CHAPTER 1

BACKGROUND

Problem Statement

During the reclamation process, the soil is removed ahead of the pit(s) and is either stockpiled to await its replacement, or hauled immediately to graded spoil areas behind the pit. One consequence of soil transportation includes subsequent compaction. Generally, compaction produces an undesirable change in the physical properties of a soil. It is a common and potentially serious problem on reclaimed, mined lands. The degree of soil compaction is a function of applied pressure, soil moisture, and soil characteristics. The equipment used to transport the soil applies pressure to the surface, which results in an increase in soil density (Dollhopf and Postle, 1988).

A highly compacted soil reduces root growth, which in turn reduces crop yields. In addition, several soil properties change as a result of soil compaction. Soil density increases as the soil particles move closer together. The mechanical resistance to penetration increases, depending on moisture content and size of soil grains. The hydraulic conductivity is reduced due to an increase in compaction (Barnhisel, 1988). These changes occur as a consequence of soil movement and restoration. Minesoils generally show little or no soil structure throughout their profile. Structure may begin to appear in minesoil within 50 years (Dollhopf and Postle, 1988).

Soil compaction is an inevitable result of soil transportation due to the break-up of its structure. Several options exist for the mine operator when treating compacted soils. Deep tillage has been used frequently to correct physical problems inherent in a dense, massive soil (Barnhisel, 1988).

After an area has been tilled, it has a tendency to return to its original compact state due to subsequent cultivation practices, which require machinery traffic. In addition, some recompaction occurs due to natural settling. Overall, this results in a reduction of pore space that was created by deep tillage (Larney and Fortune, 1986, Kouwenhoven, 1985).

Objectives

The practice of injecting propping material into fractures created in reservoir rock has been used for many years in the oil and gas industry. The material maintains the fractures and allows for an increase in well productivity by increasing the permeability of the rock (Mader, 1989).

This research effort focused on deep tillage of prime farmland subsoil and subsequent recompaction. The primary objective of this study was to determine the effects of material injection on recompaction of a deep-tilled soil. It was hypothesized that the propping effects of the injected material will reduce, or prevent, the recompaction of a deep-tilled soil. Several materials, both organic and inorganic, were introduced with air under pressure during the tillage operations. The specific objectives of this study were:

1) To determine the feasibility of injecting various materials into the voids caused by deep-tillage with the use of air pressure;
2) To determine the effects of material injection on recompaction of a deep-tilled soil; and
3) To provide information for further study.

Literature Review

Soil is a three-phase system that consists of solid, liquid and gaseous phases. These phases can be referred to as the soil matrix, soil solution and soil atmosphere, respectively. The soil matrix includes minerals that make up the soil particles and organic matter that attaches to the mineral grains and binds them together into clusters. The soil solution contains water and nutrients (Hillel, 1980).

The U.S. Department of Agriculture defines prime farmland as "land that has the best combination of physical and chemical characteristics for producing food, forage and fiber" (Soil Conservation Service, 1983). The land uses could be cropland, rangeland (pasture and hay) or forestland. Residential land is exempt from this definition. Prime farmland has the quality, growing season, and moisture supply needed to produce high yields of crops when properly managed. It is permeable to water and air and has few or no rocks. The prime farmland definition is also applicable to lands used for mining, but regulatory authorities may grant exemptions for certain areas by one of two methods. The area may either be "grandfathered" due to the company's lease agreements on the area when the 1977 law was passed, or the area may be "negatively determined" (determined not to have been historically used for cropland). If a soil is designated as prime farmland but has not been managed as such, the soil may be treated as nonprime farmland soil in some cases (Commonwealth of Kentucky, 1985).

Soil Structure. A typical undisturbed soil will have macroscopic and microscopic structure. The macroscopic structure refers to the aggregation of the primary particles into clusters or peds. These are the individual units of soil that can be seen with the naked eye. The pore spaces located between the aggregates, or secondary particles, are termed macropores and the pore spaces located within the aggregate are termed micropores. The macroscopic structure is of importance in crop production since movement of air and water and root elongation occurs primarily in the macropores. The microscopic structure, which can only be seen with the aid of a microscope, is the structure of soil fabric. The mineralogical composition and its distribution determines the nature of the fabric. New soils have an undeveloped structure, which appears as weak lines of aggregation with few macropores. In contrast, mature soils have a well defined structure with obvious aggregation and distinct profiles. Subsoil tends to have larger aggregates than topsoil (Hillel, 1980).

Soil Compaction. Soil is, by nature, a variable and complex material. Soil compaction involves the interaction of many variables both internal and external. Internal factors consist of natural soil characteristics. External factors act upon the soil and generally are induced by soil handling or cultivation practices. A description of the diverse factors is provided by Albrecht and Thompson (1984). Those factors critical to this study are:

1) Moisture content and contact pressure;
2) Texture; and
3) Structure and organic matter.

The combination of moisture content and contact pressure, or compactive effort, determines to a large extent the resulting bulk density. The Proctor compaction test provides a relationship between moisture content and compactive effort. For a given compactive effort, there is a moisture content that results in the highest bulk density value. When applying a greater compactive effort, a lower moisture content results in a higher bulk density. Gravimetric mass moisture content was used throughout this report. It is defined as the mass of water divided by the mass of dry soil and is reported as a percentage (Hanks and Ashcroft, 1980).

Soil classification, or texture, is determined by the percentage of primary particles in each size category. The USDA textural triangle utilizes the ranges of particle size as shown in Table 1:

Table 1
USDA Particle Sizes

Fraction	Size (mm)
Gravel	>2
Sand	
Very Coarse	1.00 - 2.00
Coarse	0.50 - 1.00
Medium	0.25 - 0.50
Fine	0.10 - 0.25
Very Fine	0.05 - 0.10
Fines	
Silt	0.002 - 0.05
Clay	<.002

A particle size analysis gives only the proportion of different sized particles and not the arrangement of the particles with respect to each other. The texture determines the soil's ability to compact. If the soil is well-graded, there will be small particles to fill in the voids formed by the larger particles. A poorly graded soil will compact to a lower density due to insufficient smaller particles to fill in the void spaces (Gupta and Larson, 1979).

Soil structure and organic matter combine to produce favorable soil conditions for plant growth. Soil structure develops due to interacting physical, chemical, and biological factors. Wetting and drying causes the swelling and shrinkage of clay minerals. The formation of these desiccation cracks contributes to the development of aggregated structure. Clay minerals also act as a cementing agent inside the aggregate to give it strength, which promotes a well structured soil with definite planes of weakness between the peds (Hillel, 1980).

The biological agents of soil contribute to the development of structure. The macro soil animals increase aeration and drainage through the channels and burrows they develop. Macro animals such as earthworms have been effective in reducing bulk density in compacted subsoils (Larson and Allmaras, 1971). Macro soil animals macerate the plant litter they eat to provide food for the microorganisms. The microorganisisms produce positively and negatively charged particles that bind the soil together. Root secretions also act as a cementing material. Generally, organic matter increases the stability of intra-aggregate bonding (Hillel, 1980).

Reclaimed Mine Soil. The overall success of a crop grown on a relocated and compacted soil depends primarily upon its physical condition (Barnhisel, Powell, and Hines, 1986). This is determined by the physical properties of soil such as structure, bulk density, and resistance to mechanical penetration. Figure 1 shows a comparison of an undisturbed and a reclaimed soil. In an undisturbed soil, aggregates are separated by planes of weakness that are represented by the open spaces shown in the figure. These macropores allow for air and water transportation and root exploration. The removal and stockpiling of the soil, necessary for reclamation, breaks up these aggregates so that the original structure of the soil is destroyed.

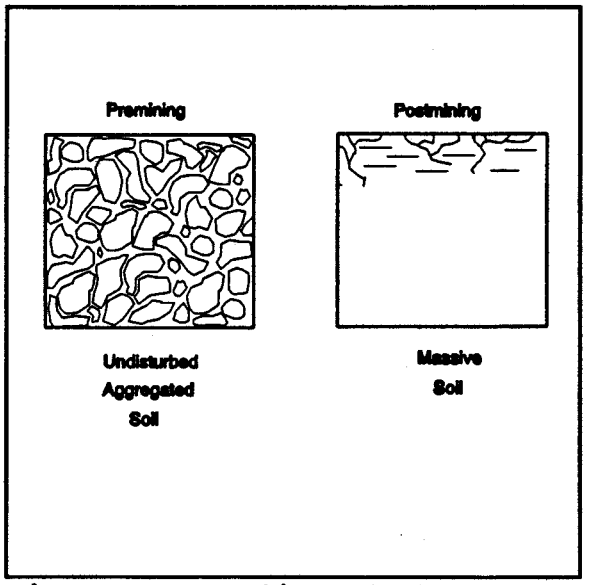

Figure 1 - Undisturbed, Aggregated Soil Versus Massive Soil

Upon removal and replacement, the soil is compacted with earth moving equipment to the extent that the original structure is destroyed and one massive unit of soil results. A crust is typically formed on the surface layers due to final grading and leveling of the soil. There are no apparent lines of weakness with the exception of desiccation cracks near the surface due to wetting and drying. This reduces water infiltration and transmission through the soil. Layers of excessively compacted soil develop at various levels in the profile due to the intensity of traffic. The pore space is greatly reduced by the loss of macropores. These factors combine to produce a soil with poor physical properties that inhibit root growth (Dollhopf, D.J. and Postle, R.C., 1988).

Methods of Alleviating Soil Compaction. Tillage is used as a corrective measure and serves a variety of purposes. It may be used to eradicate or control undesirable plants during crop production. The soil is typically inverted with a moldboard plow in order to prevent weed growth. Fertilizers, plant residues, mulch, and other soil amendments may be incorporated into the soil by inversion (Gill and Vanden Berg, 1968). Shallow tillage may also be used to insert seeds into the soil.

In the case of dense, massive soils, the physical condition can be modified. This is accomplished by loosening and breaking up the soil so that water and air may move more freely. Tillage greatly increases the macroporosity, at least temporarily (Hillel, 1980).

Instead of inverting the soil, as done in conventional tillage at shallow depths, deep tillage breaks the subsoil with a knifelike instrument. Deep tillage is performed to remedy a particular situation. On minesoils during the reclamation process, deep tillage is performed typically to reduce compaction (Barnhisel, 1988).

When deep tilling is in order to loosen the soil to enhance crop production, the performance is typically based on the following requirements (Gill and Vanden Berg, 1968):

1) Tillage must reduce clods to a desirable size;

2) The energy applied to the soil must be used efficiently in breaking up the soil;
3) The power requirements per unit of tilled soil must be low; and
4) The machine capacity must be high.

The first two items can be controlled by deep tilling at a moisture content that optimizes the shattering of the soil. Generally, a dry soil will shatter better than a wet soil. However, massive soils tend to break up into large clods regardless of the moisture content (Cooper, 1971). The third item depends upon the physical properties of the soil, such as density and strength. A highly compact soil will require more power input (Chancellor, 1977). The last item is machine dependent.

Deep tillage has been used to control wind erosion where sandy soils are underlain by clay subsoil. In this case, deep tillage increased the clay content of the surface layer and acted as a binding agent to prevent topsoil erosion (Foth and Turk, 1972).

There are several natural methods that can be employed to alleviate excessive compaction. Deep rooting legumes such as alfalfa, sweet clover, lespedeza and birdsfoot trefoil are well suited for revegetation purposes on reclaimed mine soil. In addition, legumes increase soil nitrogen and promote the growth of microorganisms that work in the organic matter (Grandt, 1988).

Freezing and thawing of the soil results in loosening. As ice crystals form, water from the local area moves toward the crystals. The water then freezes and the ice crystal develops into a lens shape and attracts water from the surrounding area. This causes the immediate pore space to be used up. Particle displacement occurs due to the growth of the ice formation. This results in expansion of the soil in the area of lens formation (Larson and Allmaras, 1971). The benefits of this method are limited to the frost zone, which in many areas does not extend to the depth of subsoil replacement (McCarthy, 1982).

Deep Tillage Failure Patterns. Four types of soil failure can occur when forces are applied: shear, plastic flow, compression, and tension. The soil's initial condition affects the mode of failure. The reaction of the soil will depend upon the bulk density, soil texture and moisture content.

When a ripper is pulled through the soil, the resulting failure is assumed to follow the Mohr-Coulomb failure criterion when moisture contents are less than the plastic limit (Stafford, 1979; Godwin and Spoor, 1977). This type of shear failure is described as crescent-shaped. The soil moves forward, upward and fans out. The crescent failure increases with increasing working depth until, at a certain depth, termed the critical depth, the soil at the ripper base will begin to flow forward and sideways only (lateral failure). The volume of soil fails along a plane of weakness developed when the combined applied stress exceeds the strength. The location of the failure plane, or slip line, is determined by the soil's characteristics, such as angle of internal friction, moisture content, bulk density and texture (Godwin and Spoor, 1977). The intersection of the shear failure (slip line) and the ripper defines the critical depth. The critical depth is sensitive to changes in soil characteristics such as density, angle of internal friction and moisture content as well as ripper configuration and operating variables.

The phenomenon of plastic flow can be observed when a ripper moves through a wet clay. Instead of shattering and developing distinct shear failure planes that can be seen on the surface, the soil flows around the subsoiler and remains a continuous mass (Gill and Vanden Berg, 1968; Stafford, 1979). The boundary between the two types of failure occur near the plastic limit (Stafford, 1979). There is an optimum moisture content at which tillage produces the maximum

number of large voids. This is equal to a gravimetric moisture content of approximately 0.9 of the soil's plastic limit (Ojeniyi and Dexter, 1979).

Compression results in increasing the bulk density. When tilling, the overall change may be a decrease in bulk density, yet the area below the tillage tool typically shows an increase in bulk density (Cooper, 1971).

Direct tension is not typically applied to soil by a tillage tool. However, failure in tension may be induced during soil manipulation (Gill and Vanden Berg, 1968).

Soil Recompaction. Subsequent to deep-tillage, certain events will reduce the pore space created by tillage operations. Several studies have been conducted on recompaction of deep-tilled soils located on areas undisturbed by mining. Larney and Fortune (1986) studied the effects of subsequent cultivation on a previously tilled area. Kouwenhoven (1986) studied the effects of natural events, such as rain, gravity and shrinkage on tilled areas. The problem of recompaction on a freshly tilled soil is due primarily to traffic that is necessary to prepare a seedbed.

The structure of a pre-tilled soil was found to affect its ability to recompact. When a dense, massive soil is deep-tilled it will break up into large clods, which will need to be further worked to prepare a desirable tilth for seed germination. Poorly structured or massive soils, such as one would find on a typical reclaimed minesite, are likely to need additional cultivation in order to prepare an adequate seedbed. While these massive soils have the greatest need for deep loosening, the additional cultivation passes required for clod breakup canceled the effects of deep tillage (Larney and Fortune, 1986).

Without traffic, some of the newly created macropores will collapse due to natural events such as rainfall, gravity and shrinkage (Kouwenhoven, 1985). A linear relationship exists between the amount of time after deep tillage and the amount of recompaction occurring naturally. Rainfall accounts for most of the naturally occurring recompaction. Gravity and shrinkage played only a minor role. In addition, natural recompaction was strongest on the coarsest soil. A silt loam soil experienced the least amount of recompaction by natural forces.

Blackwell et al. (1989) applied gypsum to vertical slots measuring 40.0 cm (15.7 in.) deep and 10.0 cm (3.9 in.) wide. The gypsum was deposited into the slot by gravity. This technique was found to increase crop yield by increasing infiltration and porosity, and provided protection from subsequent recompaction of the slot. The stronger, uncultivated soil adjacent to the slots supported the wheel load while maintaining the slot. This was contrasted to a surface application of gypsum followed by deep ripping. Recompaction was found to occur after one pass over the deep ripped zone and four passes over the slots. The injection of gypsum during deep ripping was not studied.

Recompaction of reclaimed mine soils has been documented as a byproduct of other investigations. In work conducted by Barnhisel (1986) there was a tendency for the bulk density to increase over a period of two years on ripped and nonripped areas. The density in both the ripped zone and below the ripped zone tended to increase. The cause of the increase was not investigated. Figure 2 shows a schematic of the stages of deep tillage as discussed above.

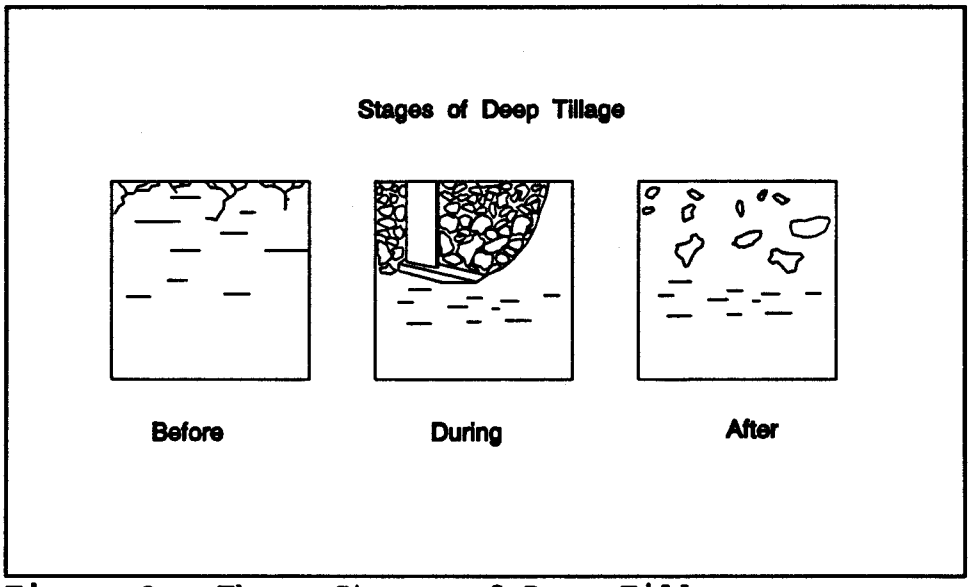

Figure 2 - Three Stages of Deep Tillage

Pressures Caused by Machinery. Pressures developed at the contact area between the soil and the machine depend upon the characteristics of both the machine and the soil. The distribution of pressure over the contact area is not uniform and depends on the characteristics of the tire or track and the soil. The pressure distributions within the soil, at a given depth below the surface, are a function of the amount of load, the size of contact area, the distribution of surface pressure within the contact area, the nature of the soil, soil moisture content, and soil bulk density. The magnitude of the stress decreases with increasing depth below the surface of the soil. An increase in load increases the depth of the stress bulb (Soehne, 1958).

An approximately equal pressure over the entire contact area can be assumed when a smooth-surfaced load is placed on a hard dry soil. This is not true for soft, moist soil. If there is plastic flow to the side of the contact area on a moist soil, then the pressure decreases toward the outside of the contact area and the pressure is more concentrated towards the center of the load (Soehne, 1958).

Typically, scrapers and dozers are used to move soil. Agricultural tractors are used to pull tillage tools through the soil. When a larger force is required to move the tool through the soil, a dozer may be used.

A summary of estimated ground pressures for various types of earthmoving equipment, which could be encountered in surface mine reclamation is given by Barnhisel (1988). Estimated scraper pressures range from 551 to 860 kPa (80 to 100 psi) for a pan capacity of 18.4 m^3 (24 yd^3). The range depends on the load of the scraper, either empty or full. Due to the rubber tires, the load is concentrated on a relatively small area. This leads to high contact pressures.

In the case of dozer tracks, the soil contact area is greater. Also, the dozer pushes the soil, instead of carrying it. This leads to lower total weights and lower average pressures. Typical dozer contact pressures range from 31.7 to 152.2 kPa (4.6 to 22.1 psi), depending on the type of dozer

(Barnhisel, 1988). Caterpillar, Inc. (1988) reports ground pressures of dozers (i.e., D7H, D8N, and D9N) ranging from 78.5 to 88.8 kPa (11.4 to 12.9 psi).

Estimated contact pressures for agricultural tractor tires are typically less than 137.7 kPa (20 psi) (Hillel, 1980). As equipment has increased in size and mass, machine designers have increased tire sizes to keep the soil surface pressure relatively constant. Taylor and Gill (1984) summarize the agricultural soil compaction problem. Pressures created by a standard agricultural tire were monitored in the subsoil at depths of 52 cm. (20.5 in.).

Methods of Measuring Soil Compaction. There are several available methods of measuring soil compaction. The three methods used in this study were bulk density, mechanical resistance and hydraulic conductivity. Background information on these methods is discussed here; however, their application to the project is described in Chapters III and IV. No single method is considered best for measurement of compactionin all cases.

Bulk Density. A common method used to measure compaction is the bulk density of the soil. Freitag (1971) reviewed methods of measuring bulk density. Wet bulk density is defined as total mass per unit volume and is expressed as g/cm^3 (lbs/ft^3). Due to varying moisture content, this is rarely reported. Dry bulk density is defined as the dry soil weight divided by wet volume and is expressed as g/cm^3 (lb/ft^3) and will be referred to as "bulk density" or "density". This value is typically reported in compaction studies. A low bulk density value corresponds to a less compact soil. As the bulk density increases, the soil particles come closer together. Smaller particles start to fill in the voids between the larger particles. Bulk density measurements may be taken gravimetrically or with a nuclear device.

Gravimetrically, bulk density is obtained by measuring the dry weight of the soil and its wet volume: Bulk Density = Dry Weight/ Wet Volume g/cm^3 (lbs/ft^3)

Several methods are available to measure the volume depending upon the soil characteristics. Core samples are best suited for soft to firm, cohesive or plastic soils. An accurate volume of brittle, rocky or cohesionless soils generally cannot be obtained with the core sampling method. Alternative techniques require the determination of the volume of the hole excavated in the soil by filling it with a free flowing material. The volume of the material is determined either by measuring the weight needed to fill the hole or by directly measuring the volume as it flows into the hole. Typical materials used are dry sand, water, and oil (Freitag, 1971).

Manufacturers of nuclear devices provide operational and scientific information for measuring bulk density (CPN Corporation, 1988). The nuclear device is referred to as "nuclear gage" or "gage" in this report. Radioactive methods measure in situ bulk density and utilize two forms of radiation: gamma and neutron. The unstable isotopes contained within the source will slowly decay to a more stable state. This act of decay produces emissions of energy as the atoms disintegrate. Two types of gages are available: single probe and dual probe. The dual probe nuclear gage contains two source isotopes in one probe (one emits gamma, one emits neutron radiation). The gamma radiation detector is located in the other probe, while the neutron radiation detector is located in the source probe. The single probe gage also contains two source isotopes, but both detectors are located at the base of the instrument, which remains on the soil surface. Due to the decay of the radioactive sources over time, new standards are established in order to calculate the soil count/standard count ratio, which is used in bulk density determinations (CPN Corporation, 1988).

For a dual probe gage with a noncollimated source, the gamma photons pass from the source to the detector in a somewhat arched path, which at the center may vary from 5.1 to 10.2 cm (2.0 to 4.0 in.) in thickness (Ayers and Bowen, 1985). This thickness is inversely related to the density of the soil. A dual probe gage measures the average density of a finite thickness. This causes errors when measuring sharply changing soil density profiles (de Vries, 1969). However, this is not a problem if the soil density profile gradually changes, or the average soil density at a specific depth is required (Ayers and Bowen, 1985). The effect of changing soil density profiles on the resolution of a noncollimated dual probe gage has been investigated (Ayers and Bowen, 1985; Vomicil, 1954; de Vries, 1969). The zone of interface influence was found to range from 5.1 to 10.2 cm (2.0 to 4.0 in.).

Mechanical Resistance. Soil strength is related to mechanical resistance and is defined as "the ability or capacity of a particular soil in a particular condition to resist or endure an applied force" (Gill and Vanden Berg, 1968).

Resistance to penetration depends upon soil properties such as texture, structure, mineralogical composition, moisture content and density. A coarse-grained soil will have a large average pore diameter and a low resistance to penetration. A soil with a well developed structure will contain macropores, which can be easily penetrated. Soils with a high moisture content have a lower resistance to penetration than a soil with a lower moisture content. Generally soils with a low bulk density have a lower resistance to penetration (Thompson, Jansen, and Hooks, 1987).

A common method used to measure the soil's resistance to penetration requires forcing a shaft with a cone-shaped tip into the soil. In addition to the above mentioned items, the mechanical resistance encountered also depends upon the interaction of the soil with the cone. This includes the cone's diameter and angle, material of composition and rate of advancement. Since there are many factors affecting the resistance to penetration, this index can be used only when all other factors are held constant (Vomocil, 1957).

There are two methods of advancing the cone penetrometer: impact and continuous-stress. Since the rate of advance affects the magnitude of the force required to cause penetration, the impact method proves to be less desirable (Freitag, 1971). The continuous-stress type is standardized with respect to cone dimensions and rate of advancement. Two sizes of cones are recommended, one for soft soil and one for hard soil. Both configurations are 30 degree right circular cones and are located at the base of a shaft (American Society of Agricultural Engineers, 1988). The resistance to penetration is recorded as a continuous function of depth with a chart recorder or with a computerized data acquisition device. Manual penetrometer readings may also be taken with a proving ring at pre-determined depth increments. The cone index is found by dividing the resistance by the cross-sectional area of the cone.

The mechanics of soil failure during penetration include shear failure, plastic flow, and compression. Direct interpretation of the penetrometer results in terms of the soil strength is currently unavailable. However, the penetration resistance is considered to be related to the strength of the soil and is termed penetrometer soil strength (Hillel, 1980).

Fluid Conductivity. Fluid conductivity of a soil is a measure of its ability to transmit a fluid. It is a function of the structure, texture, porosity (or density), pore-size distribution, moisture content, and characteristics of the permeating fluid (viscosity, density, chemical composition). Darcy's law was developed for a porous medium saturated with water. Since its development, it has been applied to unsaturated hydraulic and air conductivity.

Since the macropores conduct water at a faster rate than the more tortuous micropores, generally a soil with a lower density (more macropores) will conduct water faster than a more compact soil. However, this method of measuring compaction has not been widely used (Freitag, 1971).

Similitude. In this report, the concept of similar systems was considered to scale field tillage equipment for use in the laboratory. The relationship between the field system and the laboratory system model was determined since the same physical laws govern the behavior of both systems.

The similarity considerations were geometric (ripper dimensions), dynamic (ripper speed and acceleration) and kinematic (soil failure patterns). The kinematic similarity requirement depends upon the geometric and dynamic similarity (Wismer, Freitag, and Schafer, 1976).

Geometric Similitude. The Reynolds number is a well known dimensionless ratio that describes the phenomenon of laminar versus turbulent flow for liquids with various densities, viscosities and velocities flowing in pipes with various diameters (Mott, 1979). This ratio was developed by a technique used to analyze the dimensions of all pertinent variables involved in the system. Likewise, the operating- depth-to-the-cutting-width of the ripping tool and angle of the ripper foot off the horizontal (rake angle) are two dimensionless ratios that adequately describe the phenomenon of soil failure, all other variables (soil and operating conditions) remaining the same (Schafer, 1989). When the rake angle is measured in radians, the quantity is dimensionless.

Dynamic and Kinematic Similitude. Several studies have investigated the effect of ripper speed on soil failure patterns. To establish perspective, 50.0 cm/sec (19.7 in./sec) converts to 1.1 mph which is a typical field ripping speed.

Stafford (1979) investigated ripper speeds at various moisture contents. At very low speeds of 5.0 mm/sec (0.2 in./sec) soil failed in a manner similar to failure under field ripping speeds for a moisture content less than the plastic limit. That is, the angle of the slip line was found to be close to the theoretical value of 45 degrees minus $\theta/2$, where θ is the angle of internal friction of the soil. The soil failed as a rigid brittle material along a thin surface of maximum shear stress at regularly spaced intervals. The failure was described as crescent shaped. At very high ripping speeds, greater than 5 m/s (16 ft/sec), a change in failure occurred, from shear to plastic flow. This change occurred at a critical velocity known as the plastic propagation velocity. Therefore, soil reactions were found to be rate dependent at very high velocities. However, typical field and laboratory ripping speeds fall well below this upper limit.

Soil Failure Patterns. All other variables remaining constant, soil failure is determined by the ratio of the operating depth to the effective cutting width of the ripper (depth-to-width ratio) and the effective rake angle. The effective cutting width and effective rake angle corresponds to that part of the ripper that provides the major thrust to the soil. Generally, a ripper with a small depth-to-width ratio, develops crescent failure over the entire working depth, so that the slip line goes to the base of the ripper. As the depth-to-width ratio is increased, usually by increasing the operating depth, the crescent failure is limited to a region above a critical depth. Below this critical depth, the soil moves laterally. Any changes in soil characteristics (i.e., density, angle of internal friction and moisture content) as well as ripper configuration and operating variables will affect the critical depth (Godwin and Spoor, 1977). The rake angle has a similar effect of increasing or decreasing the depth of crescent failure. Generally, when the rake angle is decreased, the depth of crescent failure is increased (due to the downward migration of the base of the crescent failure along the

length of the ripper). These two parameters adequately describe tillage operations. There is a critical depth for all ripper shapes and configurations in a given soil condition.

Tillage Mathematical Models. Several models have been developed to predict the volume of failure caused by ripping and the forces acting upon the ripper. Payne and Tanner (1959) established basic principles of soil failure under various ripper configurations. McKyes (1977) investigated the case of crescent failure reaching the base of the ripper. Godwin and Spoor (1977) proposed a method for estimating the critical depth of soil failure when the crescent failure did not reach the full length of the operating depth.

Pneumatic Conveying. This section of the literature review pertains to design elements that are addressed in Chapter VI.

The purpose of a pneumatic conveyer is to move solids from one location to another. There are two basic classes of pneumatic conveyors: negative (vacuum) and positive pressure.

Generally, bulk solids are a mechanical mixture of grains of a solid of various sizes. Bulk solids consist of particles so small in comparison to the container that they are considered as a continuous mass.

The material used in pneumatic conveying must be at least air dry and free flowing. Generally, material that is friable and easily broken, such as straw, is not likely to be successful in pneumatic conveying, except at low pressures (Stoess, 1970).

The flow properties of granular material depends primarily upon the particle size, shape, and moisture content. Moisture affects the cohesion of particles and adhesion of the material to the container walls. Generally, cohesive materials are difficult to convey pneumatically since they do not fluidize well (i.e., not easily entrained in air).

The angle of repose (or angle of internal friction) depends upon the particle's composition and shape of the particles. The lower the angle, the more likely the material is to flow (Stepanoff, 1969).

Flow of material in air is affected by the physical properties of the material, the Reynolds number and the material-to-air ratio. Classification of material is made on its ability to flow. Pressure drops are due to the drag forces on the particle, acceleration of the particle and friction of the air (Wen, 1976).

The conveying of material through the air is broken into two main categories: dilute and dense phases. The amount of material and air flowing in the pipe determines the phase of transport. The ratio of material to air is conventionally used to describe the flow. However, a visual inspection of the flowing material is also used to determine the phase classification, as described below.

In the dilute phase, the conveyed material is distributed uniformly throughout the cross sectional area of the pipe. To achieve this, low material-to-air ratios must be maintained. The dilute phase allows for a stable transportation of material. The minimum velocity needed to carry the material without allowing them to settle out is termed the "saltation velocity" for horizontal transport and "choking velocity" for vertical transport (Wen, 1976).

In the dense phase, the material is concentrated in plugs or on the bottom of the horizontal pipe. This occurs as the material-to-air ratio is increased causing some particles to settle on the bottom of the pipe and drift along. Further increases in the ratio results in plugs of material pushed along by plugs of air. Even higher ratios cause the material to build up and become continuous in the pipe. The material on the surface will flow in the form of ripples with most of the material remaining stationary, much like a sand dune migrates. Flow of material at high ratios are typically unstable, with large fluctuations in pressures. Plugs of material cause high pressure drops as the plug is expelled (Wen, 1976).

Pressures are divided into three general categories:

low	< 103 kPa	(< 15 psi)
medium	103-310 kPa	(15-45 psi)
high	309-861 kPa	(45-125 psi)

Low pressure systems handle dry, crushed and fibrous material. Medium and high pressure systems handle competent solids (Stoess, 1970).

The type of system needed is first determined by the particle size and shape of the material to be conveyed. Tables of particle sizes and corresponding pressure ranges are available (Stoess, 1970). Generally, granular, solid material can be conveyed at any desired pressure range. Lumpy or irregularly shaped particles, such as sawdust and wood chips, can be conveyed only at low-pressures. After the type of system is determined, the necessary air requirements to transport the desired volume of material is determined. The basis for design of high pressure systems is actual experience in the handling of same or similar materials (Stoess,1970).

A variety of equipment is available to convey material pneumatically. Components of positive pressure systems are discussed by Stoess (1970).

Solids Pumps. Several types of solids pumps are available and are used in the low and medium pressure range. Fuller-Kinyon Pumps are used with fine grained material (50-200 mesh). The maximum air pressure is 310 kPa (45 psi). The material to be conveyed enters the hopper and is advanced by gravity to the impeller screw, which rests horizontally. The material is then metered into a mixing chamber. A modification of this pump uses a lower air pressure of 83 kPa (12 psi).

Blow Tanks. A blow tank is a container filled with material that is funneled into a pipeline by gravity and the energy of expanding compressed air. Blow tanks are categorized as a universal pressure system, since they are designed to operate under low, medium or high pressures. If the material in the blow tank is to be fluidized, the tank is first filled with material to a pre-determined level. Air is introduced into the tank at or near the discharge outlet. As the air permeates the material, the tank pressure forces the material out of the tank. The volume flow rate of the material is controlled by a valve located at the discharge point of the tank and by the air pressure applied. Blow tanks typically use a low ratio of material-to-air in order to maintain a dilute phase transport. The size and shape of the outlet must be designed for gravity flow, which is typically confined to the middle portion of the container. The angle of repose of the material should be less than the inclination of the funnel base. The terms "arching", "bridging", and "doming" are used to describe the stoppages of flow from material storage tanks. The free surface of the blocked material forms an arch, a bridge, or a dome. Moisture in the material can be a cause of the blockage (Stepanoff, 1969).

Metering Devices. The objective of the metering devices is to distribute the material uniformly into the air stream. Several metering devices are available and are discussed by Wen (1976). The rotary air-lock or "star wheel" feeder is the most frequently used device to feed solids uniformly. It can be used for negative or positive pressures. This device consists of an axis mounted horizontally with a paddle wheel or star wheel attached. The tips of the vanes make an air tight lock with the housing of the feeding unit (clearance of .013 cm (.005 in.)). The incoming material fills the top section of the wheel. As the wheel rotates, the material exits at the bottom position where the material is dropped by gravity into the air flow. By varying the rotation rate of the wheel, the flow rate of the material can be controlled.

Mechanical vibrators are used to maintain the flow of material. Vibrations in the horizontal plane are more effective than vibration in the vertical plane. The vibrator is attached to the outside of the tank.

Pipelines and Hoses. The conveyor lines must be designed so that flow is not restricted. Restriction of flow would cause the material to settle and stop moving, causing a blockage of flow. The pipe or hose should be as straight as possible, with as few direction changes as can physically be allowed. Any changes of direction should be made with long-radius bends. The bend-radius should be 6-12 times the pipe diameter. Pipe fittings should be flush with as few abrupt changes in inside diameter as possible. Valves are often the location of plugging. If irregularly sized material is fed into the system, it may first need to be reduced in size with a chopping device. The flow rate of the solids can be measured with an instrument that focuses a beam of light into the stream. The blockage of the light beam is used to determine the flow rate (Wen, 1976).

Fluidized Beds. A fluidized bed is a layer of solid particles with a stream of air passing upward through the particles at a velocity that sets them in motion. The range of fluidizing conditions varies from smooth to bubbling to slugging. Smooth fluidization requires minimum air velocity. The bed of particles will expand, but will remain intact. As the velocity increases, air bubbles develop and move through the expanded bed. The particles are violently agitated due to the rising bubbles. Even greater velocities will lead to the pneumatic transport of the particles. The range of velocities that allow for the transport of material is termed the slugging range (Wen, 1976).

Tillage Experiments Conducted with Air Pressure. There have been a variety of experiments done with air injection with respect to deep tillage equipment.

The use of an air film between the soil and a tillage tool was investigated by Bigsby (1961). A flat perforated surface through which air could be forced was constructed. This instrument was not successful in reducing the draft force. The draft force is defined as the resisting force that the soil exerts on the tillage tool.

In another experiment, a chisel type tillage tool was used with a series of orifices in order to reduce the draft force (Mink, Carter, and Mayeux 1964). This experiment succeeded in reducing the draft force required for tillage operations.

Fomin (1970) developed equations to calculate the distribution of air pressure to be applied at various sections of a moldboard plow in order to provide adequate lubrication.

Araya (1984, 1985) used a chisel-type tillage tool with air pressure to reduce successfully draft force, develop cracks in the soil in order to drain fields, and to dispose of sewage sludge. The nozzle was located at the leading tip of the foot and directed upward.

Another series of studies were conducted with the concept of blowing mulch into the channel created when tilling (Watson and Phillips, 1962; Hyde, et al., 1986). Crop residue was blown directly into the slot and mechanically compressed. The depths of tillage ranged from 20-61 cm (8-24 in.). The primary benefits of this method were that it controlled erosion, improved infiltration, provided for disposal of excess crop residue, and produced higher yields.

Studies involving air injection methods to reduce soil compaction were not found. The potential for compaction reduction exists in Araya's work, since cracks were created in order to drain paddy fields.

Hydraulic Fracturing. Fracturing and material injection of reservoir rocks are practiced in the oil and gas industries. Fracturing was accomplished by pumping a high-viscosity slurry (gel, emulsion, or foam) and granular material into a well. When the applied pressure exceeded the rocks' tensile and compressive stresses, fractures were formed. The fractures opened at high hydraulic pressure are kept open by support of pressure-resistant proppants, which are injected into the crack and inhibit its closure (Mader, 1989). The fractures were found to lose its fluid carrying capacity unless it was propped with granular material (Howard and Fast, 1970).

The first hydraulic fracturing jobs used natural quartz sand. Crushing of the sand limited its application. A variety of materials were tried in subsequent years, such as glass and plastic beads, metal shots, and ground walnut shells. Crushing of the glass beads and walnut shells limited their application. However, these materials were used, depending on the job site, before the invention of synthetic ceramic proppants. Since 1976, the industries have used sintered bauxite. This material resists high closure stresses (Mader, 1989).