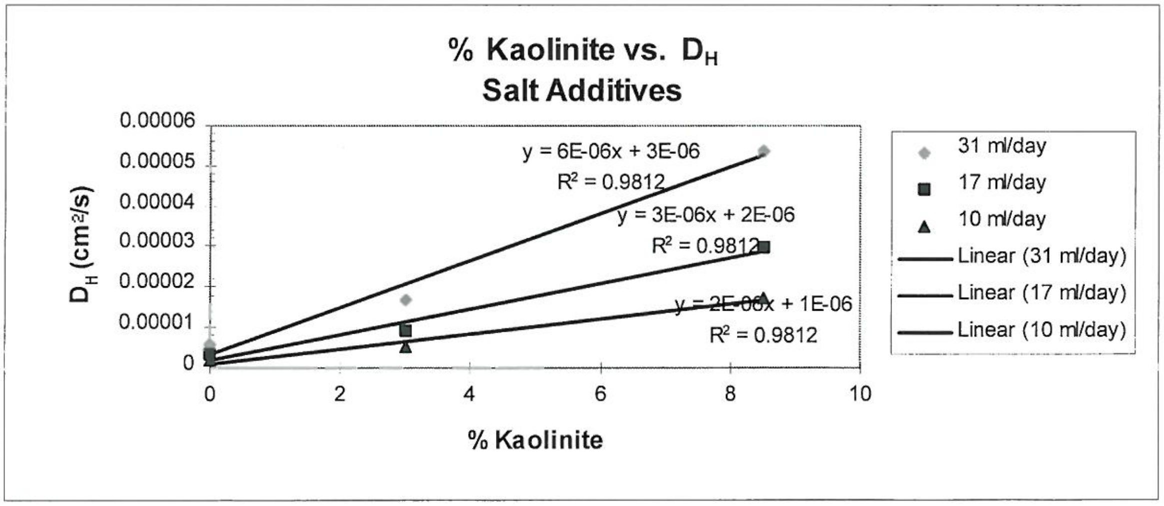
Appendix F - Calculation of Coefficients of Hydrodynamic Dispersion

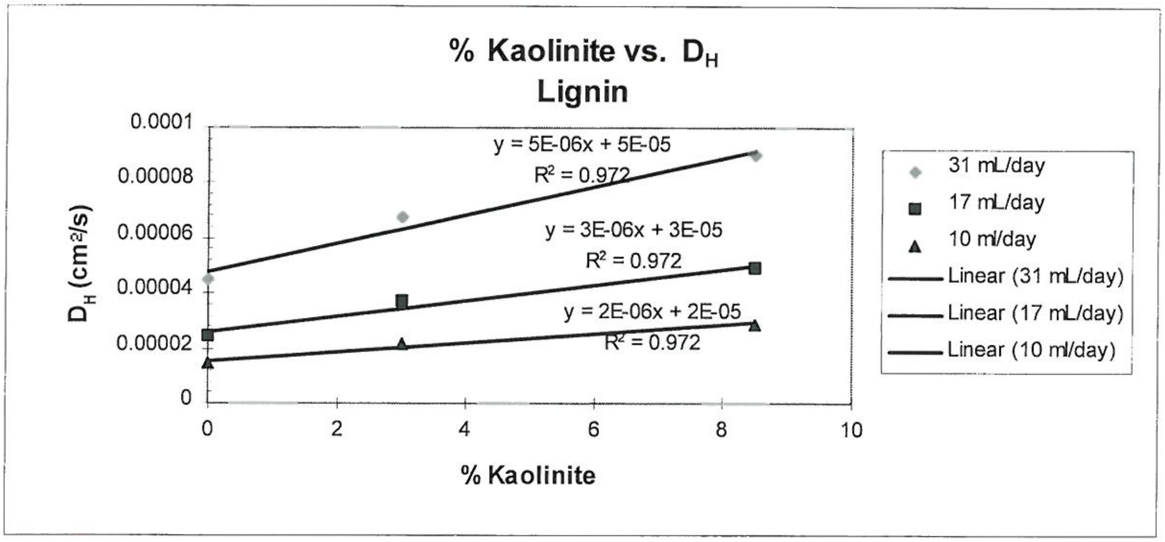
This appendix contains the following two tables that are used to calculate the Coefficients of Hydrodynamic Dispersion and generate the two plots that follow.

	Peclet number		
	Soil A	Soil B	Soil C
Salt adds	45	5	16
Lignin	6	3	4

Column Area = 20.26829916 cm^3

			Coefficient of Hydrodynamic Dispersion (cm^2/s)		
			Seepage velocity cm^3/day		
	Soil Type	% Kaolinite	31	17	10
Salt adds	soil A	0	5.99519E-06	3.28769E-06	1.93393E-06
	soil B	8.5	5.39567E-05	2.95892E-05	1.74054E-05
	soil C	3	1.68615E-05	9.24662E-06	5.43919E-06
Lignin	soil A	0	4.49639E-05	2.46576E-05	1.45045E-05
	soil B	8.5	8.99279E-05	4.93153E-05	2.9009E-05
	soil C	3	6.74459E-05	3.69865E-05	2.17567E-05




% Kaolinite vs. D_H
Lignin
0.0001
0.00008
0.00006
0.00004
0.00002
0
D_H (cm²/s)
0
2
4
6
8
10
% Kaolinite
y = 5E-06x + 5E-05
R² = 0.972
y = 3E-06x + 3E-05
R² = 0.972
y = 2E-06x + 2E-05
R² = 0.972
31 mL/day
17 mL/day
10 ml/day
Linear (31 mL/day)
Linear (17 mL/day)
Linear (10 ml/day)

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Appendix G - Runoff Data Sheets

This appendix contains the runoff data sheets from the rain simulation.

Runoff Data

Soil Type A

Additive: None

Cumm Time (min	Increm. Time (min	Cumm Runoff + Bucket (lbs)	Cumm Runoff (lbs)	Increm. Runoff (lbs)	Runoff (cm/hr)
0.00	0.00	2.00	0.00	0.00	0.00
40.00	40.00	2.00	0.00	0.00	0.00
47.50	7.50	2.10	0.10	0.10	0.13
56.00	8.50	3.10	1.10	1.00	1.11
62.50	6.50	4.00	2.00	0.90	1.30
71.00	8.50	4.75	2.75	0.75	0.83
80.00	9.00	5.60	3.60	0.85	0.89
97.00	17.00	6.80	4.80	1.20	0.66
112.00	15.00	8.00	6.00	1.20	0.75
131.00	19.00	9.50	7.50	1.50	0.74

Soil Type A

Additive: 4% CaCl2

Cumm Time (min	Increm. Time (min	Cumm Runoff Bucket (lbs)	Cumm Runoff (lbs)	Increm. unoff (lbs	Runoff (cm/hr)
0.00	0.00	2.10	0.00	0.00	0.00
9.75	9.75	2.10	0.00	0.00	0.00
22.50	12.75	2.73	0.63	0.63	0.46
31.50	9.00	3.80	1.70	1.07	1.12
39.00	7.50	5.25	3.00	1.30	1.63
47.50	8.50	6.10	4.20	1.20	1.33
59.00	11.50	8.20	6.10	1.90	1.55
75.00	16.00	10.60	8.50	2.40	1.41
89.00	14.00	12.70	10.60	2.10	1.41
105.00	16.00	14.95	12.85	2.25	1.32
120.00	15.00	17.00	14.90	2.05	1.29

Soil Type A

Additive: 4% Lignin

Cumm Time (min	Increm. Time (min	Cumm Runoff + Bucket (lbs)	Cumm Runoff (lbs)	Increm. unoff (lbs	Runoff (cm/hr)
0.00	0.00	2.10	0.00	0.00	0.00
6.25	6.25	2.10	0.00	0.00	0.00
20.50	14.25	3.45	0.35	0.35	0.23
28.00	7.50	4.55	1.45	1.10	1.38
35.00	7.00	5.50	2.40	0.95	1.28
42.50	7.50	6.45	3.35	0.95	1.19
50.45	7.95	7.30	4.20	0.85	1.01
60.50	10.05	8.60	5.50	1.30	1.22
77.00	16.50	10.85	7.75	2.25	1.28
93.00	16.00	13.25	10.15	2.40	1.41
107.00	14.00	14.90	11.80	1.65	1.11
122.00	15.00	16.75	13.65	1.85	1.16

Soil Type C

Additive: None

Cumm Time (min	Increm. Time (min	Cumm Runoff + Bucket (lbs)	Cumm Runoff (lbs)	Increm. unoff (lbs	Runoff (cm/hr)
0.00	0.00	2.15	0.00	0.00	0.00
10.50	10.50	2.15	0.00	0.00	0.00
24.50	14.00	3.00	0.85	0.85	0.57
29.50	5.00	3.70	1.55	0.70	1.32
36.50	7.00	4.75	2.60	1.05	1.41
44.50	8.00	5.75	3.60	1.00	1.18
57.00	12.50	7.45	5.30	1.70	1.28
69.50	12.50	8.85	6.70	1.40	1.05
84.50	15.00	10.65	8.50	1.80	1.13
103.00	18.50	13.50	11.35	2.85	1.45
117.00	14.00	16.10	13.95	2.60	1.75
133.00	16.00	18.20	16.05	2.10	1.24

Soil Type C
Additive: 4% CaCl2

Cumm Time (min	Increm. Time (min	umm Runoff Bucket (lbs)	Cumm Runoff (lbs)	Increm. unoff (lbs	Runoff (cm/hr)
0.00	0.00	2.15	0.00	0.00	0.00
6.50	6.50	2.15	0.00	0.00	0.00
12.00	5.50	2.55	0.40	0.40	0.68
19.00	7.00	3.40	1.25	0.85	1.14
26.00	7.00	4.30	2.15	0.90	1.21
33.00	7.00	5.30	3.15	1.00	1.34
41.00	8.00	6.30	4.15	1.00	1.18
54.00	13.00	7.80	5.65	1.50	1.09
66.50	12.50	9.30	7.15	1.50	1.13
79.00	12.50	11.15	9.00	1.85	1.39
95.00	16.00	13.25	11.10	2.10	1.24
109.00	14.00	15.00	12.85	1.75	1.18
124.00	15.00	17.00	14.85	2.00	1.25

Soil Type C
Additive: 4% Lignin

Cumm Time (min	Increm. Time (min	Cumm Runoff + Bucket (lbs)	Cumm Runoff (lbs)	Increm. Runoff (lbs)	Runoff (cm/hr)
0.00	0.00	2.15	0.00	0.00	0.00
54.00	54.00	2.15	0.00	0.00	0.00
64.50	10.50	2.70	0.55	0.55	0.49
74.00	9.50	3.80	1.65	1.10	1.09
82.00	8.00	4.90	2.75	1.10	1.29
91.00	9.00	5.85	3.70	0.95	0.99
100.00	9.00	6.75	4.60	0.90	0.94
114.00	14.00	8.00	5.85	1.25	0.84
127.00	13.00	9.15	7.00	1.15	0.83

Appendix H - Infiltration Data Sheets

This appendix contains the infiltration data sheet from the rain study.

Infiltration Data

Infiltration Rates and assosiated water contents

1"/Hr storm with a 2-Hr Duration

Soil Type	Additive	Dry Density (pcf)	Compaction water Content (%)	Initial Water Content (%)	Final Water Content (%)	Weight Water Infiltrated (g)	Ave. Infiltratio Rate (in/hr)	Ave. Infiltration Rate (cm/hr)
A	None	132.5	8.96	1.61	7.50	116.10	0.25	0.65
A	4% $CaCl_2$	135.47	8.11	4.75	6.96	45.40	0.10	0.25
A	4% Lignin	138.55	7.60	3.51	4.59	22.54	0.05	0.12
C	None	135.98	7.91	1.30	4.97	75.50	0.17	0.42
C	4% $CaCl_2$	139.3	7.74	4.50	6.00	32.60	0.07	0.18
C	4% Lignin	140.25	8.49	3.98	4.31	7.20	0.02	0.04

Appendix I - Runoff-Additive Concentration Data Sheets

The following appendix contains the additive concentration data from the rain study.

Additive Concentration Data

Soil Type: A
Additive: None

time(min)	Cumm. Runoff Bucket(lbs)	Cumm. Runoff (lbs)	Cumm. Runoff(gallons)	Cumm. Runoff(liters)	Inc. Runoff (liters)	Calcium mg/L as $CaCO_3$	Calcium mg/L	Chloride mg/l	Total Calcium	Total Chloride
0.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
40.00	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
47.50	2.10	0.10	0.01	0.05	0.05	120.00	48.00	37.00	2.18	1.68
56.00	3.10	1.10	0.13	0.50	0.45	88.00	35.20	33.00	15.98	14.98
62.50	4.00	2.00	0.24	0.91	0.41	100.00	40.00	32.00	16.34	13.07
71.00	4.75	2.75	0.33	1.25	0.34	95.00	38.00	31.00	12.93	10.55
80.00	5.60	3.60	0.43	1.63	0.39	105.00	42.00	31.00	16.20	11.96
97.00	6.80	4.80	0.58	2.18	0.54	102.00	40.80	29.00	22.22	15.79
112.00	8.00	6.00	0.72	2.72	0.54	100.00	40.00	28.00	21.78	15.25
131.00	9.50	7.50	0.90	3.40	0.68	118.00	47.20	28.00	32.13	19.06

139.76 102.34 mg
483.02 204.68 mg/m^2

Soil Type: A
Additive: 4% CaCl2

time(min)	Cumm. Runoff + Bucket(lbs)	Cumm. Runoff (lbs)	Cumm. Runoff(gallons)	Cumm. Runoff(liters)	Inc. Runoff (liters)	Calcium mg/L as $CaCO_3$	Calcium mg/L	Chloride mg/l	Total Calcium	Total Chloride
0.00	2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
9.75	2.10	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22.50	2.73	0.63	0.08	0.29	0.29	1100.00	440.00	1400.00	125.80	400.28
31.50	3.80	1.70	0.20	0.77	0.49	620.00	248.00	740.00	120.43	359.35
39.00	5.25	3.15	0.38	1.43	0.66	520.00	208.00	470.00	136.88	309.29
47.50	6.10	4.00	0.48	1.82	0.39	380.00	152.00	330.00	58.64	127.30
59.00	8.20	6.10	0.73	2.77	0.95	320.00	128.00	210.00	121.99	200.14
75.00	10.60	8.50	1.02	3.86	1.09	235.00	94.00	135.00	102.39	147.04
89.00	12.70	10.60	1.27	4.81	0.95	220.00	88.00	105.00	83.87	100.07
105.00	14.95	12.85	1.54	5.83	1.02	190.00	76.00	86.00	77.61	87.82
120.00	17.00	14.90	1.79	6.76	0.93	185.00	74.00	74.00	68.85	68.85

896.45 1800.14 mg
3098.09 3600.29 mg/m^2

Soil Type: A
Additive: 4% Lignin

time(min)	Cumm. Runoff + Bucket(lbs)	Cumm. Runoff (lbs)	Cumm. Runoff(gallons)	Cumm. Runoff(liters)	Inc. Runoff (liters)	Lignin %	Total Lignin
0.00	3.10	0.00	0.00	0.00	0.00	0.00	0.0000
6.25	3.10	0.00	0.00	0.00	0.00	0.00	0.0000
20.50	3.45	0.35	0.04	0.16	0.16	4.00	0.0064
28.00	4.55	1.45	0.17	0.66	0.50	2.90	0.0145
35.00	5.50	2.40	0.29	1.09	0.43	1.90	0.0082
42.50	6.45	3.35	0.40	1.52	0.43	1.60	0.0069
50.75	7.30	4.20	0.50	1.91	0.39	1.50	0.0058
60.50	8.60	5.50	0.66	2.50	0.59	1.50	0.0088
77.00	10.85	7.75	0.93	3.52	1.02	1.40	0.0143
93.00	13.25	10.15	1.22	4.61	1.09	1.30	0.0142
107.00	14.90	11.80	1.41	5.36	0.75	1.20	0.0090
122.00	16.75	13.65	1.64	6.19	0.84	1.30	0.0109

0.0989 liters lignin
0.3418 l/m^2 lignin

Soil Type: C
Additive: None

time(min)	Cumm. Runoff Bucket(lbs)	Cumm. Runoff (lbs)	Cumm. Runoff(gallons)	Cumm. Runoff(liters)	Inc. Runoff (liters)	Calcium mg/L as $CaCO_3$	Calcium mg/L	Chloride mg/l	Total Calcium	Total Chloride
0.00	2.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
10.50	2.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24.50	3.00	0.85	0.10	0.39	0.39	70.00	28.00	54.00	10.80	20.83
29.50	3.70	1.55	0.19	0.70	0.32	78.00	31.20	47.00	9.91	14.93
36.50	4.75	2.60	0.31	1.18	0.48	74.00	29.60	43.00	14.11	20.49
44.50	5.75	3.60	0.43	1.63	0.45	84.00	33.60	37.00	15.25	16.79
57.00	7.45	5.30	0.64	2.41	0.77	88.00	35.20	33.00	27.16	25.46
69.50	8.85	6.70	0.80	3.04	0.64	84.00	33.60	31.00	21.35	19.70
84.50	10.65	8.50	1.02	3.86	0.82	94.00	37.60	31.00	30.72	25.32
103.00	13.50	11.35	1.36	5.15	1.29	91.00	36.40	30.00	47.08	38.80
117.00	16.10	13.95	1.67	6.33	1.18	84.00	33.60	30.00	39.65	35.40
133.00	18.20	16.05	1.92	7.28	0.95	80.00	32.00	29.00	30.50	27.64
									246.52	245.37 mg
									851.95	490.73 mg/m^2

Soil Type: C
Additive: 4% $CaCl_2$

time(min)	Cumm. Runoff Bucket(lbs)	Cumm. Runoff (lbs)	Cumm. Runoff(gallons)	Cumm. Runoff(liters)	Inc. Runoff (liters	Calcium mg/L as $CaCO_3$	Calcium mg/L	Chloride mg/l	Total Calcium	Total Chloride
0.00	2.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6.50	2.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
12.00	2.55	0.40	0.05	0.18	0.18	2050.00	820.00	3300.00	148.86	599.06
19.00	3.40	1.25	0.15	0.57	0.39	990.00	396.00	1950.00	152.76	752.23
26.00	4.30	2.15	0.26	0.98	0.59	1050.00	420.00	1350.00	247.79	796.48
33.00	5.30	3.15	0.38	1.43	0.84	640.00	256.00	960.00	214.94	806.01
41.00	6.30	4.15	0.50	1.88	1.04	600.00	240.00	800.00	250.52	835.06
54.00	7.80	5.65	0.68	2.56	1.52	540.00	216.00	600.00	328.40	912.21
66.50	9.30	7.15	0.86	3.24	1.72	510.00	204.00	480.00	351.81	827.80
79.00	11.15	9.00	1.08	4.08	2.36	420.00	168.00	420.00	396.47	991.18
95.00	13.25	11.10	1.33	5.04	2.68	390.00	156.00	340.00	417.71	910.40
109.00	15.00	12.85	1.54	5.83	3.15	390.00	156.00	330.00	492.05	1040.88
124.00	17.00	14.85	1.78	6.74	3.59	380.00	152.00	315.00	544.97	1129.37
									3546.28	9600.69 mg
									12255.85	19201.39 mg/m^2

Soil Type: C
Additive: 4% Lignin

time(min)	Cumm. Runoff + Bucket(lbs)	Cumm. Runoff (lbs)	Cumm. Runoff(gallons	Cumm. Runoff(liters)	Inc. Runoff (liters)	Lignin %	Total Lignin
0.00	2.10	0.00	0.00	0.00	0.00	0.00	0.0000
54.00	2.10	0.00	0.00	0.00	0.00	0.00	0.0000
64.50	2.70	0.60	0.07	0.27	0.27	0.95	0.0026
74.00	3.80	1.70	0.20	0.77	0.50	1.15	0.0057
82.00	4.90	2.80	0.34	1.27	0.50	1.00	0.0050
91.00	5.85	3.75	0.45	1.70	0.43	0.90	0.0039
100.00	6.75	4.65	0.56	2.11	0.41	0.85	0.0035
114.00	8.00	5.90	0.71	2.68	0.57	0.85	0.0048
127.00	9.15	7.05	0.85	3.20	0.52	0.70	0.0037
							0.0291 liters
							0.1007 liters/m^2

Appendix J - Post Evaporation Additive Profiles

This appendix contains evaporation data compiled following the rain study to determine the additive profiles following the drying of the soil.

Evaporation Data

A + None			C + None			A + 4% CaCl2		
Depth (cm	Ca (mg/kg	Cl (mg/kg)	Depth (cm	Ca (mg/kg	Cl (mg/kg)	Depth (cm	Ca (mg/kg	Cl (mg/kg)
1.25	14.49	6.56	1.25	6.18	6.32	1.25	2476.19	3888.89
3.75	11.22	4.95	3.75	5.38	5.83	3.75	2402.02	3476.61
6.25	12.80	5.12	6.25	4.34	5.42	6.25	1312.16	2132.27
8.75	12.91	5.16	8.75	5.13	6.37	8.75	1439.58	2253.89
11.25	13.16	5.73	11.25	5.19	5.99	11.25	1585.74	2370.44

Evaporation Data

A + 4% Lignin		C + 4% Lignin		C + 4% CaCl2		
Depth(cm)	Lignin (ml/kg	Depth(cm)	Lignin (ml/kg)	Depth (cm	Ca (mg/kg	Cl (mg/kg)
1.25	22.04	1.25	31.92	1.25	1573.25	2228.78
3.75	4.35	3.75	7.37	3.75	763.17	1244.30
6.25	4.00	6.25	4.09	6.25	473.99	716.49
8.75	2.81	8.75	3.87	8.75	473.36	697.90
11.25	10.11	11.25	6.86	11.25	701.71	1127.75

Appendix K - Runoff-Erosion Data Sheets

Appendix K contains the erosion data from the rain study.

Erosion Data

Soil A + No Adds. | Soil A + 4% CaCl2 | Soil A + 4% Lignin

Soil A + No Adds. Total Runoff	Sed. Rate	Soil A + 4% CaCl2 Total Runoff	Sed. Rate	Soil A + 4% Lignin Total Runoff	Sed. Rate
Liters	gm/L	Liters	gm/L	Liters	gm/L
0.05	0.85	0.29	4.76	0.16	4.49
0.50	0.76	0.77	4.12	0.66	4.60
0.91	0.79	1.43	3.06	1.09	3.19
1.25	0.68	1.82	2.27	1.52	2.44
1.63	0.57	2.77	1.66	1.91	2.09
2.18	0.52	3.86	1.09	2.50	1.86
2.72	0.41	4.81	0.84	3.52	1.91
3.40	0.43	5.83	0.69	4.61	1.44
		6.76	0.92	5.36	0.75
				6.19	0.36

Erosion Data

Soil C + No Adds. Total Runoff	Sed. Rate	Soil C + 4% CaCl2 Total Runoff	Sed. Rate	Soil C + 4% Lignin Total Runoff	Sed. Rate
Liters	gm/L	Liters	gm/L	Liters	gm/L
0.39	5.32	0.18	21.07	0.27	2.07
0.70	4.20	0.57	25.01	0.77	3.67
1.18	3.11	0.98	11.53	1.27	3.40
1.63	2.63	1.43	8.58	1.70	2.03
2.41	2.02	1.88	6.00	2.11	1.84
3.04	1.72	2.56	3.68	2.68	0.97
3.86	1.73	3.24	4.74	3.20	1.02
5.15	1.32	4.08	2.91	3.60	0.88
6.33	1.32	5.04	2.25		
7.28	1.28	5.83	1.63		
		6.74	1.67		

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