# *STRENGTH and DENSITY MODIFICATION of UNPAVED ROAD SOILS DUE to CHEMICAL ADDITIVES*

By

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## Disclaimer

# Abstract

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This paper presents information on laboratory tests conducted to determine the effects of additives on the stabilization of unpaved road surfaces. Laboratory tests can be an efficient method of determining which additive will best stabilize a given unpaved road surface, but correlation between laboratory tests and road applications is necessary. For the three soils and three chemical additives tested, lignin sulfonate produced the greatest changes in unconfined compressive strength. However, inspection of an application of lignin sulfonate to a road surface did not show the increase in stability indicated by laboratory tests. This failure of lignin sulfonate to perform as expected is the result of the method of application, and the high solubility of lignin sulfonate.

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# CHAPTER 1
# INTRODUCTION

## Problem Statement

There are many advantages to the construction and use of unpaved roads. The greatest advantage is that construction costs are much less than those of paved roads. Unpaved roads provide economically acceptable routes of transportation for seasonal travel, haul roads, and low traffic volume residential and agricultural travel. Unfortunately, unpaved road surfaces are often rough and dusty, making them unpleasant and sometimes dangerous to use. Agencies responsible for road construction and maintenance are aware of comfort and safety factors inherent in rough-dusty roads. These agencies often mix additives with the road surface soil to increase user comfort and safety.

Concern for the comfort and safety of the users is only one reason these agencies apply additives to unpaved roads. Additives can also reduce the cost of maintenance. When one considers that there are over 1,600,000 miles (2,576,000 km) of unpaved roads in the United States (Larson, 1991), it is apparent that the cost of maintenance is considerable. The U.S. Department of Agriculture Forest Service is responsible for 60,000 miles (96600 km) of unpaved roads and one of the greatest reasons for their use of additives is to protect the monetary investment that these roads represent (Moats, 1993). The use of additives can help to reduce the loss of fines (particles smaller than 0.075 mm) carried away in the form of dust or by water erosion. However, if the additives are ineffective in stabilizing the road surface or if the benefit gained by the application of additives is short-lived, the cost of maintenance may be increased and not reduced.

It is often difficult to predict which additive might best improve user comfort and reduce maintenance costs. One way to eliminate the need to make this prediction would be to pave all unpaved roads. Unfortunately the cost of paving all unpaved roads is prohibitive, and in some situations, impractical. For example, some haul roads are used for relatively short time spans, and the land may have to be reclaimed when the road is abandoned. The cost of paving a temporary road is normally unacceptable. Because paving is impractical in may cases, another method of improving unpaved roads must be found. Good design, construction, and maintenance practices can do much to improve a road's performance.

However, it may be found that good design, construction, and maintenance practices are insufficient in themselves. For example, if the soil at a particular site is wholly or partially unsuited to meet construction or performance requirements, one is left with three options (Ingles & Metcalf, 1973):

1. Accept the site material as it is, and attempt to design within this restriction.
2. Remove the site material, and replace it with a superior material.
3. Alter the properties of the existing soil so as to better meet the performance requirements.

Option 1 is often unacceptable, either because the road would be impassable for many months of the year, or because the maintenance costs would be too high. Option 2 is often employed in road construction, but hauling costs usually require that the material be obtained near the construction site. While this material may be superior to the in-situ material, it may not have all the qualities desired for construction, and the strength and/or durability of the surface material may need to be improved. Therefore, option 2 is often combined with option 3 to produce materials that are both economically and structurally suitable. Option 3 can and often does involve the use of chemical additives, since chemical stabilization can be an economically acceptable alternative to paving.

In an effort to increase user comfort and safety, and to reduce maintenance costs, agencies responsible for unpaved roads often apply chemical additives, such as lignin sulfonate, calcium chloride and magnesium chloride to road surfaces. Sometimes the additive reduces dust and maintenance, sometimes it only reduces dust, and sometimes it is nearly ineffective in reducing dust or maintenance. The reason why these additives work on some roads and not on others is puzzling and complex. There have been many attempts to discover which additives best control dust, but few attempts to determine which additive might be most successful in stabilizing a particular unpaved road. To help fill the need for information about stabilization using chemical additives, this paper describes a project designed to determine strength and density modifications of unpaved road soils due to chemical additives.

## History of Additive Use

The use of admixtures to stabilize soil is a very old idea. It dates back as far as 3000 B.C. when lime was used with clay and quartz as a filler between stone blocks (Straub, 1952). As knowledge of materials grew, the methods and number of products used to stabilize soil increased. Brown, et al. (1939) in a book containing articles reprinted from six 1938 issues of Roads and Streets stated that,

"General methods for accomplishing stabilization may be enumerated as follows:

1. Selection of natural soils with granular materials and binder which furnishes high stability.
2. Adding soil binder to granular materials, or adding granular material to clays.
3. Treating graded soils with deliquescent materials (materials that absorb water from the air).
4. Waterproofing soils with bituminous materials.
5. Using combinations of 1 or 2 and 3, or, 1 or 2 and 4.
6. Densifying of natural soils by special manipulation, in combination with admixtures of physical or chemical materials other than soil, to eliminate permanently those colloidal and clay properties productive to volume change."

Studies of admixtures to stabilize soils in general have continued, but for unpaved road surfaces most studies are related to dust control by the use of chemicals such as magnesium and calcium chlorides. These studies led to chemicals being applied to control dust, with stabilization being a side issue. Even today, the standard practice for dust control is often the application of chemicals at rates of approximately ½ gallon per square yard (2.27 $l/m^2$) of road surface. Methods of application vary, and this influences the actual percentage (by dry weight of road soil) of chemical in the additive-soil mix.

In the past, testing an additive for its stabilization properties was a matter of trial and error. For example, an additive was applied to a section of road, and if the additive produced the desired effect, it was used on other roads. If the additive did not meet expectations, another chemical was tried. Unfortunately, soil properties of unpaved roads vary to such an extent that this method often resulted in an expensive experiment that did not yield fundamental knowledge. Even if an additive does stabilize a given road section, it may or may not stabilize other road sections.

Methods for unpaved road stabilization continue to be developed and many ideas are published by organizations such as the Transportation Research Board and distributed by organizations like the Wyoming Technology Transfer Center. The exchange of ideas is also being advanced at regularly held conferences like the International Conferences on Low Volume Roads.

## Objectives

The overall objective of this project is to provide people responsible for stabilizing unpaved road surfaces with a method for selecting an additive and a procedure for applying that additive to best stabilize an unpaved road surface. To accomplish this goal, tests were conducted on combinations of three soils using three additives, and an application of an additive to a road surface was monitored. The procedures for the conduction and evaluation of tests, the results of the tests conducted, and the conclusions and recommendations developed during this study are presented. A review of pertinent past literature on dust control and soil stabilization is also presented.

The purpose of the laboratory tests was to determine how the moisture-density relationship and the shear strength of a soil is changed by the application of additives. Successful determination of changes in moisture-density relationships and in shear strength may provide a cost-effective method of evaluating the advantage of one additive over another. By monitoring the effects of an application of an additive to a road surface, one may be able to better determine if the test results can be correlated to a road application. With information gathered by comparison of laboratory tests to road experience, one may evaluate additives and application methods that result in the most effective use of additives. The information gathered during this study also forms the basis of recommendations for further study.

# CHAPTER 2

# LITERATURE REVIEW

## Introduction to Literature Review

This literature review focuses on publications that discuss the effect of additives on soil stability, and hence on unpaved road stability. First, factors that influence soil stability are reviewed. Next, the use of additives to stabilize roads is considered. Finally, publications that present information on tests that best characterize engineering soil properties are summarized.

Many papers discuss additives used in dust control. In these papers, the primary emphasis is on dust control. Therefore, soil stabilization, if discussed at all, is considered mainly as an additional benefit resulting from the use of dust palatives. However, chemical additives used for dust control often produce changes in soil characteristics that influence stabilization. Consequently, papers on dust control often contain information relevant to unpaved road stabilization.

Lignin sulfonate, calcium chloride, and magnesium chloride are the additives most commonly used for dust control on unpaved roads. Because of their common use, this review covers these additives in the most detail. Appendix A summarizes briefly the use of other additives, such as petroleum based emulsions.

## Factors Influencing Stabilization

Because unpaved roads are made of soil, stabilization of an unpaved road requires the stabilization of soil. Soil stabilization is the process of improving certain soil properties (Kezdi, 1979; McCarthy, 1993; Mitchell, 1993). Ingles and Metcalf (1973) define soil stabilization as "the alteration of soil properties to meet specific engineering requirements . . .."

The soil properties that require improvement are described by Kezdi (1979) ". . . stabilization includes strength and durability increases alike, with certain selected soil properties playing a similarly important role such as the elimination of shrinkage, frost hazards, or high compressibility . . .." Ingles and Metcalf (1973) state that "The chief properties of a soil with which the construction engineer is concerned are volume stability, strength, permeability and durability." The soil properties of strength, durability, and small volume changes are constant themes throughout papers on soil stabilization.

The property of soil strength is usually thought of as the soil's ability to support a load. McCarthy says that "The ability of a soil deposit to support an imposed loading . . . is governed by the shear strength of the soil. As a result, the shearing strength of the soil becomes of primary importance in foundation design, highway and airfield design, . . .." In his book *Stabilized Earth Roads*, Kezdi (1979) relates shear strength and soil stabilization; "Soil stabilization means, therefore, increase of the shear strength of that soil corresponding to the given requirements . . .."

Shear strength is influenced by several factors. Mitchell (1993) gives an excellent description of these factors:

“These factors may be divided into two groups: Compositional factors and environmental factors. Compositional factors determine the potential range of values for any property. Included in this group are:

1. Type of minerals;
2. Amount of each mineral;
3. Type of adsorbed cation;
4. Shapes and size distribution of particles;
5. Pore water composition.”

“Environmental factors determine the actual value of any property. They include:

1. Water content;
2. Density;
3. Confining pressure;
4. Temperature;

5. Fabric;
6. Availability of water."

Therefore, by Mitchell's statement these compositional and environmental factors combine to determine a soil's shear strength.

Shear strength can be divided into two components, referred to as internal friction and cohesion. These are the two main components influencing aggregate surfaced road stability (Gow et al., 1961; Public Works, 1990). The relationship between shear strength, internal friction and cohesion is given by the equation (Mitchell, 1993)

$$\tau = \bar{c} + \bar{\sigma} \tan \bar{\phi} \tag{2.1}$$

where

$\tau$ = shearing strength,

$\bar{c}$ = cohesion

$\bar{\sigma}$ = effective normal stress in the plane of failure, and

$\bar{\phi}$ = the angle of internal friction .

According to equation (2.1) if a soil lacks cohesion (that is, $c$=0), shear strength depends only on normal stress and the angle of internal friction. In turn, internal friction depends on certain factors. To paraphrase Rowe (1962), internal friction depends on the sum of three contributions, sliding resistance at contacts, particle rearrangements, and dilation. To this, Mitchell (1993) includes the factor of particle crushing as confining pressure increases and void ratio decreases.

As density increases, these four factors produce changes in internal friction. Therefore, in soil studies internal friction is expressed in terms of an angle of internal friction $\phi$, and the angle of internal friction is related to shear strength $\tau$ as shown in equation (2.1). According to Wright, and Paquette (1987), "For a dry sand, $\phi$ is primarily dependent on density (void ratio); the lower the void ratio (higher density) the higher the value of ϕ. . . . The angle of internal friction is relatively independent of the moisture content for sands; ϕ for a wet sand will be only slightly, if any, lower than ϕ for a dry sand, other conditions being the same." In addition, unconfined compression (UC) tests relate stress to cohesion c, by the equation (McCarthy, 1993),

$$c = \frac{1}{2} q_u \tag{2.2}$$

where

$q_u$ = is the axial stress from a UC test required to fail the soil specimen and is a function of $c$ $\sigma$, and $\phi$.

Cohesion is the other component of soil stability and shear strength. According to Mitchell (1993) there are two types of cohesion, true cohesion and apparent cohesion. True cohesion's proposed sources are:

1. cementation (chemical bonding between particles),
2. electrostatic and electromagnetic attractions (significant for closely spaced particles of small size), and
3. primary valence bonding and adhesion.

Apparent cohesion is generated by:

1. capillary stresses (a combination of water attraction to soil particle surfaces and the surface tension of water), and
2. apparent mechanical forces (caused by interlocking rough surfaces) (Mitchell, 1993).

Application of various additives can increase internal friction and/or cohesion (Hemwall, et al., 1962). However, soils react differently to different additives. The stability of some soils is improved by the addition of certain additives, whereas the stability of other soils is unaffected or reduced (Nicholls and Davidson, 1958; Hoover, et al., 1960).

The reaction of a soil to an additive depends on both the soil and the additive's physical and chemical properties. Two soils can have different physical and chemical properties, though they have nearly the same grain size distribution and liquid and plastic indices. Particle sizes may be similar, but the surface texture and shape of the particles may be distinct. Also, two soils with the same liquid and plastic indices may have different chemical properties. Soil chemical makeup is a result of parent material and weathering. Even soils with the same parent material can have differing chemical makeups depending on how much and what type of weathering took place (Mitchell, 1993).

A soil's composition, history, present state, and environment are reflected in its fabric and interparticle force system. These fabric and interparticle force systems compose the structure of a soil (Mitchell, 1993).

Mitchell (1993) states that "The term fabric refers to the arrangement of particles, particle groups, and pore spaces in a soil." The fabric of a soil is changed by:

1. rearranging the soil particles,
2. changing the size or composition of particle groups, or
3. changing the size or number of pore spaces in the soil (Mitchell, 1993).

For instance, particle rearrangement might occur with the addition of lignin. This is because lignin may cause the clay fraction of some soils to disperse (Gow, et al, 1961). Fabric change might also occur due to the solubility of some common road soils. By increasing solubility some additives may provide additional cementing agents. When the soil dries, these agents are available to cement particles into larger groups (Ross, 1988).

The stability of a road depends not only on the shear strength of the surface layer but also on its thickness. Therefore, if the surface layer is thin, the overall road stability depends on the shear strength of the layer supporting the surface layer. According to Huang (1993) the stability of paved or unpaved roads depends on the strength of the entire road-layer system. Unpaved roads often have two layers: a surface layer, made up of imported graded soil, and a subgrade layer of native soil. The application of an additive to the surface layer may result in the formation of a third layer. This third layer is composed of a soil-additive mix that acts like a pavement layer that may or may not be more stable than the soil alone, depending on the soil-additive interaction.

Thus, the introduction of an additive to the surface layer forms a road system with three layers:

1. a surface "pavement" layer, made up of a soil-additive mix,
2. a layer that now acts like the base layer in a pavement system, and
3. the subgrade layer.

The performance of the unpaved road depends on this three-layered system. Huang (1993) declares that if the subgrade has a low shear strength, more or stronger base material is needed, and that if the base material is weak, a thicker or stronger surface material is required. Huang uses the following equation to show the relationship between the depth in a layer and the stress that will be applied to the surface directly below that depth:

$$\sigma_z = q\left[1 - \frac{z^3}{(a^2 + z^2)^{1.5}}\right] \qquad \textbf{(2.3)}$$

where

$\sigma_z$ = the stress at a depth z, beneath the center of a flexible plate (in this case a vehicle tire) subjected to a uniform pressure,

$q$ = the uniform pressure applied to the flexible plate,

$z$ = the depth z in the layer below the center of the plate, and

$a$ = the radius of the circular plate.

According to Huang (1993) a flexible plate subjected to a uniform pressure, exerts a load on the surface layer similar to that exerted by a pressurized tire. Equation (2.3) indicates that, as the thickness of the surface layer increases, the traffic load applied to the layer under it decreases (this is due to the greater depth *z* in the layer).

Normally, only a thin surface layer is affected by the surface application of additives. Because the surface layer is thin, the base layer must support most of the applied load. For example, if a surface layer is ½ inch (12.7 mm) thick and a uniform pressure of 80 psi (552 kPa) is applied over a radius of 3 inches (76.2 mm) , then by equation (2.3)

$$\sigma_z = 80\left[1 - \frac{0.5^3}{\left(3^2 + 0.5^2\right)^{1.5}}\right] = 79.6\,psi \qquad \textbf{(2.3a)}$$

This means that the base layer must support a pressure of 79.6 psi (549 kPa).

### Lignin Sulfonate (Lignin)

Lignin sulfonate is primarily a cementing agent (Davidson and Handy, 1960; Ingles and Metcalf, 1973; Langdon and Williamson, 1983; ). Therefore, the cementing effect of lignin increases the true cohesion between soil particles. Gow, et al., (1961) state that the "Hygroscopicity of the wood sugars present (in lignin) may also contribute to strength by retarding evaporation, thus benefiting cohesion." It should be noted that retardation of evaporation also tends to increase apparent cohesion. According to both Gow, et al. (1961) and Davidson and Handy (1960) lignin also tends to increase soil stabilization by causing dispersion of the clay fraction. Gow, et al. (1961) explain that "Dispersion of the clay fraction benefits stability of the soil-aggregate mix by: (a) plugging voids and consequently improving watertightness and reducing frost susceptibility, (b) eliminating soft spots caused by local concentrations of binder soil, © filling voids with fines thus increasing density, and (d) increasing the effective surface area of the binder fraction which results in greater contribution to strength from cohesion." Additional benefit may be gained by lignin's high water solubility (Sultan, 1976; Langdon and Williamson, 1983; Apodaca and Huffmon, 1990) allowing it to penetrate the soil readily.

Unfortunately, the high solubility of lignin is also a disadvantage, because it allows lignin to be easily leached by water from the road surface ( Gow, Davidson, and Sheeler, 1961; Langdon and Williamson, 1983; Apodaca and Huffmon, 1990). Some authors report success in reducing the rate at which lignin is leached from soils. Nicholls and Davidson (1958) report that the addition of lignin to a soil-organic cationic chemical mixture might further improve waterproofing and strength characteristics. Sultan (1979) successfully reduced the solubility of lignin products by mixing a waterproofing agent called F125 into the soil-lignin combination.

Reports of stabilization using lignin vary. For example, Apodaca and Huffmon (1990) report that, "The results of this test show that lignin sulfonate is the most effective and cost efficient product tested." Sultan (1976) also reports good results from the use of lignin products. In an extensive test, Sultan found that 8 of 45 chemicals successfully met durability standards. Of the eight chemicals, 5 contained lignin sulfonate as their base material. Sultan's durability tests include resistance to "erosion due to wind and traffic under freeze-thaw, wet-dry, and rain-dry cycles and various curing temperatures." Gow, et al. (1961) report that the best results are in mixes rich in binder soil (which fills in the void spaces). This report also suggests that soil-lignin mixtures produce higher densities than the same soil without lignin. However, Hoover et al. (1960) observe that for glacial till [A-6 (11), clay PI = 23.1] a slight increase in unconfined compressive strength occurs only for a mixture containing 0.25% lignin. Hoover et al. also note that no increase in unconfined compressive strength occurs for gunbotil [A-7-5 (20), clay PI=52.6]. Nicholls and Davidson (1958) report a loss of stability, and conclude that lignin is detrimental (to stability) when used with organic cationic chemicals to stabilize soils with medium to high clay content.

## Calcium Chloride ($CaCl_2$)

Calcium chloride ($CaCl_2$) is widely used as a soil additive to control dust on unpaved roads. However, $CaCl_2$ also produces changes in soils that influence stabilization. One statement frequently made about $CaCl_2$ is that it aids in compaction (Mainfort, 1955; Lambe and Moh, 1957; Gow, et al., 1961;

Sheeler and Hofer, 1961; Ross, 1988). However, the benefits of $CaCl_2$, like those of lignin, are controversial. For example, Ingles and Metcalf (1973) report that "calcium chloride has similar effects to sodium chloride, but with two added disadvantages, namely that it has an adverse effect on compaction, ..."

Calcium chloride may aid in the compaction of some soils by providing lubrication between soil particles (i.e., by reducing friction between the particles) ( Gow, et al., 1961; Ross, 1988). The additional lubrication provided by $CaCl_2$ results in higher densities than when soils are compacted using water alone. Thus, greater densities are achieved without increasing compactive effort. However, for unpaved roads the most probable method of increased density, according to Wright and Paquette (1987), is when $CaCl_2$ is used in "soil-aggregate mixes in order to expedite the compaction process by slowing the rate of evaporation of moisture from the mixture during compaction."

Gow et al. (1961) suggest that another benefit of $CaCl_2$ is that it supplies $Ca^{2+}$ ions to the soil. These ions neutralize the negative surface charges in clays and may set up valence bonds between neighboring clay micelles. However, while Mitchell (1993) agrees that the introduction of divalent cations will affect the clay fraction of soils, he explains that the effect is to reduce spacing between clay particles and thereby increase flocculation. Increasing flocculation results in a stronger (greater shear strength), yet less dense, clay soil.

Another effect of $CaCl_2$ is that as $CaCl_2$ is added to the soil, the surface tension in the pore solution increases (Hillel, 1980). Soil strength can improve as surface tension increases (Shepard et al., 1991), since greater surface tension causes an increase in apparent cohesion.

Apparently, the major benefit of $CaCl_2$ as a soil additive is that it lowers vapor pressure in the soil structure. At lower vapor pressures, soils maintain a higher moisture content ( Mainfort, 1955; Ross, 1988; Shepard et al., 1991). A higher moisture content increases apparent cohesion, and according to Wright and Paquette (1987) $CaCl_2$ "aids in maintaining the moisture content at that desired for maximum stability, prevents raveling of the surface, and reduces dust." For $CaCl_2$ to be effective in maintaining an increased moisture content, the relative humidity must be above 29 to 40 percent (relative humidity requirements for moisture retention are temperature dependent)( Langdon and Williamson, 1983; Ross, 1988; Apodaca and Huffmon, 1990; Shepard et al., 1991).

If conditions such as soil type and relative humidity are favorable, the use of $CaCl_2$ can improve the shear strength of some road surface materials ( Wood, 1960; Gow et al., 1961; Apodaca, and Huffmon, 1990). This improved shear strength could reduce road maintenance requirements (Apodaca and Huffmon, 1990; Public Works, 1990). The use of $CaCl_2$ can also reduce maintenance costs caused by frost damage ( Wood, 1960; Ingles and Metcalf, 1973; Apodaca and Huffmon, 1990), since $CaCl_2$ lowers the freezing point of the soil moisture solution. The degree to which the freezing point is lowered depends on the $CaCl_2$ concentration.

Reports of the amount and number of applications necessary to provide continuing benefit from $CaCl_2$ vary. Apodaca and Huffmon (1990) indicate that one application of 0.25 gallons per square yard (1.14 $l/m^2$) per year is sufficient. Another application rate of 0.3 to 0.35 gallons per square yard (1.36 to 1.59 $l/m^2$) twice per year is suggested in an article in Public Works (1990). Ross (1988) recommends increasing the number of applications, claiming that "reapplication of $CaCl_2$ is usually required two or three times per year."

Calcium chloride can improve the performance of unpaved roads through the methods given above, but there are some negative aspects to using $CaCl_2$. One is that $CaCl_2$ is corrosive when it contacts steel (Truitt, 1983; Apodaca and Huffmon, 1990). Another problem with $CaCl_2$ is that high concentrations can be toxic to the ecosystem (Apodaca and Huffmon, 1990). Calcium chloride has the potential to damage vegetation (plants) near areas of application. Movement of $CaCl_2$ by wind and water erosion can result in high concentrations of salt in soils near the roadway. Higher salt concentration in soils may cause greater surface tension in water solutions, which can elevate capillary pressure (Corey, 1986). Increasing capillary pressure reduces a plant's ability to take in water. A plant's ability to take in water can also be reduced by increased osmotic pressure. Increasing osmotic pressure causes the soil solution to retain water, thereby making it more difficult for plants to absorb water. Osmotic pressure is important because, as Zumdahl (1989) states, "a small concentration of solute produces a relatively large osmotic pressure." If the $CaCl_2$ (salt) concentration is sufficiently high, plants may wilt or be damaged by a lack of water.

### Magnesium Chloride ($MgCl_2$)

Magnesium chloride has many of the beneficial properties found in $CaCl_2$. Magnesium chloride also has all of the negative aspects of $CaCl_2$. Some positive properties of $MgCl_2$ are that it is hygroscopic and deliquescent. According to Hansen (1982) these properties keep the soil-$MgCl_2$ mix in a moist or semi-moist condition if the relative humidity is greater than 32%. Besides retaining moisture, Apocaca and Huffmon (1990) believe that $MgCl_2$ aids in compaction. Applications of $MgCl_2$ may also increase road stability and reduce maintenance ( Hansen, 1982; Rural Technical, 1984; Apodaca, and Huffmon, 1990).

The main differences in the use of $MgCl_2$ as compared to $CaCl_2$ are:

1. $MgCl_2$ does not lower the freezing point of the soil structure as much as $CaCl_2$, and
2. the recommended concentrations for application are higher for $MgCl_2$.

Apodaca, and Huffmon (1990) advise an application of 0.5 gallons (2.27 $l/m^2$) of $MgCl_2$ per square yard per year (the water-$MgCl_2$ solution should be 27.4 percent $MgCl_2$). Information in the Rural Technical Assistance Program Newsletter (1984) prescribes 0.5 gallons per square yard (2.27 $l/m^2$) of road surface, but does not suggest the percent $MgCl_2$ solution concentration. However, Hansen (1982) recommends the use of 2% solution, by dry weight of the road surface soil, for the top 2 inches (50.8 mm) of road surface soil (water-$MgCl_2$ should be 30% $MgCl_2$). Based on Hansen's recommendation, the concentration of $MgCl_2$ would vary with the density of the surface soil. For example, if the soil density is 125 pounds per cubic foot (19.6 $kN/m^3$), and the $MgCl_2$ penetrates 2 inches(50.8 mm), than the rate of application is approximately 0.6 gallons per square yard (2.73 $l/m^2$).

Harker (1994) reports that the city of Cheyenne, Wyoming, was originally using $MgCl_2$ for dust control, but after noticing an additional benefit of improved road performance the city has begun to look at the use of $MgCl_2$ for stabilization. The soils on most of the city's unpaved roads have not been classified. However, Harker believes that most unpaved roads in the city are highway base material. In Cheyenne $MgCl_2$ is usually applied to the road surfaces twice per year and the rate of $MgCl_2$ applied varies. Harker indicates that when a road is receiving $MgCl_2$ for the first time, the amounts applied are greater than when a road is receiving a successive application. Harker says that the best results are after the second or third application, and that while washboarding is not eliminated by this process, rutting is greatly reduced.

## Other Additives

Some commercial additives with particular brand names contain significant portions of lignin, $CaCl_2$, or $MgCl_2$. Other commercial additives, for example, an additive that contains beet extract, is still being tested. Hence, no conclusive information is available on these products. Still others have some characteristic that makes them undesirable for unpaved road surfaces. For instance, cement will improve the bearing capacity of many soils, but becomes too hard to allow smoothing of the road surface by common maintenance practices. Some available additives and the pros and cons of their use are presented in Appendix A.

## Tests

There are many useful tests for evaluating an aggregate-additive mixture for use on unpaved roads. Of most interest are tests that give moisture-density relationships and a strength parameter, such as unconfined compressive strength (UCS). McCarthy (1993) writes "The most widely used laboratory tests for studying the shear strength and related deformations of soils include the direct shear test (single and double shear), the triaxial compression test, and the unconfined compression test." To obtain the strength parameter, tests like the unconfined compression (UC) test or California Bearing Ratio (CBR) are most often used (Hoover et al., 1960; Gow et al., 1961; Pagen and Jagannath, 1968; Majidzadeh and Guirguis, 1973; Sheeler and Hofer; Ross, 1988). Moisture-density relationships are usually obtained from standard or modified Proctor tests (McCarthy, 1993).

Whichever test is used, the test mold size will determine the soil particle sizes for test specimens. Maximum soil particle size should be at least 6 to 10 diameters smaller than the diameter of the mold (ASTM, 1991; McCarthy, 1993). Commonly, materials passing the 4.76 mm and 2.0 mm sieves are used (Mainfort, 1955; Rural Technical, 1984). For example, material passing the 4.76 mm sieve is the upper limit for particle size in the standard moisture-density tests [AASHTO designation T-99 (McCarthy, 1993)].

## Conclusions From the Literature Review

The literature reviewed suggests that changes must take place in soil properties for stabilization to occur. These changes are necessary to improve the soil's performance as a surface for an unpaved road. McCarthy (1993) states that "The ability of a soil deposit to support an imposed loading or for a soil volume to support itself is governed by the shear strength of the soil." This statement implies that the most important requirement of the stabilization of a soil by an additive is that the additive increases and maintains shear strength.

Lignin, $CaCl_2$, or $MgCl_2$ can produce desired changes in some soils but not in others. This is because the effect of these additives is influenced by climatic conditions, soil characteristics and additive concentrations. These influences are difficult to quantify, resulting in mixed reports on soil-additive reactions and on the benefits of various additives.

For efficient use of additives for road improvement, a method of deciding which additive and the amount to apply to a given soil must be found. The use of standard moisture-density tests and UC tests can help decide if the properties of a particular soil-additive mix are improved. Improvement means an indication of increased and maintainable shear strength.

# CHAPTER 3

# TEST METHODS AND PROCEDURES

## Introduction

A set of carefully conducted tests is required to properly characterize soil-additive mixes. Tests should be conducted using well-defined procedures to provide consistent interpretation of test results. The test methods used in the present study closely follow standards established by the American Society for Testing and Materials (ASTM) and the American Association of State Highway and Transportation Officials (AASHTO).

The characterization of a soil-additive mix and the evaluation of its performance on a road surface depends on the:

1. soil,
2. additives used,
3. type of tests performed on the mix,
4. test procedures and controls,
5. accurate analysis of the test data, and
6. the application of the soil-additive mix to a road surface, and the evaluation of its performance under traffic conditions.

## Terms and Definitions

The following terms and definitions are presented to help the reader better understand the procedures and results given in this paper.

*Unconfined Compressive Strength (UCS)* - The maximum force that can be applied to a specimen under axial loading without confining force being applied to the sides of the specimen. For example, a load applied to the surface of a Harvard Miniature specimen as in Figure 3-1 (the load is applied perpendicular to and over the entire cross hatched area). Thus, UCS is in units of force per unit area [pounds per square inch (psi), pounds per square foot (psf) or kilonewtons per square meter (kN/m$^2$)].

*Moisture Content* - The weight of moisture (water, additive, etc.) divided by the dry weight of the soil, represented as a percentage of the dry weight of the soil.

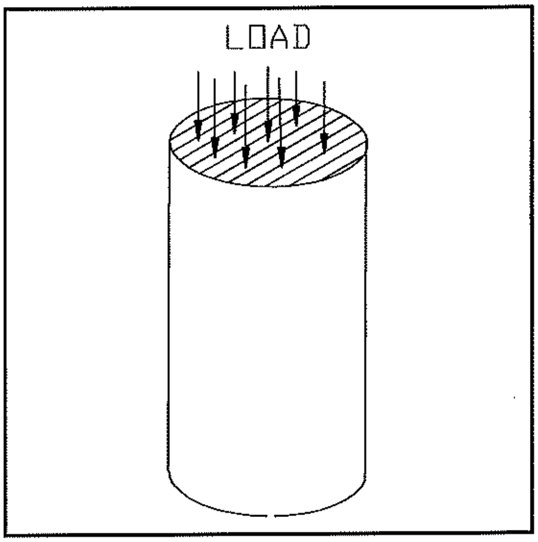

**Figure 3-1. Axial Load, Harvard Miniature Specimen.**

### Selection of a Road Surface Soil

Each soil that is used to surface a road may react differently to chemical additives. Therefore, the test soil should be taken from the road surface if an additive is to be applied to the existing road surface, particularly if additives were previously employed. Residual additives may interact in an unknown manner with the new application of additives. Use of stockpile soils for testing may be desirable if the material is to be used for road resurfacing. Stockpile soils are also acceptable for testing of recently resurfaced roads.

In the present study, the decision of which soils and soil-additives to test was partially the result of a cooperative effort between the U.S. Department of Agriculture Forest Service and researchers at the University of Wyoming. After being informed of a Forest Service plan to apply lignin sulfonate to sections of six roads, researchers from the University obtained permission to take specimens from the road sections before and after application. After the specimens were collected the Forest Service decided to limit the lignin application to a section of approximately 1.7 miles (2.74 km) on one road. This decision was based on cost and time constraints.

Before Forest Service personnel limited the lignin application to one road, UW researchers gathered soil specimens from 16 locations on six roads in the Medicine Bow National Forest. The specimens included soil from the road surface and the subsurface. Surface specimens contained approximately the top 3 inches (76.2 mm) of road material. After removing the surface materials, subsurface specimens were collected to a depth of about 9 inches (229 mm). The material below the top 3 inches (76.2 mm) was imported base material in some locations and native subgrade in others. All 32 specimens were classified according to the Unified Soil Classification System (USCS) and by AASHTO designation M-145.

Four of the original six roads were chosen for additional study. These roads were chosen because they are within reasonable driving distances from Laramie, Wyoming, and are surfaced from different pits. Materials from these roads provided a comparison between the original surfacing material (materials from the pits) and the material from road surface specimens.

Surfacing material for one of the four roads was taken from a pit that was later reclaimed. In this pit, specimens were collected from the top 6 inches (152 mm) of soil. The other three pits had existing stockpiles and specimens were taken from these stockpiles. Classification of materials from the four pits was by the Unified Soil Classification System (USCS) and AASHTO M-145.

After classifying the road and pit specimens, the specimens were evaluated according to AASHTO M 147-65, "Standard Specification for Materials for Soil-Aggregate Subbase, Base, and Surface Courses" (AASHTO, 1993). The AASHTO grading requirements for aggregate surface courses are presented in Table 3-1. Normally determination of a soil's suitability as a road surface material is made by evaluating the soil's characteristics according to either AASHTO or ASTM standards. While all of the road surface specimens and two of the pit specimens met at least one of the surface course gradation requirements for AASHTO M 147-65, none met the plasticity index (PI) requirements. This is because all of the surface specimens had very low PI ($PI \approx 0$). AASHTO M 147-65 suggests a plasticity index of between 4 and 9 for unpaved road surface material (AASHTO, 1993).

Table 3-2 shows the gradation, liquid limit, plasticity index, AASHTO classification, and USCS classification for 29 of the road and pit specimens (the remaining three specimens were subsurface specimens from the two roads not used in the study). Only four of the subsurface specimens and the specimen from the Fallen Pine Pit had PIs greater than zero. The surface of the Fallen Pine Pit was too hard to specimen with the hand auger and may not have been representative of the pit.

**Table 3-1. AASHTO M 147-65** (Surface Course Materials

| Sieve Designation | | Mass Percent Passing | | | |
|---|---|---|---|---|---|
| Standard mm | Alternate | Grading C | Grading D | Grading E | Grading F |
| 50.0 | 2 in. | - | - | - | - |
| 25.0 | 1 in. | 100 | 100 | 100 | 100 |
| 9.5 | 3/8 in. | 50-85 | 60-100 | - | - |
| 4.75 | No. 4 | 35-65 | 50-85 | 55-100 | 70-100 |
| 2.00 | No. 10 | 25-50 | 40-709 | 40-100 | 55-100 |
| 0.425 | No. 40 | 15-30 | 25-45 | 20-50 | 30-70 |
| 0.075 | No. 200 | 8-15 | 8-20 | 8-20 | 8-25 |
| LL | | <35 | <35 | <35 | <35 |
| PI | | 4-9 | 4-9 | 4-9 | 4-9 |

Table 3-2 indicates that many road soils in the area are nonplastic. Gow et al. (1961) suggest that the use of nonplastic soil is necessary in many areas, primarily because high-quality materials with the proper PI may not be readily available. Since nonplastic soils are used extensively on road surfaces, information on the reaction of nonplastic soils to additives is needed.

The need for information on both nonplastic soils and soils that meet AASHTO standards led to the decision to test three soils. These three soils were:

1. soil 1B with a PI=0,
2. soil 1Bk with a PI between 4 and 6, and
3. soil H-1c with a PI of about 9.

Each of these three soils fit AASHTO M 147-65, except that soil 1B did not meet the required PI.

Soil 1B was from a pit-site stockpile. This stockpile provided the source of resurfacing material for the Fox Park Road in the Medicine Bow National Forest to which the Forest Service applied lignin to a section 1.7 miles (2.74 km) long. Since this was the only road treated, soil 1B was the only soil that allowed a comparison of lab results and road application.

The second test soil (1Bk) was a mixture of the Fox Park Pit (soil 1B) material and kaolinite. Soil 1Bk contained 8.5% kaolinite by dry weight of the Fox Park Road soil. This mixture brought the Fox Park Road soil to a PI within AASHTO standards and provided a soil with a PI of 6 to mix with the additives.

**Table 3-2. Road and Pit Specimens**

| Specimen No. | Road Section | +4.75 mm (%) | 4.75 - 0.075 mm | -0.075 mm (%) | LL | PI | AASHTO | USS |
|---|---|---|---|---|---|---|---|---|
| 1 | FOX P | 27.9 | 42.5 | 29.6 | 28.9 | 10.7 | A-2-4 | SC |
| 2(s) | FOX P | 24.5 | 58.2 | 17.3 | 0 | 0 | A-1-b | SM |
| 3(s) | FOX P | 14.4 | 71.4 | 14.2 | 0 | 0 | A-1-b | SM |
| 4 | FOX P | 7.5 | 72.7 | 19.8 | 0 | 0 | A-2-4 | SM |
| 5(s) | FOX P | 20.7 | 65.7 | 13.6 | 0 | 0 | A-1-b | SM |
| 6 | FOX P | 23.1 | 56.9 | 20.0 | 0 | 0 | A-1-b | SM |
| 7(s) | Rd 500 | 22.2 | 56.0 | 21.8 | 0 | 0 | A-1-b | SM |
| 8 | Rd 500 | 5.8 | 46.2 | 48.0 | 25.5 | 6.6 | A-4 | CL |
| 9(s) | Rd 500 | 29.9 | 51.8 | 18.3 | 0 | 0 | A-1-b | SM |
| 10 | Rd 500 | 11.3 | 61.8 | 26.9 | 0 | 0 | A-2-4 | SM |
| 11(s) | Rd 500 | 22.1 | 62.0 | 15.9 | 0 | 0 | A-1-b | SM |
| 12 | Rd 500 | 25.8 | 53.2 | 21 | 0 | 0 | A-1-b | SM |
| 13(s) | F PINE | 40.3 | 46.7 | 13.0 | 0 | 0 | A-1-b | SM |
| 14 | F PINE | 35.5 | 33.1 | 31.4 | 26.1 | 8.9 | A-2-4 | SC |
| 15(s) | F PINE | 44.9 | 42.0 | 13.1 | 0 | 0 | A-1-b | SM |
| 16 | F PINE | 52.1 | 27.6 | 20.3 | 24.1 | 7.0 | A-2-4 | GC |
| 17(s) | LAKE | 28.1 | 50.8 | 21.1 | 0 | 0 | A-1-b | SM |
| 18(s) | LAKE | 37.3 | 44.1 | 18.6 | 0 | 0 | A-1-b | SM |
| 19 | LAKE | 32.3 | 40.6 | 27.1 | 0 | 0 | A-2-4 | SM |
| 20(s) | LAKE | 45.7 | 40.1 | 14.2 | 0 | 0 | A-1-b | SM |
| 21 | LAKE | 36.9 | 40.8 | 22.3 | 0 | 0 | A-1-b | SM |
| 8A(s) | HOG P | 34.4 | 43.9 | 21.7 | 0 | 0 | A-1-b | SM |
| 2A(s) | HOG P | 35.4 | 40.7 | 23.9 | 0 | 0 | A-1-b | SM |
| 4A(s) | HOG P | 48.1 | 34.0 | 17.9 | 0 | 0 | A-1-b | SM |
| 6A(s) | JACK | 44.2 | 37.2 | 18.6 | 0 | 0 | A-1-b | SM |
| 10A(s) | JACK | 28.0 | 50.1 | 21.9 | 0 | 0 | A-1-b | SM |
| 1B | FP P | 27.2 | 60.1 | 12.7 | 0 | 0 | A-1-b | SM |
| 3B | L P | 53.8 | 35.0 | 11.2 | 0 | 0 | A-1-a | GM |
| 4B | P P | 65.4 | 19.9 | 14.7 | 25 | 6 | A-2-4 | GC |

Fox P = Fox Park, F PINE = Fallen Pines, LAKE = Sand Lake, HOG P = Hog Park, JACK = Jack Creek, FP P = Fox Park Pit, L P = Sand Lake Pint, P P = Fallen Pine Pit. Specimen No. followed by (s) indicates surface specimens.

A blended soil was also used for the third test soil. The mixture was a combination of clay from a road cut on U.S. 34 near Laramie, Wyoming, and a soil designated H-1 by the Albany County Road Commission in Wyoming (soil H-1 classified as A-1-b by AASHTO, its source pit is the Granite Canyon Quarry east of Laramie, Wyoming). These soils were combined at the percentage of 12% clay by dry weight of the H-1 soil. Both the 1Bk and H-1c soils were mixed by combining the kaolinite or clay, respectively, with the total specimen. The mix was then split on the 4.76 mm or 2.0 mm sieve, and the passing soil was used depending on which test was to be conducted.

### *Amounts of Soil Required*

The quantity of soil needed for testing was based on the amounts of soil passing the 4.76 mm and number 2.00 mm sieves. Total specimen quantities required were calculated using the following equation:

$$S = \left(\frac{8lb.}{\%_{-4.76mm}}\right)(N_{M-D}+1) + \left(\frac{8lb.}{\%_{-2.00mm}}\right)(N_{UC}+1) \qquad \mathbf{(3.1)}$$

where

$S$ = the amount of soil required for unconfined compression (UC) and moisture-density tests,

$\%_{-4.76}$ = the percent of material passing the 4.76 mm sieve,

$N_{M-D}$ = the number of moisture-density relationship tests,

$\%_{-2.00}$ = the percent of material passing the 2.0 mm sieve, and

$N_{UC}$ = the number of soil-additive combinations that will be tested for UC.

## Additive Choice

Three additives, lignin sulfonate, calcium chloride, and magnesium chloride, are commonly used and readily available in the project area. In fact, these three additives appear to be the most commonly used throughout the United States. Availability and common use makes these additives ideal for testing. Common usage also makes evaluating past performance possible by reviewing publications and by contacts with users or contractors.

### *Additive Concentrations*

Soil specimens were prepared by adding 1.00%, 1.75%, 2.50%, and 3.25% of an additive by dry weight of the soil. These additive concentrations covered the spectrum of common application practice.

Common practice calls for an application of approximately ½ gallon of additive per square yard (2.27 $l/m^2$) of road surface area. If this application rate results in an additive penetration of approximately 2 inches (50.8 mm), then about 1.5 $ft^3$ (0.043 $m^3$) of surface material is influenced by the ½ gallon (1.9 l) of additive. If the dry density of the surface material is 130 $lb./ft^3$ (20.4 $kN/m^3$) and the specific gravity of the additive is 1.33, then the resulting additive concentration is approximately 2.85% by dry weight of the soil. Other factors such as sorption or past applications may affect the application rate. However, even with the many variables that can influence application rates, the concentrations given above should cover most soil-additive concentration ranges.

## Procedures for Choosing Tests

Decisions on which tests to conduct were based on the following criteria:

1. obtaining the desired information, (soil classification, moisture-density relationship, and change in shear strength)
2. whether tests could be conducted in standard soils labs, and
3. conducting tests that will require a minimum time investment.

Soil classification requires sieve analysis and Atterburg limits (liquid and plastic limits). Moisture-density relationships were determined by ASTM Standard D 698-87$^{\epsilon 1}$ Method A-A. Because unconfined compression (UC) tests provide sufficient information with reasonable time requirements, they were used to obtain the soils' shear strength. In addition, a hydrometer test was conducted and the specific gravity found for each soil. Hydrometer tests established the clay content for each soil. Specific gravity information is used to find the zero air void curve on moisture-density plots.

Equipment for conducting the tests listed above is readily available in engineering soils laboratories. Conducting UC tests requires a minimal time investment compared to tests such as the tri-axial test. Normally, any soil under consideration for use in road surfacing undergoes testing to establish its classification and moisture-density relationship.

## Test Procedures

As stated previously, test procedures closely followed ASTM and AASHTO standards. Slight modification of several of these standards was necessary to account for the additive mixtures. Detailed descriptions of the test procedures are given in the following sections.

### *Soil Classification*

Sieve analysis and Atterberg limits were necessary for soil classification. Project test procedures called for a sieve analysis on each soil using 4.76, 2.0, 0.84, 0.42, 0.149 and 0.074 mm sieves. After determination of the percent passing each sieve, a line chart of percent passing versus particle diameter was drawn. Atterberg limits were found by following ASTM Standard Test Method D 4318-84.

### *Moisture-Density Relationships*

Moisture-density relationships were obtained by preparing specimens of various additives and soil and testing these specimens. Soil specimens were prepared by adding 0.00% 1.00%, 1.75%, 2.50%, and 3.25% of an additive by dry weight of the soil (as described in Section 3-3.a).

After adjusting the additive concentration for each specimen, the moisture content of each mixture was brought to a beginning point. Tests were conducted at increasing moisture contents, in steps of about

1.5%, until the optimum moisture content was exceeded. For example, the procedure used to obtain the soil-lignin-water moisture-density relationship involved the following steps:

1. preparing four specimens using -4.76 mm material,
2. bringing each specimen to one of the four desired lignin contents,
3. using water, bringing the moisture content of all specimens to about 5%,
4. testing the soil-additive-water mix by ASTM Standard D 698-87$^{\epsilon 1}$ Method A-A,
5. using water, increasing the moisture content in each specimen to approximately 6.5% and test as in step 4, and
6. continuing testing at increasing moisture contents until the optimum moisture content is reached and passed by a minimum of 1.5%.

### *Unconfined Compression (UC) Tests*

Test specimen preparation for UC tests was similar to that for moisture-density relationships. However, instead of using materials that passed the 4.76 mm sieve, UC tests used material that passed the 2.0 mm sieve. Also, compaction for UC tests was done in Harvard Miniature molds using a 30-pound (133 N) ram. Soils 1B and 1Bk were compacted in 6 layers with 30 blows of the ram per layer. Soil H-1c was compacted in 6 layers with 32 blows per layer.

The difference in compactive effort resulted from correlating dry densities in the standard 4 inch (101.6 mm) molds with those obtained using the Harvard Miniature molds according to the procedure outlined in ASTM D 4609-86. Density correlation was obtained by the following steps:

1. finding the optimum moisture content and dry density using ASTM D698,
2. adjusting the compactive effort in the Harvard Miniature mold until the dry densities are nearly equal.

Water was the additive used for density correlation. Linking densities from moisture-density tests and Harvard Miniature densities provided a reference point of equal dry density.

After correlation of dry densities, UC test procedures call for formation of four specimens at each additive and water concentration. For example, four Harvard Miniature specimens were made at 1.0% $MgCl_2$ and 4% water. After compaction of the specimens, two specimens were extruded, measured, and tested immediately. The remaining two specimens were extruded and air dried for seven days before being measured and tested. After the four specimens were tested at 1.0% $MgCl_2$ and 4% water, four additional specimens were made and tested at 1.0% $MgCl_2$ and 5.5% water. This process of testing continued until the moisture content was 1.5% higher than the optimum moisture content. Additional tests were done on soil specimens with water as the additive.

### *Wet-Dry Durability Test for Lignin-Treated Soils*

Initial tests indicated large UCS gains in the air-dried specimens of the soil 1B-lignin mix. Also, observation of the Fox Park Road showed crack healing with wet-dry cycles. The combination of strength gains and crack healing led to a consideration of the effect of wet-dry cycles on lignin-treated soils. A testing procedure was designed to show whether the lignin-soil mix retained its strength through many wet-dry cycles.

A test specimen was prepared by mixing 3.25% lignin with soil 1B, and then bringing the mix to approximately 8% moisture content. Next, the mix was tested using both wet and dry UC tests. After making the first specimens, the mix was allowed to air dry for 7 days. At the end of 7 days the mix was returned to about 8% moisture content, and UC tests were conducted. The specimen was subjected to four cycles of wetting and drying.

### *Combinations of Additives*

Curiosity about the effect of combining additives led to further testing a mixture of additives. A mix containing 1/2% $MgCl_2$, 2.5% lignin, and soil 1B was used. Tests for UCS were conducted on this mix at various moisture contents as in Section 3-5.c. Because of time constraints, this was the only combination tested.

## Repeatability of Tests

To assure test repeatability, additional tests were conducted at different additive concentrations. Test procedures remained the same, but the personnel and additive concentrations differed. The soil and additive concentrations chosen for checking tests were soil 1B at 2 and 3% lignin, $CaCl_2$, or $MgCl_2$.

## Evaluation of Test Data

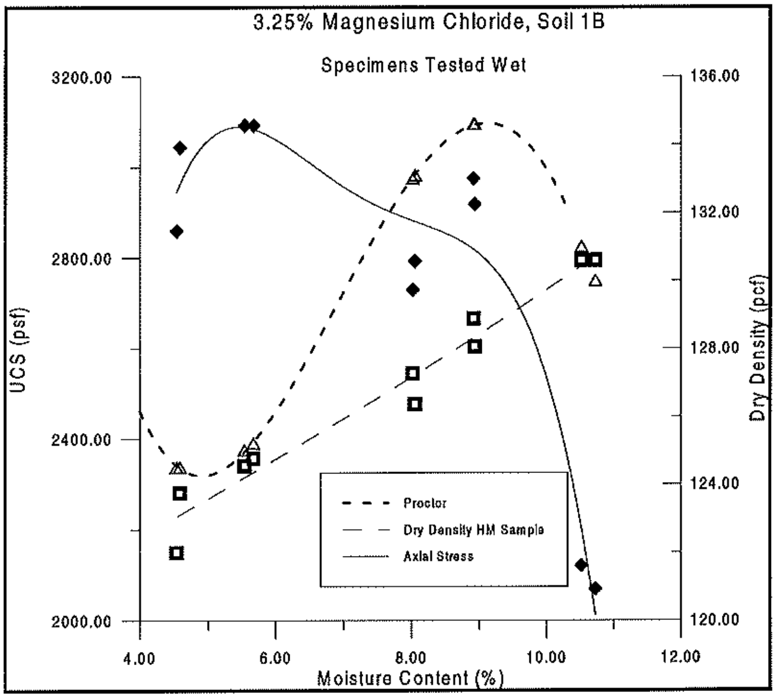

**Figure 3-2. Sample Plot of Test Data** (1 pcf = 157 N/m$^3$, 1 psf = 48 Pa).

The large amount of data which results from UC tests necessitated the development of a procedure for presentation and evaluation of the results. Because three dimensional plots indicate trends well, and because a large amount of information can be collected in one plot, this form of presentation will be used.

Test results for each soil-additive mix were first plotted in two dimensions. From these plots a relationship between density and moisture content, or strength and moisture content was found. Using these relationships, equations were established that represented the best fit of data points. For example, Figure 3-2 shows a two-dimensional plot of the results of mixing soil 1B and 3.25% $MgCl_2$. The plot shows the relationship between ASTM D 698 dry density, Harvard Miniature dry density, and the unconfined compressive strength versus moisture content. Unconfined compressive strengths shown are from UC tests on Harvard Miniature specimens that were tested wet. On the plot the square, triangular, and diamond symbols represent data points, and lines represent best fit approximations.

Best fit equations used moisture content as the independent variable. The best fit equations from each soil at various concentrations of a single additive were then plotted in three dimensions. For instance, a three-dimensional plot of soil 1B with 1%, 1.75%, 2.5%, and 3.25% lignin consists of the dry density from moisture-density tests versus water content and additive concentration (Figure 3-3,). In each of the three dimensional plots throughout the remainder of this paper, the spacing on the axis of additive concentrations is not equal. This is due to the format of the computer program used to generate the plots. However, the lines running perpendicular to the additive concentration axis are lines of equal additive concentration.

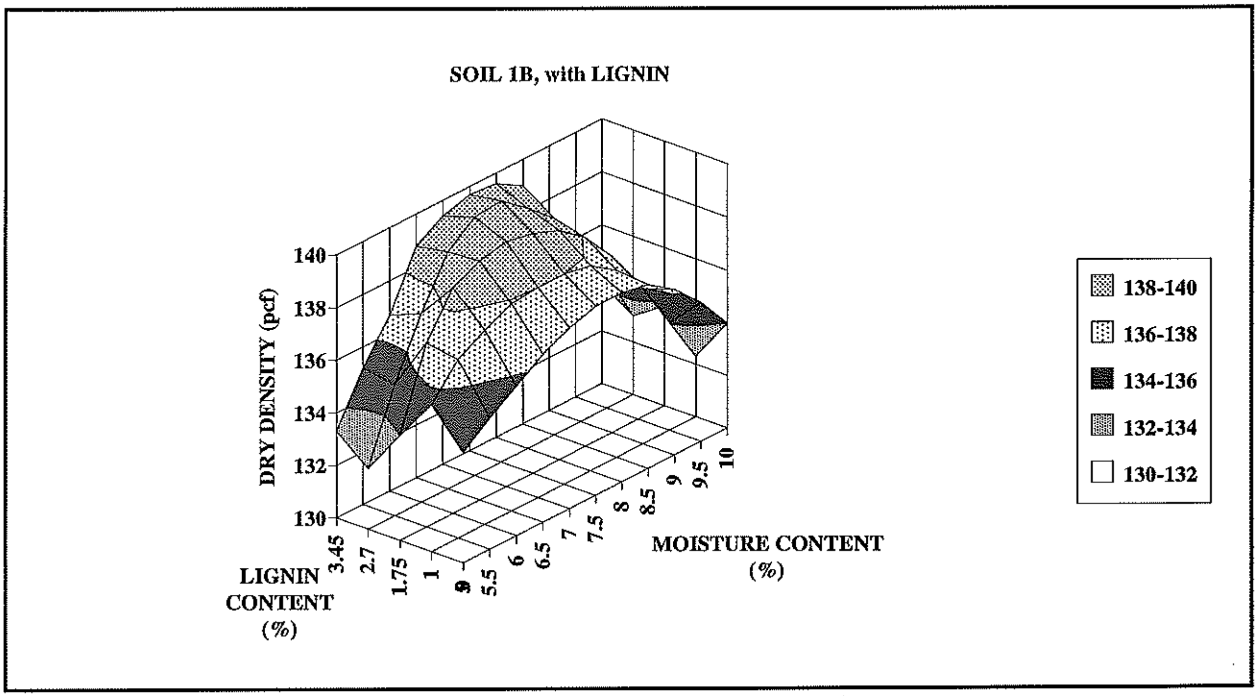

**Figure 3-3. Specimen Plot of Moisture-Density Test Data** (1 pcf = 157 N/m$^3$).

## Monitoring Road Surface Performance

To better understand the result of the application of lignin sulfonate to 1.7 miles (2.74 km) of the Fox Park Road, the method of application must be known. First, the road surface was scarified to a depth of approximately 2 inches (50.8 mm). Next, using a grader, lignin and water were worked into the road soil in two applications of 1/6 gallons of lignin per square yard (0.76 $l/m^2$)(water content unknown as rain occurred during this operation). The road was then brought to its final cross sectional shape, and an another application of 1/6 gallon per square yard (0.76 $l/m^2$) was applied. Finally, the road surface was roller compacted (Moats, 1993).

Visual inspection and specimen gathering were used to monitor the Fox Park Road soon after the lignin application. Visual inspection included photographing portions of the road surface. Sampling consisted of taking surface specimens and specimens from 1/4 to 2 inches (6.35 to 50.8 mm), 2 to 4 inches (50.8 to 102 mm), and 4 to 6 inches (102 to 152 mm) depth at various locations on the road. Surface specimens consisted of surface crust to approximately 1/4 inch (6.35 mm).

Visual inspection and sampling were repeated at 6, 13, 20, 28, and 69 days after the lignin application. At 69 days snow covered portions of the road surface. The road received a final inspection 1 year after the lignin application.

## Determination of Lignin Content by Nuclear Magnetic Resonance (NMR)

If a particular additive concentration results in a stable road surface, then the additive concentration should be maintained at that level. However, some additive loss can be expected due to wind and water erosion and by leaching. This lost additive must be replaced to insure continued stabilization. Before the additive can be replaced, the amount of residual additive in the soil must be known. Otherwise too much or too little additive may be applied. This, in turn, requires some form of testing the soil for residual additives. An ASTM standard exists for chlorides (ASTM designation D1411-82), but no standard exists for lignin. In an attempt to establish a process by which lignin could be measured, Daniel

A. Netzel at the University of Wyoming Research Corporation, Western Research Institute, tested various concentrations of lignin and soil mixtures. Netzel's procedures, results, and conclusions are presented in Appendix C.

## Summary of Procedure Chapter

Many soils found on unpaved roads do not meet AASHTO standards for surfacing material. Often this is because the soils are nonplastic. By choosing a nonplastic soil and soils with a variation of plasticity, one can obtain information about a wide range of material types.

The three additives tested (lignin, $MgCl_2$, and $CaCl_2$) are the ones most commonly applied to unpaved roads. Data obtained for the soils and additives tested should be sufficient to show how test results may be applied. Additional tests, such as the wet-dry cycle test, may show some indication of additive deterioration over time.

The test procedures are designed to find changes in soil characteristics. Of particular interest are the trends in changes in soil cohesion and density as affected by additive concentration. Cohesion and density changes may help determine which additive, if any, best stabilizes a soil. The information gathered may also be useful in deciding which method of application best suits a soil-additive combination.

# CHAPTER 4

# TEST RESULTS

## Introduction

Results for this project are given in the following sections according to the action taken, the soil tested, or the tests conducted. The first two results presented are the classification of specimens taken from sections of roads in the Medicine Bow National Forest, and the results of monitoring the application of lignin to the Fox Park Road. Next, the results of moisture-density and UCS tests for soils 1B, 1Bk and H-1c are presented. Following these test results, the effects of wet-dry cycles on lignin-treated soil, and the effects of combining additives are considered. Finally, the results of test verification are presented.

The evaluation of test results is based upon observed changes in dry density and UCS. The results are given as a comparison between specimens formed with water only as the additive, and specimens formed with lignin sulfonate (lignin), calcium chloride ($CaCl_2$), or magnesium chloride ($MgCl_2$), as the additive. Specimens tested wet were formed, extruded, measured, and tested without allowing time for drying. Specimens tested dry were extruded and air dried for seven days before being measured and tested. Summary sheets of peak values for each soil-additive tested are presented in Appendix B.

## Specimens from the Medicine Bow National Forest

Thirty-two specimens were tested. They were composed of material from the Medicine Bow National Forest; sixteen were road surface materials, three were pit stock materials, one was material taken from a reclaimed pit, and the remaining twelve were materials taken from road base or subbase soils. All 16 road surface specimens were classified as SM by the Uniform Soil Classification System (USCS) (ASTM designation D-2487), and A-1-b by the American Association of State Highway and Transportation Officials (AASHTO) system. Each of the sixteen road surface specimens met at least one of AASH-

TO's grading requirements for surface course aggregates. None met the requirement of having a plasticity index (PI) ranging from 4 to 9 (all had PI = 0) (AASHTO, 1993).

Of the three specimens taken from pit stock piles, specimen 1B was classified as A-1-b (PI=0) and met AASHTO surface course aggregate grading requirements D, E, and F. AASHTO classification of specimen 3B was A-1-a (PI=0) and the specimen met AASHTO grading requirement C. Specimen 4B was classified as A-2-4 (PI=6.31), and did not meet any of AASHTO's grading requirements. Specimen 2B was taken from a reclaimed pit and had some top soil mixed with the aggregate. This soil classified as A-2-4 (PI=9.66) and did not meet any of AASHTO's surface course grading requirements.

Classifications for the road base and subgrade soil specimens varied. The specimens taken from Fox Park Road are the only specimens significant to this study, so only the classifications of those specimens are reported. Of the subgrade specimens from the Fox Park Road, the AASHTO classification for specimen 1 is between A-2-4 and A-2-6. Specimen 2 classifies as A-2-4, and specimen 3 classifies as A-1-b.

## Results of Applying Lignin to Fox Park Road

### *6 Days (8-18-93)*

Observation and sampling of Fox Park Road began six days after an application of lignin to 1.7 miles (2.74 km) of the road surface course. The application of lignin resulted in the formation of a crust approximately 1/4 inch (6.35 mm) thick. The soil under this crust was moist in all the test holes. In some locations, the road showed signs of wear, but generally the road was in good condition. Two indications of wear were some raveling at the road center line and the crust being broken in a few spots. At one location (near a survey stake marked point 4) the center of the road was beginning to break up and small potholes were forming. Apparent depth of lignin varied from 2 to 6 inches (50.8 to 152 mm) with the average depth being about 4.5 inches (114 mm). A treaded dozer had moved down the road and damage caused by the treads was visible. No dust was observed from passing cars.

### *13 Days (8-25-93)*

At some time after the 6-day observation the area received rain. Some lignin had apparently washed from the road surface and the dark liquid was evident in the ditches. The color of the road surface was lighter than during the previous observation. Test holes showed an average depth of 4.5 inches (114 mm) of lignin-darkened soil, and soil under the 1/4-inch (6.35 mm) crust was moist. The areas of raveling had increased in size and spread toward the road edge. At point 4, some corrugations were forming where the crust was broken and alligator cracks were apparent in the remaining crust. Long, shallow wave corrugations were also forming at one location were the crust was still intact. Damage previously caused by a heavy treaded vehicle was partially healed and the lignin application continued to control dust.

### *20 Days (9-1-93)*

The Fox Park area received light rain the day before this inspection. At a few locations where the surface crust had not broken, the road was reasonably smooth. There were alligator cracks and loose materials over most of the road surface. Areas of broken crust had expanded, especially along the center line of the road. Old areas of broken crust were heavily washboarded. Low places in the ditches were dark-colored from lignin that was washed from the road surface. Traffic-related dust was minimal.

### *28 Days (9-9-93)*

The area received heavy rains just before this inspection. Water was still standing in the ditches, and it was colored dark brown from lignin that had washed from the road surface. This inspection was made two days after the Labor Day weekend, so the road probably had been subjected to a high volume of traffic since the last inspection. The entire road surface had deteriorated considerably since the previous inspection. The entire length [1.7 miles (2.74 km)] of the road had potholes, particularly near the center line of the road. The potholes were largest in areas where the crust had been previously broken. Most of the alligator cracks had disappeared. However, loose fines had washed from the road surface to the road edges and in some areas into the ditches. A logging truck that passed during the inspection caused a small amount of dust.

### *69 days (10-20-93)*

The road is now in very bad shape. Condition of the road is worse in areas of apparent poor drainage. In some areas snow or water cover the road.

### *Approximately 1 Year After Application (8-1-94)*

There was no evidence on the road surface of the previous year's lignin application. In low areas of some ditches there was dark colored soil, probable due to lignin accumulating there. The Fox Park Road was heavily corrugated and dusty.

## Soil 1B

Soil 1B was taken from the Fox Park Pit stock pile in the Medicine Bow National Forest. This soil is classified as A-1-b by AASHTO designation M-145, and SM by USCS. Soil 1B meets grading requirement for surface course aggregates from AASHTO designation 147-65, except that it has a plasticity index of zero.

### *Moisture-Density Tests*

The addition of lignin to soil 1B increased the dry density of the soil over compaction with water alone. This increase occurred at moisture contents between 6% and 9% for all lignin concentrations tested. At lower moisture contents, lignin reduced dry density and at higher moisture contents lignin had little or no effect on dry density (see Figures 4-1 and 4-4).

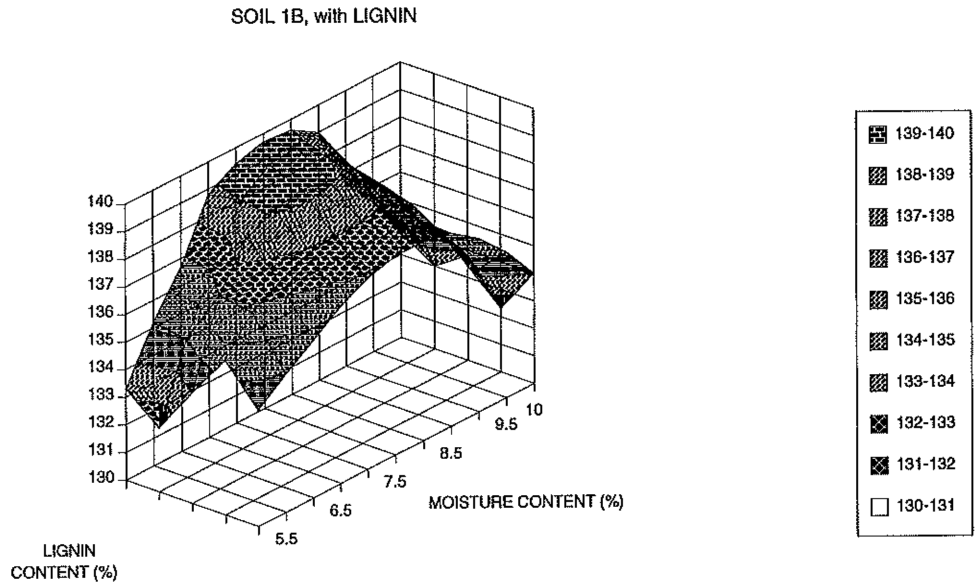

**Figure 4-1. Soil 1B & Lignin, Moisture-Density Relationship** (1 pcf = 157 N/m$^3$).

The addition of $CaCl_2$ decreased dry density when compared to soil compacted with water only, at a concentration of 1%. After this initial decrease, dry density increased as the concentration of $CaCl_2$ increased until at a $CaCl_2$ concentration of 3.25%, peak dry density was equal to that of compaction with water alone (see Figures 4-2 and 4-4).

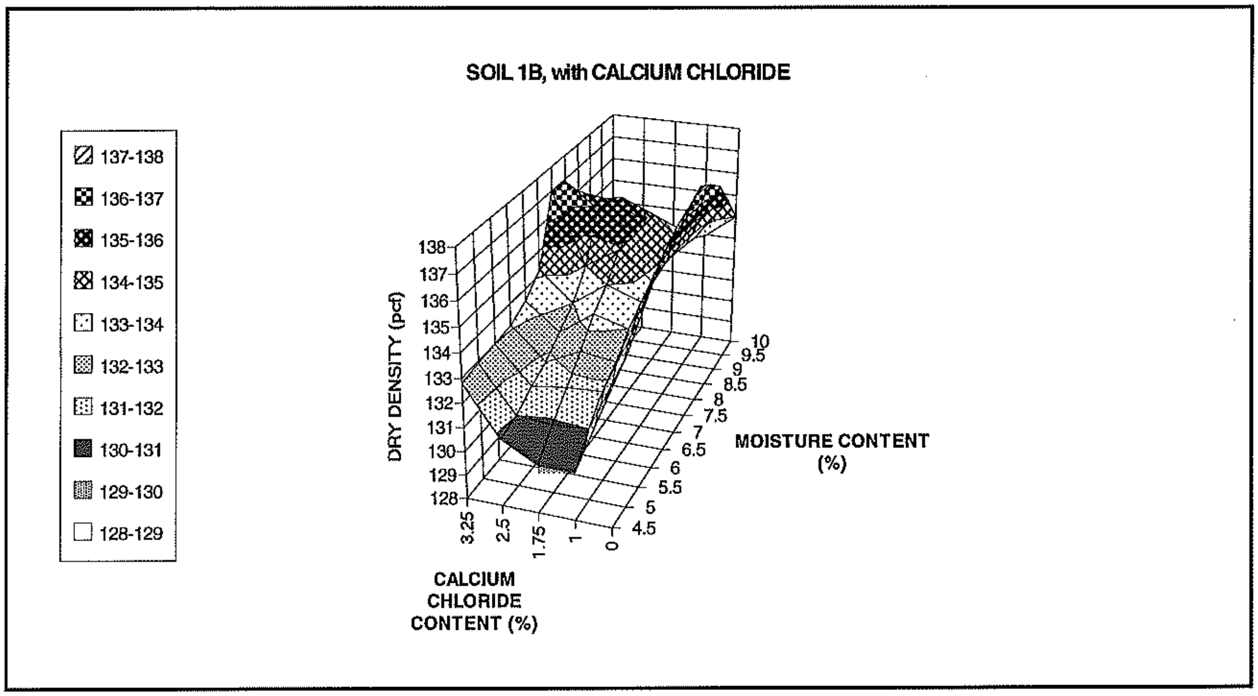

**Figure 4-2. Soil 1B & CaCl$_2$, Moisture-Density Relationship** (1 pcf = 157 N/m$^3$).

The addition of MgCl$_2$ decreased the dry density of soil 1B, for constant compactive effort, at all concentrations tested. At moisture contents between 4.5% and 7%, densities decreased markedly, while at moisture contents above 7% the trend was toward only slight reductions in density (see Figures 4-3 and 4-4).

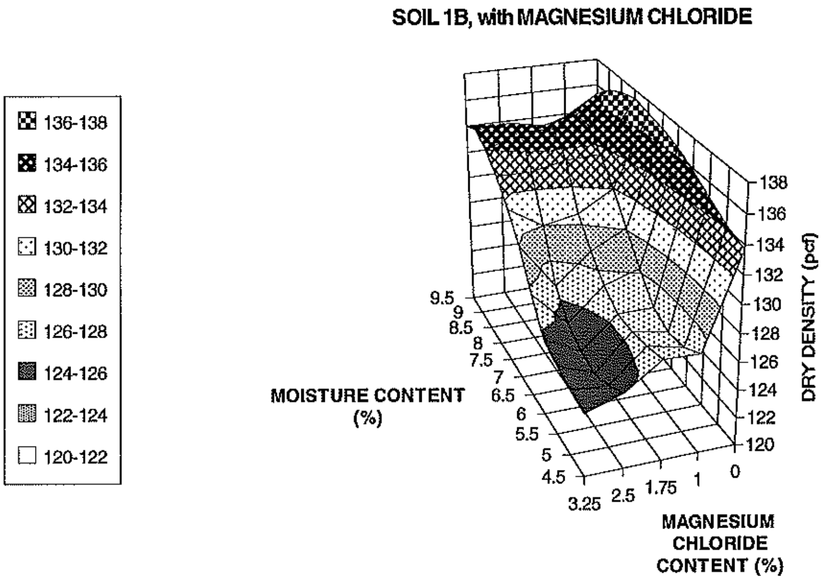

Figure 4-3. **Soil 1B & $MgCl_2$, Moisture-Density Relationship** (1 pcf = 157 N/m$^3$).

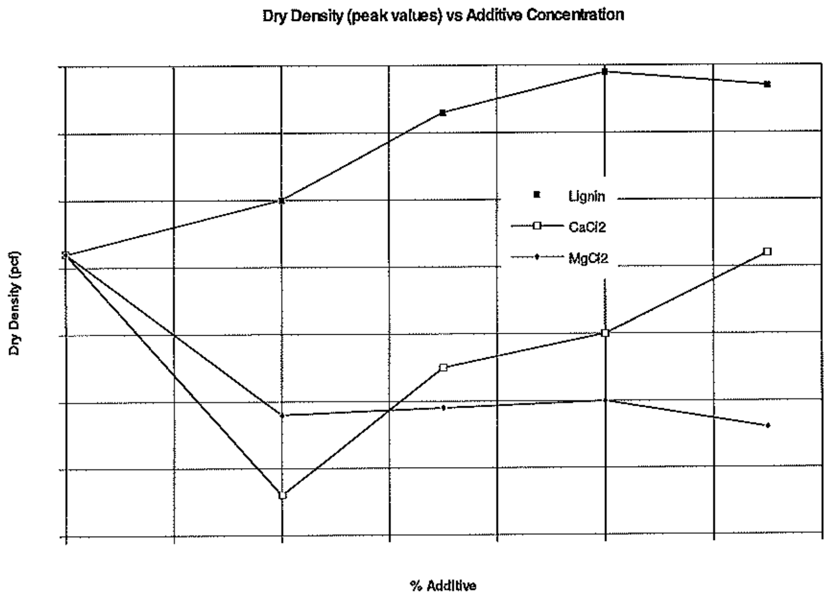

**Figure 4-4. Soil 1B, Average Peak Dry Density versus Additive Concentration.** (1 pcf = 157 N/m$^3$).

### *Unconfined Compressive Strength (UCS), Specimens Tested Wet*

The increase in dry density caused by adding lignin was not reflected in changes in UCS when the specimens were tested wet, immediately after formation. Specimens compacted with lignin or $CaCl_2$ decreased in strength at all concentrations when the specimens were tested wet. A slight increase in strength occurs with 1% $MgCl_2$, but a decrease in strength occurs at all other concentrations compared to water alone (Figure 4-5).

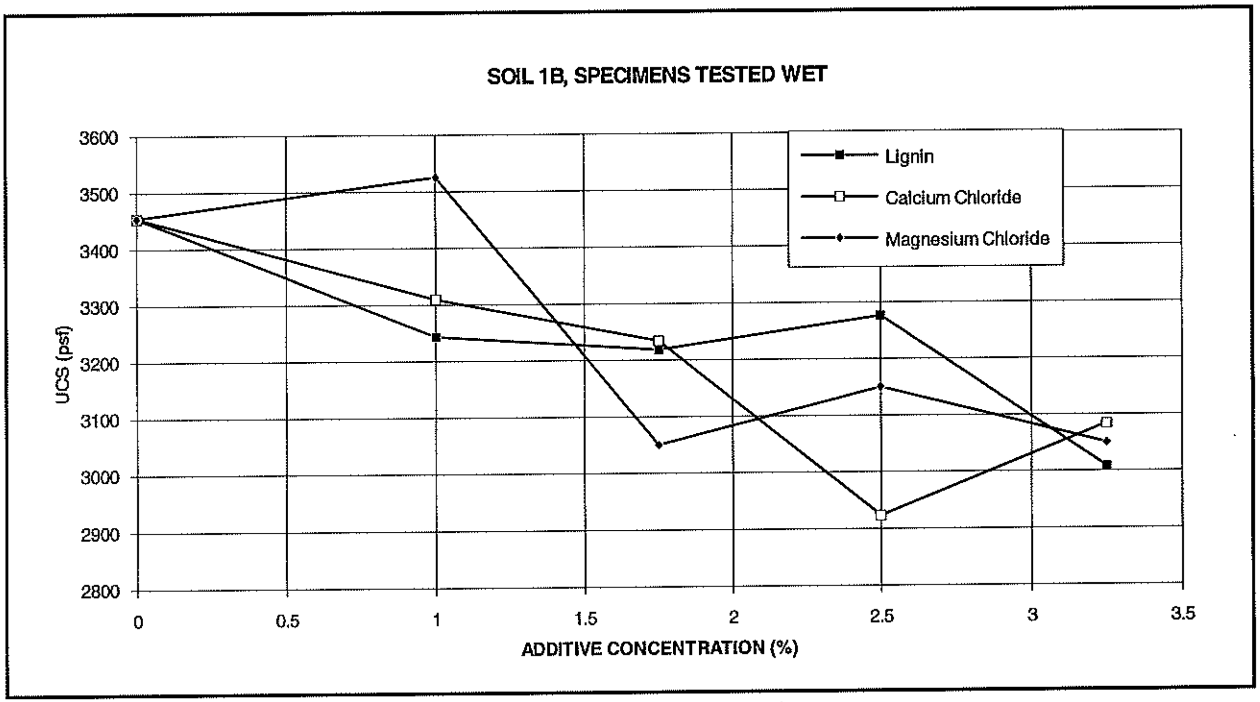

**Figure 4-5. Average Peak UCS, Specimens Tested Wet** (1 psf = 48 Pa).

### *Unconfined Compressive Strength (UCS), Specimens Tested Dry*

Specimens containing lignin that were tested after air drying for seven days exhibited large strength increases. Strength increased with both additive and moisture content (see Figure 4-6). Observation of specimens containing lignin that were tested dry showed that the outer edge of the specimens was darker in color than the interior of the specimen. This was especially true of specimens formed at the higher moisture contents.

Changes in UCS were not as consistent for specimens formed with $CaCl_2$ or $MgCl_2$. Figure 4-7 shows that when $CaCl_2$ was added to soil 1B, there was an increase in axial strength at 1% additive, but a decrease in strength at all other concentrations.

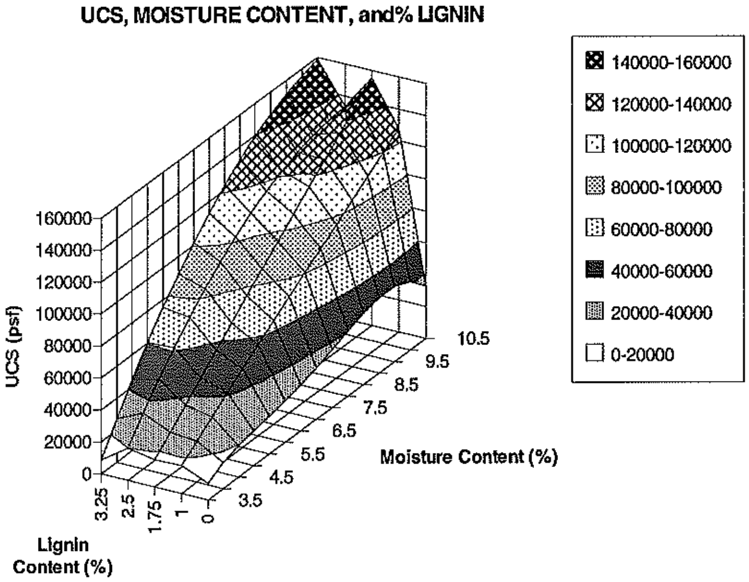

**Figure 4-6. Soil 1B with Lignin, UCS, Specimens Tested Dry** (1 psf = 48 Pa).

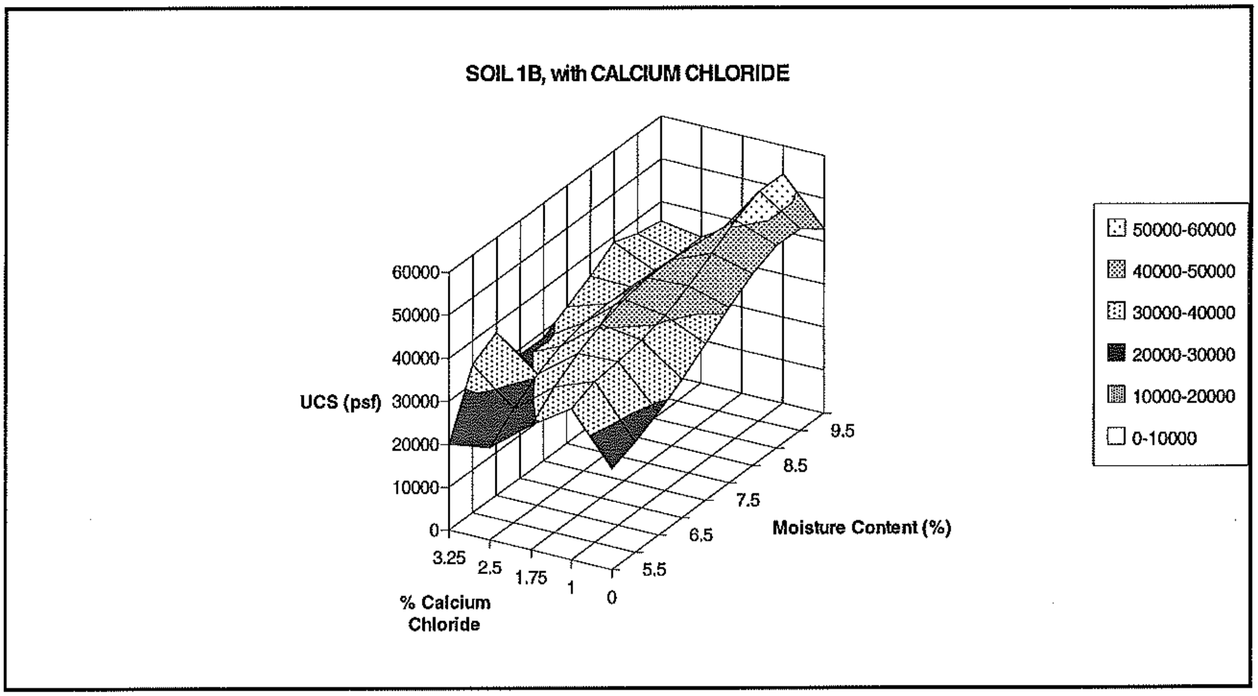

**Figure 4-7. Soil 1B with CaCl$_2$, UCS, Specimens Tested Dry** (1 psf = 48 Pa).

Magnesium Chloride treated specimens increased in UCS at 1% and 3.25% and decreased at 1.75 and 2.5% (see Figure 4-8). The peak strength with 3.25% MgCl$_2$ additive was slightly greater than the peak strength of specimens formed with water alone.

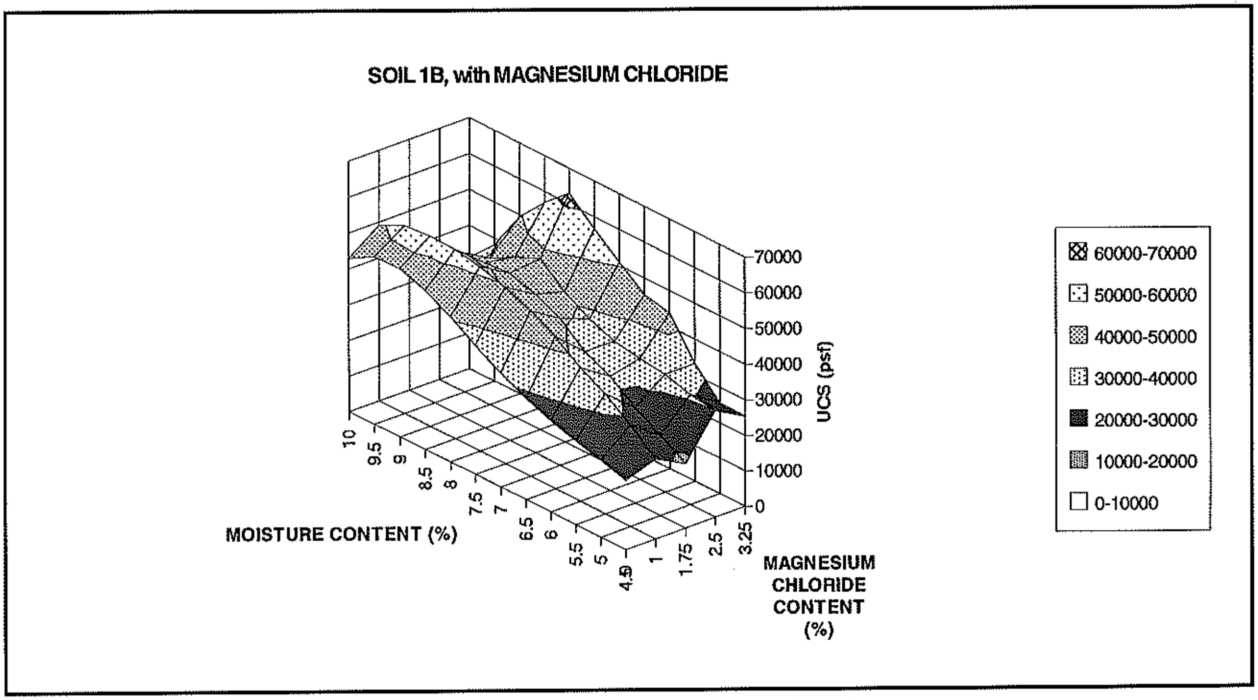

Figure 4-8. Soil 1B with $MgCl_2$, UCS, Specimens Tested Dry (1 psf = 48 Pa).

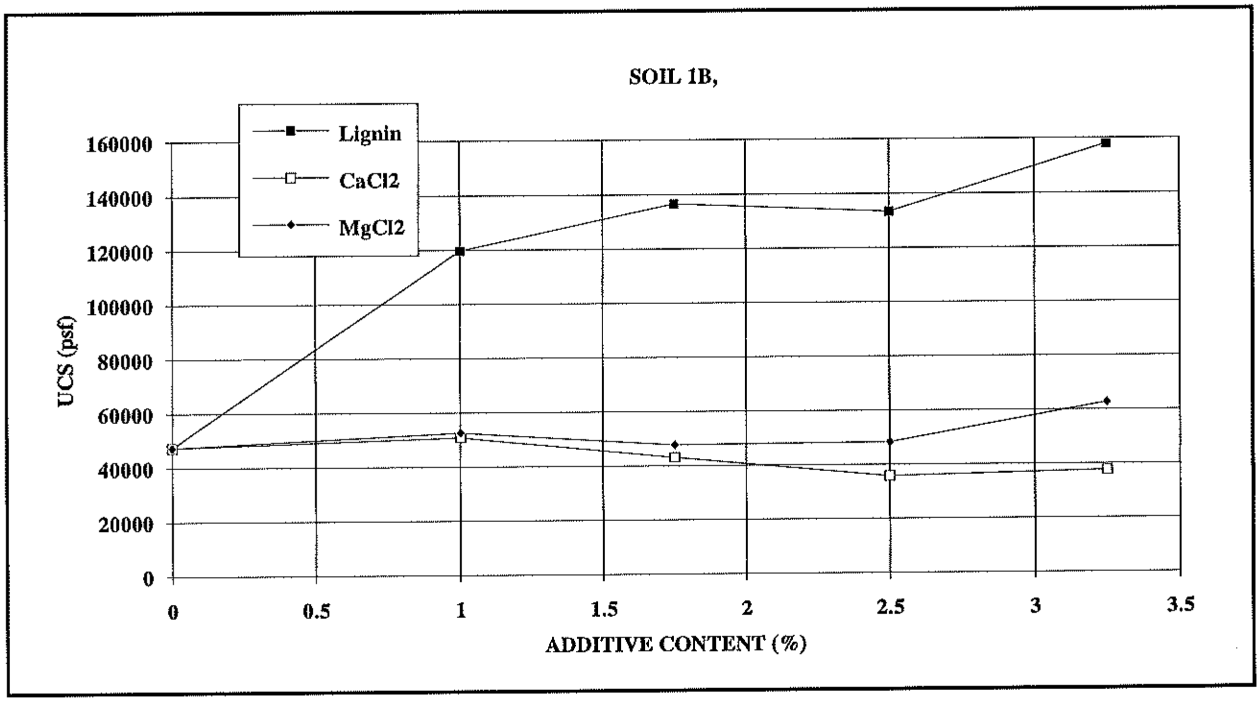

Figure 4-9, Soil 1B, Average UCS, Specimens Tested Dry (1 psf = 48 Pa).

## Soil 1Bk

Soil 1Bk is a mixture of soil 1B and 8.5% kaolinite clay. This soil was developed by adding 8.5% by dry weight clay to soil 1B. This mixture resulted in a soil that meets AASHTO Designation M 147-65, Grading F, and has a PI of approximately 6.

### *Moisture-Density Relationships*

Lignin sulfonate tended to be detrimental to compaction of soil 1Bk. Dry density decreased from 0% to 2.5% lignin and then increased from 2.5% to 3.25% lignin, but dry density at 3.25% lignin was lower than that of specimens formed with water alone. Very little change occurred in dry density for specimens formed with $CaCl_2$ and all points were within 1 pcf (157 $N/m^3$) of compaction with water alone. Magnesium Chloride decreased dry density in soil 1Bk at lower additive concentrations, but dry density was near that of water alone at the concentration of 3.25% (see Figure 4-10). The greatest variation in average peak value for dry density between all concentrations of lignin, $CaCl_2$, or $MgCl_2$ was 1.43% of the mean value (135.1 pcf, 21.2 $kN/m^3$). This variation for dry density was within ASTM standard single operator error of 1.9% of mean value.

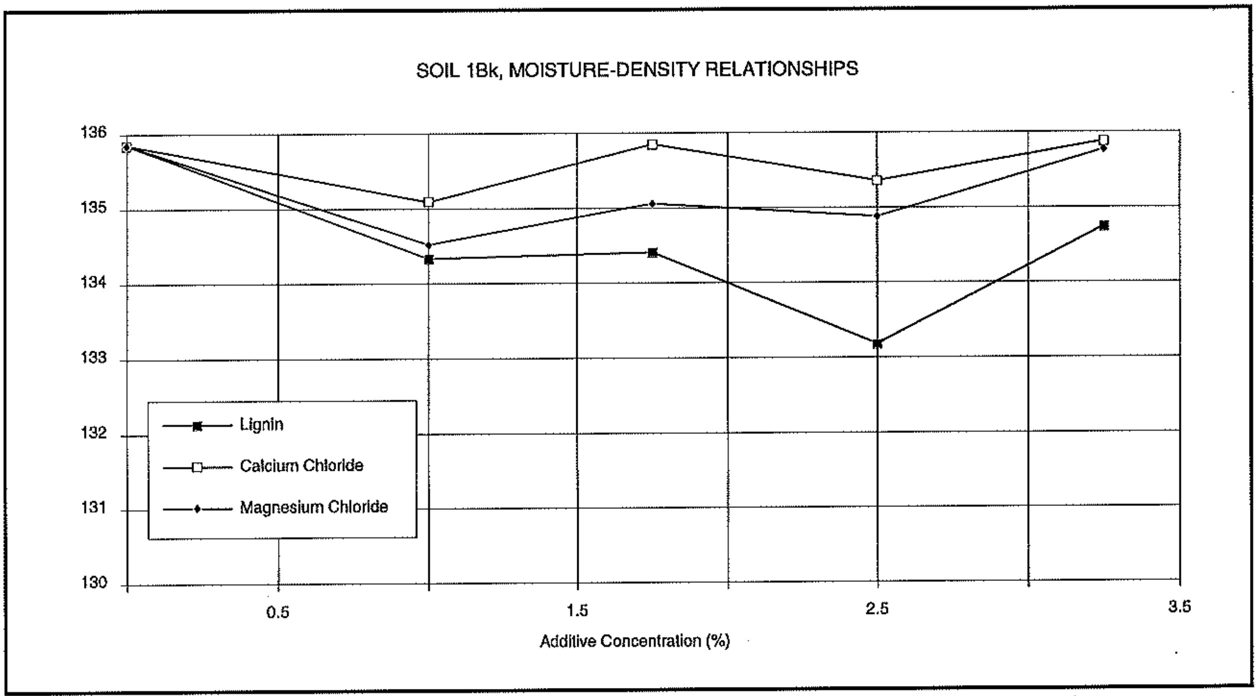

**Figure 4-10, Soil 1Bk, Maximum Dry Density versus Additive Concentration** (1 pcf = 157 N/m$^3$).

### *Unconfined Compressive Strength (UCS), Specimens Tested Wet*

Figure 4-11. shows average maximum unconfined compressive strength versus additive concentration for specimens that were tested immediately after formation. For soil 1Bk, with lignin or $MgCl_2$ as the additive, strength decreased as additive concentration increased. Soil 1Bk with $CaCl_2$ increased in strength for a $CaCl_2$ concentration of 1.75% but decreased at all other concentrations.

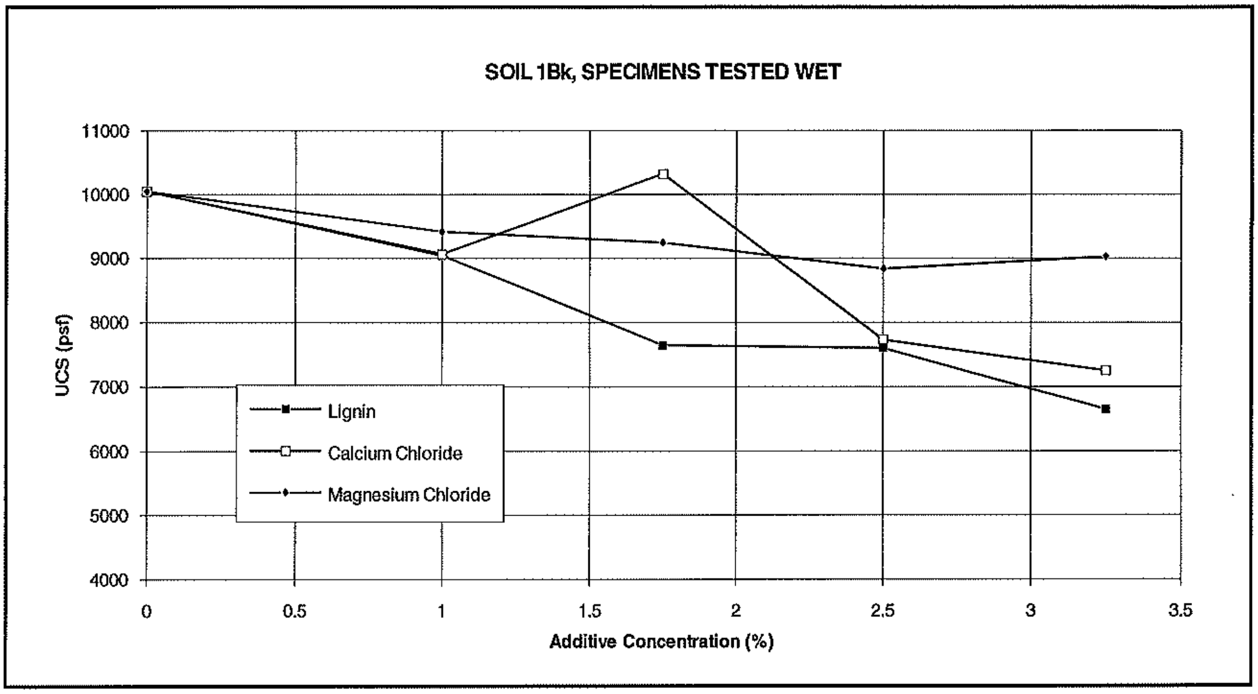

**Figure 4-11. Soil 1Bk, Average UCS, Specimens Tested Wet** (1 psf = 48 Pa).

### *Soil 1Bk, Unconfined Compressive Strength (UCS), Specimens Tested Dry*

Unconfined compressive strength of soil 1Bk treated with lignin increased from concentrations of 0% to 2.5% when the specimens were tested dry. Figure 4-12 shows these increases and a slight decrease in strength from 2.5% to 3.25% lignin. Specimens of soil 1Bk and $CaCl_2$ showed a sharp decrease in strength from 0% to 1.0% $CaCl_2$ concentrations. However, from 1.0% to 3.25% $CaCl_2$, little change in strength was observed (see Figure 4-13). For $MgCl_2$, strength decreases for concentrations from 0% to 1%, then increases from 1% to 2.5% concentration (see Figure 4-14). A 3.25% concentration of $MgCl_2$ produced strengths well below that of specimens with water only.

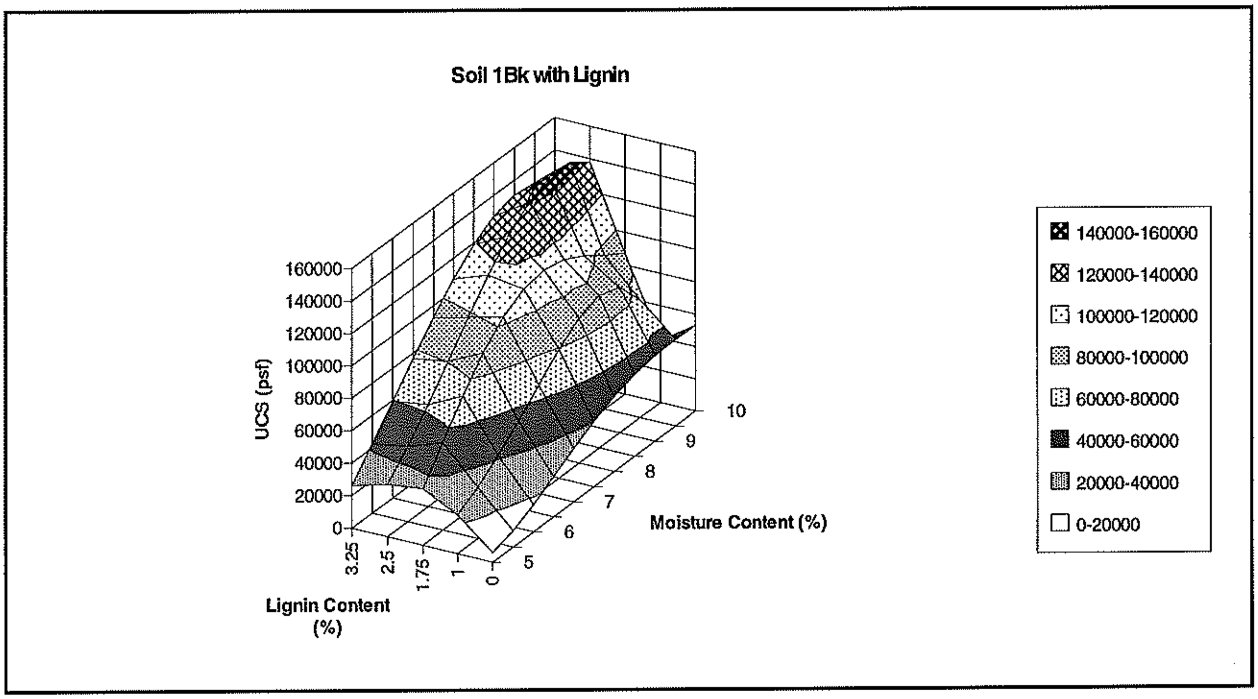

Figure 4-12. Soil 1Bk with Lignin, UCS, Specimens Tested Dry (1 psf = 48 Pa).

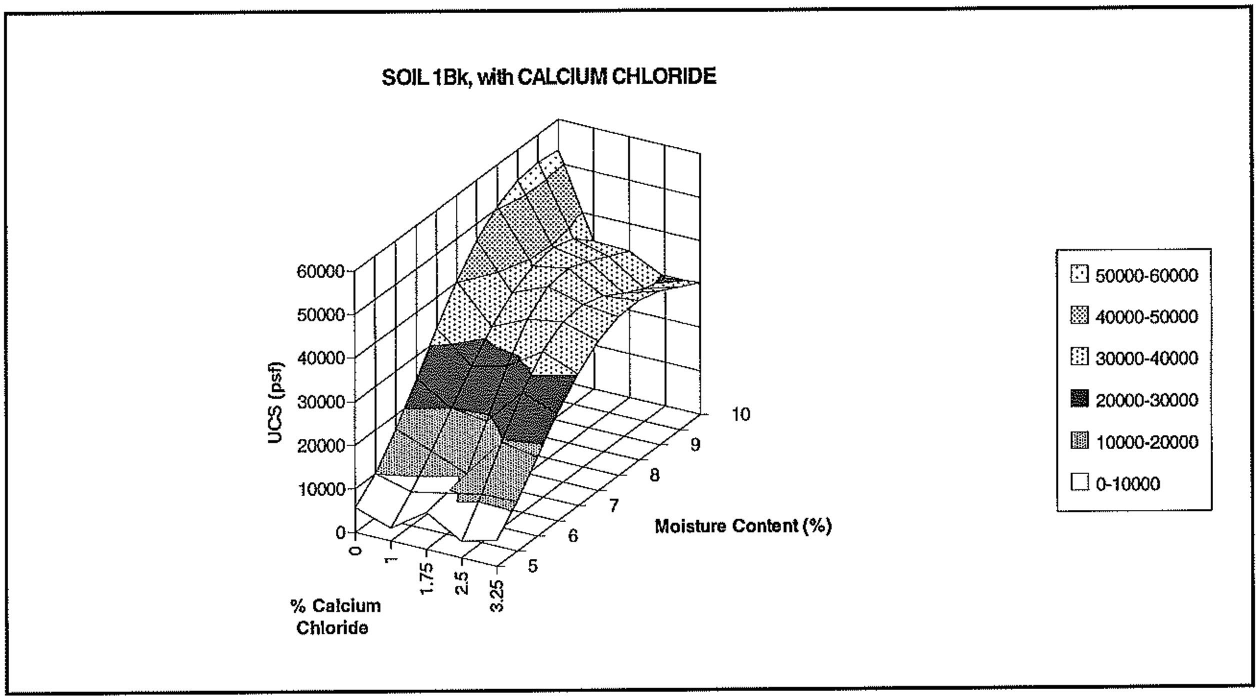

Figure 4-13, Soil 1Bk with $CaCl_2$, UCS, Specimens Tested Dry (1 psf = 48 Pa).

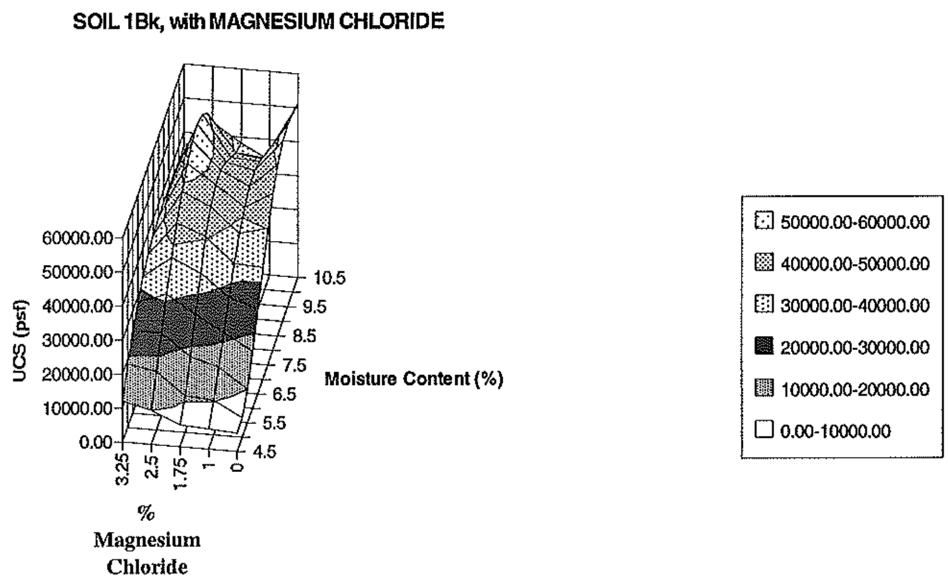

**Figure 4-14. Soil 1Bk with $MgCl_2$, UCS, Specimens Tested Dry** (1 psf = 48 Pa).

## Soil H-1c

Soil H-1c is a mixture of road base soil H-1 and 12% clay. H-1c has an AASHTO classification of A-2-4, and is classified as SC by USCS. Soil H-1c meets AASHTO M 147-65 surface course grading requirements for grading B, and E, with a PI of 9.

### *Soil H-1c Additive Density Relationships*

Additive-density relationships are shown in Figure 4-15 for soil H-1c with lignin, $CaCl_2$ and $MgCl_2$. Specimens containing lignin show a slight decrease in dry density at 1% additive concentration. From 1.0% to 2.50% lignin, dry density increased steadily, then remained constant from 2.5% to 3.25% lignin. Dry density for soil H-1c increases at 1% concentration with both $CaCl_2$ and $MgCl_2$. After the initial increase, dry density decreases steadily for $MgCl_2$ concentrations greater than 1%, but remain slightly higher than specimens compacted with water alone. For specimens compacted with the additive

$CaCl_2$, dry density drops below that of specimens compacted with water alone for the additive concentration of 1.75% $CaCl_2$ and then increases steadily to an additive concentration of 3.25%.

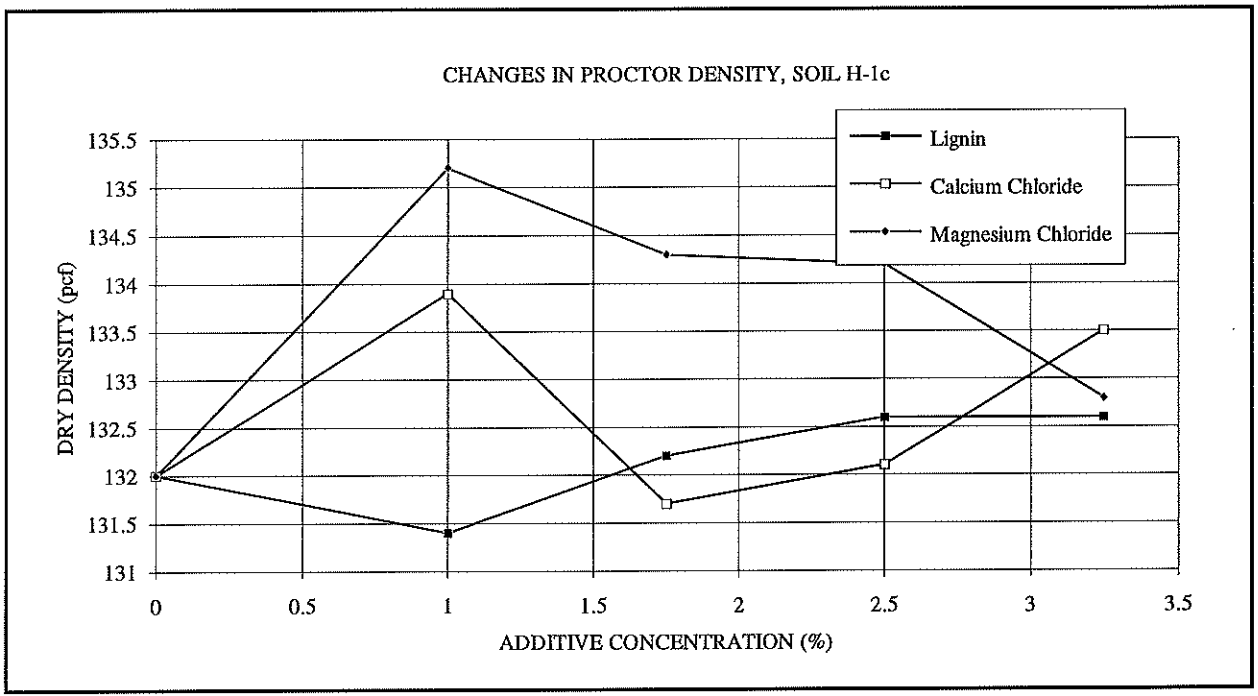

**Figure 4-15. Soil H-1c, Average Peak Values, Additive-Density Relationships** (1 pcf = 157 $N/m^3$).

### *Soil H-1c, Unconfined Compressive Strength (UCS), Specimens Tested Wet*

For soil H-1c, with lignin, $CaCl_2$ or $MgCl_2$, the UCS of specimens tested wet decreased nearly constantly as additive concentrations increased. The decrease was greatest for $CaCl_2$ and least for lignin (see Figure 4-16).

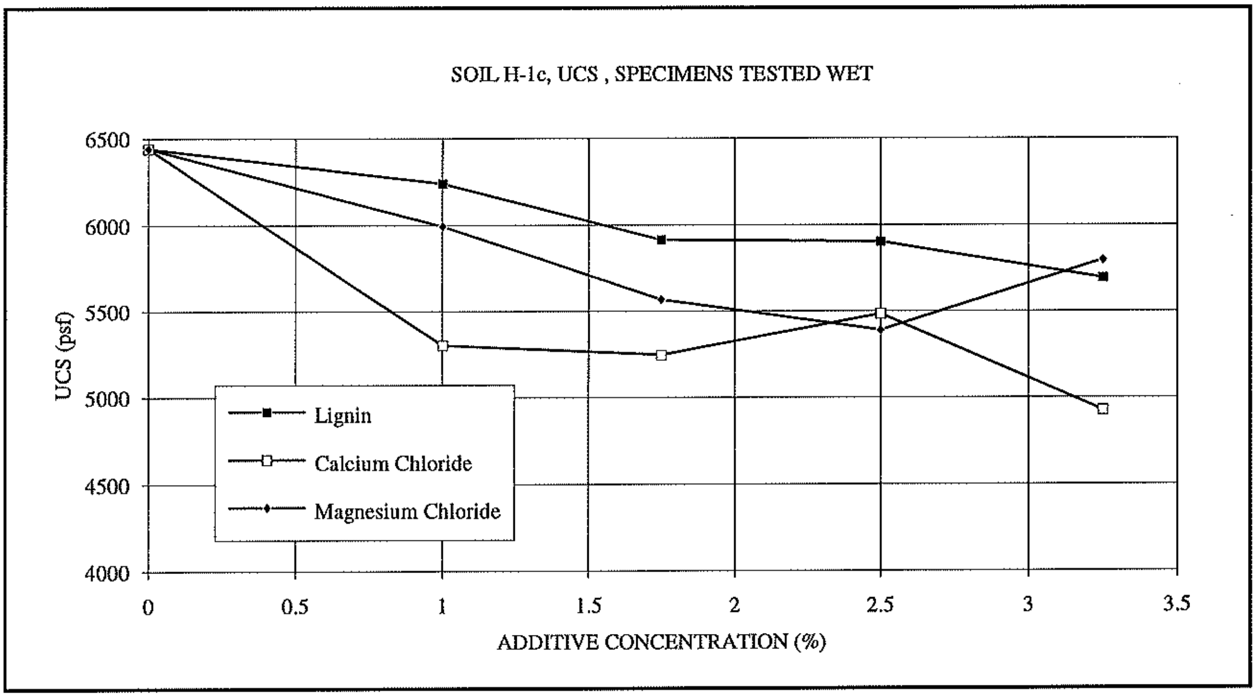

**Figure 4-16. Soil H-1c, Average UCS, Specimens Tested Wet** (1 psf = 48 Pa).

### *Soil H-1c, Unconfined Compressive Strength (UCS), Specimens Tested Dry*

Specimens of soil H-1c containing lignin showed a consistent increase in strength from 0% to 3.25% additive (see Figure 4-17). The greatest increases were at 8.0% to 9.0% moisture content with peak strength occurring near 8.5% moisture and 3.25% lignin. Strengths decrease consistently from 0% to 3.5% additive content for soil H-1c with both $CaCl_2$, and $MgCl_2$ (see Figures 4-18 and 4-19).

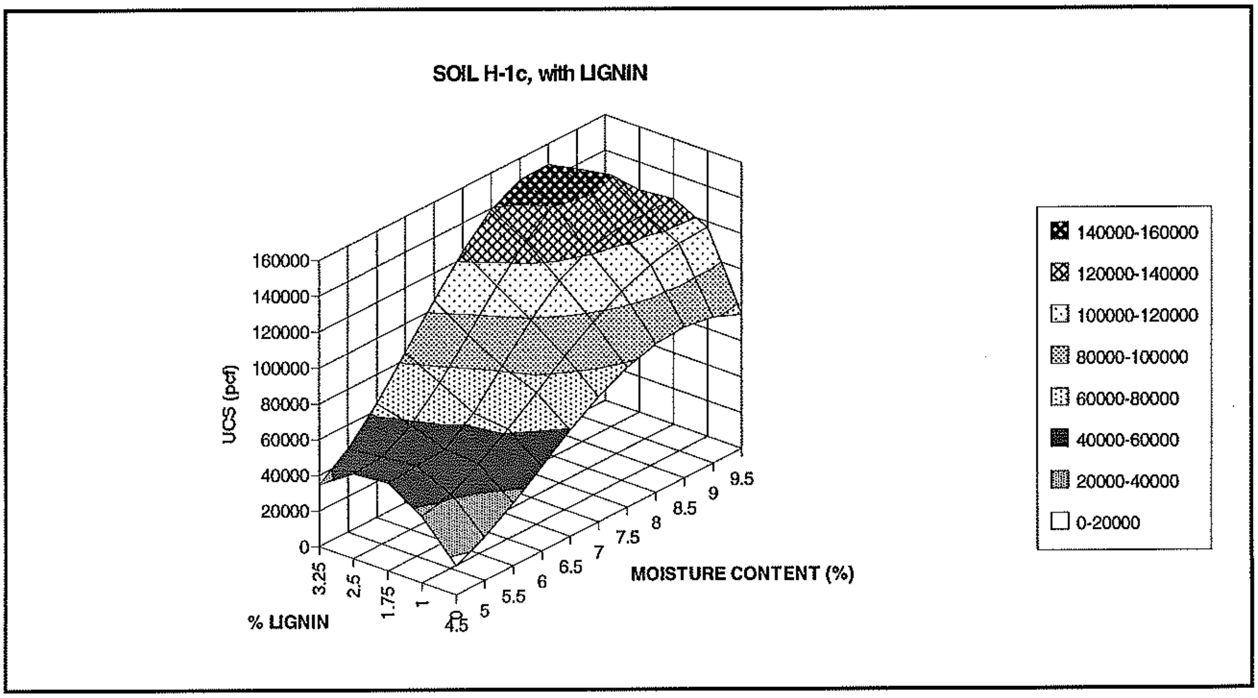

**Figure 4-17. Soil H-1c with Lignin, UCS, Specimens Tested Dry** (1 psf = 48 Pa).

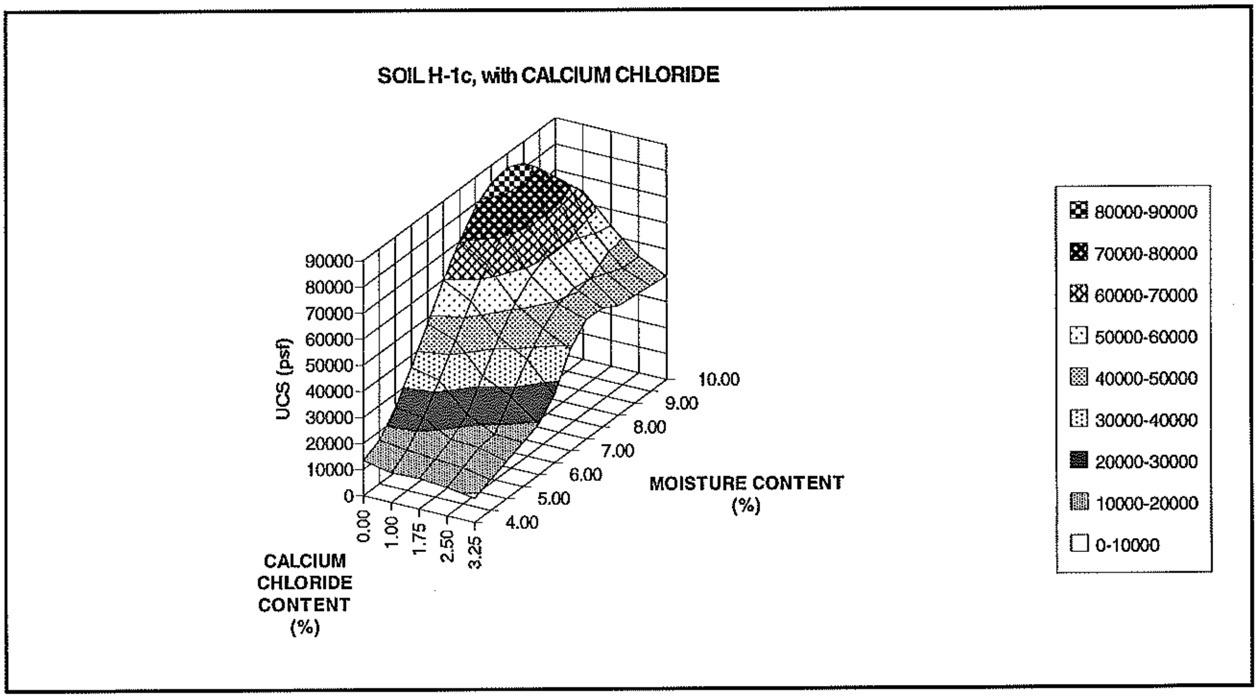

**Figure 4-18. Soil H-1c with $CaCl_2$, UCS, Specimens Tested Dry** (1 psf = 48 Pa).

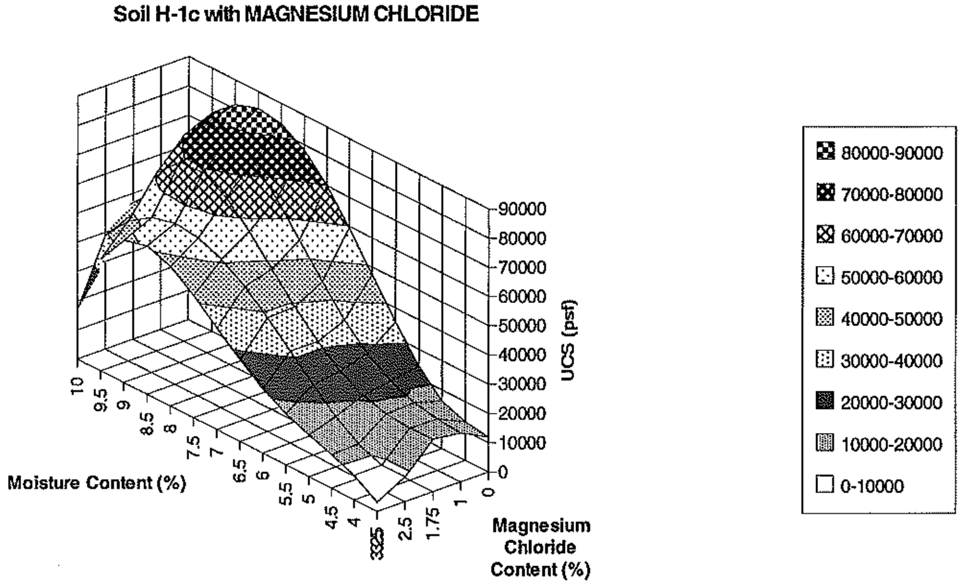

**Figure 4-19. Soil H-1c. with $MgCl_2$, UCS, Specimens Tested Dry** (1 psf = 48 Pa).

## Effects of Kaolinite on Soil 1B

Data given in this section are for soils with water as the additive. Adding kaolinite to soil 1B caused the optimum water content to shift from 8% for soil 1B to 8.5% for soil 1Bk. Peak dry densities from moisture-density tests were approximately 137 pcf (21.5 kN/m$^3$) and 136 pcf (21.4 kN/m$^3$) for soils 1B and 1Bk, respectively. Dry density peaks from Harvard Miniature specimens were nearly identical. UC tests for specimens tested wet, resulted in a peak UCS of 3,370 psf (162 kPa) for soil 1B, and 10,000 psf (480 kPa) for soil 1Bk. Peak values of UCS for specimens that were allowed to air dry for 7 days, were 47,300 psf (2270 kPa) and 52,900 psf (2539 kPa) for soils 1B and 1Bk, respectively.

## Effect of Wet-Dry Cycle on Lignin in Soil 1B

For specimens tested wet, overall strength tended to decrease with time (see Figure 4-20). Figure 4-21 shows a slight increase with time in specimens tested dry. An inconsistency occurred for both wet and dry specimens at 14 days. Data points shown in Figures 4-20 and 4-21 are averages of 2 specimens. The variation in moisture content from 8% was - 0.02 and + 0.12.

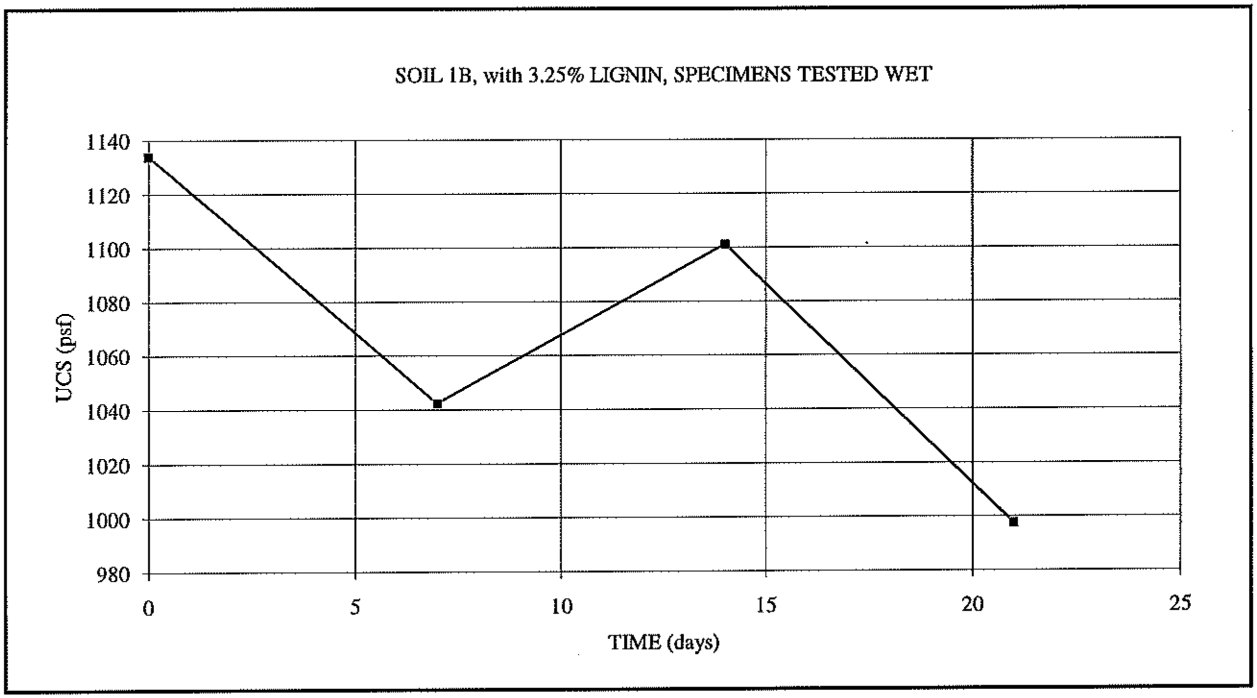

**Figure 4-20. Soil 1B with Lignin, Wet-Dry Cycle, Average Peak UCS, Specimens Tested Wet** (1 psf = 48 Pa).

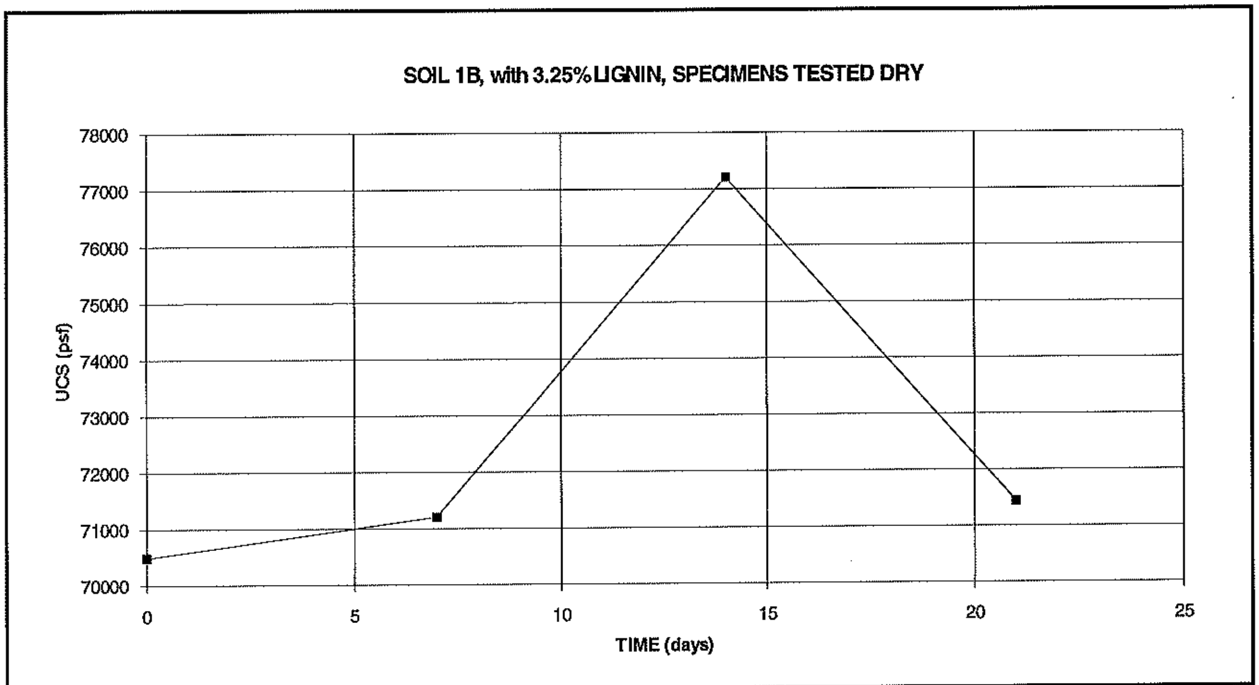

**Figure 4-21. Soil 1B with Lignin, Wet-Dry Cycle, Average Peak UCS, Specimens Tested Dry** (1 psf = 48 Pa).

## Combined Additives

To test the effect of a combination of additives, concentrations of both $MgCl_2$ and lignin were added to a specimen of soil 1B. A combination of 0.5% $MgCl_2$ and 2.5% lignin resulted in peak strengths greater than those gained by $MgCl_2$ alone, but less than those gained by lignin alone. Peak UCS for the $MgCl_2$-lignin mix was 109,000 psf (5232 kPa). By comparison, peak strength were 62,600 psf (3004 kPa) and 158,000 psf (7584 kPa) for soil 1B with $MgCl_2$ and lignin, respectively.

## Consistency of Tests, Soil 1B

To determine if test results would be consistent with a change in technicians, tests of soil 1B with lignin, $CaCl_2$ or $MgCl_2$ were repeated. Dry density results were consistently lower with change of operator. Figure 4-22 shows a plot of the dry density results for soil 1B with $MgCl_2$ combined with the results of the specimen type of test done on soil 1B with $MgCl_2$, but with a different technician conducting the tests. Although the results are lower they are within ASTM standard precision for both $CaCl_2$ and $MgCl_2$; differences for lignin were 1.14% greater than the standard for multi laboratory precision.

The second operator's moisture-density tests also resulted in a shift in optimum water content. This shift was from approximately 8% optimum water content to 9.5% optimum water content (acceptable multi laboratory precision is 9.5% of mean value). Dry densities for specimens formed in the Harvard Miniature molds were also lower for the second operator.

Results for UCS were lower with the second set of tests (tests done by a different lab technician). Figure 4-23 shows the change in strength for soil 1B with lignin as the additive (specimens tested after air drying 7 days). This trend in reduced dry density and strength occurred throughout the tests performed by the second operator.

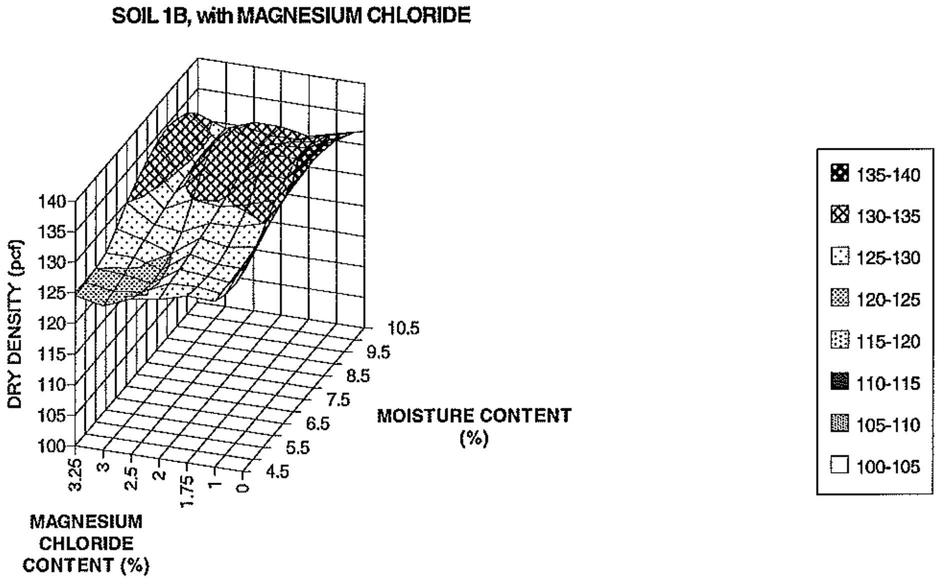

**Figure 4-22. Soil 1B & $MgCl_2$, Dry Density, Two Operators** (1 pcf = 157 N/m$^3$).

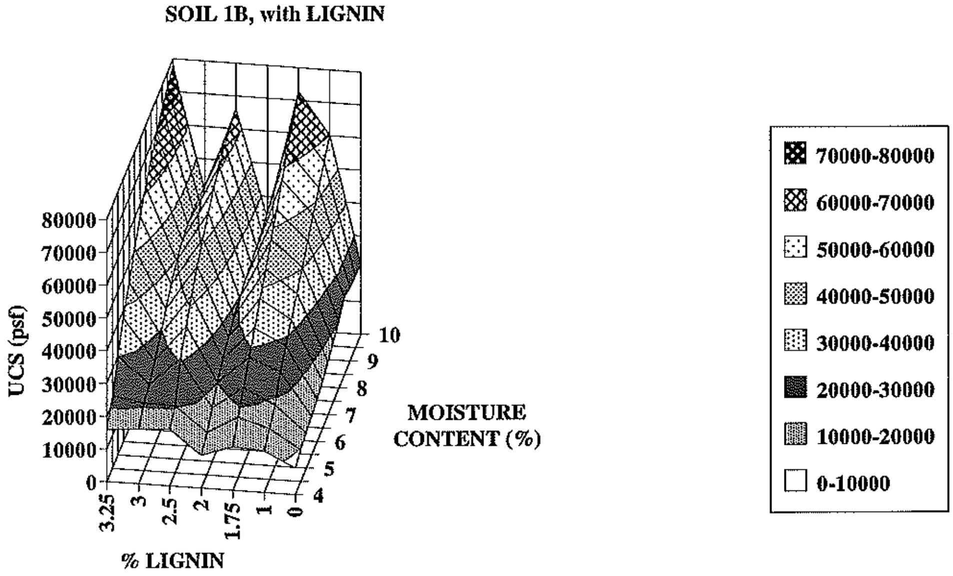

**Figure 4-23. Soil 1B with Lignin, UCS, Specimens Tested Dry, Two Operators** (1 psf = 48 Pa).

## Nuclear Magnetic Resonance Test for Residual Lignin

Attempts to use NMR for determining the residual amounts of lignin in a road surface soil were unsuccessful. This procedure uses the carbon 13 in organic substance as its measurable quality. Because the percentages of lignin used on road surfaces is small, the lignin-soil mix does not contain high percentages of carbon. Therefore, NMR was unable to produce good results (see Appendix C for the complete report).

## Time and Soil Requirements

Soil classification requires approximately 4 hours per soil. The following time requirements for both moisture-density and UC tests are for one soil with three separate additives at four different additive concentrations and for the soil with water alone. In other words there were 13 specimens of each soil each specimen containing a different additive or additive concentration.

Testing for moisture-density relationships takes approximately 24.5 hours and involves approximately 65 repetitions of ASTM Method A-A for each soil. Each soil-additive mix takes about 8 pounds (3.63 kg) of minus 4.76 mm material. The UC test requires approximately 97.5 hours for 260 Harvard Miniature specimens per soil. Each soil-additive mix uses about 8 pounds (3.63 kg) of minus 2.0 mm material. Total time to complete all steps of the procedures for each soil is about 126 hours.

# CHAPTER 5

# CONCLUSIONS

## Introduction

Chapter 4 presented results from tests conducted on three soils and three additives. In addition, results were presented on tests of a soil with a combination of additives and on cyclic wetting and drying of a soil-additive mix. From these test results, conclusions were drawn as to the mechanical property changes of the soils due to additives. In turn, these conclusions can be used to decide which additive and method of application may best be used to stabilize a road surface constructed of these soils.

Similar tests may be conducted by personnel responsible for road maintenance and construction, to better predict which additive might best stabilize the road surfaces under their care. To aid in this process, test results given in Chapter 4 are used to draw conclusions about stabilization of unpaved roads. These conclusions are given in the following paragraphs.

## The Fox Park Road and Soil 1B

The application of lignin to Fox Park Road was effective in controlling dust for approximately 28 days. After 28 days, the amount of dust caused by passing vehicles was noticeable. However, there appeared to be some improvement compared to the dust conditions before the application. Within 69 days, nearly all signs of stabilization had disappeared. This short-lived stabilization may have been due, in part, to poor quality control during the lignin application (Moats, 1994). Other factors may have contributed to the loss of road stability. For example, lignin may have leached out of the upper portion of the road surface or it may have been removed by erosion.

The method of lignin application could also affect the life span of road stabilization (see Chapter 3, Section 3-9). Scarifying the road surface before applying lignin and mixing the lignin and soil as the application was made resulted in lignin being found to an average depth of 4 inches (102 mm) below the road surface. Specimens taken from the Fox Park Road were found to have a dry-hard crust about 1/4 inch (6.35 mm) thick, and an average of 3.75 inches (95 mm) of moist soil-lignin mix below the surface crust (Chapter 4, Section 4-3b.). Figure 4-5 shows that the UCS of soil 1B when tested wet (the soil used to surface Fox Park Road) was decreased when lignin was added. Thus, a weak layer of soil-lignin mix may have existed under the strong surface crust.

By equation (2.3) it can be shown that if a surface layer is 1/4 inch (6.35 mm) thick, then over 99% of the loads imposed by vehicles would be applied to the layer directly below the surface layer. Therefore, most of the traffic loads would have to be supported by the weak 3.75-inch (95 mm) layer of moist soil-lignin mix of the Fox Park Road.

Since the Fox Park Road had an average 3.75-inch (95 mm) layer of moist soil-lignin mix below the surface layer, it is reasonable to assume that the Fox Park Road surface failures, such as alligator cracks, resulted from this weak layer. Cracks in the surface layer might allow the break-up of the surface, creating a mechanism for the formation of pot holes and corrugations.

Surface deterioration in the Fox Park Road may be accelerated due to the effects of a weak layer under the surface layer combined with poor drainage. If during wet weather water sits in poorly drained areas, a temporarily high water table will result. The wet soil-lignin mix and high water table can produce a combination of reduced UCS and reduced effective stress. This in turn, will result in decreased shear strength. For example, the Fox Park Road surface material (soil 1B with lignin) displays a reduced UCS when specimens are tested wet (see Figure 4-5), and effective stress is reduced by a rising water table (increased pore water pressure). This combination of weakening factors may be due to the added moisture results in some of the lignin going into the liquid state. In this state lignin losses much of its ability to act as a cementing agent, and the cohesion of the soil-additive mix is reduced. In addition, the increase in pore water results in lower normal effective stress. This results in a weakened road surface.

By equation 2.1, if $c$ is reduced, and $\sigma$ is reduced by a rising water table (increased pore water pressure), then the shear strength of the road surface is reduced. This reduced shear strength may explain the deterioration observed on poorly drained sections of Fox Park Road (see Chapter 3, Section 3-4e.).

Soon after lignin was applied to the Fox Park Road there was a notable stabilization of the road surface. Unfortunately this stabilization was short-lived. This stabilization is explained by test results on the soil 1B-lignin mix, and by estimating the percentage of lignin in the road surface soil. For an average depth of lignin mix of 4 inches (102 mm), a soil density of 130 pcf (20.4 kN/m$^3$), and for the specific gravity 1.25 of lignin, the percent additive is:

$$\%\,Additive = \frac{(\frac{1}{2}gal)\left(\frac{0.13368ft^3}{gal}\right)(62.4pcf)(1.25)}{(130pcf)(9ft^2)\left(\frac{4}{12}ft\right)}100\% = 1.34\%$$

Figure 4-6 shows that 1.34% lignin results in substantial increases in UCS for specimens tested dry (degree of increase also depends on the moisture content at time of compaction). In addition, Figure 4-1 shows an increase in dry density of soil 1B even at small lignin concentrations. This increased density could be expected to increase shearing strength (McCarthy, 1993). In fact, for the conditions that the surface crust remain dry, with UCS increasing over 100%, the shear strength of soil 1B (the surface crust) should be greatly increased. This increase in shear strength should provide a strong surface layer that will stabilize a road surface constructed of soil 1B as long as the layer remains intact.

### Soil 1B

Some general conclusions can be drawn about the use of lignin sulfonate, calcium chloride ($CaCl_2$), magnesium chloride ($MgCl_2$) and clay as additives to soil 1B. First, while the addition of lignin increases dry density, adding $CaCl_2$, $MgCl_2$, or 8.5% clay does not. Next, only the addition of clay increased UCS for the soil tested wet. Other additives cause a decrease in UCS for specimens tested wet.

For specimens tested after air drying 7 days, both lignin and 8.5% clay increased UCS for soil 1B; whereas, adding $CaCl_2$ and $MgCl_2$ either decreased or did not change the UCS of specimens tested dry. Several conclusions may be drawn from these results; namely, to increase the shear strength and thereby increase the stability of a road constructed with soil 1B, one should do one, or a combination, of the following:

1. Add 8.5% kaolinite clay to soil 1B, which should result in both a stronger surface and a stronger layer under the surface crust.
2. Add lignin to the surface of the road in a way that would result in the lignin being in a very thin surface crust [about ½ inch (12.7 mm) thick].
3. Add 8.5% kaolinite clay to soil 1B, and then place a thin [about ½ inch (12.7 mm) thick] layer of a soil 1B-lignin mix.

Tests show that option 3 should produce the strongest layer system for soil 1B. This result is due to the slight increase in axial strength shown by soil 1B with kaolinite for specimens tested wet, and the large increase in axial strength for soil 1B-lignin specimens tested dry (see Figure 4-6).

## Soil 1Bk

The addition of lignin, $CaCl_2$, or $MgCl_2$ caused little change in peak values of the dry density of soil 1Bk. Relative to soil 1Bk specimens compacted with water alone, all specimens of soil 1Bk with additives exhibited decreased strength when tested wet, except for specimens of soil 1Bk with 1.75% $CaCl_2$ whose peak UCS remained about that of soil 1Bk compacted with water alone.

For specimens of soil 1Bk with lignin tested dry, UCS increased. This increase was greatest with 2.5% lignin, in which case axial strength was over 100% greater than that of specimens compacted with water alone (see Figure 4-12). Soil 1Bk with $CaCl_2$ decreased in axial strength for specimens tested dry, and the 1Bk-$MgCl_2$ mixture showed a small increase in peak UCS at a concentration of 2.5% only. Therefore, stabilization of roads constructed with soil 1Bk might be best accomplished by using either a thin layer [about ½ inch (12.7 mm) thick] of approximately 2.5% lignin-soil mix as the surface course, or a thin surface layer [about ½ inch (12.7 mm) thick] of 2.5% $MgCl_2$-soil mix. Of these options, the lignin-soil mix should best stabilize the road, due to its increase in UCS of more than 100%.

## Soil H-1c

The addition of lignin to soil H-1c produced no measurable effect on dry density. It may be concluded that lignin does not aid or hinder compaction of this soil. Furthermore, the application of lignin does not increase UCS due to densification.

Figure 5-1 shows that concentrations of 1% and 2.25% $CaCl_2$ produced increases in peak dry density over compaction using water alone. Increased density at these concentrations may be the result of two separate soil-additive reactions. For example, the addition of $CaCl_2$ may have increased the free water in the soil structure by cation exchange of the divalent $Ca^{++}$ with exchangeable ions. Secondly particle repulsions caused by reduced diffuse double layer thickness may allow the particles to slide by each other during shear. This may be the process that Ross (1988) and Grow et al. (1964) called an increase in lubrication between particles (see Chapter 2, Section 2-4). Determination of the method by which densification occurred is beyond the scope of this study.

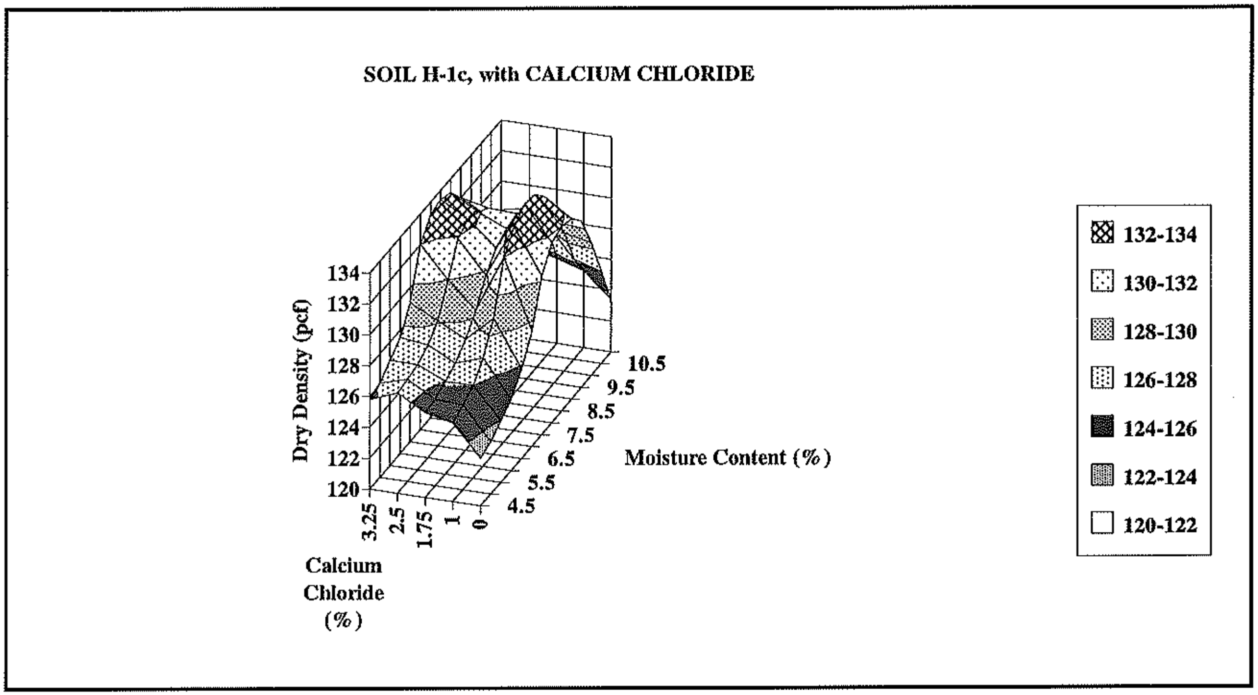

**Figure 5-1. Soil H-1c with CaCl$_2$, Moisture-Density Relationships** (1 pcf = 157 N/m$^3$).

Figure 5-2 shows that the addition of MgCl$_2$ to soil H-1c caused a shift in the optimum moisture content with little change in peak values of dry density. The trend of increased density at lower moisture contents is reduced as the concentration of MgCl$_2$ increases. Again, a study of this phenomenon is beyond the scope of this project. However, knowledge of this reaction could save water haul cost, since for a 1% MgCl$_2$-soil mix the amount of water required to reach a prescribed dry density could be reduced.

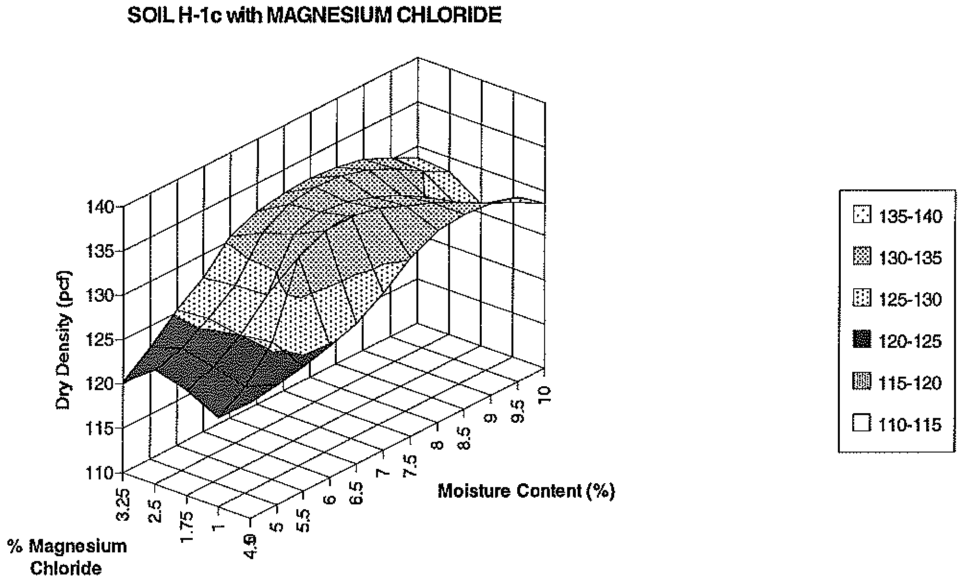

**Figure 5-2. Soil H-1c with $MgCl_2$, Moisture-Density Relationship** (1 pcf = 157 N/m$^3$).

Additions of lignin, $CaCl_2$ and $MgCl_2$ all had the effect of reducing UCS for specimens tested wet, but only the addition of lignin resulted in increased UCS for specimens tested dry. These test results narrow the options for stabilization of soil H-1c. Therefore, stabilization of a road surface constructed of soil H-1c would best be accomplished by adding a thin surface mixture of soil H-1c with 2.5% to 3.25% lignin.

## Wet-Dry Cycle for Lignin

For soil 1B, cycles of wetting and drying had the effect of reducing UCS of specimens' tested wet, but had little effect on UCS of specimens tested dry (see Figures 4-20, and 4-21). Therefore, a road surface containing a mix of soil 1B and lignin could be wetted and graded smooth without losing stabilization in the upper crust. However, simultaneously the moist soil under the dry crust could be expected to have a reduced axial strength. While these conclusions are backed up by laboratory tests, transferring these results to field conditions may be difficult. In the laboratory the lignin content remains constant in the specimen; in the field, spreading water on the soil-lignin mix could cause leaching of the lignin from the road surface soil.

## Conclusions from Consistency Tests

Additional tests were conducted to determine whether or not the data from previous tests could be repeated. It was found that dry densities and UCS were lower than in previous tests. This result could be due to several factors. However, the major factor was probably that a different operator performed the later tests. This person was very conscious of the need to compress the Harvard Miniature hammer only slightly to achieve the spring force wanted. As a result, the compactive effort was reduced compared to that of previous operators. Reduced compactive effort results in a higher optimum water content and a reduced dry density (Daniel, 1984). Consequently, it appears likely that the changes in dry density and strength are mainly the result of changing lab technicians. To reduce error caused by changes in operators, tests on a single soil should be conducted by the same technician. The use of a mechanical compaction device such as a kneading compactor might also provide a more consistent compactive force to the specimen.

## All Soils and Additives

A review of the data from all the tests suggests that peak UCS for specimens tested dry occurred within ± 1.5% of optimum moisture content. This was true of both the original tests and the later tests conducted by the second operator. Using this fact, the number of UC tests required to find peak strengths for soil-additive mixes may be reduced. By testing for UCS at optimum moisture content and at 1.5% on either side of optimum, the peak value of UCS for the combined soil-additive mix may be approximated fairly accurately. However an exception to this rule occurred with the soil 1B-lignin mix, since UCS for the soil 1B-lignin mix continued to increase with increased moisture content (Figure 4-6). Because no peaks for UCS were reached with the lignin and moisture contents tested, it is impossible to establish a deviation from optimum moisture content that would include the greatest UCS increases in soil 1B.

Another conclusion may be drawn by observing the increase in strength of the soil 1B-lignin mix associated with increasing moisture content, and by inspecting air dried specimens after they were tested. Inspection of the broken specimens shows that the outer portion of the specimen is darker than the interior portion. Figure 5-3 shows this schematically. Because lignin is dark colored, this change in color is probably due to increased lignin concentrations at the outer edge of the specimens. This effect is greatest with high concentrations of lignin in specimens that were formed at high moisture contents.

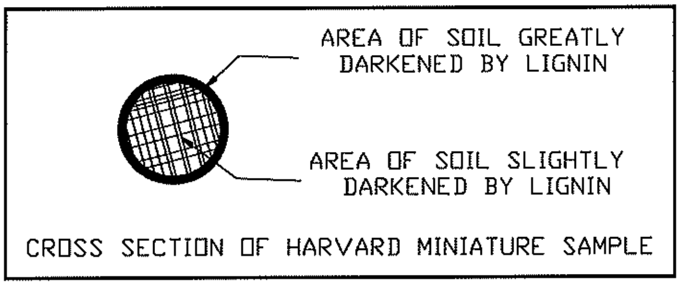

**Figure 5-3. Graphic of Lignin Migration.**

Apparently, lignin is transported along with water as it migrates from the interior of the specimen to the surface as the specimen dries. This process produces an outer shell with relatively high lignin concentrations.

Movement of lignin as the soil dries was also observed on Fox Park Road. After lignin was applied to Fox Park Road, specimens were taken from the road surface. The surface crusts in these specimens were darker near the road surface. Again this color change was probably due to lignin being drawn to the surface along with water as water moved to the surface and evaporated. Presently, the effect of lignin migration on specimen strength and on road stabilization is unknown. However, the unconfined compressive strength of soil 1B increased with lignin concentration, so a reasonable conclusion might be that the migration of lignin increases stabilization near the road surface. This migration of lignin to the surface would also make it more susceptible to erosion from the road surface.

## Caution

One should use caution in attempting to transfer the conclusions drawn from results of the three soils and additives tested to other soil-additive combinations. This is because different road surface soils may react differently to the application of an additive. As demonstrated in these tests, slight changes in soil type or clay content can cause large changes in UCS and peak dry densities. Consequently, each soil should be tested with the additives that are being considered for use.

## Summary of Conclusions

Correlation between tests of the soil 1B-lignin mixes and the application of lignin to Fox Park Road were quite good. Soil 1B with lignin is quite strong when dry, and the surface crust of Fox Park Road was initially strong. Weakness of the subsurface layer, as demonstrated by the results from testing specimens wet, could easily explain the cracking and break up of the surface of Fox Park Road. The loss of UCS in specimens of lignin-soil mixtures tested wet may be due to reduced friction between the soil particles. Reduced friction could be caused by ionic exchange resulting in reduced attraction between particles. When the specimen dries, the reduction in friction is overcome by cementation of the soil particles.

For each of the soils tested, lignin provided the greatest increases in strength as determined by UC tests. However, increases in UCS are not the only means by which a road may be stabilized. One should keep in mind that the strengths determined by UC tests are functions of cohesion, internal friction, and normal stress (see Chapter 2, Section 2-2, eq. 2.3) with cohesion playing a major role. Therefore, changes in UCS shown in the plots of the data may not be representative of the other factors that could increase shear strength.

Another factor that was not included in these tests was the difference in boundary conditions from UC tests to the road surface. On the road surface there will be some confining forces, whereas in the UC tests there is not. This means that the cohesive effect of an additive like lignin may not change the shear strength of the road surface as dramatically as it did the UCS.

Other additional strength variations and the resulting effects on stabilization may result from mixing soils and chemical additives. That is not to say that increases in cohesion are to be ignored. Indeed, cohesion changes are probably the most important result of adding chemicals to cohesionless soils.

In this case the development of cohesion in soils used to surface unpaved roads should greatly improve stabilization.

# CHAPTER 6

# RECOMMENDATIONS

## Introduction

The continuing need for improved unpaved road surfaces and reduced maintenance costs prompted this study. Recommendations given in this chapter on application rates, application methods and further study are intended to help achieve these goals.

## Soil Additive Concentrations

In Chapter 5, the use of various additive concentrations was suggested for stabilizing roads constructed of soils 1B, 1Bk, and H-1c. These suggestions were based on the results of testing additive concentrations between 1% and 3.25%. For some soil-additive mixes the apparent largest strength gains came within the range of concentrations tested. However, Figure 4-6 shows that for soil 1B the maximum unconfined compressive strength (UCS) occurred at 3.25% lignin sulfonate, which was the maximum concentration tested. Figure 4-6 also shows that UCS continued to increase with increased moisture content. For this soil, greater strengths might be obtained by higher concentrations of lignin or by compaction at higher moisture contents. If a soil-additive mix were to show these same trends, higher additive concentrations and moisture contents should be tested. This testing should continue until further increases in additive concentrations or moisture contents no longer produce an increase in UCS, or until additive concentrations become so great that they are no longer economically practical.

Another factor that influences additive concentrations is the rate at which additives are lost from the soil. Additive loss may be caused by wind or water erosion and by leaching. As an additive is removed from the soil, stabilization of the road surface may be reduced. If leaching is of concern, and if long-term stabilization or dust control is the objective of an additive application, it may be necessary to increase the additive concentration or to make additional additive applications over a given time period. This is to insure that the additive in the soil remains near the concentration that produces the greatest stabilization. The decision whether to use one application at higher concentrations, or to make additional application throughout the given time period, should be based upon strength test results and upon the costs associated with both methods.

Correct economic considerations can best be produced if the rate of additive loss is known. If one type of additive leaches from the soil more rapidly than another, then the additive that remains in the soil the longest should produce the greatest long-term benefit (all other factors being equal). Determining which additive will remain in a road surfacing soil the longest requires knowing the rate of additive leaching. A project currently under way at the University of Wyoming will attempt to find the rate at which additives leach from road surface soils.

For any road surfacing soil, the concentration of additive that produces the best results for dust control may be different from the most effective concentration for stabilization. That is, the concentration of an additive that best controls dust may produce little stabilization or even be ineffective or detrimental for stabilization. As an example, 3.25% $MgCl_2$ in soil H-1c may be very effective in controlling dust, but Figure 4-18 shows that this concentration of $MgCl_2$ reduces UCS in soil H-1c. When this is the case, some balance in concentration between the requirements for dust control and requirements for stabilization is necessary. This balance should depend on whether dust control or stabilization is the primary objective.

## Application Methods

The recommendations for application methods are also dependent on test results as demonstrated in Chapter 5, Sections 5-3, 5-4, and 5-5. If a soil-additive mix shows decreased strength when the specimens are tested wet (as did most of the soils tested in this study), then little of the mix should remain in a moist condition after application. This can be achieved by a shallow application of the additive [the additive being applied to about the top ½ inch (12.7 mm) of the road surface soil].

If the shearing strength of a dry soil is influenced by the moisture content at the time of compaction, then moisture content of the road surface should be at or near the content that produces peak strength. Sometimes this moisture content may be greater than optimum. If this is true, one must balance the moisture content that produces high density, with the moisture content that most improves UCS.

When both peak UCS and peak dry density occurs at or near optimum moisture contents, one should use compaction methods that result in a soil being compacted to within 95% of dry density at ± 2% of optimum moisture content. Also, the compaction equipment used should match the soil type. Hausmann (1990) says that smooth wheel rollers, static or vibrating, are most suitable for well-graded sand-gravel mixtures and for crushed rock. Typical applications for this type of compaction equipment are running surfaces, base courses, and subgrades for roads and runways. Hausmann also says that rubber-tired rollers are most-suitable for coarse-grained soils with some fines. By using proper compaction methods, equipment, and moisture contents, greater benefit can be obtained from an additive application.

If a liquid additive is detrimental to compaction, then compaction should take place before the additive is applied. Here, the method of additive application must include some system of insuring that the additive will be mixed with the top ½ inch (12.7 mm) of road surface soil. The City of Cheyenne, Wyoming, has developed such a system for applying magnesium chloride ($MgCl_2$) to unpaved road surfaces (Harker, 1994). The system used for application is as follows:

1. The day before $MgCl_2$ is to be applied
    - a. the road is scarified to a depth of 4 to 6 inches (102 to 152 mm)(must get below the bottom of any pot holes or corrugations)
    - b. water is added
    - c. the road surface is smoothed using a grader blade
    - d. the road surface is compacted using a rubber-tired roller.

2. The day of application
   - a the surface is scratched (usual using grader scarifiers) to a depth of about ½ inch (12.7 mm)
   - b. $MgCl_2$ is applied
   - c. the road surface is compacted with a rubber-tire roller.

The purpose of preparing the road surface before applying $MgCl_2$ is to provide a solid well-compacted base. Scratching the surface before applying the additive helps the additive mix with the top ½ inch (12.7 mm) of soil. Compaction after the application seals the road surface, and helps slow the loss of $MgCl_2$. The process of applying $MgCl_2$ is usually repeated twice per year, usually in the late spring or early summer when crews can plan on a 24-hour drying time, and again in the fall before the frost.

Besides controlling additive concentrations and moisture content, application methods must insure good quality control. If application practices result in widely varying additive concentrations on the road surface, weak spots may develop. These weak spots provide points for starting corrugations or the formation of pot holes.

One point at which the concentration of an additive can vary is during the process of scarifying and mixing the soil and additive. If the road surface is scarified uniformly (to a consistent depth), and the additive is well mixed, then the final grading need only provide a uniform thickness to insure a consistent concentration of additive. However, if scarification depth varies and mixing is insufficient, the resulting road surface will have areas of varying additive concentration (weak spots).

## Recommendations for Further Studies

A correlation of laboratory results with road performance is recommended. One method of accomplishing this goal would be to find roads suitable for study and then to test the soils from these roads in the laboratory. In choosing road sections to test, each section must be constructed of a single soil. This is to insure that soil-additive reactions will vary only due to the additive and not to changes in soil. If more than one soil is to be considered, then road sections constructed of that soil can be added. Each test section should have the same geometry both vertical and horizontal. This is to eliminate variations in performance caused by changing vertical grades or horizontal drainage. For instance, if one test section is on a slope and another is on level ground, differences in road surface roughness may be the result of vehicle acceleration or braking rather than soil-additive reactions. Also changes in horizontal drainage may result in variations in leaching rates, and these in turn could result in unplanned variations in additive concentrations.

Once road test sections have been chosen, the next step is to conduct laboratory tests on the road surface soils. These tests should be conducted in the manner described in Chapter 3. Laboratory test results can then be used to select additive concentrations and application methods for a variety of field test sections. The test sections should be monitored to discover the relationships between the laboratory tests and road performance.

A second recommendation is that economic analysis of additive applications be undertaken. This study should focus on the actual economic benefit, if any, of chemical additive stabilization. Some questions that should be answered by an economic study are:

1. Do reduced maintenance costs justify the cost of an additive application?
2. If an additive is to be applied for dust control, would the increased costs of applying an additive that also stabilizes the soil be justified by reduced maintenance costs?
3. When an additive is to be applied for dust control, what are the economic advantages of different applications of the additive so that stabilization will also occur (scarifying, grading and compacting the soil before or during the dust palliative application)?
4. Would there be a long-term economic advantage to chip-sealing unpaved roads rather than using chemical additive applications?

Some of these question could be answered by conducting an economic analysis in conjunction with the study to correlate laboratory test results and road performance.

A third recommendation is that an updated construction and maintenance manual for unpaved roads be produced. This manual should include good construction practices such as proper drainage, and the use of appropriate materials, as well as the economics of using in-situ soils and of importing higher-quality soils. The manual should also include good maintenance practices and address the choice of additives, methods of additive applications, and the economics of maintenance practices. While there are manuals that cover construction of unpaved roads, most are outdated and others address unpaved roads as though a base for paving was being constructed (Terrel et al., 1997). Soil stabilization is covered as though it were part of a pavement structure, and the use of stabilized soil as a long-term surface course is not covered. Compiling information on unpaved roads in a single volume might result in greater use of the material.

## Summary

There are many miles of unpaved roads that may need dust control or soil stabilization. While chemical additive use for dust control has been studied in detail, unpaved road soil stabilization using chemical additives has not. The literature review suggests that to stabilize a soil its shearing strength must be improved. The literature review also shows that the use of a particular additive may increase the shearing strength of some soils and not that of other soils.

Because each soil may react differently to the application of a particular additive, each soil should be tested with the additives being considered for purposes of dust control or stabilization. This testing can be done more economically in laboratories than in the field. Laboratory test results can then be used to recommend additive choices, additive concentrations, and application methods that have the best chance of improving the stability of an unpaved road's surface.

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# APPENDIX A

Apodaca and Huffmon (1990), Kezdi (1979), Scholen and Coghlan (1990) and Srombom (1987) gave, as part of their respective books or papers, recommendations on the use of various dust palliatives. The following is a list of additives and the pro's and con's of their use as stabilizing agents compiled from these authors' writings.

PRODUCT DESCRIPTION: Magnesium Chloride - a concentrated brine that pulls water out of the air. This product sinks into the road and creates a tight, hard, compact surface that resists abrasion. Dust control is by keeping the surface of the road damp. (Magnesium chlorides from industrial metal recovery are not recommended for use.)

| Pro's | Con's |
|---|---|
| 1. Aids in road surface compaction<br>2. Readily available<br>3. Road can be re-graded<br>4. Rainfall does not totally deteriorate product.<br>5. Limited hazard to workers<br>6. Lowers freezing point<br>7. Increases road stability | 1. May corrode steel<br>2. Rain may cause sloppy conditions.<br>3. Minimum curing time of 24 hours.<br>4. Requires that relative humidity be greater then (32% @ 77°)<br>5. No cementing action.<br>6. High concentration can be toxic to ecosystem. |

PRODUCT DESCRIPTION: Calcium Chloride - attracts and absorbs moisture from the atmosphere and environment. Dust control is by keeping the road surface damp.

| Pro's | Con's |
|---|---|
| 1. Provides some stability<br>2. Blading may be reduced<br>3. Saves aggregate<br>4. Reduces frost heave<br>5. Effective for approximately one year | 1. Requires that relative humidity be greater then (29% @ 77°)<br>2. Tends to migrate downward through soil.<br>3. Slightly corrosive to steel<br>4. May cause sloppy wet conditions<br>5. High concentrations of leachate may be toxic to ecosystem<br>6. Gets hot when mixed with water (may burn skin)<br>7. No cementing action |

PRODUCT DESCRIPTION: Lignin Sulfonate - a waste product of the wood pulping process, that is processed to form ammonium or calcium Lignin sulfonate containing approximately 50 percent solids, usually as concentrated water solutions. Dust control is by gluing and bonding soil particles together.

| Pro's | Con's |
|---|---|
| 1. Remains slightly plastic, can be regraded.<br>2. May increase load bearing strength<br>3. Environmentally safe<br>4. May mix with calcium carbonate slurry to counteract corrosive effects and increase dust laying capability<br>5. No relative humidity requirements<br>6. Limited hazard to workers<br>7. Weak cementing action<br>8. Lowers freezing point<br>9. Adding 0.5% lime extends the effectiveness and provides a tighter road surface with less aggregate loss. | 1. Sulfuric acid based product<br>2. Brown/red colored product on vehicles and in runoff<br>3. Water soluble and heavy leaching under wet conditions<br>4. May increase biochemical oxygen demand in water<br>5. Surface develops rough crust<br>6. Surface crust failures quickly spread<br>7. Wearing surface needs 4-8% fines<br>8. May cause corrosion of aluminum<br>9. Becomes slippery when wet and brittle when dry. |

PRODUCT DESCRIPTION: Bioenzymes - provide a bacterial culture in an enzyme solution. Exposure to $CO_2$ causes bacteria to multiply rapidly and produce large organic molecules which attach to the clay molecules in the aggregate. This action blankets the ion exchange points in the clay preventing absorption of moisture. During hydration, after compaction, linkages between closely packed particles proved cementing bonds.

| Pro's | Con's |
|---|---|
| 1. Clay lumps lose plasticity<br>2. Uninterrupted light traffic use<br>3. Non-corrosive<br>4. Long term stabilization | 1. Ineffective in non-clay soils<br>2. 5 days cure time required<br>3. High initial cost |

PRODUCT DESCRIPTION: Petroleum based emulsions (Resins combined with wetting solutions) - dust control by cohering to and coating dust particles, to form cohesive membranes that adhere to other particles.

| Pro's | Con's |
|---|---|
| 1. Long term effectiveness<br>2. Not water soluble when dry (no leaching after cured)<br>3. Provides soil stability<br>4. Suitable for a wide range of soils<br>5. No relative humidity requirements<br>6. Does not attract animals<br>7. Limited hazard to workers<br>8. Strong cementing action | 1. Requires special equipment for application<br>2. Potholes may develop<br>3. Does not lower freezing point<br>4. Long term application may cause road surface to become too hard for blading maintenance |

PRODUCT DESCRIPTION: Fly ash - when mixed with low grade aggregates and shales this produce increases durability. Usually blade mixed with road surfacing soil at 3 to 15 percent fly ash, watered to optimum and compacted. The optimum fly ash content must be determined by tests such as ASTM D-593 and ASTM D-689. Two types of fly ash are used, Class F which is usually mixed with lime or portland cement, and Class C which is self-cementing. Class C Fly ash is most common in the west (Hudson et. al. 1987).

| Pro's | Con's |
|---|---|
| 1. Reduction in surface blading<br>2. Increase in stability<br>3. Stable in wet weather<br>4. Effective over long term | 1. High PI sections may become slippery when wet (the addition of lime may be used to reduce the PI)<br>2. Requires curing periods of from 5 to 10 days<br>3. Fly ash may contain ecology undesirable materials |

There are other agents that can be used to stabilize unpaved road surfaces. Some of these agents (such as Lime Kiln Dust) may harden the surface to such an extent that they cannot be cut with blade or scarifiers (Scholen & Coghlan 1990). Others may be cost prohibitive at this time, (such as Phosphate Mining Waste due to the cost of removing impurities) but improved technology may allow their application in the future (Figueroa 1987).

The preceding list does not include all of the dust palliatives, and stabilizing agents available; however, many commercial agents are basically composed of one or more of these agents. (see trade names listed by Apodaca 1990, Scholen & Coghlan 1990). Some of these products have had other chemicals added to improve their performance.

(Appendix A was reprinted in part from MPC Report No.93-22, Boresi and Palmer, 1993.)

# APPENDIX B

This appendix includes data sheets that summarize the peak values for: dry density from Standard Proctor tests, axial stress, and dry density as calculated from Harvard Miniature samples.

Values of dry density under the heading Samples Tested Dry are found by taking the sample weight at time of sample formation, and dividing this weight by the sample volume after the sample has air dried from 7 days times 1 plus the moisture content at the time of sample formation.

$$\frac{\text{Sample weight at formation}}{\text{Sample volume after air drying 7 days} \times (1 + \text{Moisture content})}$$

| Soil 1B with Water | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Samples tested wet | | | Samples tested dry | | | Avg. | Proctor | |
| | Axial | Dry | | Axial | Dry | Axial | | Dry |
| Moilsture | Stress | Density | Moilsture | Stress | Density | Stress | Moisture | Density |
| (%) | (psf) | (pcf) | (%) | (psf) | (pcf) | (psf) | (%) | (pcf) |
| 3.22 | 1911.16 | 125.60 | 3.26 | 7471.01 | 125.97 | 6732.44 | 2.38 | 130.98 |
| 3.33 | 2508.23 | 126.60 | 3.26 | 5993.87 | 126.10 | | 3.99 | 133.28 |
| 5.68 | 3191.07 | 130.10 | 5.73 | 23599.85 | 128.28 | 24641.33 | 5.63 | 134.34 |
| 5.77 | 3490.51 | 130.60 | 5.73 | 25682.81 | 129.58 | | 7.17 | 136.89 |
| 7.30 | 2514.69 | 130.50 | 7.47 | 34501.64 | 129.95 | 35491.92 | 8.70 | 136.61 |
| 7.63 | 2388.95 | 132.00 | 7.47 | 36482.20 | 130.55 | | 9.87 | 134.08 |
| 8.49 | 3296.18 | 135.50 | 8.59 | 44644.64 | 131.88 | 47283.39 | | |
| 8.69 | 3453.10 | 135.50 | 8.59 | 49922.13 | 123.80 | | | |
| 8.88 | 3156.44 | 134.50 | 8.98 | 45932.15 | 133.01 | 45342.53 | | |
| 9.07 | 2621.74 | 135.11 | 8.98 | 44752.91 | 129.51 | | | |
| 9.99 | 2899.35 | 134.80 | 10.00 | 42642.41 | 133.60 | 43017.22 | | |
| 10.01 | 2755.90 | 135.20 | 10.00 | 43392.02 | 132.21 | | | |

| Soil 1B, with Lignin | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Samples Tested Wet | | | Samples Tested Dry | | | Avg. | Proctor | |
| | | Axial | Dry | | Axial | Dry | Axial | | Dry |
| Lignin | Moisture | Stress | Density | Moisture | Stress | Density | Stress | Moisture | Density |
| (%) | (%) | (psf) | (pcf) | (%) | (psf) | (pcf) | (psf) | (%) | (pcf) |
| 1 | 3.53 | 2839.71 | 125.36 | 3.51 | 20981.84 | 125.67 | 21239.1 | 4.51 | 134.34 |
| 1 | 3.50 | 2850.02 | 125.03 | 3.51 | 21496.39 | 125.56 | | 5.83 | 137.20 |
| 1 | 4.69 | 2869.35 | 125.85 | 4.72 | 31364.65 | 126.22 | 31588.4 | 7.98 | 137.80 |
| 1 | 4.74 | 2676.36 | 125.58 | 4.72 | 31812.14 | 126.19 | | 9.05 | 135.90 |
| 1 | 6.20 | 2918.09 | 128.17 | 6.23 | 60875.4 | 428.42 | 62300.9 | | |
| 1 | 6.26 | 2790.18 | 128.16 | 6.23 | 63726.49 | 128.59 | | | |
| 1 | 8.68 | 2941.65 | 132.30 | 8.73 | 97455.7 | 132.39 | 98009.4 | | |
| 1 | 8.78 | 2852.57 | 131.82 | 8.73 | 98563.08 | 132.59 | | | |
| 1 | 9.75 | 3275.97 | 133.93 | 9.85 | 118961.79 | 134.03 | 119612 | | |
| 1 | 9.95 | 3209.57 | 133.49 | 9.85 | 120261.67 | 132.75 | | | |
| | | | | | | | | | |
| 1.75 | 3.52 | 2973.63 | 123.96 | 3.52 | 23657.99 | 124.30 | 23488.4 | 5.31 | 135.60 |
| 1.75 | 3.53 | 2973.63 | 124.98 | 3.52 | 23318.82 | 123.91 | | 6.83 | 139.29 |
| 1.75 | 4.79 | 2973.63 | 126.03 | 4.87 | 36804.52 | 125.20 | 36235.5 | 7.79 | 138.89 |
| 1.75 | 4.96 | 2725.92 | 125.02 | 4.87 | 35666.56 | 125.09 | | 9.91 | 134.02 |
| 1.75 | 6.50 | 2512.91 | 122.89 | 6.54 | 81476.46 | 129.01 | 77273.6 | | |
| 1.75 | 6.58 | 2918.05 | 129.32 | 6.54 | 73070.8 | 127.63 | | | |
| 1.75 | 8.42 | 3030.47 | 132.11 | 8.50 | 116515.61 | 133.49 | 114614 | | |
| 1.75 | 8.57 | 2892.6 | 132.94 | 8.50 | 112713.03 | 132.91 | | | |
| 1.75 | 9.36 | 3267.15 | 133.16 | 9.40 | 137837.68 | 133.60 | 136546 | | |
| 1.75 | 9.43 | 3169.38 | 133.67 | 9.40 | 135253.61 | 133.40 | | | |
| | | | | | | | | | |
| 2.5 | 3.58 | 2502.91 | 122.74 | 3.57 | 22657.11 | 121.51 | 26008.2 | 5.80 | 136.11 |
| 2.5 | 3.55 | 2790.11 | 123.40 | 3.57 | 29359.22 | 123.05 | | 7.34 | 140.02 |
| 2.5 | 4.46 | 2770.4 | 124.06 | 4.46 | 39985.03 | 121.28 | 40852.7 | 8.68 | 137.47 |
| 2.5 | 4.46 | 2712.03 | 123.73 | 4.46 | 41720.31 | 119.09 | | 10.14 | 132.92 |
| 2.5 | 6.14 | 2431.32 | 127.87 | 6.14 | 90868.55 | 128.70 | 89796.2 | | |
| 2.5 | 6.15 | 2761.23 | 127.82 | 6.14 | 88723.91 | 128.00 | | | |
| 2.5 | 8.82 | 3306.87 | 133.95 | 8.86 | 127077.17 | 133.34 | 125267 | | |
| 2.5 | 8.91 | 3245.72 | 133.72 | 8.86 | 123456.48 | 132.87 | | | |
| 2.5 | 10.52 | 2264.5 | 131.61 | 10.57 | 139173.38 | 135.19 | 133293 | | |
| 2.5 | 10.66 | 2200.24 | 131.31 | 10.57 | 127412.65 | 134.30 | | | |
| | | | | | | | | | |
| 3.25 | 4.35 | 2601.91 | 122.70 | 4.36 | 39654.01 | 122.55 | 40971.2 | 4.80 | 131.68 |
| 3.25 | 4.37 | 2671.51 | 123.72 | 4.36 | 42288.31 | 122.88 | | 4.47 | 131.81 |
| 3.25 | 4.40 | 2432.91 | 123.34 | 4.42 | 39803.02 | 122.40 | 40047.6 | 5.58 | 136.11 |
| 3.25 | 4.43 | 2601.99 | 123.71 | 4.42 | 40292.16 | 123.52 | | 6.51 | 137.45 |
| 3.25 | 7.07 | 2838.78 | 129.34 | 7.10 | 110281.02 | 129.18 | 116007 | 8.13 | 138.72 |
| 3.25 | 7.13 | 2690.56 | 128.98 | 7.10 | 121733.79 | 129.70 | | 8.96 | 136.56 |
| 3.25 | 9.11 | 2972.35 | 132.48 | 9.10 | 149878.16 | 133.45 | 145568 | | |
| 3.25 | 9.10 | 3043.49 | 132.85 | 9.10 | 141257.04 | 132.24 | | | |
| 3.25 | 10.06 | 2760.55 | 133.19 | 10.18 | 156135.39 | 135.50 | 157909 | | |
| 3.25 | 10.30 | 2520.37 | 132.96 | 10.18 | 159682.75 | 135.19 | | | |

| Soil 1B with Magnesium Chloride | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | Samples tested wet | | | Samples tested dry | | | | Proctor | |
| MgCl2 (%) | Moisture (%) | Axial Stress (psf) | Dry Density (pcf) | Moisture (%) | Axial Stress (psf) | Dry Density (pcf) | Avg. Axial Stress (psf) | Moisture (%) | Dry Density (pcf) |
| 1 | 3.87 | 2369.91 | 126.02 | 3.94 | 14722.01 | 120.07 | 14909.68 | 4.65 | 126.99 |
| 1 | 4.01 | 2863.79 | 122.61 | 3.94 | 15097.35 | 120.61 | | 6.12 | 126.90 |
| 1 | 4.68 | 3397.23 | 122.01 | 4.76 | 25555.11 | 121.42 | 25663.52 | 7.21 | 130.68 |
| 1 | 4.84 | 3340.89 | 122.09 | 4.76 | 25771.92 | 122.13 | | 9.07 | 134.77 |
| 1 | 6.45 | 3224.11 | 124.25 | 6.62 | 42900.46 | 128.88 | 43765.45 | 10.80 | 129.96 |
| 1 | 7.17 | 3267.65 | 122.95 | 6.62 | 44630.43 | 128.24 | | | |
| 1 | 8.24 | 2900.25 | 126.88 | 8.26 | 57999.84 | 126.16 | 52539.93 | | |
| 1 | 8.28 | 2950.46 | 127.63 | 8.26 | 47080.01 | 125.31 | | | |
| 1 | 10.34 | 2629.78 | 129.12 | 10.40 | 51381.98 | 127.35 | 45302.27 | | |
| 1 | 10.35 | 2837.64 | 129.04 | 10.40 | 39222.55 | 128.55 | | | |
| | | | | | | | | | |
| 1.75 | 4.06 | 3016.37 | 122.03 | 4.40 | 15163.93 | 122.64 | 16425.51 | 4.70 | 127.20 |
| 1.75 | 4.15 | 3030.71 | 122.92 | 4.40 | 17687.08 | 121.32 | | 6.01 | 126.50 |
| 1.75 | 4.95 | 2975.99 | 123.26 | 5.00 | 24031.59 | 122.70 | 22161.75 | 7.62 | 131.30 |
| 1.75 | 5.04 | 3307.46 | 122.1 | 5.00 | 20291.90 | 122.30 | | 8.79 | 134.85 |
| 1.75 | 7.26 | 2799.69 | 126.16 | 7.28 | 41828.31 | 124.75 | 42657.16 | 10.67 | 129.84 |
| 1.75 | 7.3 | 2743.61 | 125.75 | 7.28 | 43486.00 | 125.01 | | | |
| 1.75 | 8.3 | 2697.77 | 127.05 | 8.30 | 54774.29 | 126.19 | 47700.34 | | |
| 1.75 | 8.31 | 2774.07 | 127.34 | 8.30 | 40626.39 | 125.53 | | | |
| 1.75 | 10.28 | 2732.39 | 129.22 | 10.40 | 39791.51 | 128.52 | 41671.57 | | |
| 1.75 | 10.48 | 2430.43 | 130.13 | 10.40 | 43551.62 | 128.51 | | | |
| | | | | | | | | | |
| 2.5 | 4.26 | 2806.82 | 122.38 | 4.10 | 16148.84 | 120.73 | 16497.7 | 4.85 | 124.70 |
| 2.5 | 4.28 | 2915.73 | 122.38 | 4.10 | 16846.55 | 122.02 | | 6.59 | 125.20 |
| 2.5 | 5.28 | 3276.35 | 123.95 | 5.31 | 32281.13 | 123.96 | 32616.09 | 7.78 | 131.66 |
| 2.5 | 5.34 | 2958.29 | 124.01 | 5.31 | 32951.05 | 122.81 | | 8.89 | 135.00 |
| 2.5 | 6.54 | 3326.22 | 126.11 | 6.65 | 32626.60 | 124.85 | 36041.52 | 10.70 | 130.08 |
| 2.5 | 6.76 | 2914.98 | 125.1 | 6.65 | 39456.44 | 124.44 | | | |
| 2.5 | 7.96 | 2856.94 | 127 | 8.06 | 45984.74 | 125.66 | 48254.42 | | |
| 2.5 | 8.16 | 2869.73 | 127.44 | 8.06 | 50524.10 | 126.06 | | | |
| 2.5 | 10.4 | 2300.11 | 132.35 | 10.60 | 29147.53 | 134.04 | 28405.42 | | |
| 2.5 | 10.67 | 1979.43 | 128.54 | 10.60 | 27663.30 | 127.97 | | | |
| | | | | | | | | | |
| 3.25 | 4.53 | 2859.85 | 122 | 4.55 | 26302.88 | 121.99 | 24921.38 | 5.32 | 125.00 |
| 3.25 | 4.58 | 3043.77 | 123.74 | 4.55 | 23539.87 | 122.71 | | 6.23 | 126.20 |
| 3.25 | 5.54 | 3092.19 | 124.54 | 5.60 | 36179.92 | 129.04 | 35194.4 | 7.56 | 131.65 |
| 3.25 | 5.67 | 3091.98 | 124.76 | 5.60 | 34208.88 | 128.91 | | 9.03 | 134.55 |
| 3.25 | 8.02 | 2729.66 | 127.27 | 8.04 | 62855.67 | 126.76 | 62725.56 | 10.58 | 130.50 |
| 3.25 | 8.05 | 2792.73 | 126.36 | 8.04 | 62595.44 | 127.64 | | | |
| 3.25 | 8.91 | 2974.85 | 128.88 | 8.92 | 54042.83 | 126.44 | 49481.23 | | |
| 3.25 | 8.93 | 2918.73 | 128.06 | 8.92 | 44919.63 | 127.45 | | | |
| 3.25 | 10.52 | 2120.79 | 130.6 | 10.60 | 26573.49 | 127.92 | 31369.6 | | |
| 3.25 | 10.73 | 2069.13 | 130.6 | 10.60 | 36165.70 | 127.83 | | | |

| Soil 1B with Calcium Chloride | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | Samples Tested Wet | | | Samples Tested Dry | | | Avg | Proctor | |
| | | Axial | Dry | | Axial | Dry | Axial | | Dry |
| CaCl2 | Moisture | Stress | Density | Moisture | Stress | Density | Stress | Moisture | Density |
| (%) | (%) | (psf) | (pcf) | (%) | (psf) | (pcf) | (psf) | (%) | (pcf) |
| 1 | 4.40 | 3373.79 | 122.66 | 4.40 | 20915.89 | 121.23 | 22096.35 | 5.12 | 130.99 |
| 1 | 4.37 | 3244.54 | 121.53 | 4.40 | 23276.80 | 121.49 | | 7.08 | 133.35 |
| 1 | 5.27 | 2923.78 | 123.62 | 5.26 | 35613.91 | 127.83 | 34642.70 | 8.48 | 133.63 |
| 1 | 5.26 | 3231.30 | 123.85 | 5.26 | 33671.48 | 128.05 | | 9.64 | 133.25 |
| 1 | 6.70 | 2679.03 | 124.27 | 6.71 | 36882.82 | 125.42 | 38348.54 | | |
| 1 | 6.72 | 2771.64 | 125.00 | 6.71 | 39814.26 | 124.59 | | | |
| 1 | | | | 9.00 | 49384.04 | 125.89 | 50754.06 | | |
| 1 | 9.06 | 2883.52 | 127.34 | 9.00 | 52124.08 | 125.46 | | | |
| 1 | 10.88 | 2382.40 | 130.56 | 10.90 | 39020.71 | 129.38 | 40079.62 | | |
| 1 | 10.92 | 2190.95 | 130.47 | 10.90 | 41138.52 | 127.51 | | | |
| | | | | | | | | | |
| 1.75 | 4.41 | 2792.14 | 121.79 | 4.43 | 12662.14 | 121.64 | 14292.02 | 5.41 | 131.21 |
| 1.75 | 4.46 | 3155.40 | 122.75 | 4.43 | 15921.89 | 121.62 | | 7.05 | 133.96 |
| 1.75 | 5.36 | 3262.16 | 124.33 | 5.39 | 29300.06 | 128.26 | 29735.40 | 8.05 | 135.21 |
| 1.75 | 5.42 | 3205.28 | 124.39 | 5.39 | 30170.74 | 127.41 | | 9.64 | 133.53 |
| 1.75 | 6.60 | 2678.53 | 126.08 | 6.60 | 33562.13 | 125.02 | 34782.31 | | |
| 1.75 | 6.61 | 2822.85 | 126.04 | 6.60 | 36002.49 | 125.61 | | | |
| 1.75 | 8.05 | 3046.26 | 128.23 | 7.15 | 39553.76 | 126.96 | 43094.80 | | |
| 1.75 | 8.26 | 2758.64 | 127.70 | 7.15 | 46635.84 | 126.90 | | | |
| 1.75 | 10.61 | 2388.18 | 126.66 | 10.60 | 39701.86 | 133.18 | 37097.53 | | |
| 1.75 | 10.64 | 2374.47 | 130.20 | 10.60 | 34493.20 | 129.20 | | | |
| | | | | | | | | | |
| 2.5 | 5.19 | 2982.04 | 123.55 | 5.28 | 15593.47 | 123.03 | 14687.89 | 5.54 | 131.32 |
| 2.5 | 5.25 | 2864.55 | 122.97 | 5.28 | 13782.31 | 123.04 | | 7.20 | 133.21 |
| 2.5 | 5.77 | 2791.11 | 125.23 | 5.80 | 32244.88 | 128.48 | 30885.39 | 7.81 | 135.80 |
| 2.5 | 5.84 | 2972.46 | 124.67 | 5.80 | 29525.89 | 127.88 | | 9.75 | 133.40 |
| 2.5 | 6.61 | 2619.28 | 126.51 | 6.71 | 26812.54 | 125.24 | 27442.20 | | |
| 2.5 | 6.80 | 2934.37 | 125.83 | 6.71 | 28071.86 | 125.37 | | | |
| 2.5 | 8.50 | 2661.77 | 129.09 | 8.60 | 33916.00 | 127.24 | 35708.60 | | |
| 2.5 | 8.70 | 2594.42 | 129.31 | 8.60 | 37501.20 | 126.21 | | | |
| 2.5 | 10.55 | 1949.44 | 132.41 | 10.70 | 34199.12 | 128.98 | 34990.07 | | |
| 2.5 | 10.77 | 1675.14 | 129.58 | 10.70 | 35781.01 | 129.37 | | | |
| | | | | | | | | | |
| 3.25 | 5.71 | 3038.96 | 124.57 | 5.74 | 22567.33 | 129.44 | 22397.95 | 5.96 | 133.07 |
| 3.25 | 5.76 | 2699.29 | 124.13 | 5.74 | 22228.56 | 128.69 | | 6.80 | 133.70 |
| 3.25 | 6.07 | 2919.40 | 124.42 | 6.11 | 38074.24 | 128.60 | 37056.41 | 7.36 | 136.64 |
| 3.25 | 6.16 | 3247.76 | 124.34 | 6.11 | 36038.58 | 128.51 | | 9.63 | 133.82 |
| 3.25 | 6.98 | 2698.47 | 126.67 | 7.12 | 21288.08 | 125.97 | 26137.20 | | |
| 3.25 | 7.25 | 2833.81 | 126.19 | 7.12 | 30986.32 | 125.55 | | | |
| 3.25 | 8.86 | 3165.46 | 129.11 | 8.97 | 39474.28 | 128.60 | 37680.41 | | |
| 3.25 | 9.09 | 2898.41 | 128.83 | 8.97 | 35886.53 | 128.28 | | | |
| 3.25 | 10.37 | 2115.67 | 127.79 | 10.40 | 39233.17 | 129.92 | 34665.60 | | |
| 3.25 | 10.35 | 2146.76 | 130.27 | 10.40 | 30098.02 | 134.42 | | | |

| Soil 1B with 2% and 3% Lignin (Second Operator) | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| | Samples Tested Wet | | | Samples Tested Dry | | | | |
| Lignin (%) | Moisture Content (%) | Dry Density (pcf) | Axial Stress (psf) | Moisture Content (%) | Axial Stress (psf) | Avg. Axial Stress (psf) | Proctor Moisture Content (%) | Proctor Dry Density (pcf) |
| 2 | 4.91 | 124.07 | 1803.2 | 4.94 | 34992 | 31672 | 5.11 | 126.26 |
| 2 | 4.96 | 125.26 | 1999.6 | 4.94 | 28352 | | 6.87 | 128.29 |
| 2 | 6.60 | 126.70 | 1864 | 6.59 | 53213 | 52433 | 8.48 | 130.01 |
| 2 | 6.58 | 126.73 | 1836.6 | 6.59 | 51653 | | 9.60 | 131.53 |
| 2 | 8.19 | 128.36 | 1608.53 | 8.14 | 67728 | 62621.5 | 11.35 | 128.27 |
| 2 | 8.09 | 128.73 | 1615 | 8.14 | 57515 | | | |
| 2 | 9.90 | 130.71 | 1668.5 | 9.88 | 66225 | 66896 | | |
| 2 | 9.86 | 130.89 | 1867.6 | 9.88 | 67567 | | | |
| 2 | 10.90 | 129.53 | 1430.5 | 10.82 | 58406 | 63603 | | |
| 2 | 10.73 | 131.37 | 1672.5 | 10.82 | 68800 | | | |
| | | | | | | | | |
| 3 | 5.08 | 125.76 | 1812 | 5.09 | 46048 | 45587.5 | 5.35 | 126.41 |
| 3 | 5.09 | 124.98 | 1781 | 5.09 | 45127 | | 6.87 | 128.93 |
| 3 | 6.72 | 126.72 | 1704 | 6.67 | 68325 | 68542 | 8.49 | 130.55 |
| 3 | 6.61 | 127.28 | 1695 | 6.67 | 68759 | | 9.70 | 131.13 |
| 3 | 8.59 | 128.99 | 1553 | 8.66 | 90225 | 85537 | 11.36 | 127.39 |
| 3 | 8.72 | 129.67 | 1684 | 8.66 | 80849 | | | |
| 3 | 9.78 | 129.96 | 1541 | 9.76 | 81025 | 82033.5 | | |
| 3 | 9.74 | 130.91 | 1774 | 9.76 | 83042 | | | |
| 3 | 11.44 | 129.76 | 1211 | 11.44 | 70761 | 68128 | | |
| 3 | 11.44 | 129.61 | 1255 | 11.44 | 65495 | | | |

| Soil 1B, 2% and 3% Calcium Chloride (Second Operator) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | Samples tested wet | | | Samples tested dry | | | | | |
| CaCl2 (%) | Moisture (%) | Axial Stress (psf) | Dry Density (pcf) | Moisture (%) | Axial Stress (psf) | Dry Density (pcf) | Average Axial Stress (psf) | Proctor Moisture % | Dry Density (pcf) |
| 2 | 5.14 | 1931.1 | 124.22 | 5.13 | 8399.9 | 124.17 | 8311.50 | 5.62 | 124.07 |
| 2 | 5.12 | 2052.9 | 123.77 | 5.13 | 8223.1 | 124.48 | | 6.75 | 126.43 |
| 2 | 6.83 | 1789 | 125.88 | 6.82 | 10816.4 | 125.90 | 10066.45 | 8.27 | 128.16 |
| 2 | 6.81 | 1884.3 | 126.12 | 6.82 | 9316.5 | 125.69 | | 9.60 | 129.41 |
| 2 | 7.83 | 1599.6 | 126.22 | 7.82 | 13826.3 | 126.35 | 13891.85 | 10.65 | 130.19 |
| 2 | 7.80 | 1703.8 | 127.00 | 7.82 | 13957.4 | 126.65 | | 10.78 | 129.44 |
| 2 | 9.25 | 1769.4 | 128.58 | 9.25 | 19600.5 | 128.35 | 19042.75 | 12.29 | 126.18 |
| 2 | 9.24 | 1821.4 | 129.62 | 9.25 | 18485 | 128.36 | | | |
| 2 | 10.81 | 1826.4 | 129.89 | 10.71 | 16699.3 | 129.65 | 16477.75 | | |
| 2 | 10.61 | 2024.45 | 131.04 | 10.71 | 16256.2 | 127.73 | | | |
| | | | | | | | | | |
| 3 | 5.24 | 1989.1 | 124.15 | 5.24 | 6457.1 | 124.65 | 6327.05 | 5.73 | 125.50 |
| 3 | 5.24 | 1916.9 | 123.61 | 5.24 | 6197 | 124.28 | | 6.80 | 126.38 |
| 3 | 6.61 | 1801.3 | 126.14 | 6.59 | 7814.1 | 126.17 | 7466.50 | 8.22 | 128.99 |
| 3 | 6.56 | 1880.7 | 126.05 | 6.59 | 7118.9 | 126.03 | | 9.65 | 130.09 |
| 3 | 8.06 | 1532.5 | 127.28 | 8.04 | 9909 | 127.60 | 9793.25 | 10.96 | 129.40 |
| 3 | 8.01 | 1563.2 | 127.25 | 8.04 | 9677.5 | 126.29 | | 12.31 | 126.22 |
| 3 | 9.27 | 1781.5 | 129.85 | 9.26 | 14312.2 | 128.90 | 13891.15 | | |
| 3 | 9.24 | 1904.1 | 130.65 | 9.26 | 13470.1 | 129.19 | | | |
| 3 | 10.86 | 1665.6 | 130.94 | 10.81 | 13064.4 | 129.76 | 12976.55 | | |
| 3 | 10.76 | 1933.8 | 129.26 | 10.81 | 12888.7 | 129.25 | | | |
| | | | | | | | | | |

Soil 1B with 2% and 3% Magnesium Chloride (Second Operator)

| | Samples tested Wet | | | Samples Tested Dry | | | Avg. | Proctor | |
|---|---|---|---|---|---|---|---|---|---|
| Mag (%) | Moisture Content (%) | Dry Density (pcf) | Axial Stress (psf) | Moisture Content (%) | Dry Density (pcf) | Axial Stress (psf) | Axial Stress (psf) | Moisture Content (%) | Dry Density (%) |
| 2.00 | 4.90 | 124.63 | 1922.7 | 4.89 | 124.62 | 8458.2 | 8297.1 | 5.22 | 126.63 |
| 2.00 | 4.88 | 124.26 | 2007.7 | 4.89 | 125.00 | 8136 | | 6.90 | 128.70 |
| 2.00 | 6.35 | 125.71 | 1877.4 | 6.38 | 125.94 | 12377.9 | 11652.85 | 8.45 | 129.79 |
| 2.00 | 6.41 | 125.52 | 1941.7 | 6.38 | 125.54 | 10927.8 | | 9.56 | 131.57 |
| 2.00 | 7.83 | 127.56 | 1602.9 | 7.83 | 127.44 | 13674 | 13329 | 11.34 | 129.03 |
| 2.00 | 7.82 | 126.40 | 1554.8 | 7.83 | 126.72 | 12984 | | | |
| 2.00 | 9.58 | 127.99 | 1666.4 | 9.61 | 129.24 | 18540.5 | 18371.9 | | |
| 2.00 | 9.63 | 130.15 | 1726.8 | 9.61 | 128.98 | 18203.3 | | | |
| 2.00 | 10.90 | 128.93 | 1811.2 | 10.83 | 129.52 | 16157.4 | 16429.65 | | |
| 2.00 | 10.76 | 128.58 | 1864.4 | 10.83 | 129.80 | 16701.9 | | | |
| | | | | | | | | | |
| 3.00 | 4.94 | 124.28 | 1813.3 | 4.95 | 124.33 | 6543 | 6089.55 | 5.46 | 124.68 |
| 3.00 | 4.95 | 124.03 | 1762.5 | 4.95 | 123.81 | 5636.1 | | 6.78 | 126.88 |
| 3.00 | 6.27 | 125.98 | 1693.6 | 6.31 | 126.02 | 8162.6 | 8064.3 | 8.07 | 128.16 |
| 3.00 | 6.35 | 125.45 | 1722.8 | 6.31 | 126.41 | 7966 | | 9.33 | 129.52 |
| 3.00 | 7.78 | 127.64 | 1480 | 7.76 | 126.71 | 10504.1 | 10104.3 | 10.8 | 128.93 |
| 3.00 | 7.73 | 127.85 | 1594 | 7.76 | 125.84 | 9704.5 | | 11.96 | 126.15 |
| 3.00 | 9.30 | 130.02 | 1827 | 9.27 | 129.29 | 14104.7 | 14409.5 | | |
| 3.00 | 9.24 | 130.23 | 1948.4 | 9.27 | 129.42 | 14714.3 | | | |
| 3.00 | 10.68 | 129.86 | 1759.8 | 10.66 | 129.78 | 13453.8 | 13080.2 | | |
| 3.00 | 10.64 | 130.57 | 1610 | 10.66 | 128.81 | 12706.6 | | | |

| Soil 1Bk with Water | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | | | |
| Sample tested wet | | | Sample tested dry | | | Avg. | Proctor | |
| Moisture Content % | Axial Stress (psf) | Dry Density (pcf) | Moisture Content % | Axial Stress (psf) | Dry Density (pcf) | Axial Stress (psf) | Moisture Content % | Dry Density (pcf) |
| 4.53 | 4709.4 | 119.83 | 4.58 | 6013.26 | 121.42 | 5248.2 | 6.06 | 125.31 |
| 4.63 | 4462.72 | 121.38 | 4.58 | 4483.14 | 121.64 | | 7.39 | 133.25 |
| 5.63 | 7090.28 | 119.42 | 5.65 | 12592.06 | 119.91 | 11874.01 | 8.45 | 135.83 |
| 5.67 | 7942.03 | 120.4 | 5.65 | 11155.95 | 119.69 | | 9.37 | 133.86 |
| 7.51 | 10202.16 | 129.78 | 7.54 | 39550.99 | 129.79 | 40855.01 | | |
| 7.58 | 9884.54 | 129.84 | 7.56 | 42159.03 | 131.25 | | | |
| 8.95 | 6296.46 | 135.49 | 8.99 | 54087.28 | 138.89 | 52947.3 | | |
| 9.02 | 6007.36 | 134.45 | 8.99 | 51807.32 | 128.55 | | | |
| 10.9 | 1349.67 | 129.56 | 10.95 | 50146.78 | 137.006 | 49812.64 | | |
| 11 | 1282.29 | 129.65 | 10.95 | 49478.5 | 136.96 | | | |

| Soil 1Bk with Lignin | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | Sample tested wet | | | Sample tested dry | | | Avg. | Proctor | |
| Lignin % | Moisture Content % | Axial Stress (psf) | Dry Density (pcf) | Moisture Content % | Axial Stress (psf) | Dry Density (pcf) | Axial Stress (psf) | Moisture Content % | Dry Density (pcf) |
| 1 | 3.82 | 3783 | 122.06 | 3.83 | 12977 | 121.64 | 12085 | 5.71 | 124.14 |
| 1 | 3.84 | 4239 | 121.41 | 3.83 | 11193 | 121.47 | | 7.00 | 129.66 |
| 1 | 4.86 | 6184 | 120.11 | 4.96 | 22285 | 119.90 | 23324 | 8.20 | 134.33 |
| 1 | 5.02 | 5912 | 120.47 | 4.96 | 24364 | 120.70 | | 9.76 | 133.27 |
| 1 | 6.37 | 9204 | 125.45 | 6.40 | 54048 | 126.05 | 51117 | 10.49 | 131.00 |
| 1 | 6.44 | 8881 | 125.81 | 6.40 | 48187 | 125.54 | | | |
| 1 | 8.05 | 8021 | 135.88 | 8.07 | 92975 | 135.26 | 90493 | | |
| 1 | 8.09 | 7645 | 135.78 | 8.07 | 88011 | 136.66 | | | |
| 1 | 9.41 | 1928 | 134.10 | 9.43 | 80464 | 139.49 | 76324 | | |
| 1 | 9.44 | 1945 | 133.74 | 9.43 | 72183 | 140.29 | | | |
| | | | | | | | | | |
| 1.75 | 3.93 | 3679 | 120.26 | 3.96 | 12889 | 120.95 | 12879 | 5.85 | 124.55 |
| 1.75 | 3.99 | 4038 | 120.54 | 3.96 | 12869 | 120.57 | | 7.06 | 129.87 |
| 1.75 | 4.98 | 6482 | 119.36 | 5.00 | 30466 | 120.65 | 34659 | 8.36 | 134.41 |
| 1.75 | 5.01 | 6037 | 119.53 | 5.00 | 38853 | 121.37 | | 9.50 | 132.19 |
| 1.75 | 6.32 | 8143 | 118.58 | 6.40 | 84484 | 128.73 | 87281 | | |
| 1.75 | 6.49 | 7147 | 124.80 | 6.40 | 90077 | 128.97 | | | |
| 1.75 | 8.49 | 4934 | 136.14 | 8.58 | 119058 | 139.53 | 110264 | | |
| 1.75 | 8.67 | 4151 | 135.13 | 8.58 | 101471 | 140.71 | | | |
| 1.75 | 10.60 | 1025 | 130.24 | 10.62 | 87552 | 136.28 | 83099 | | |
| 1.75 | 10.63 | 996 | 129.15 | 10.62 | 78646 | 137.14 | | | |
| | | | | | | | | | |
| 2.5 | 3.39 | 3168 | 120.36 | 3.38 | 12341 | 120.51 | 11574 | 5.87 | 125.94 |
| 2.5 | 3.36 | 3747 | 120.84 | 3.38 | 10808 | 120.91 | | 7.31 | 130.96 |
| 2.5 | 5.64 | 7992 | 121.93 | 5.63 | 46906 | 123.03 | 50348 | 8.23 | 133.18 |
| 2.5 | 5.62 | 6794 | 122.00 | 5.63 | 53791 | 122.25 | | 9.42 | 133.10 |
| 2.5 | 6.77 | 7687 | 127.70 | 6.85 | 91325 | 127.16 | 92764 | 9.95 | 132.19 |
| 2.5 | 6.92 | 7515 | 127.70 | 6.85 | 94202 | 127.75 | | | |
| 2.5 | 8.60 | 3545 | 125.29 | 8.61 | 140167 | 139.55 | 142928 | | |
| 2.5 | 8.63 | 3919 | 125.19 | 8.61 | 145690 | 140.17 | | | |
| 2.5 | 10.61 | 879 | 130.13 | 10.57 | 115428 | 137.17 | 115633 | | |
| 2.5 | 10.53 | 949 | 129.80 | 10.57 | 115839 | 137.91 | | | |
| | | | | | | | | | |
| 3.25 | 6.06 | 6302 | 122.24 | 6.08 | 60564 | 122.75 | 62305 | 5.85 | 122.28 |
| 3.25 | 6.10 | 6681 | 123.24 | 6.08 | 64045 | 122.89 | | 6.55 | 129.93 |
| 3.25 | 7.52 | 6741 | 132.01 | 7.56 | 106824 | 132.19 | 108698 | 8.54 | 134.74 |
| 3.25 | 7.59 | 6558 | 132.35 | 7.56 | 110572 | 132.20 | | 9.84 | 131.78 |
| 3.25 | 8.65 | 3051 | 134.61 | 8.70 | 120949 | 139.89 | 129099 | | |
| 3.25 | 8.74 | 2701 | 134.64 | 8.70 | 137249 | 139.23 | | | |
| 3.25 | 10.57 | 835 | 130.32 | 10.58 | 112386 | 136.11 | 104152 | | |
| 3.25 | 10.59 | 832 | 129.38 | 10.58 | 95917 | 136.59 | | | |

| Soil 1Bk with Calcium Chloride | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | Sample tested wet | | | Sample tested dry | | | AVG. | Proctor | |
| CaCl2 % | Moisture Content % | Axial Stress (psf) | Dry Density (pcf) | Moisture Content % | Axial Stress (psf) | Dry Density (pcf) | AXIAL STRESS (psf) | Moisture Content % | Dry Density (pcf) |
| 1 | 3.23 | 2356 | 119.61 | 3.31 | 3818 | 120.32 | 3709 | 5.32 | 121.75 |
| 1 | 3.38 | 2544 | 121.12 | 3.31 | 3600 | 120.94 | | 7.63 | 132.53 |
| 1 | 6.25 | 9538 | 122.55 | 6.27 | 15540 | 123.43 | 17112 | 8.26 | 135.09 |
| 1 | 6.28 | 8596 | 122.39 | 6.27 | 18684 | 124.31 | | 9.03 | 134.40 |
| 1 | 7.32 | 7433 | 127.10 | 7.48 | 30000 | 128.45 | 31467 | | |
| 1 | 7.63 | 9583 | 127.28 | 7.48 | 32935 | 129.83 | | | |
| 1 | 8.86 | 5399 | 135.32 | 8.88 | 39431 | 138.45 | 39544 | | |
| 1 | 8.90 | 5745 | 135.97 | 8.88 | 39657 | 138.34 | | | |
| 1 | 10.22 | 2956 | 133.77 | 10.24 | 29025 | 138.79 | 31094 | | |
| 1 | 10.26 | 3069 | 132.28 | 10.24 | 33162 | 138.56 | | | |
| | | | | | | | | | |
| 1.75 | 3.87 | 2698 | 119.87 | 3.95 | 3816 | 119.56 | 4085 | 6.13 | 128.17 |
| 1.75 | 4.03 | 3227 | 119.28 | 3.95 | 4353 | 119.54 | | 7.33 | 132.90 |
| 1.75 | 5.02 | 6303 | 119.36 | 5.08 | 8130 | 118.63 | 8493 | 8.53 | 135.85 |
| 1.75 | 5.14 | 6064 | 118.47 | 5.08 | 8855 | 119.20 | | 9.50 | 133.56 |
| 1.75 | 6.43 | 9970 | 124.73 | 6.56 | 20810 | 124.10 | 20077 | | |
| 1.75 | 6.69 | 10668 | 125.91 | 6.56 | 19343 | 124.45 | | | |
| 1.75 | 7.64 | 9069 | 131.06 | 7.81 | 40450 | 132.55 | 38285 | | |
| 1.75 | 7.98 | 7609 | 132.02 | 7.81 | 36121 | 131.86 | | | |
| 1.75 | 8.52 | 6693 | 137.32 | 9.25 | 37737 | 139.68 | 37040 | | |
| 1.75 | 8.54 | 6787 | 136.18 | 9.25 | 36343 | 139.24 | | | |
| 1.75 | 9.75 | 3115 | 132.43 | 9.75 | 36241 | 138.86 | 35547 | | |
| 1.75 | | | | 9.75 | 34853 | 138.77 | | | |
| | | | | | | | | | |
| 2.5 | 3.80 | 3106 | 120.05 | 3.88 | 3828 | 119.68 | 4281 | 6.08 | 130.79 |
| 2.5 | 3.96 | 4261 | 118.61 | 3.88 | 4734 | 119.91 | | 7.71 | 134.38 |
| 2.5 | 5.66 | 7344 | 120.29 | 5.69 | 15689 | 122.23 | 14394 | 8.49 | 135.36 |
| 2.5 | 5.71 | 8112 | 120.81 | 5.69 | 13099 | 122.30 | | 9.30 | 133.53 |
| 2.5 | 7.57 | 6962 | 134.09 | 7.59 | 37379 | 135.41 | 36995 | | |
| 2.5 | 7.60 | 6234 | 133.14 | 7.59 | 36611 | 134.81 | | | |
| 2.5 | 9.07 | 3826 | 135.12 | 9.15 | 33240 | 140.28 | 32036 | | |
| 2.5 | 9.23 | 3711 | 134.67 | 9.15 | 30833 | 140.05 | | | |
| 2.5 | 9.93 | 2717 | 133.17 | 9.98 | 32725 | 139.08 | 30425 | | |
| 2.5 | 10.03 | 2600 | 133.04 | 9.98 | 28125 | 138.93 | | | |
| | | | | | | | | | |
| 3.25 | 3.91 | 4066 | 120.25 | 3.94 | 4451 | 119.94 | 4506 | 6.16 | 131.25 |
| 3.25 | 3.96 | 4313 | 122.22 | 3.94 | 4560 | 120.09 | | 7.55 | 134.02 |
| 3.25 | 5.49 | 8195 | 122.87 | 5.56 | 13059 | 122.77 | 12234 | 8.51 | 135.88 |
| 3.25 | 5.63 | 6303 | 121.98 | 5.56 | 11409 | 122.19 | | 9.60 | 133.17 |
| 3.25 | 7.35 | 6635 | 133.21 | 7.37 | 30559 | 134.43 | 33332 | | |
| 3.25 | 7.38 | 7017 | 132.99 | 7.37 | 36105 | 134.52 | | | |
| 3.25 | 8.27 | 4893 | 135.55 | 8.29 | 36932 | 140.62 | 36756 | | |
| 3.25 | 8.30 | 4982 | 135.65 | 8.29 | 36580 | 140.36 | | | |
| 3.25 | 9.43 | 3178 | 134.10 | 9.47 | 33410 | 141.38 | 33006 | | |
| 3.25 | 9.51 | 3004 | 134.96 | 9.47 | 32602 | 140.49 | | | |

| Soil 1Bk, with Magnesium Chloride | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | |
| | Samples tested wet | | | Samples tested dry | | | Avg. | Proctor | |
| MgCl2 | Moisture | Axial | Dry | Moisture | Axial | Dry | Axial | Moisture | Dry |
| % | % | Stress | Density | % | Stress | Density | Stress | % | Density |
| | | (psf) | (pcf) | | (psf) | (pcf) | (psf) | | (pcf) |
| 1 | 4.34 | 4516.88 | 116.26 | 4.36 | 5941.64 | 113.98 | 5196.335 | 5.94 | 125.86 |
| 1 | 4.38 | 4598.23 | 116.42 | 4.36 | 4451.03 | 113.73 | | 7.25 | 129.63 |
| 1 | 4.94 | 6215.8 | 114.28 | 4.98 | 10341.86 | 114.72 | 10079.15 | 8.05 | 134.52 |
| 1 | 5.03 | 6459.84 | 114.31 | 4.98 | 9816.43 | 112.78 | | 10.08 | 132.31 |
| 1 | 6.39 | 9659.76 | 120 | 6.4 | 25906.91 | 120.03 | 26559.54 | | |
| 1 | 6.41 | 9169.82 | 119.08 | 6.4 | 27212.17 | 119.56 | | | |
| 1 | 7.68 | 8659.11 | 125.87 | 7.69 | 40353.67 | 131.52 | 39430.23 | | |
| 1 | 7.7 | 8535.41 | 126.25 | 7.69 | 38506.79 | 131.69 | | | |
| 1 | 10.14 | 1520.52 | 132 | 10.14 | 36916.45 | 139.18 | 37672.45 | | |
| 1 | 10.14 | 1399.57 | 131.94 | 10.14 | 38428.45 | 138.96 | | | |
| | | | | | | | | | |
| 1.75 | 4.44 | 5488.46 | 115.91 | 4.48 | 6626.75 | 114.31 | 6409.09 | 6.04 | 126.87 |
| 1.75 | 4.52 | 5450.42 | 114.64 | 4.48 | 6191.43 | 114.53 | | 7.08 | 132.37 |
| 1.75 | 5.09 | 6642.67 | 114.11 | 5.1 | 12119.05 | 114.59 | 12108.77 | 8.5 | 135.06 |
| 1.75 | 5.11 | 6859.45 | 115.09 | 5.1 | 12098.48 | 113.84 | | 10.34 | 131.19 |
| 1.75 | 6.56 | 9421.84 | 121.8 | 6.58 | 35600.84 | 120.69 | 35117.98 | | |
| 1.75 | 6.61 | 9069.18 | 120.69 | 6.58 | 34635.11 | 121.59 | | | |
| 1.75 | 7.74 | 8050.21 | 128.15 | 7.79 | 45107.43 | 133.39 | 46568.4 | | |
| 1.75 | 7.85 | 8023.2 | 128.56 | 7.79 | 48029.36 | 134.15 | | | |
| 1.75 | 10.73 | 1187.98 | 129.81 | 10.9 | 40320.36 | 136.79 | 39199.08 | | |
| 1.75 | 11.08 | 834.01 | 129.35 | 10.9 | 38077.8 | 137.67 | | | |
| | | | | | | | | | |
| 2.5 | 4.36 | 5818.24 | 115.23 | 4.4 | 8424.05 | 113.59 | 8639.035 | 6.08 | 129.09 |
| 2.5 | 4.44 | 5777.05 | 114.66 | 4.4 | 8854.02 | 114.12 | | 7.3 | 132.38 |
| 2.5 | 5.01 | 8015.92 | 115.59 | 5.03 | 17146.17 | 115.44 | 17621.81 | 8.65 | 134.88 |
| 2.5 | 5.06 | 8022.97 | 117.18 | 5.03 | 18097.45 | 111.74 | | 10.26 | 131.28 |
| 2.5 | 6.16 | 8907.27 | 119.91 | 6.2 | 33809.19 | 119.28 | 33892.55 | | |
| 2.5 | 6.23 | 8767.07 | 121.85 | 6.2 | 33975.91 | 120.55 | | | |
| 2.5 | 8.07 | 6692.99 | 131.09 | 8.18 | 53822.43 | 136.77 | 53605.23 | | |
| 2.5 | 8.3 | 6136.3 | 128.48 | 8.18 | 53388.02 | 136.17 | | | |
| 2.5 | 10.91 | 834.08 | 129.61 | 10.97 | 32065.23 | 137.57 | 33437.21 | | |
| 2.5 | 11.05 | 808.99 | 129.18 | 10.97 | 34809.19 | 136.71 | | | |
| | | | | | | | | | |
| 3.25 | 4.64 | 6614.66 | 114.48 | 4.77 | 17677.86 | 113.46 | 15803.8 | 6.11 | 130.19 |
| 3.25 | 4.91 | 6874.06 | 114.83 | 4.77 | 13929.73 | 113.12 | | 7.3 | 134.33 |
| 3.25 | 5.14 | 8845.99 | 117.42 | 5.21 | 28948.55 | 115.9 | 30346.14 | 8.34 | 135.77 |
| 3.25 | 5.29 | 9205.44 | 117.31 | 5.21 | 31743.73 | 116.23 | | 9.66 | 131.99 |
| 3.25 | 6.54 | 8394.11 | 124.16 | 6.56 | 31653.87 | 113.85 | 31839 | | |
| 3.25 | 6.58 | 8470.98 | 123.78 | 6.56 | 32024.12 | 122.18 | | | |
| 3.25 | 9.01 | 2083.97 | 134.75 | 9.03 | 35260.79 | 140.85 | 36426.47 | | |
| 3.25 | 9.04 | 2162 | 135.12 | 9.03 | 37592.14 | 141.27 | | | |
| 3.25 | 11.2 | 619.63 | 128.45 | 11.24 | 35890.52 | 136.62 | 35846.98 | | |
| 3.25 | 11.29 | 667.33 | 128.02 | 11.24 | 35803.44 | 136.89 | | | |

| Soil H-1c with Water Alone | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | AVG. | | |
| Samples Tested Wet | | | Samples Tested dry | | | AXIAL | Proctor | |
| Moisture | Axial Stress | Dry Density | Moisture | Axial Stress | Dry Density | STRESS | Moisture | Dry Density |
| % | (psf) | (pcf) | % | (psf) | (pcf) | (psf) | % | (pcf) |
| 3.72 | 4026.3 | 115.76 | 4.38 | 15124.8 | 114.1 | 14970.95 | 4.56 | 123.1 |
| 3.86 | 3895.8 | 115.76 | 4.38 | 14817.1 | 113.72 | | 6.3 | 125 |
| 5.27 | 5402.6 | 118.26 | 5.35 | 34409.4 | 119.2 | 31746.55 | 7.6 | 130.8 |
| 5.43 | 5339.5 | 117.94 | 5.35 | 29083.7 | 119.38 | | 9.29 | 131.2 |
| 6.2 | 6440.4 | 122.45 | 6.48 | 63812.5 | 124.15 | 59056.65 | 10.32 | 126.5 |
| 6.75 | 5704.9 | 123.01 | 6.48 | 54300.8 | 122.96 | | | |
| 8.47 | 5317.3 | 131.18 | 8.51 | 75703.1 | 129.32 | 84268.3 | | |
| 8.55 | 5154.2 | 131.48 | 8.51 | 92833.5 | 131.2 | | | |
| 9.84 | 3278.9 | 130.02 | 9.9 | 68798.1 | 135.36 | 66873.6 | | |
| 9.95 | 3164.6 | 132.01 | 9.9 | 64949.1 | 125.63 | | | |

| Soil H-1c with Lignin Sulfonate | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Samples Tested Wet | | | Samples Tested Dry | | | AVG | Proctor | |
| Lignin | Moisture | Axial Stress | Dry Density | Moisture | Axial Stress | Dry Density | AXIAL | Moisture | Dry Density |
| % | % | (psf) | (pcf) | | (psf) | | STRESS | % | |
| 1 | 4.57 | 4756.2 | 120.99 | 4.58 | 38934.4 | 119.83 | 38220.6 | 4.19 | 125.3 |
| 1 | 4.59 | 5155 | 120.56 | 4.58 | 37506.7 | 120.40 | | 6.48 | 128.2 |
| 1 | 5.19 | 6133.5 | 118.84 | 5.17 | 44065.4 | 123.15 | 43083.9 | 7.96 | 133.9 |
| 1 | 5.15 | 6055.8 | 120.17 | 5.17 | 42102.3 | 119.25 | | 9.29 | 133.9 |
| 1 | 6.57 | 5319.6 | 122.64 | 6.46 | 73342.3 | 124.66 | 74539.3 | 10.76 | 125.9 |
| 1 | 6.34 | 6177.4 | 122.81 | 6.46 | 75736.3 | 125.08 | | | |
| 1 | 7.48 | 6239.6 | 127.86 | 7.55 | 96257.6 | 128.79 | 96178.9 | | |
| 1 | 7.63 | 5793.6 | 129.36 | 7.55 | 96100.1 | 129.75 | | | |
| 1 | 8.92 | 5120.8 | 132.40 | 8.80 | 111687.3 | 136.50 | 115291 | | |
| 1 | 9.07 | 4480.9 | 131.52 | 8.80 | 118894.2 | 137.54 | | | |
| 1 | 10.11 | 2718.6 | 127.87 | 10.38 | 113761.5 | 136.10 | 112783 | | |
| 1 | 10.65 | 2172.8 | 124.08 | 10.38 | 111805 | 135.13 | | | |
| | | | | | | | | | |
| 1.75 | 4.73 | 5403.6 | 120.25 | 4.65 | 46046.6 | 119.89 | 49585.9 | 4.73 | 125.8 |
| 1.75 | 4.62 | 5571.4 | 118.72 | 4.65 | 53125.15 | 120.89 | | 6.41 | 126.9 |
| 1.75 | 5.62 | 5488.8 | 119.93 | 5.60 | 51850.2 | 119.87 | 52138.1 | 7.88 | 130.4 |
| 1.75 | 5.58 | 5412.6 | 119.74 | 5.60 | 52426 | 120.48 | | 9.30 | 131.2 |
| 1.75 | 6.65 | 5779.8 | 124.50 | 6.68 | 90145.4 | 124.38 | 87196.4 | 10.95 | 125.7 |
| 1.75 | 6.71 | 5522.7 | 124.07 | 6.68 | 84247.3 | 123.93 | | | |
| 1.75 | 7.47 | 5913.1 | 127.92 | 7.45 | 119331 | 129.92 | 112978 | | |
| 1.75 | 7.43 | 5752.5 | 127.13 | 7.45 | 106625.5 | 127.50 | | | |
| 1.75 | 9.00 | 4128.5 | 130.41 | 8.97 | 122184.8 | 136.40 | 125435 | | |
| 1.75 | 8.95 | 4085.7 | 131.45 | 8.97 | 128684.9 | 136.93 | | | |
| 1.75 | 9.56 | 3560.3 | 129.50 | 9.65 | 125102.5 | 133.77 | 127063 | | |
| 1.75 | 9.74 | 3164.8 | 127.52 | 9.65 | 129023.7 | 134.24 | | | |
| | | | | | | | | | |
| 2.5 | 4.88 | 5673.7 | 119.59 | 4.76 | 46371 | 119.61 | 46737.7 | 4.89 | 126.7 |
| 2.5 | 4.65 | 4446.6 | 118.62 | 4.76 | 47104.4 | 120.22 | | 6.48 | 127.9 |
| 2.5 | 5.57 | 5108 | 118.77 | 5.58 | 60164.2 | 121.02 | 61780.1 | 7.86 | 132.1 |
| 2.5 | 5.60 | 5902.1 | 120.31 | 5.58 | 63395.9 | 120.27 | | 9.44 | 130.5 |
| 2.5 | 7.02 | 5502.6 | 126.44 | 7.10 | 117380.7 | 126.40 | 113186 | 10.92 | 126 |
| 2.5 | 7.19 | 4095.6 | 126.26 | 7.10 | 108990.7 | 125.71 | | | |
| 2.5 | 7.90 | 5075.2 | 131.27 | 7.81 | 139855.6 | 132.37 | 137822 | | |
| 2.5 | 7.72 | 5107.4 | 130.22 | 7.81 | 135787.7 | 131.84 | | | |
| 2.5 | 9.43 | 3214.8 | 130.83 | 9.62 | 114755.7 | 135.23 | 118004 | | |
| 2.5 | 9.82 | 2637.4 | 129.79 | 9.62 | 121251.6 | 135.91 | | | |
| | | | | | | | | | |
| 3.25 | 4.42 | 4565.9 | 118.61 | 4.48 | 32444.3 | 118.71 | 34589.9 | 5.18 | 126.4 |
| 3.25 | 4.54 | 5326.5 | 119.01 | 4.48 | 36735.48 | 118.54 | | 6.64 | 129.4 |
| 3.25 | 5.81 | 5610.4 | 121.27 | 5.79 | 74889 | 121.16 | 74131.1 | 7.83 | 133.5 |
| 3.25 | 5.77 | 5692.1 | 121.49 | 5.79 | 73373.2 | 121.49 | | 9.45 | 130.7 |
| 3.25 | 6.91 | 5135.6 | 125.83 | 6.96 | 129876.9 | 127.34 | 124968 | 10.83 | 126.4 |
| 3.25 | 7.01 | 5624.8 | 126.10 | 6.96 | 120058.6 | 127.92 | | | |
| 3.25 | 7.58 | 4887.4 | 130.24 | 7.66 | 141419.2 | 130.63 | 141271 | | |
| 3.25 | 7.73 | 4720.9 | 128.68 | 7.66 | 141122.6 | 130.81 | | | |
| 3.25 | 9.61 | 2672.9 | 126.88 | 9.51 | 115123.7 | 135.51 | 113149 | | |
| 3.25 | 9.40 | 2930.9 | 129.37 | 9.51 | 111174.7 | 134.45 | | | |

| Soil H-1c with Calcium Chloride | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Samples Tested Wet | | | Samples Tested Dry | | | AVG | Proctor | |
| CaCl2 | Moisture | Axial Stress | Dry Density | Moisture | Axial Stress | Dry Density | AXIAL | Moisture | Dry Density |
| % | % | (psf) | (pcf) | | (psf) | | STRESS | % | |
| 1 | 3.66 | 4111.4 | 115.91 | 3.64 | 11952.4 | 116.50 | 11719.6 | 4.19 | 125.3 |
| 1 | 3.62 | 4249.4 | 116.29 | 3.64 | 11486.8 | 116.61 | | 6.48 | 128.2 |
| 1 | 4.86 | 4221.2 | 116.55 | 4.90 | 21659.8 | 118.03 | 21459.6 | 7.96 | 133.9 |
| 1 | 4.93 | 4252.6 | 116.68 | 4.90 | 21259.3 | 118.49 | | 9.29 | 131.2 |
| 1 | 6.73 | 5228.14 | 123.93 | 6.72 | 57124.8 | 124.25 | 58611.5 | 10.76 | 125.9 |
| 1 | 6.70 | 5301.3 | 123.98 | 6.72 | 60098.2 | 124.00 | | | |
| 1 | 8.71 | 3982.5 | 129.74 | 8.64 | 78329.6 | 132.74 | 77000.5 | | |
| 1 | 8.57 | 4795.9 | 130.81 | 8.64 | 75671.3 | 132.78 | | | |
| 1 | 9.99 | 2934.2 | 131.39 | 10.10 | 63501.6 | 136.29 | 62861.2 | | |
| 1 | 10.20 | 2746.2 | 130.12 | 10.10 | 62220.7 | 135.08 | | | |
| | | | | | | | | | |
| 1.75 | 4.38 | 4212.9 | 117.28 | 4.23 | 12821.2 | 117.41 | 13075.2 | 4.73 | 125.8 |
| 1.75 | 4.07 | 3730.1 | 116.88 | 4.23 | 13329.1 | 116.78 | | 6.41 | 126.9 |
| 1.75 | 5.32 | 3669.5 | 117.70 | 5.31 | 18413.1 | 118.68 | 19244.6 | 7.88 | 130.4 |
| 1.75 | 5.29 | 3928.6 | 117.55 | 5.31 | 20076.1 | 118.81 | | 9.30 | 131.2 |
| 1.75 | 6.67 | 5324.2 | 124.18 | 6.68 | 45665.3 | 123.42 | 46351.1 | 10.95 | 125.7 |
| 1.75 | 6.69 | 5244.2 | 123.49 | 6.68 | 47036.8 | 123.30 | | | |
| 1.75 | 8.46 | 4241.7 | 129.64 | 8.39 | 60689.63 | 131.20 | 60595.8 | | |
| 1.75 | 8.33 | 4866.7 | 130.56 | 8.39 | 60502 | 131.84 | | | |
| 1.75 | 9.88 | 2782.3 | 131.01 | 9.86 | 51291.43 | 135.62 | 53930.6 | | |
| 1.75 | 9.84 | 2798 | 133.72 | 9.86 | 56569.7 | 135.43 | | | |
| | | | | | | | | | |
| 2.5 | 3.88 | 4192.2 | 116.11 | 3.91 | 9761.7 | 116.61 | 10282 | 4.89 | 126.7 |
| 2.5 | 3.94 | 3363.5 | 117.78 | 3.91 | 10802.2 | 116.11 | | 6.48 | 127.9 |
| 2.5 | 5.74 | 4128.7 | 120.30 | 5.68 | 21274.2 | 119.51 | 21071.5 | 7.86 | 132.1 |
| 2.5 | 5.61 | 5030.1 | 119.68 | 5.68 | 20868.7 | 120.04 | | 9.44 | 130.5 |
| 2.5 | 6.78 | 4820.6 | 125.34 | 6.74 | 42662.2 | 124.01 | 40979 | 10.92 | 126 |
| 2.5 | 6.70 | 5482.8 | 126.10 | 6.74 | 39295.8 | 124.44 | | | |
| 2.5 | 8.27 | 4741.2 | 133.18 | 8.32 | 48039.3 | 132.39 | 50524.8 | | |
| 2.5 | 8.36 | 4392.7 | 132.40 | 8.32 | 53010.3 | 132.84 | | | |
| 2.5 | 10.19 | 2321.5 | 130.19 | 10.20 | 43287.2 | 136.72 | 45753.4 | | |
| 2.5 | 10.27 | 2288.9 | 130.05 | 10.20 | 48219.6 | 136.83 | | | |
| | | | | | | | | | |
| 3.25 | 4.50 | 4512.44 | 117.75 | 4.52 | 10908.97 | 117.03 | 11899.9 | 5.18 | 126.4 |
| 3.25 | 5.54 | 4858.2 | 117.79 | 4.52 | 12890.8 | 117.70 | | 6.64 | 129.4 |
| 3.25 | 6.33 | 5438.7 | 123.03 | 6.34 | 21724.8 | 122.93 | 21126.9 | 7.83 | 133.5 |
| 3.25 | 6.35 | 4645.7 | 123.06 | 6.34 | 20529 | 122.63 | | 9.45 | 130.7 |
| 3.25 | 7.29 | 4894.1 | 126.96 | 7.30 | 44297.04 | 126.46 | 44091.3 | 10.83 | 126.4 |
| 3.25 | 7.30 | 4925 | 127.70 | 7.30 | 43885.5 | 127.07 | | | |
| 3.25 | 8.46 | 4022.2 | 132.82 | 8.33 | 45604.1 | 134.30 | 42357 | | |
| 3.25 | 8.20 | 4053.5 | 131.29 | 8.33 | 39109.84 | 134.22 | | | |
| 3.25 | 10.14 | 2454.4 | 131.09 | 10.00 | 39274.9 | 136.38 | 39790.4 | | |
| 3.25 | 9.93 | 2589.9 | 130.50 | 10.00 | 40305.8 | 137.49 | | | |

| Soil H-1c with Magnesium Chloride | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Samples Tested Wet | | | Samples Tested Dry | | | AVG | Proctor | |
| MgCl2 | Moisture | Axial Stress | Dry Density | Moisture | Axial Stress | Dry Density | AXIAL | Moisture | Dry Density |
| % | % | (psf) | (pcf) | | (psf) | | STRESS | % | |
| 1 | 3.99 | 4844.6 | 117.5 | 3.99 | 19073.8 | 118.07 | 17422.4 | 4.48 | 121.6 |
| 1 | 3.98 | 4457.9 | 117.9 | 3.99 | 15770.9 | 117.62 | | 5.79 | 128.3 |
| 1 | 5.51 | 5444.1 | 118.9 | 5.52 | 28229.3 | 120.29 | 28037.2 | 6.63 | 135.2 |
| 1 | 5.52 | 5713.2 | 119.5 | 5.52 | 27845.1 | 120.14 | | 8.62 | 121.7 |
| 1 | 6.72 | 5992.9 | 123.2 | 6.68 | 43942.5 | 123.52 | 48036.9 | | |
| 1 | 6.63 | 5994.8 | 123.2 | 6.68 | 52131.2 | 123.83 | | | |
| 1 | 8.37 | 4639.3 | 129.1 | 8.31 | 77738 | 131.40 | 77418.5 | | |
| 1 | 8.24 | 4791.1 | 127.5 | 8.31 | 77098.9 | 130.67 | | | |
| 1 | 9.48 | 3308.3 | 129.8 | 9.58 | 66773.6 | 135.96 | 68485.4 | | |
| 1 | 9.68 | 3457.1 | 130.7 | 9.58 | 70197.1 | 135.88 | | | |
| | | | | | | | | | |
| 1.75 | 3.97 | 5344.1 | 118.69 | 3.97 | 16761.7 | 118.86 | 17818.7 | 4.64 | 122.2 |
| 1.75 | 3.97 | 5947.3 | 119.3 | 3.97 | 18875.66 | 119.95 | | 6 | 128 |
| 1.75 | 5.04 | 5221.2 | 119.66 | 5.06 | 21990.69 | 120.58 | 21252.8 | 7 | 134.3 |
| 1.75 | 5.09 | 5565.7 | 119.65 | 5.06 | 20515 | 120.17 | | 8.51 | 131.6 |
| 1.75 | 6.81 | 5556.1 | 124.17 | 6.79 | 43858.35 | 124.5 | 44263.2 | | |
| 1.75 | 6.76 | 5182.6 | 123.2 | 6.79 | 44668 | 124.86 | | | |
| 1.75 | 8.24 | 4603.5 | 129.81 | 8.3 | 69728.9 | 132.44 | 67806.5 | | |
| 1.75 | 8.36 | 4662.4 | 129.88 | 8.3 | 65884.1 | 132.57 | | | |
| 1.75 | 9.63 | 2982.3 | 129.84 | 9.69 | 55844 | 136.45 | 55342.2 | | |
| 1.75 | 9.74 | 3075 | 129.78 | 9.69 | 54840.4 | 135.18 | | | |
| | | | | | | | | | |
| 2.5 | 3.79 | 4718.6 | 115.07 | 3.77 | 7846.9 | 116.35 | 8186.35 | 4.97 | 123.7 |
| 2.5 | 3.75 | 4559.5 | 115.35 | 3.77 | 8525.8 | 116.46 | | 5.96 | 127.8 |
| 2.5 | 5.29 | 5337.4 | 119.17 | 5.31 | 20879.4 | 120.87 | 21220.7 | 7.33 | 134.2 |
| 2.5 | 5.33 | 5344.9 | 119.93 | 5.31 | 21562 | 120.54 | | 9.21 | 130.2 |
| 2.5 | 6.55 | 5386.9 | 123.41 | 6.53 | 39850.2 | 125.07 | 39263 | | |
| 2.5 | 6.51 | 5108.7 | 123.59 | 6.53 | 38675.8 | 124.35 | | | |
| 2.5 | 7.93 | 4545 | 128.26 | 7.98 | 53752.7 | 130.16 | 54115.1 | | |
| 2.5 | 8.03 | 4772.5 | 129.13 | 7.98 | 54477.4 | 131.17 | | | |
| 2.5 | 8.72 | 3932.3 | 131.77 | 8.81 | 53469.4 | 136.35 | 53276.6 | | |
| 2.5 | 8.9 | 4120.6 | 131.73 | 8.81 | 53083.8 | 137.07 | | | |
| 2.5 | 9.81 | 2720.1 | 130.37 | 9.67 | 43815.7 | 136.22 | 45307.3 | | |
| 2.5 | 9.53 | 3143.5 | 130.63 | 9.67 | 46798.8 | 136.66 | | | |
| | | | | | | | | | |
| 3.25 | 3.75 | 4343.4 | 116.28 | 3.81 | 7752.9 | 117.33 | 6805.65 | 5.22 | 123.7 |
| 3.25 | 3.97 | 4521.8 | 115.43 | 3.81 | 5858.4 | 116.66 | | 5.94 | 127.3 |
| 3.25 | 5.3 | 4078.4 | 119.44 | 5.31 | 14924 | 120.76 | 16049.2 | 7.72 | 132.8 |
| 3.25 | 5.32 | 5795.5 | 120.17 | 5.31 | 17174.3 | 120.88 | | 9.83 | 128.9 |
| 3.25 | 6.53 | 5168.6 | 125.06 | 6.51 | 22197.7 | 125.5 | 27866.7 | | |
| 3.25 | 6.48 | 5401.5 | 124 | 6.51 | 33535.6 | 125.76 | | | |
| 3.25 | 8.22 | 4569.9 | 131.33 | 8.18 | 49390.4 | 132.78 | 49273.8 | | |
| 3.25 | 8.14 | 4368.1 | 130.23 | 8.18 | 49157.1 | 133.24 | | | |
| 3.25 | 9.4 | 2910 | 129.63 | 9.44 | 40483.6 | 136.76 | 40005 | | |
| 3.25 | 9.48 | 2836.2 | 129.61 | 9.44 | 39526.4 | 136.53 | | | |

| | | | | | |
|---|---|---|---|---|---|
| Soil 1B with 1/2% Magnesium Chloride and 2.50% Lignin | | | | | |
| | | | | | |
| Samples Tested Dry | | | Avg. | | |
| Moisture | Dry | Axial | Axial | | |
| (%) | Density | Stress | Stress | | |
| | (pcf) | (psf) | (psf) | | |
| 6.40 | 129.58 | 56884.93 | 56409.48 | | |
| 6.40 | 130.52 | 55934.02 | | | |
| 7.55 | 133.57 | 73072.18 | 72041.57 | | |
| 7.55 | 131.02 | 71010.96 | | | |

# APPENDIX C

## NMR STUDY OF LIGNIN SULFONATE MIXED WITH ROAD SURFACE SOILS

by

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## INTRODUCTION

As additives leach from the road surface the soil stabilization that occurred after the additive application may be lost. These loss can be offset by reapplying the additive. However, one must have some means of estimating the residual additive concentration. If residual concentrations are not known the reapplication may result in final additive concentrations greater than those that produce the largest strength gains. This requires some method of measuring the residual additive concentration. Nuclear Magnetic Resonance (NMR) can measure carbon concentrations and may be one method of determining residual organic materials such as Lignin. The following study was carried out to determine if NMR could measure residual carbon from Lignin in road soils .

## EXPERIMENTAL

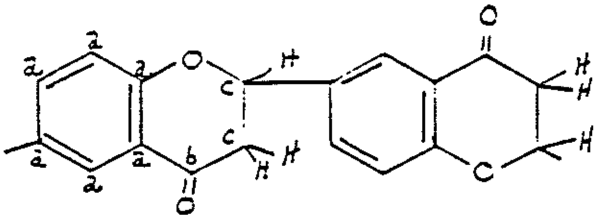
Materials: Soil 1B was obtained from the pit that provided surfacing soil for Fox Park Road located near Fox Park, Wyoming. The AASHTO soil classification is A-1-b. Soil 1Bk is soil 1B with the addition of 8.5% kaolinite clay. The AASHTO classification for this soil is also A-1-b. Soil H-1c is a mixture of soil H-1 and clay. Soil H-1 was obtained from the Granite Canyon Quarry west of Cheyenne, Wyoming,, and the clay was acquired 10 miles east of Bosler, Wyoming. This soil contains 12% clay by dry weight of soil H-1 and is classified as A-2-4 by the AASHTO system.

The Lignin Sulfonate solution was obtained from Envirotech Services, Inc. Located in Kersey, Colorado. This solution contains 16% solids by weight of the Lignin Sulfonate solution. The solid material contains mostly Lignin Sulfonate and small amounts of other undefined components. For the purpose of the report, the solid material will be designated as "lignin sulfonate". Elemental analysis of the dried lignin sulfonate shows it to contain 37.59% carbon by weight.

Instrumentation: A chemagnetics CMX-100/200 solids NMR spectrometer was used to obtain solid state carbon-13 NMR spectra of the lignin sulfonate and mixtures of lignin sulfonate containing varying amounts of soil. The spectra were obtained at ambient temperature using the technique of cross-polarization with magic angle spinning. The static magnetic field was fixed at 2.35 T (25 MHz carbon frequency). The spin-lock field was adjusted to 50 KHz (pulse width of 5 μs). In addition a contact time of 1 ms, pulse delay of 1 sec, and a sweep width of 16 KHz were used to obtain the spectra. The number of spectral acquisition varied from 3600 to 20,000 depending upon the amount of carbon in the soil-lignin mixture.

## RESULTS AND DISCUSSION

The chemical structure for "Russell lignin" is shown in Structure I.



Structure I

It may be that this material is sulfonated (using sulfuric acid?) to yield the lignin sulfonate used in this study. Figure 1 shows the $^{13}C$ spectrum of the air-dried lignin sulfonate. The aromatic carbons of the lignin (labeled a in structure I) are assigned to the region between 110-150 ppm. The carbonyl carbon (b in structure I) is tentatively assigned to the resonance at 180 ppm. The aliphatic carbons in the lignin (c in structure I) are assigned to the resonance peaks between 15 and 100 ppm.

A study was conducted to determine minimum concentration of lignin sulfonate that could be detected in soil 1B, 1BK and H-1C. Figures 2-5 show the $^{13}C$ NMR spectra of the lignin sulfonate solution mixed with varying amounts of Soil 1B. Table 1 gives the carbon weight percent in the soil 1B lignin sulfonate mixtures.

As the concentration of lignin sulfonate decreases, the number of NMR acquisitions (number of scans) must be increased to obtain reasonable signal-to-noise ratio. Lignin sulfonate (37.6% carbon) took only one hour to obtain a good spectrum (Figure 1). Figure 2 shows the spectrum of a soil-lignin mixture having a carbon content of 20.9%. One hour of spectrum accumulation would also be sufficient for good signal-to-noise. However, if the carbon content is reduced to 5.2% for a soil-lignin mixture, five hours or more are needed to obtain a reasonably good spectrum (Figure 3). Figure 4 shows the spectrum of a soil-lignin mixture containing 1.5% carbon. This spectrum was obtained after three hours. However, an overnight spectral accumulation would be necessary to obtain a reasonably good spectrum for this level of carbon in the soil. Figure 5 shows no $^{13}C$ signal after six hours of spectral accumulation in which the carbon content for this soil-lignin mixture was 0.3%. This level of carbon cannot be detected by NMR in any reasonable time.

Figures 6 and 7 show the carbon-13 spectrum of soils 1BK and H-1C after 1 and 2 hours of spectral accumulation. Each soil contained 0.8% by weight of lignin sulfonate which equates to 0.3% carbon by weight. In Figure 7, a small signal is observed between 100-175 ppm and may be due to additional organic material in the soil other than the added lignin sulfonate. Figure 8 shows the $^{13}C$ spectrum of 5% dried lignin sulfonate added to soil 1B. The carbon content for this mixture is about 1.9%. Even though the carbon signal is detectable after 20,000 scans, only broad peaks are observed for the aromatic and aliphatic carbons.

## CONCLUSIONS

It can be concluded that solid-state carbon-13 NMR cannot be used effectively to identify lignin sulfonate mixed with soils below 25% by weight of the lignin sulfonate solution. This level far exceeds the levels of 1 to 3% normally used to treat gravel roads. However, NMR could be useful to study the interactions of this or similar additives with soils or the breakdown of lignin sulfonate under acidic or basic environment.

**Table 1. Experimental Data for Soils Mixed with Lignin Sulfonate Solution.**

| $^{13}$C NMR Figure No. | Soil (Type) | Weight of Lignin Sulfonate Solution (g) | Weight of Lignin Sulfonate (g) | Weight of Dried Soil | Weight Percent of Lignin Sulfonate | Weight Percent of Carbon | No. of NMR Spectral Acquisition |
|---|---|---|---|---|---|---|---|
| 1 | | | | | 100 | 37.59 | 3,600 |
| 2 | IB (A-1-B) | 50 | 8 | 10 | 55.6 | 20.9 | 16,532 |
| 3 | IB | 25 | 4 | 25 | 13.8 | 5.2 | 16,500 |
| 4 | IB | 12.5 | 2 | 50 | 4.0 | 1.5 | 10,015 |
| 5 | IB | 5.1 | 0.81 | 101.1 | 0.8 | 0.3 | 20,000 |
| 6 | IBK (A-1-B) | 4.98 | 0.80 | 101.1 | 0.8 | 0.3 | 4,496 |
| 7 | II-IC | 5.01 | 0.80 | 101.5 | 0.8 | 0.3 | 8,684 |
| 8 | IB (A-2-4) | | | | 5.0 | 1.9 | 20,000 |

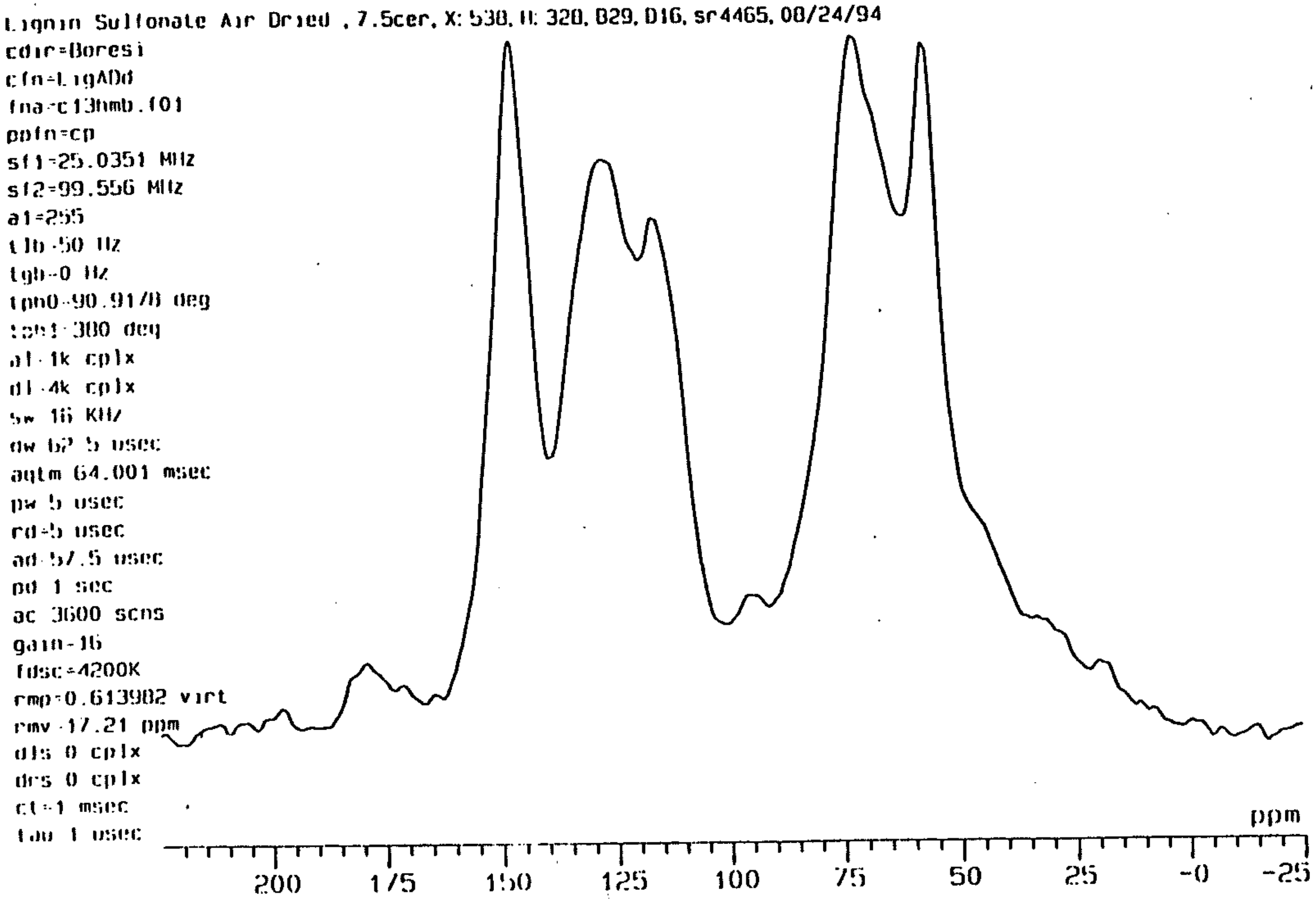
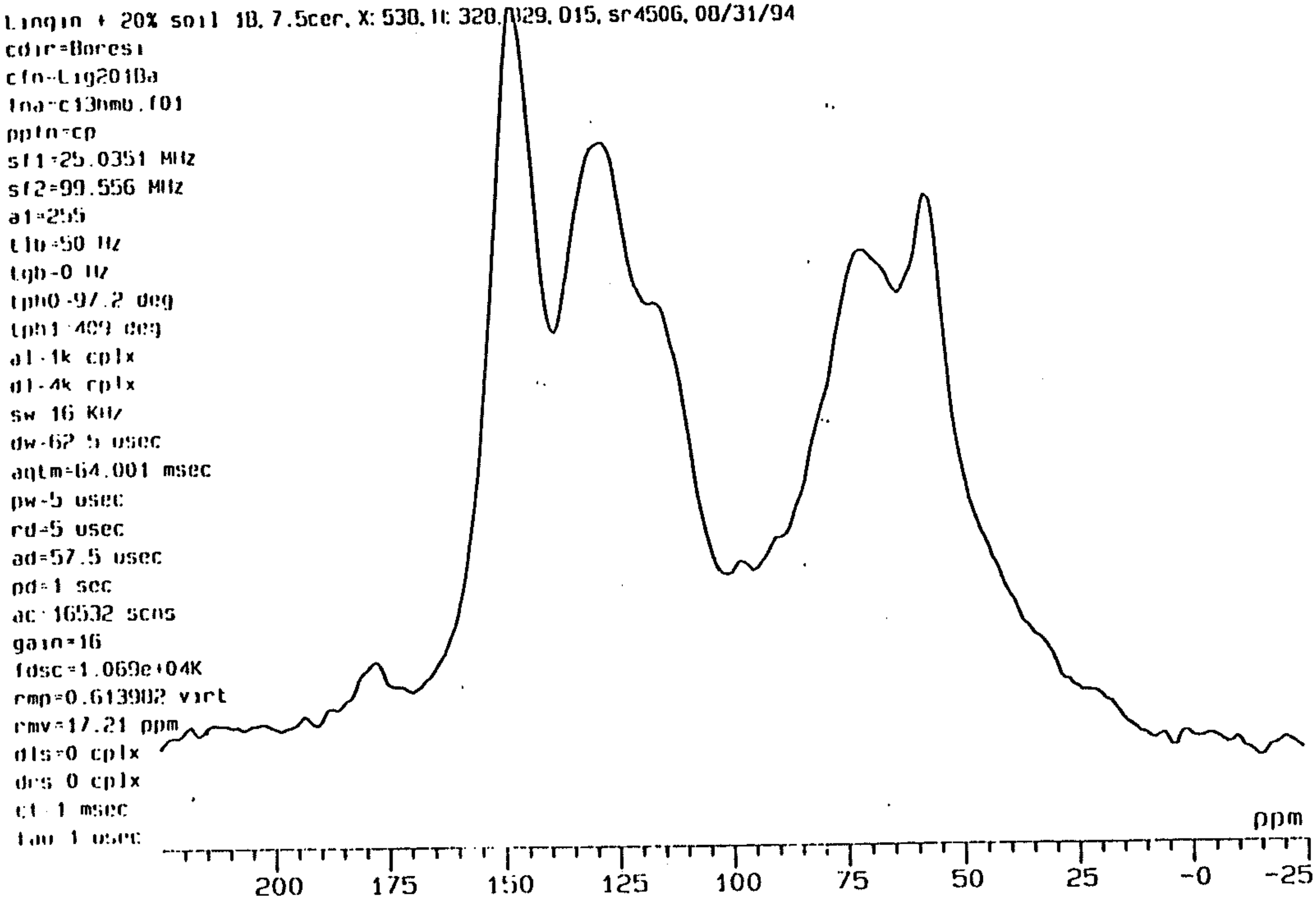


Figure 1. Carbon-13 NMR Spectrum of Air Dried Lignin Sulfonate



```
Lignin + 20% soil 1B, 7.5cer, X: 530, H: 320, 029, 015, sr4506, 08/31/94
cdir=Boresi
cfn=Lig201Ba
fna=c13nmb.f01
pptn=cp
sf1=25.0351 MHz
sf2=99.556 MHz
a1=255
tlb=50 Hz
tgb=0 Hz
tph0=-97.2 deg
tph1=409 deg
al=1k cplx
dl=4k cplx
sw=16 KHz
dw=62.5 usec
aqtm=64.001 msec
pw=5 usec
rd=5 usec
ad=57.5 usec
pd=1 sec
ac=16532 scns
gain=16
fdsc=1.069e+04K
rmp=0.613902 virt
rmv=17.21 ppm
dls=0 cplx
drs=0 cplx
ct=1 msec
tau=1 usec
```

Figure 2. Carbon-13 NMR Spectrum of Soil 1B with 55.6% by Weight of Lignin Sulfonate

```
Lignin + 50% soil 1B,  7.5cer, X: 538, H: 328, 829, D16, sr4566, 09/09/94
cdir=Boresi
cfn Lig501Ba
fna-c13hmb.f01
ppfn=cp
sf1=25.0351 MHz
sf2=99.556 MHz
a1=255
tlb-50 Hz
tgb 0 Hz
tph0-97 2 deg
tph1-499 deg
al=1k cplx
dl-4k cplx
sw 16 KHz
dw 62 5 usec
aqtm 64.001 msec
pw 5 usec
rd=5 usec
ad=57 5 usec
pd=1 sec
ac 16500 scns
gain=16
fdsc-5000K
rmp=0 613982 virt
rmv 17.21 ppm
dls 0 cplx
drs 0 cplx
ct=1 msec
tau 1 usec
```

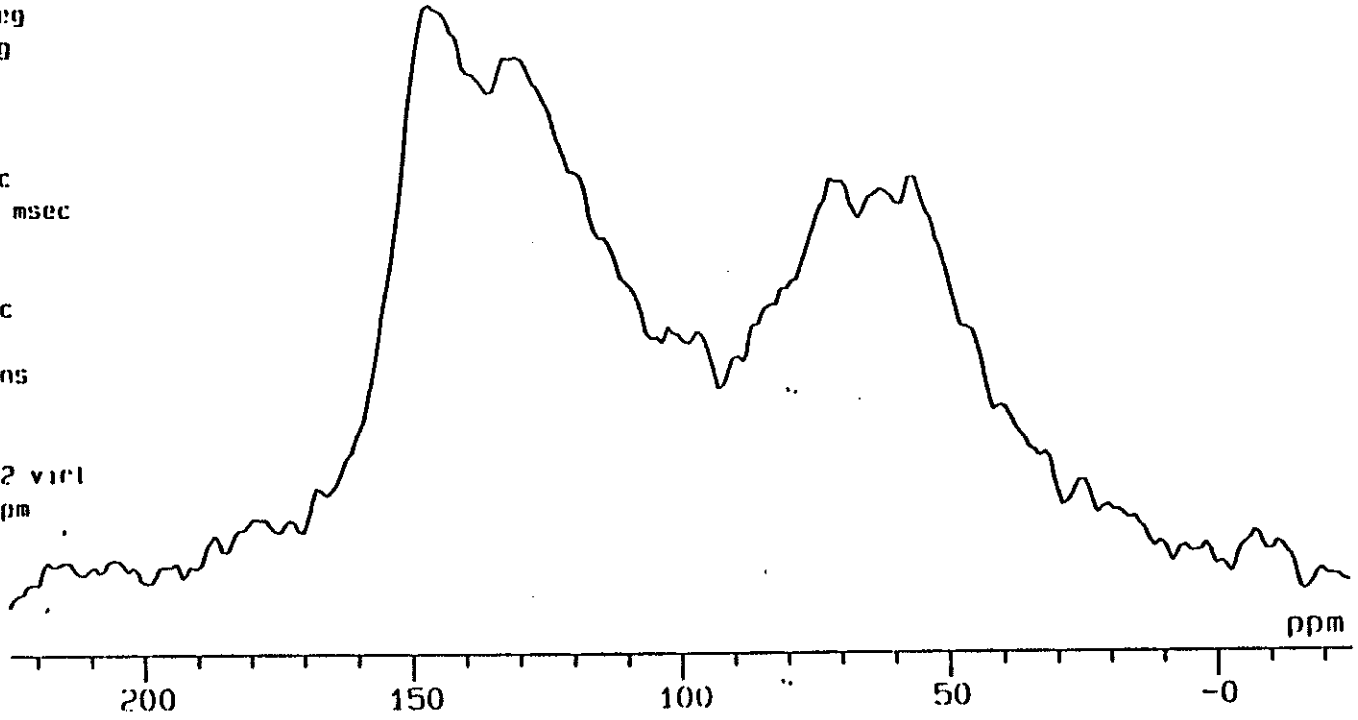


Figure 3. Carbon-13 NMR Spectrum of Soil 1B with 13.8% by Weight of Lignin Sulfonate

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Lignin + ~~2~~5% soil 1B, 7.5cer. X: 538. H: 328. 029. 016. sr4566. 09/09/94

```
cdir=Boresi
cfn=lig251B
fnd c13hmb.f01
pptn=cp
sf1 25.0351 MHz
sf2=99.556 MHz
a1=255
lb=50 Hz
fgb 0 Hz
tpn0 97.2 deg
tpn1 409 deg
al 1k cplx
dl=4k cplx
sw 16 KHz
dw 62.5 usec
aqtm=64.001 msec
pw 5 usec
rd=5 usec
ad 57.5 usec
pd 1 sec
ac 10015 scns
gain=16
fdsc=1000K
rmp=0.613982 vert
rmv 17.21 ppm
dls 0 cplx
drs 0 cplx
ct=1 msec
tau 1 usec
```

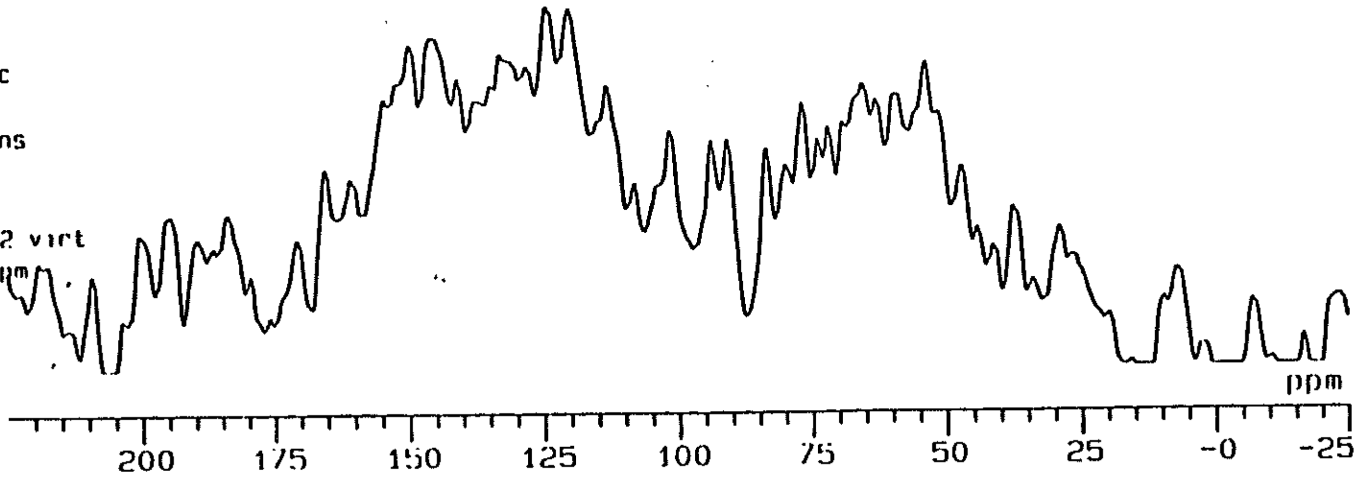
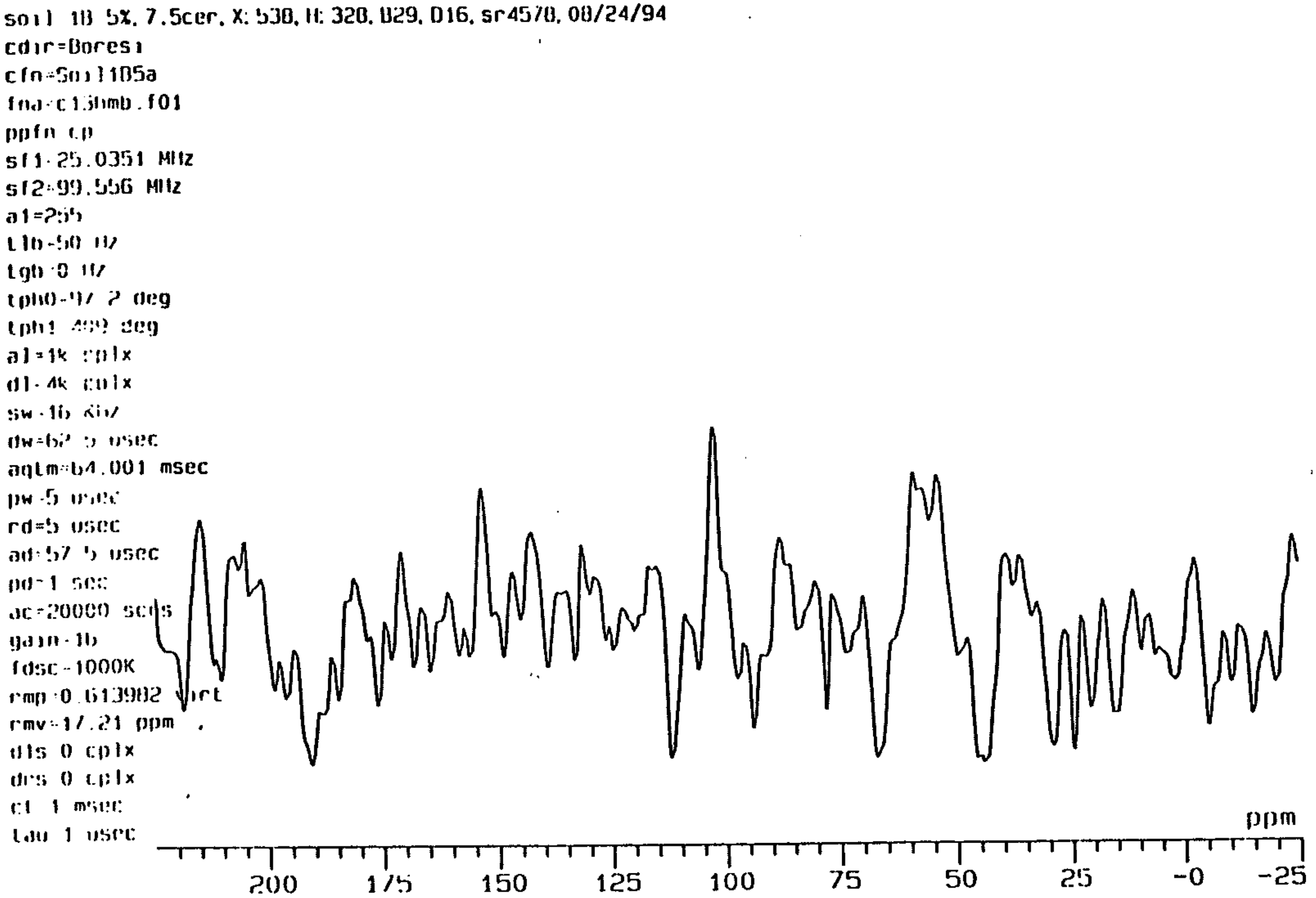
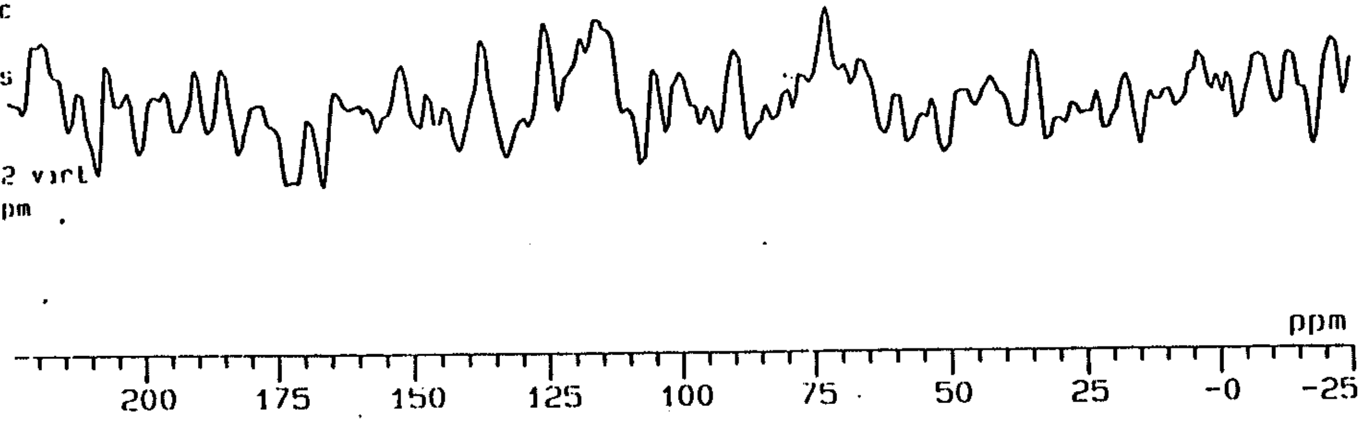


Figure 4. Carbon-13 NMR Spectrum of Soil 1B with 4.0% by Weight of Lignin Sulfonate



```
soil 1B 5%, 7.5cer, X: 538, H: 328, B29, D16, sr4578, 08/24/94
cdir=Boresi
cfn=Soil105a
fna=c13hmb.f01
ppfn=cp
sf1=25.0351 MHz
sf2=99.556 MHz
a1=255
tlb=50 Hz
tgb=0 Hz
tph0=97.2 deg
tph1 499 deg
al=1k cplx
dl=4k cplx
sw=16 KHz
dw=62.5 usec
aqtm=64.001 msec
pw=5 usec
rd=5 usec
ad=57.5 usec
pd=1 sec
ac=20000 scns
gain=16
fdsc=1000K
rmp=0.613982 vrt
rmv=17.21 ppm
dls 0 cplx
drs 0 cplx
ct 1 msec
tau 1 usec
```

Figure 5. Carbon-13 NMR Spectrum of Soil 1B with 0.8% by Weight of Lignin Sulfonate



```
soil 1BK 5%, 7.5cer, X: 530, H: 320, 829, 016, sr4592, 08/25/94
cdir=Boresi
cfn=Soil1BK5
fna=c13nmb.101
ppfn=cp
sf1=25.0351 MHz
sf2=99.556 MHz
a1=255
tlb=50 Hz
tgb=0 Hz
tph0=97.2 deg
tph1=409 deg
al=1k cplx
dl=4k cplx
sw=16 KHz
dw=62.5 usec
aqtm=64.001 msec
pw=5 usec
rd=5 usec
ad=57.5 usec
pd=1 sec
ac=4496 scns
gain=16
fdsc=1000K
cmp=0.613982 vert
cmv=17.21 ppm
dls=0 cplx
drs=0 cplx
ct=1 msec
tau=1 usec
```

Figure 6. Carbon-13 NMR Spectrum of Soil 1BK with 0.8% by Weight of Lignin Sulfonate

```
Soil H-1C, 5%, 7.5cer, X: 538, H: 328, 829, 016, sr4637, 08/25/94
cdir=Boresi
cfn=SoilH1C5a
fna=c13hmb.f01
ppfn=cp
sf1=25.0351 MHz
sf2=99.556 MHz
a1=255
tlb=50 Hz
tgb=0 Hz
tph0=97.2 deg
tph1=409 deg
al=1k cplx
ol=4k cplx
sw=16 KHz
dw=62.5 usec
aqtm=64.001 msec
pw=5 usec
rd=5 usec
ad=57.5 usec
pd=1 sec
ac=8684 scns
gain=16
fdsc=1000K
rmp=0.613982 virt
rmv=17.21 ppm
dls=0 cplx
drs=0 cplx
ct=1 msec
tau=1 usec
```

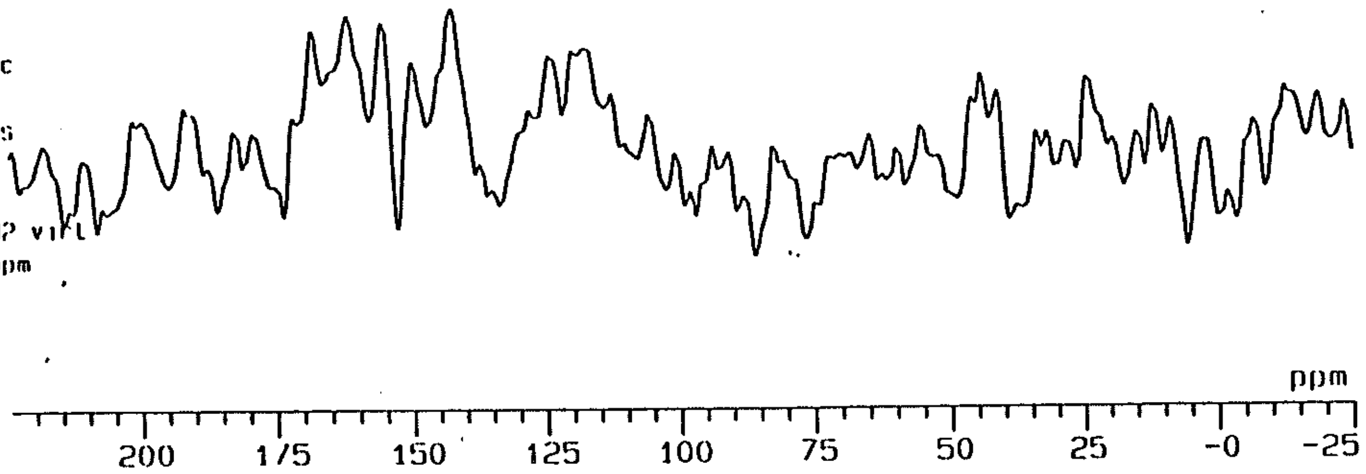


Figure 7. Carbon-13 NMR Spectrum of Soil H-1C with 0.8% by Weight of Lignin Sulfonate

```
Soil 1B +5%Lignin, 7.5cer, X: 530, H: 320, 829, 015, sr4523, 08/26/94
dir-Dores)
fn-Soil1B5L
ppln=cp
sf1=25.0351 MHz
sf2=99.556 MHz
pw=5 usec
pd=1 sec
ct=1 msec
sw=16 KHz
al=1k cplx
dl=4k cplx
ac=20000 scns
flb=50 Hz
gain=16
tph0=88.6263 deg
tph1=276 deg
rmp=0.613982 virt
rmv=17.21 ppm
ad=57.5 usec
rd=5 usec
fdsc=5000K
```

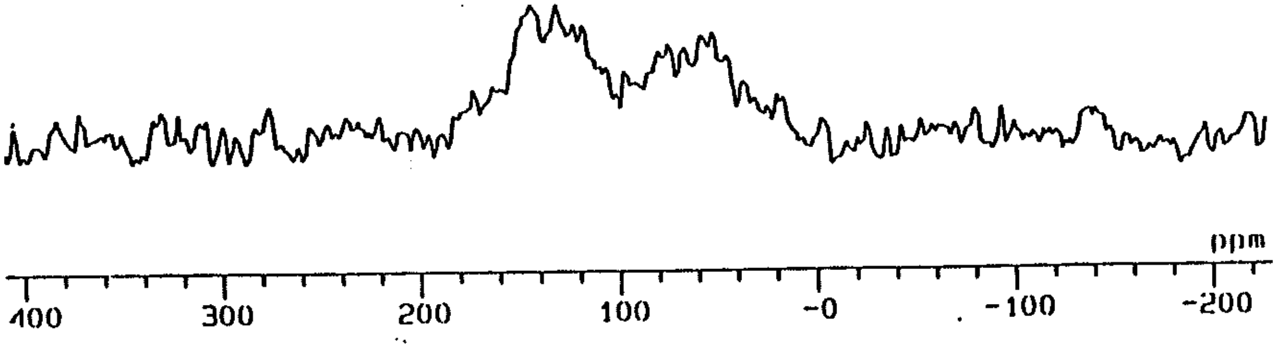


Figure 8. Carbon-13 NMR Spectrum of Soil 1B Physically Mixed with 5.0% by Weight of Lignin Sulfonate