SOIL STRENGTH AND BULK DENSITY CONDITIONS FOLLOWING AN IMPOSED METAL TO SOIL SLIDING ACTION

By

LOYD RAYMOND STONE

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Oklahoma State University

Stillwater, Oklahoma

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Thesis Approved:

James M. Davidson
Thesis Adviser

[signature]

D. D. Durham
Dean of the Graduate College

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CHAPTER I

INTRODUCTION

Early soil-water stress and inadequate nutrient supplies frequently limit crop production in many areas. These problems are generally much more acute where tillage pans or other root restricting layers exist in the soil. The development of deep and extensive root systems is of importance if water and nutrient stresses are to be alleviated and crop production increased or maintained at a high level.

It is an established fact that mechanical impedance can frequently affect root distribution within profiles of arable soils. An important factor contributing to mechanical impedance is soil compaction. Soil compaction, and thus mechanical impedance, is influenced greatly by the soil-water content at the time of compaction and by the type and amount of compaction imposed. In agricultural systems, excessive rather than inadequate compaction is generally the problem.

The effect of mechanical impedance on root penetration percentage has been studied extensively. However, a more reasonable approach would be the study of the effect mechanical impedance has on root elongation and distribution. Also, the effect of compactive effort on compaction has been studied, but this compactive effort has generally been a vertical load, not the sliding effort that exists in most tillage operations.

The objectives of this study were as follows:

1.) To evaluate the effect of soil-water content and a metal to soil sliding action on soil strength and bulk density.

2.) To compare the soil strengths obtained from vertical forces to those soil strengths obtained by sliding forces.

3.) To determine the effect of drying on soil strength.

4.) To determine the effect of soil-water content and sliding forces on soil-water characteristics.

5.) To measure root growth as a function of soil strength.

CHAPTER II

LITERATURE REVIEW

"Soil strength is the ability or capacity of a particular soil in a particular condition to resist or endure an applied force" (12). Many soil conditions and natural field soil processes affect the magnitude of soil strength. Factors of importance to soil strength development are: rate of drying, temperature, wetting and drying cycles, extent of drying, texture, exchangeable cation, soil-water content, and compaction.

Soil texture or the combination of the various size separates have been shown to affect soil strength. Mathers et al. (19) found an increase in a soil's clay content resulted in an increase in soil strength throughout the range from molding water content to dryness. The influence of exchangeable cations on soil strength has been shown by Gerard (9). He found soil strength increased with higher exchangeable sodium contents. A study (19) using soil briquets showed sodium saturated soils had a greater dry strength than did calcium or aluminum saturated soils.

Soil-water content generally has a pronounced effect upon soil strength. Several workers (2, 20, 27, 29) have shown that at a constant bulk density, soil strength increased as soil-water content decreased. The strength of soil briquets was shown to increase with decreasing soil-water content, reaching a maximum when the soil-water content was reduced to an average 2 to 3 monomolecular layers of water (9). Mathers et al. (19) also found briquet strength to be a minimum when measured at the molding water content. Briquet strength increased with drying and reached a maximum at a water content of 3 to 6 percent by weight. As drying continued, the strength decreased, but increased as complete dryness was approached. Several workers (9, 10) have shown that the rate of drying influences the packing arrangement of the soil particles and thus soil strength. Gerard et al. (10) presented results which indicated that a slow rate of water loss intensified particle packing and soil strength. Photomicrographs of thin sections of briquets dried at a fast and a slow rate illustrated the disruptive influence of fast drying and the dispersed action of slow drying (9). Gerard et al. (10) concluded that the influence of temperature on the rate of soil-water loss was the main influence of temperature on soil strength.

It has been shown (16, 17) that as granule size increases the over-all rate of soil drying increases. Also, as the compaction effort decreases, the over-all rate of soil drying increases. The effect of granule size on the soil drying rate tends to decrease with the application of increasing compaction efforts. Working with root-restricting pans in the Southern Plains area, Taylor et al. (28) concluded that regardless of the fundamental reason for a higher soil strength, soil drying was the activating mechanism that caused root-restricting features in most of the pans they observed. Gerard et al. (10) obtained results which indicate that the number of wetting and drying cycles also influences the packing of soil particles and soil strength. The particle packing arrangement approached an equilibrium after 6 to 7 wetting and drying cycles. Their results indicate that the influence of water treatments on arrangement of soil particles is not reversible upon rewetting.

Many workers (2, 20, 27, 29) have shown that compaction and bulk density increases result in a greater soil strength. They have shown that for a constant soil-water content the soil strength will increase with each bulk density increase. Gerard et al. (10) presented data which indicated that the greater the surface-applied force at a particular soil-water content the greater the resulting soil strength. Lotspeich (18) used various mixtures of kaolinite and glass beads to study the effect of glass bead packing and interstitial clay binding on strength and bulk density. Multicomponent beads compacted to a greater extent than a one-component bead and at lower water contents. The dry strength was greater for the multicomponent beads than in the one-component bead.

Davidson et al. (6) have shown, using a constant load application, that as organic matter content decreases, the maximum obtainable bulk density increases and the soil-water content at which it occurs decreases. In a test using three subsoils, Meredith and Patrick (21) found an increase in clay content was associated with a lower maximum bulk density and a higher soil-water content at which it occurred. Bruce (5) and Soehne (24) have shown that as compaction effort increases, the maximum bulk density obtained increases and the soil-water content at which it occurs decreases.

Weaver and Jamison (33) in a compaction study show that as the water content increased in the lower water content regions of a loam and a clay soil, there was an associated decrease in bulk density. As the water content increased the bulk density obtained for a specific compactive effort increased. The maximum bulk density was obtained at a water content slightly below the lower plastic limit. After this maximum bulk density was obtained further increases in water content resulted in a decrease in bulk density.

The following conclusions were drawn in a report (15) on compaction of a loamy chernozem as a function of soil-water content under different compaction efforts.

(a) At low compaction efforts, the soil density decreases initially with increasing water content, then increases, reaches a maximum, and declines again.

(b) At moderate compaction efforts (10 to 11 bars), the density initially remains constant, then increases to a maximum, and then declines with additional water content increases.

(c) At high compaction efforts, the density increases from the very beginning, reaches a maximum, and then declines with further water content increases.

Vomocil et al. (32) conducted field experiments on a Yolo fine sandy loam to measure the effect of implement speed and drawbar load on soil compaction caused by the rear wheels of a tractor. They found that both increased drawbar load and low implement speeds increased the degree of compaction at each of three moisture contents studied, but the effects were small when compared to changes resulting from alterations in the soil-water content. Bekker (4) states that the dimensions of the ground contact area have a great significance on compaction. A tire or track with a long, narrow ground contact area produces less compaction than a short wide contact of like area.

Vomocil and Flocker (31) report field compaction of a Yolo loam over a 6 year period resulted in some significant changes in soil physical characteristics. Remolded briquets of crushed and sieved soil from the plots receiving extra compactive effort had a modulus of rupture of 3.3 bars; while briquets of soil from plots receiving only a minimum traffic had a modulus of rupture of 1.2 bars. They concluded that apparently the compaction treatments had changed the aggregate shape from granular to platy by orienting the plate-like clay particles in a parallel arrangement. This parallel orientation was apparently not destroyed by crushing and sieving and caused higher soil strengths in the briquets prepared from the compacted plots.

Day and Holmgren (7) microscopically examined compressed specimens of soil to determine the nature of the changes occurring in moist soil during the application of pressure. Photomicrographs show that volume changes are attributable primarily to plastic deformation of the aggregates. Deformation occurred readily at the lower plastic limit, causing a progressive closing of the interaggregate spaces as the pressure was increased. At water contents below this limit, deformation appeared to be localized in the areas of contact between aggregates and consisted mainly of flattening of the aggregates against one another. The incomplete closing of the interaggregate spaces at low water contents was attributed to the increased shearing strength of the aggregates at lower water contents.

Vomocil and Flocker (30) state that when a soil is compressed, pore size distribution generally suffers greater relative change than bulk density or total porosity. This change in pore size distribution with compaction is towards a smaller proportion of the larger pores.

Hill and Sumner (14), working with nine different soils, have shown that the effect of compaction on soil-water characteristics varies widely with the texture of the soil. In sands they found, increasing bulk density results in an increased capacity to retain water at a constant soil-water pressure, the magnitude of the effect decreasing with decreasing soil-water pressure. Increasing the bulk density increases water-holding capacity of clay and clay loam soils, the magnitude of the effect increasing with decreasing soil-water pressure. In sandy clay loam and sandy loam soils, increasing bulk density decreases the capacity for retaining water at high soil-water pressures, and at low soil-water pressures the capacity for retaining water is increased. The range of soil-water pressure used in their study was from -0.1 bar to -10.0 bars. Taylor and Box (26) working with Millville silt loam, showed that the soil-water pressure increases with an increase in bulk density caused by a confining pressure. Release of the confining pressure results in a decrease in the soil-water pressure. Their study was conducted at soil-water pressures ranging from -0.10 to -0.60 bar.

Aubertin and Kardos (1) determined the effect of rigid and nonrigid glass bead systems with various pore diameters on the growth of maize seedlings. Their data indicated that both the rigidity of the system and the size of the pores present in the system had an influence on root growth. Maize roots did not grow into rigid porous systems which had pore diameters smaller than approximately 138μ, and when the pore diameters were smaller than approximately 412μ a reduction in root growth was observed. Maize roots were found to grow equally well in all nonrigid bead systems, regardless of the size of the pores.

Stolzy and Barley (25) designed a study to measure directly the force exerted by a pea radicle growing into soil. When a pea root encountered a soil core, the root developed its maximum force, approximately 60 g wt, in 15 to 20 hours. After the root tip had entered the soil core, part of the force developed by the portion of the root elongating within the soil was balanced by a skin friction of 20 g wt. Barley et al. (2) found that pea radicle elongation was delayed for as long as 24 hours when stronger soil cores were encountered. During this lag period the radius of the radicles increased from 0.7 to 1.3 mm. A comparison of forces produced by a root and that produced by a probe moving into a soil shows more soil resistance to the probe than to the root. This difference in resistance arises from the tapered shape of the root and the smoother nature of the surface. The ability of the root tip to grow along planes of weakness reduces the resistance encountered by it as compared to a rigid probe (25).

Taylor and Gardner (27) using cotton plants grown in cylinder assemblies and a force-gauge penetrometer for soil strength measurements, studied the effect of soil strength, bulk density, and water content on the penetration of cotton seedling taproots. Strength determinations were made at the end of a 12 day germination and growth period on the upper surface of the soil cores. The data showed root penetration decreasing as soil strength increased. No root penetration occurred at soil strengths greater than 29 bars. Their data did not support the concept that any one critical bulk density exists for the Amarillo fine sandy loam, but it did confirm that the bulk density at which no roots penetrated was dependent upon the soil-water content. They concluded that neither soil aeration nor soil-water pressure caused differential root growth pressures within the -1/5 to -2/3 bar soil-water pressure range. Also, soil strength, not soil bulk density, was the critical impedance factor controlling root penetration in the sandy soils of the Southern Great Plains. Taylor et al. (29) observed no cotton seedling taproots penetrated any core with a strength of 25 bars or greater, regardless of the soil series used. Their study further verified the conclusions of Taylor and Gardner (27) that soil strength is the critical factor controlling cotton seedling root penetration through Southern Great Plains soils at soil-water pressures of -1/5 to -2/3 bar.

The coefficient of sliding friction increases with an increase in clay content (8). Rowe and Barnes (23) found draft increases resulting from increasing the speed of a tillage tool. They attributed this increase in draft to the increase found in soil shearing strength at higher operating speeds. The coefficient of sliding friction increases as soil-water content increases, reaches a maximum, and then decreases with further water additions (8, 13, 22). Baver (3) states that the maximum coefficient of sliding friction occurs near the upper plastic limit where adhesion is at a maximum. Nichols (22) states that the soil-water content at which adhesion first occurs depends not only upon the capacity of the soil to hold water, but also upon the attractive force of the metal to wet soil.

In reviewing the literature available on laboratory compaction studies it was noted that in general these studies have consisted of a vertical load as the source of force. In tillage the force causing compaction is a resultant force consisting of a vertical and a horizontal component. In this study a procedure was designed to give both a vertical and horizontal load, and thus simulate the action occurring in tillage. The effect of this action upon various soil physical conditions was studied. To date the majority of the root growth studies have been concerned with root penetration, or lack of penetration, through a high strength layer. Soil strength should be considered a property affecting root elongation and distribution, rather than a limiting condition. This study considers root elongation, not root penetration percentage, as a function of soil strength.

CHAPTER III

MATERIALS AND METHODS

The soil used in this study has been mapped as a Norge loam. It was taken from the NW corner of the NW¼ of the SW¼ of sec. 2, T. 19 N., R. 1 W., Payne County, Oklahoma. Only the surface soil (0-15cm) was taken.

The soil was air dried in the laboratory and forced through a 6 mm. square-hole screen. After screening, the soil was placed in the constant temperature laboratory (approximately 21°C) where the study was conducted. Selected physical and chemical properties of the soil were measured and are given in Table I.

Compaction studies in the past have been conducted using only a vertical force as the source of compactive effort. Owing to the sliding action that occurs between a tillage implement and the soil, a more realistic approach in tillage compaction studies would be to use a sliding force as the source of compactive effort. This study was concerned with the importance of this sliding action on soil strength and the resulting bulk density. Various sliding forces were applied to the soil at different soil-water contents. This procedure provided a measurement of soil strength and bulk density as a function of sliding resultant pressure and soil-water content. To illustrate the importance of considering the source of compactive effort in tillage compaction studies, soil strength was compared using equal magnitudes of compactive effort

TABLE I

CHARACTERISTICS OF NORGE LOAM USED IN STUDY

Particle size distribution		
Sand	(> 50μ)	44.0%
Coarse silt	(20μ - 50μ)	24.3%
Fine silt	(2μ - 20μ)	10.4%
Clay	(< 2μ)	21.3%
Percent organic matter		1.89
Upper plastic limit		28
Lower plastic limit		20
Cation exchange capacity		
(m. e. per 100 grams)		14.1

arising from two sources. The resultant compactive effort applied to the soil was from two sources; (1) a pressure made up of both the vertical and horizontal component, and (2) a pressure made up of only the vertical component.

The effect of sliding resultant pressure and soil-water content on soil strength and bulk density was determined using the following procedure. The water content of the large soil mass (approximately 500 kilograms) in the laboratory was determined and the amount of water necessary to bring the soil to a desired water content added. After screening the soil through the 6 mm. square-hole screen, samples for soil-water content determination were taken. The soil was then covered with plastic and allowed to stand 18 hours. The screening and 18-hour waiting period were used to ensure a thorough and even distribution of water in the soil. After equilibrating for 18 hours, the soil was placed in two wooden containers 100 cm long, 19.2 cm deep, and 14.5 cm wide (inside dimensions). The ends of each soil container could be removed in small sections. The wet soil was added to each container in 4.6 kg increments on an oven dry basis; 7 increments of soil in all were added to each container. After each 4.6 kg equivalent of oven dry soil (plus water) had been added, each end of the container was dropped 5 times from a height of 15 cm, alternating the dropping sequence with each soil addition. Preliminary tests indicated that very slight soil volume changes occurred after dropping 5 times. Tests conducted at 0.09 and 0.17 gm/gm water content showed little difference in soil bulk density along the length of the container. It was therefore concluded that this filling procedure would give a soil volume of uniform density. After the 7 increments of soil had been added, the top portion of soil was removed by means of a flat metal scraper such that a soil depth of 12.5 cm remained. This procedure was followed for each soil-water content and vertical load application.

Before any sliding force was applied, soil strength measurements were made using a static penetrometer similar in design to that described by Barley et al. (2). The penetrometer included a single proving ring with a 0-220 newton capacity. The dial indicator used read deflections in the proving ring of 0.0003 cm. The penetrometer shaft had a 0.80 cm-diameter blunt tip. The penetrometer shaft (not free to rotate) was forced into the soil by means of a threaded rotating shaft (6¼ revolution/cm depth) at a rate of one revolution per five seconds. The deflection of the proving ring was a direct measure of the applied load. Using the calibration curve provided with the proving ring, the applied loads were determined. From the applied load (force) and the area of the penetrometer tip, the pressure in bars was calculated. All strength measurements presented in this study are the maximum pressure necessary to penetrate the soil surface 0.5 cm.

The strength measurements made before any sliding force was applied (4 from each container) were compared each time with a duplicate container. These were used as a check to ensure that no irregular packing had occurred. These strength measurements are reported as having received zero resultant applied pressure. After the initial strength measurements, the container of soil was positioned in the force applying apparatus and the sliding force applications made.

The sliding force applications were achieved by moving a weighted steel implement shaped similar to a sled across the soil surface. The portion of the implement in contact with the soil was polished and was

26 cm long and 8.9 cm wide. The front portion of the implement curved upward giving the implement an overall length of 39 cm. The interior of the implement was used to hold lead bricks which were used to vary the normal load applied to the soil. Normal loads of 0, 222, 445, 667, and 890 newtons were used. The implement was drawn across the soil surface at a constant speed (4 meters/min.) by using a winch that had a 3 to 1 gear ratio and a 4000 newton capacity. The force required to move the weighted implement across the soil surface was measured with spring scales accurate to 5 newtons. The resultant force on the soil was calculated from the vertical and horizontal forces. The coefficient of sliding friction was determined by dividing the horizontal force by the vertical, or normal, force.

After the sliding force had been applied, the strength of the soil surface was determined at 5 predetermined positions along the soil container. The strength measurements were made using the penetrometer described earlier. Four core samples were then taken from each soil container and used in determining soil bulk density. From four combinations of force and water content (2 forces and 2 water contents), six cores were taken from each container. These samples were used in the soil-water characteristics study to be described later. However, four of these six cores were also used in bulk density calculations. Core samples were obtained using a brass ring that was tapered on the end pushed into the soil. The ring was 5.08 cm in diameter and 1.74 cm in height, giving a volume of 35.2 cm^3. The samples were dried in an oven at 105°C for 24 hours. After the soil was removed from the oven, the oven dry mass of each sample was determined and bulk density (grams/cm^3) calculated. Soil-water content samples were taken at the same time soil strength measurements and bulk density samples were taken. All measurements and samples were taken from the middle 60 cm, thus excluding 20 cm of either end of the containers.

In order to separate the importance of the sliding action on soil strength from the same resultant force applied in the vertical direction only, a container of soil was prepared identically as stated earlier through the scraping step. A vertical pressure equal to the sliding resultant pressure was applied to the soil surface for approximately 10 seconds. The compaction implement was a circular steel plate 8.9 cm in diameter upon which lead bricks of varying weight could be added. Three locations of compaction were used in each container and three strength readings taken at each location. These strength measurements will be referred to as vertical compaction. From the region between the vertical compaction areas, two bulk density samples were taken. These are referred to as bulk density values for zero resultant pressure.

The soil-water content versus soil-water pressure relation for each of four water content-resultant pressure combinations was determined. Twelve cores were available for determination of each curve, six coming from each of the two containers. Four of the 12 cores from each combination were used to determine water content versus soil-water pressure relations at 0, -0.1 and -0.2 bar soil-water pressure, using a tension table. Another four of the 12 cores were used to determine the water content versus soil-water pressure relation at -0.4 bar soil-water pressure, using a ceramic plate-pressure cooker apparatus. Another four of the 12 cores were used in determining the water content versus soil-water pressure relation at -1.0 bar soil-water pressure, using the same apparatus used at the -0.4 bar determination.

The moisture release curve for Norge loam soil at the average bulk density with zero resultant pressure was also determined. Brass rings 1.77 cm tall and 5.08 cm in diameter were filled with soil and compressed to the average bulk density received with zero resultant pressure. The soil at time of compaction had a water content of 0.105 gm/gm. The moisture release curve from 0 to -1.0 bar was determined as described above. The curve was then extended to -10.0 bars using the ceramic pressure plate apparatus.

To measure the effect of drying on soil strength, two containers of soil at a soil-water content of 0.144 gm/gm were prepared. The vertical force imposed to each container was 890 newtons. The force was imposed in a sliding manner as described earlier. Immediately, and at specific time intervals thereafter during the drying period, the soil strength and water content were measured. Readings were discontinued when the strength values reached a point where further strength increases with drying might cause damage to the proving ring.

To determine the effect of soil strength on root elongation the following experiment was conducted. Soil cores were prepared in aluminum rings, 7.6 cm in diameter and 7.6 cm high. Enough soil, on an oven dry mass basis, was added to each aluminum ring to achieve a specified bulk density. The initial soil-water content was 0.105 gm/gm. The soil was compressed, using a Carver hydraulic press, into the lower 250 cm^3 of the ring. Six rings, each with a different bulk density, were then placed on the tension table apparatus. The soil cores were allowed to saturate (six hours) and then were subjected to a soil-water pressure of -0.2 bar until equilibrium was reached. After equilibrium

(13 hours), the cores were removed from the tension table and the soil strength of each core immediately determined. Four cotton seeds (Gossypium hirsutum) were then placed on the soil cores in such a manner as to avoid the three small holes made during the strength measurements. The seeds were covered with two cm of loose soil with a water content of 0.10 gm/gm. The cover soil received a vertical pressure of 0.4 bar for approximately 10 seconds. The cores were again placed on the tension table and allowed to saturate (six hours) before applying a soil-water pressure of -0.2 bar (13 hours). The soil cores were removed and the bottom and top of each core covered with transparent plastic to prevent evaporation during seed germination. The cores were then placed in a growth chamber for 8 hours at 30°C with lights on, 10 hours at 25°C with lights out, and finally 14 hours at 30°C with lights on. After 32 hours in the growth chamber, the cores were removed. The taproots were recovered from the cores and the distance between the junction point of root and stem and the end of the rootcap measured. The total time from planting until root recovery was 51 hours.

CHAPTER IV

RESULTS AND DISCUSSION

The coefficient of sliding friction for various soil-water contents for each of the normal loads used is given in Figure 1. The coefficient of sliding friction did not change appreciably in the 0.07 to 0.09 gm/gm soil-water content range, but as the soil-water content increases above 9% (0.09 gm/gm) the coefficient of sliding friction increased significantly. The soil-water content region where the coefficients change only slightly is referred to by Nichols (22) as the compression phase. He states that in this region adhesion does not occur because of inadequate soil particle water films that would cause implement-soil-water attraction. The coefficients of sliding friction are produced by actual soil-metal friction. Various vertical loads produce different coefficients due to the increased soil-metal contact points with increased compaction. This increase in number of contact points causes the coefficients of sliding friction to increase with the heavier loads. At greater than 9% soil-water content the coefficients of sliding friction increase sharply. This range of soil-water content where the coefficients increase is referred to by Nichols (22) as the adhesion phase. With water additions above 9% soil-water content, the water films around the soil particles become larger and are attracted to the surface of the implement. These water films are connecting films between the soil particles and the implement. To produce implement

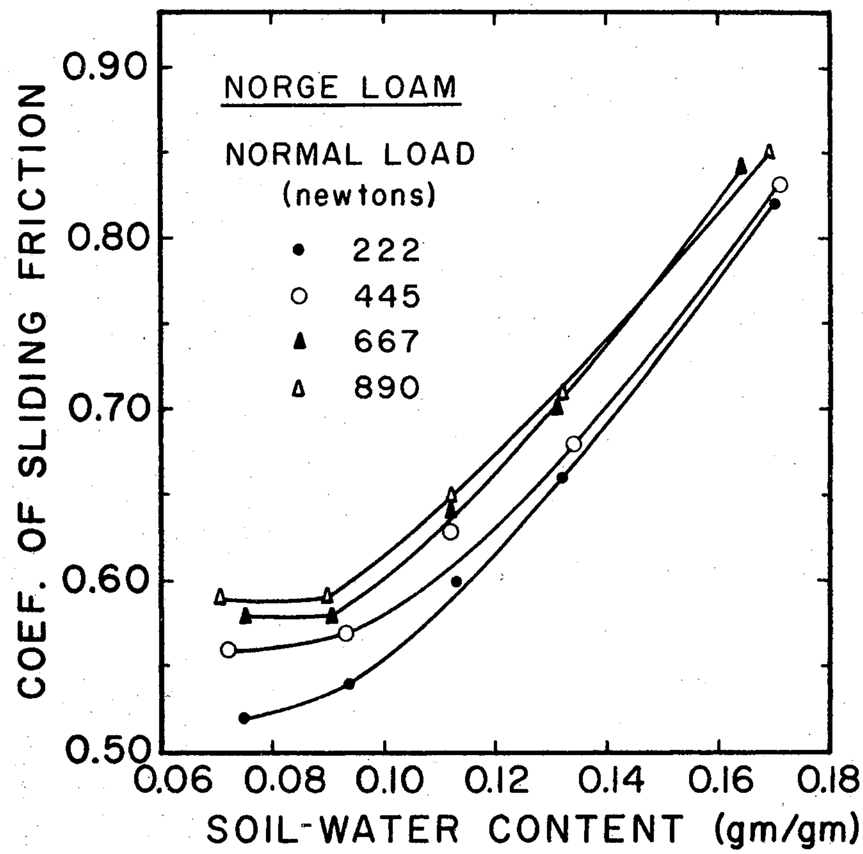

Figure 1. Coefficient of Sliding Friction Versus Soil-Water Content of Norge Loam. Each curve is for the normal load indicated.

movement this force of adhesion must be overcome and the friction curves illustrate this increase. The greater the soil-water content in the adhesion phase, the greater the number of attraction points and the higher the coefficient of sliding friction. This increase in number of attraction points is due to the thickening of water films and to increased compaction, thus placing more of these water films in contact with the implement. The coefficients vary with the amount of load in the adhesion phase, but note that the coefficient difference between loads decreases with increasing water content. It would appear that at the higher soil-water contents the attractive forces between the implement and the wet soil are approaching a fixed value and the differences due to load are smaller.

Soil-water content versus soil-water pressure relations for the four compacted surfaces used in the water characteristics study are presented in Figure 2. The water content at the time of testing and the normal load component of the sliding force are given for each curve. Also listed is the bulk density resulting from each compactive effort. An inspection of Figure 2 shows that when the implement, with two vertical forces, was pulled across the Norge loam at a water content of 11.2%, similar water release characteristics were obtained. The effect of sliding force on porosity and water release characteristics at this soil-water content appears to be slight. However, when the soil was compacted at 17% soil-water content the effect of the sliding force on porosity and water release characteristics was very apparent. At saturation, the soil compacted at 17% water content had a lower water content by volume than the soil compacted at 11.2% water content. The soil compacted at 17% water content, therefore, has a lower total

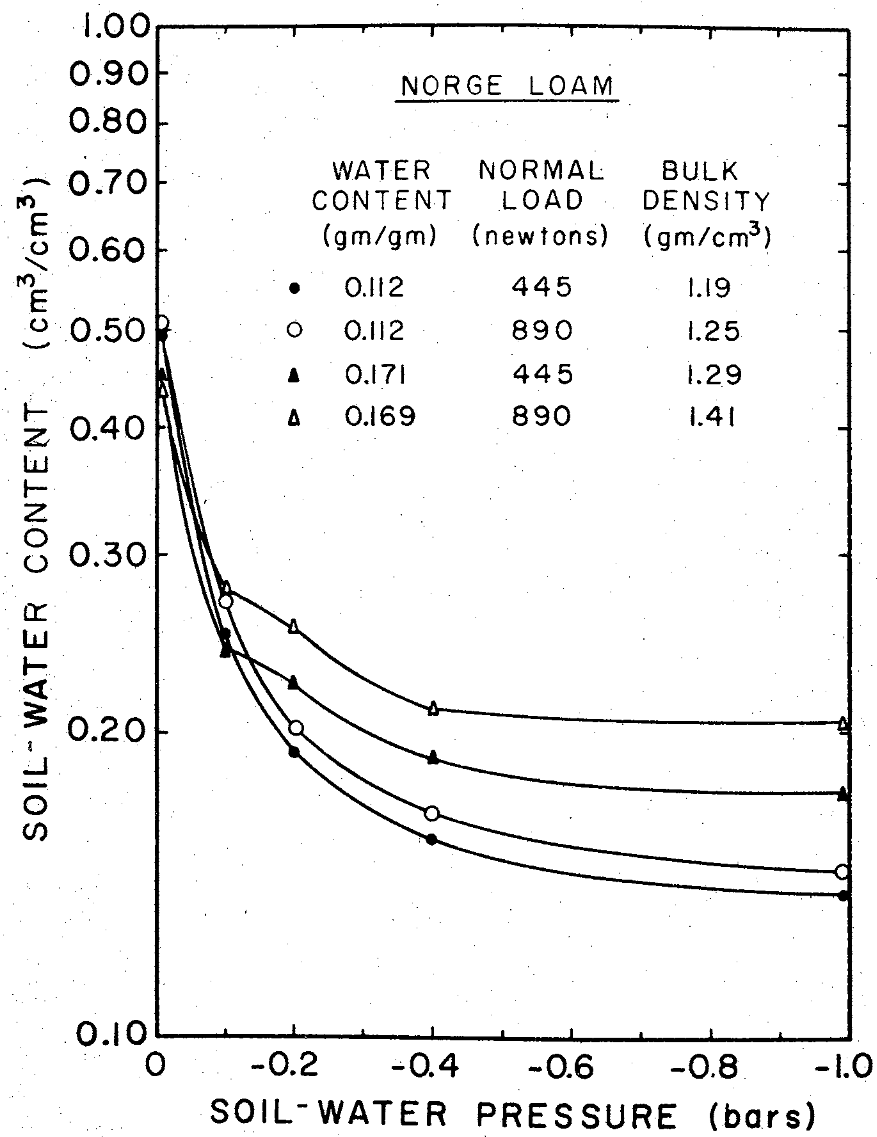

Figure 2. Soil-Water Content Versus Soil-Water Pressure for Norge Loam Samples Subjected to Two Sliding Forces and Two Initial Soil-Water Conditions. Bulk density shown is that of compacted soil layer.

porosity than the soil compacted at 11.2% water content as illustrated by the increase in bulk density. At lower than -0.2 bar soil-water pressures the soil compacted at 17% water content held more water than the soil compacted at 11.2% water content. This indicates a greater amount of small pores in the soil surface compacted at 17% soil-water content. For the initial soil-water content of 17% the heavier load increased the number of small pores significantly.

Figure 3 is the water characteristics curve for the Norge loam at a bulk density of 1.13 gm/cm^3 (the bulk density of the soil layer before application of sliding forces). Converting the water content in Figure 3 to a volumetric basis it can be compared with Figure 2. The curves in Figure 2 from soil compacted at 11.2% soil-water content compared with that in Figure 3 for no compaction shows only a slight decrease in water content at saturation and practically no difference in water content at less than -0.2 bar of soil-water pressures. The soil compacted at 17% soil-water content had less water at saturation but more water at soil-water pressures less than -0.2 bar than did the soil before application of the sliding forces. Thus indicating a decrease in total porosity and an increase in the number of smaller pores when the force was applied to the Norge loam at a 17% water content. The effect of compaction on the porosity of Norge loam at the two soil-water contents and sliding forces used can be summarized as follows:

1.) Compaction at a soil-water content of 0.112 gm/gm had little effect upon the water retained by the soil at any one pressure for either of the two forces used. Only a slight decrease in total porosity as measured by the soil-water content was detected.

2.) Compacting at a soil-water content of 0.17 gm/gm decreased

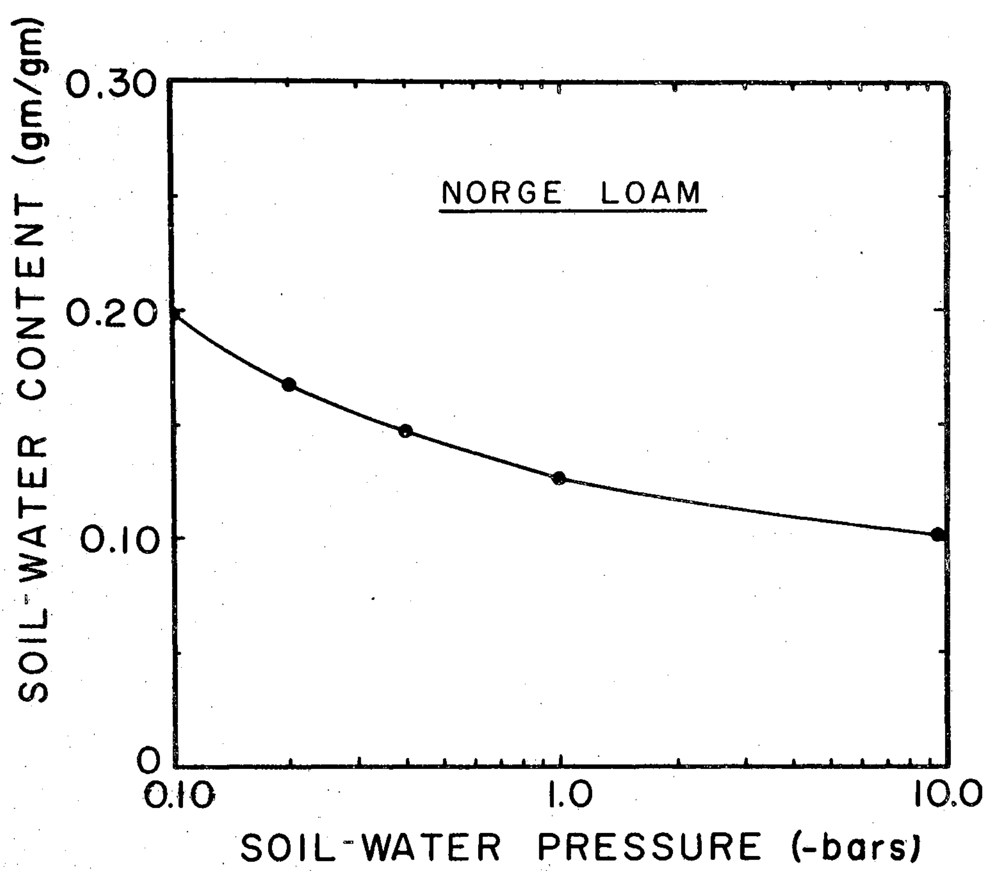

Figure 3. Soil-Water Content Versus Soil-Water Pressure for Norge Loam at a Bulk Density of 1.13 gm/cm^3

the amount of water held at high soil-water pressures, but increased the number of smaller pores and water held at low soil-water pressures. The number of smaller pores was greatly affected by the magnitude of normal load. The percent of smaller pores being larger with the greater normal load.

The physical explanation for the changes in porosity noted in the summary is based on the rearrangement of soil aggregates. At lower soil-water contents compaction is achieved through aggregates being flattened against one another. There is no disruption within the aggregate and the only detectable change in soil porosity as measured by the water content is a slight decrease in total porosity. When the Norge loam was compacted with the sliding implement at higher soil-water contents the aggregates are disrupted and a decrease in larger pores and an increase in the number of smaller pores is noted.

The bulk density of the Norge loam as affected by initial soil-water content and resultant pressure is shown in Figure 4. Bulk density increases at all soil-water contents with an increase in resultant pressure. Figure 4 shows that in general the bulk density increases as soil-water content increases for each resultant pressure. However, note that the magnitude of the resultant force influences the rate at which the bulk density increases. Also, note a small decrease in bulk density with increasing soil-water content in the lower left hand corner of Figure 4. The decrease lessens in intensity and occurs at lower soil-water contents as resultant pressure increases. Joffe and Revut (15) reported similar decreases were found using a loamy chernozem. Their explanation for the decreases is as follows: when enough water has been added to dry soil the small pores fill with water and loose

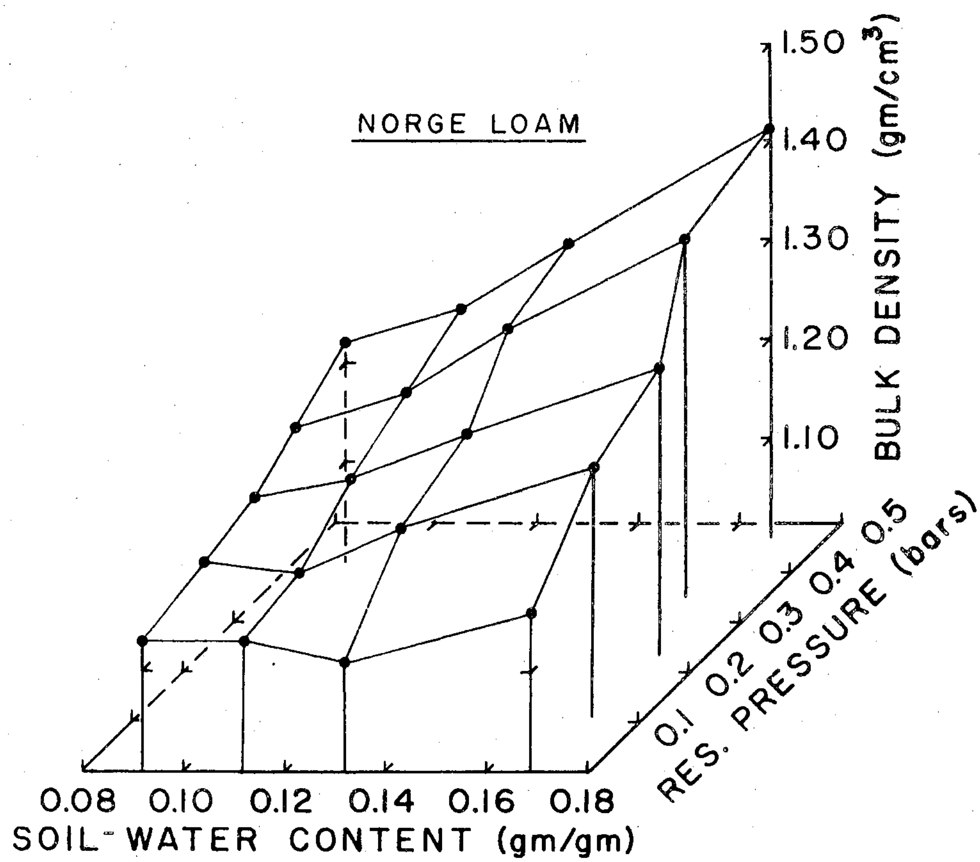

Figure 4. Bulk Density of Norge Loam as Affected by Soil-Water Content and Resultant Pressure

aggregates are formed with mixing, lowering the soil bulk density. If a small external force is applied to the soil, the decrease in bulk density will be less and will occur at a lower soil-water content. With large external forces the decrease in soil bulk density was absent in the soil-water content range used.

Sliding forces and favorable soil-water contents cause soil particles to assume a position with a larger contact area. At higher soil-water contents the soil water has a lubricating effect upon the soil particles. Since the lubrication of soil particles increases with soil-water content, at higher soil-water contents the orientation and compaction of soil particles will be greatly enhanced. Thus, producing the large increases in soil bulk density at higher soil-water contents with the greater resultant pressures as shown in Figure 4.

Soil strength as affected by soil-water content and resultant pressure is illustrated in Figure 5. For a constant soil-water content, and an increase in resultant pressure, an increase in soil strength was observed. Note that the strength of the Norge loam decreases as soil-water content increases for a constant resultant pressure. Small changes in soil strength from 0.07 to 0.09 gm/gm soil-water content with each of the resultant pressures is noted. The soil strengths for 0.33 and 0.44 bar resultant pressure decreased with increasing soil-water content and showed no sharp decreases in soil strength. The soil strengths for 0, 0.11, and 0.22 bar resultant pressure decreased sharply after 0.09 gm/gm soil-water content.

A physical explanation for the strength patterns shown in Figure 5 is as follows. The lack of soil strength changes from 0.07 to 0.09 gm/gm soil-water content suggests that there was only a slight decrease

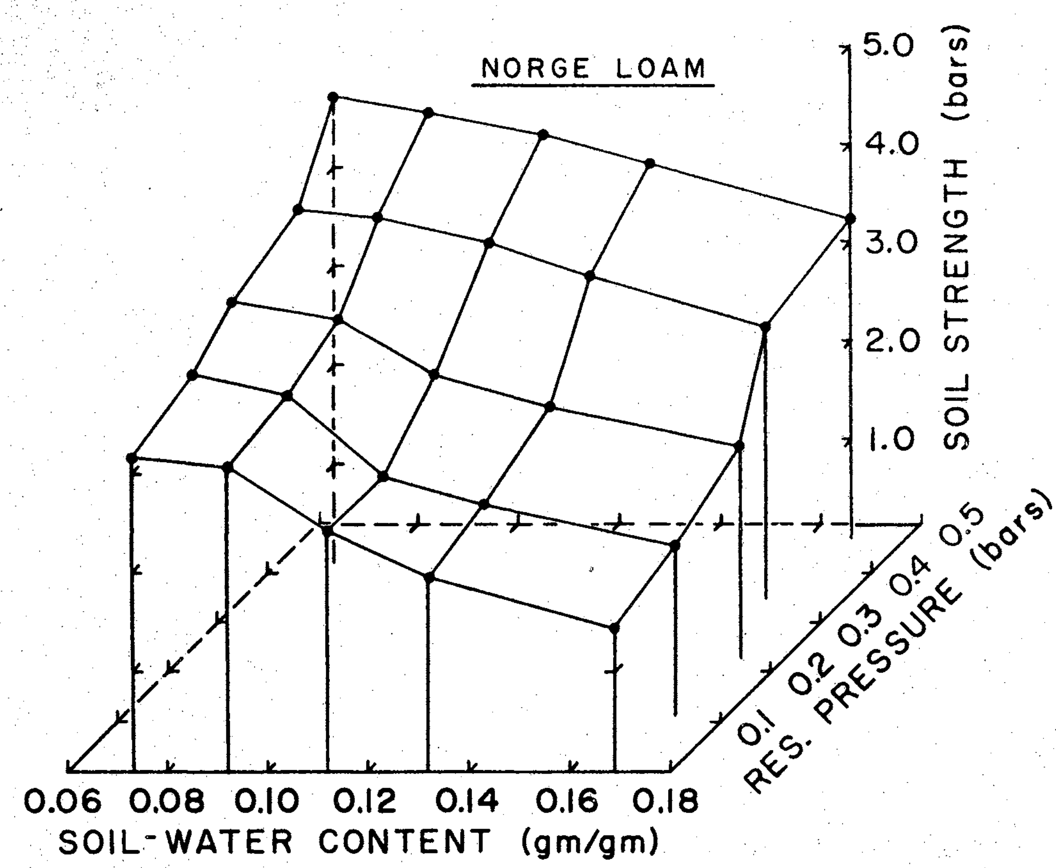

Figure 5. Soil Strength of Norge Loam as Affected by Soil-Water Content and Resultant Pressure

in soil consistency with the additional water. The water films were so thin that even a water addition did not change them to the point of significantly decreasing soil consistency. However, after 9% soil-water content, additional water did thicken the moisture films, decreasing soil consistency measurably. As discussed earlier, at soil-water contents greater than 0.09 gm/gm, adhesion occurs due to the thickening of soil particle moisture films. The increases in bulk density (Figure 4) were not sufficient to compensate for the decrease in consistency and the sharp decreases in strength were obtained at the lower resultant pressures. At resultant pressures of 0.33 and 0.44 bar the increases in bulk density overcame enough of the decreases in soil consistency to prevent the sharp decreases in soil strength.

A comparison of Figures 4 and 5 suggests that if the Norge loam soil-water content is variable and the resultant pressure is constant, soil strength and bulk density produced by the sliding forces are inversely related. The exception to this being found where bulk density decreases with increasing soil-water content. If the resultant pressure is variable and soil-water content constant, soil strength and bulk density produced are directly related.

Soil strengths developed by equal forces arising from two different sources are compared in Figure 6. Soil strength developed by sliding forces is on the ordinate and soil strength developed by vertical forces only is on the abscissa. The dashed line from upper right to lower left is a 45° line. Figure 6 shows that at every combination of sliding force and soil-water content, the soil strength developed from the sliding force is greater than that developed from a vertical force of equal magnitude. This is explained by particle orientation caused

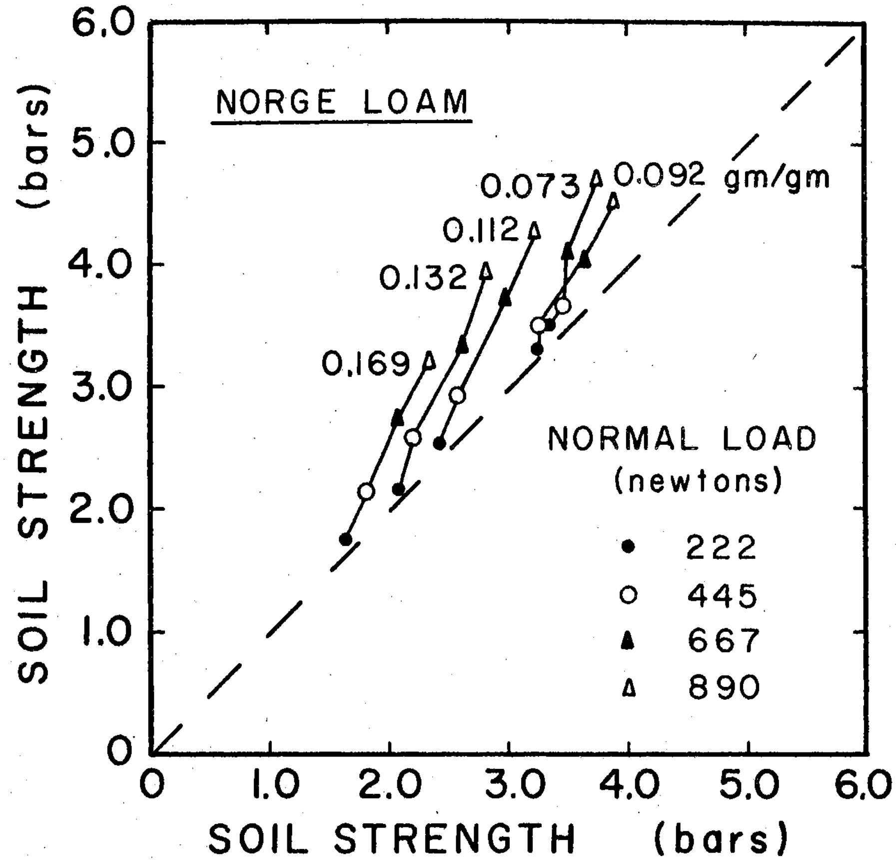

Figure 6. Soil Strength Developed by Sliding Force (Ordinate) Versus Soil Strength Developed by Vertical Force Only (Abscissa). Soil-water content and normal load component of sliding force are shown.

during the sliding action. The sliding forces cause soil particles to orient themselves parallel to the direction of movement of the implement. This produces a soil surface with higher strength than one with random particle orientation.

Soil strength versus soil-water content is illustrated in Figure 7. Curve A was obtained by using a sliding force with a vertical component of 890 newtons. This sliding force was imposed at various soil-water contents and the soil strength measured immediately. Curve B was obtained by applying a sliding force with a vertical component of 890 newtons to the Norge loam at a water content of 0.144 gm/gm. Soil strength and water content measurements were taken immediately and at specific time intervals thereafter. Figure 7 shows that when dried to a soil-water content of 0.08 gm/gm Curve B had a strength of approximately 16 bars, but the soil strength in Curve A was approximately 4.5 bars. This illustrates the significant increase in soil strength associated with drying when the soil is compacted at high water contents. Possible explanations for this are: 1.) Bulk density was higher in Curve B than in any comparable position of Curve A (except at 0.144 gm/gm soil-water content), and 2.) The influence of particle orientation caused by applying the sliding force to the wet Norge loam is accentuated upon soil drying. Both of the above reasons probably affected the soil strength, but explanation 2 probably would affect it to a much greater extent.

Soil strength versus bulk density for the Norge loam is given in Figure 8. These bulk densities were obtained using the Carver hydraulic press. Note that all soil strength values reported in Figure 8 were taken at a soil-water pressure of -0.2 bar. Soil strength is shown to

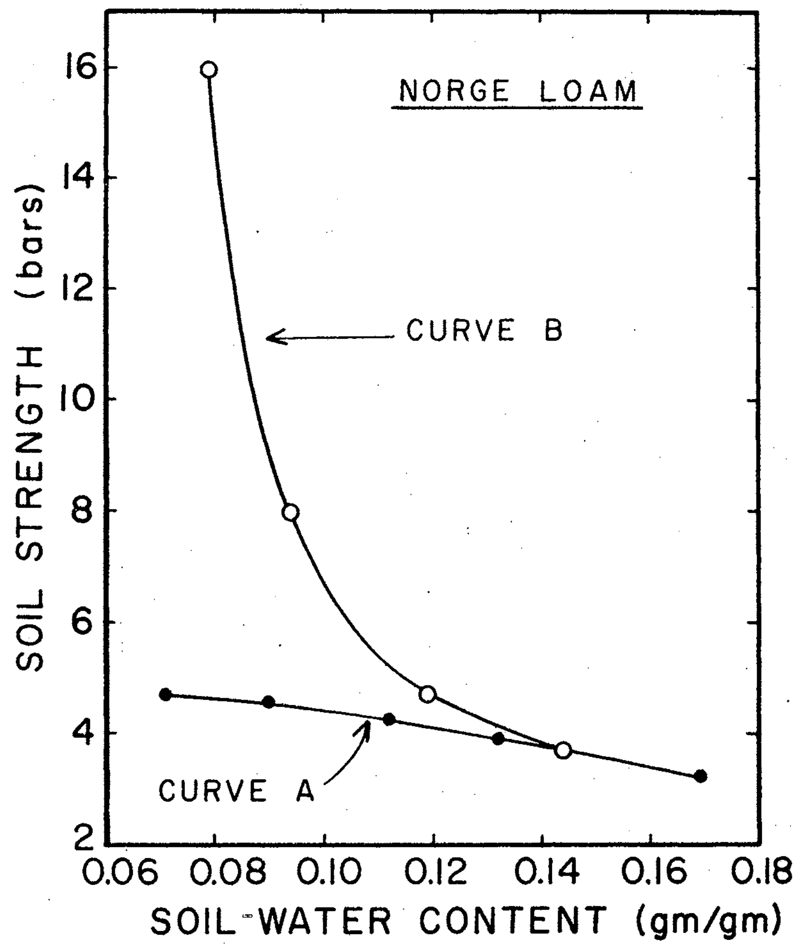

Figure 7. Soil Strength Versus Soil-Water Content. Curve A: Force Application Made on Norge Loam at Indicated Soil-Water Content With No Soil Drying. Curve B: Force Application Made at 0.144 gm/gm Soil-Water Content and Additional Strength Measurements Made During Soil Drying. Vertical component of sliding force was 890 newtons for each curve.

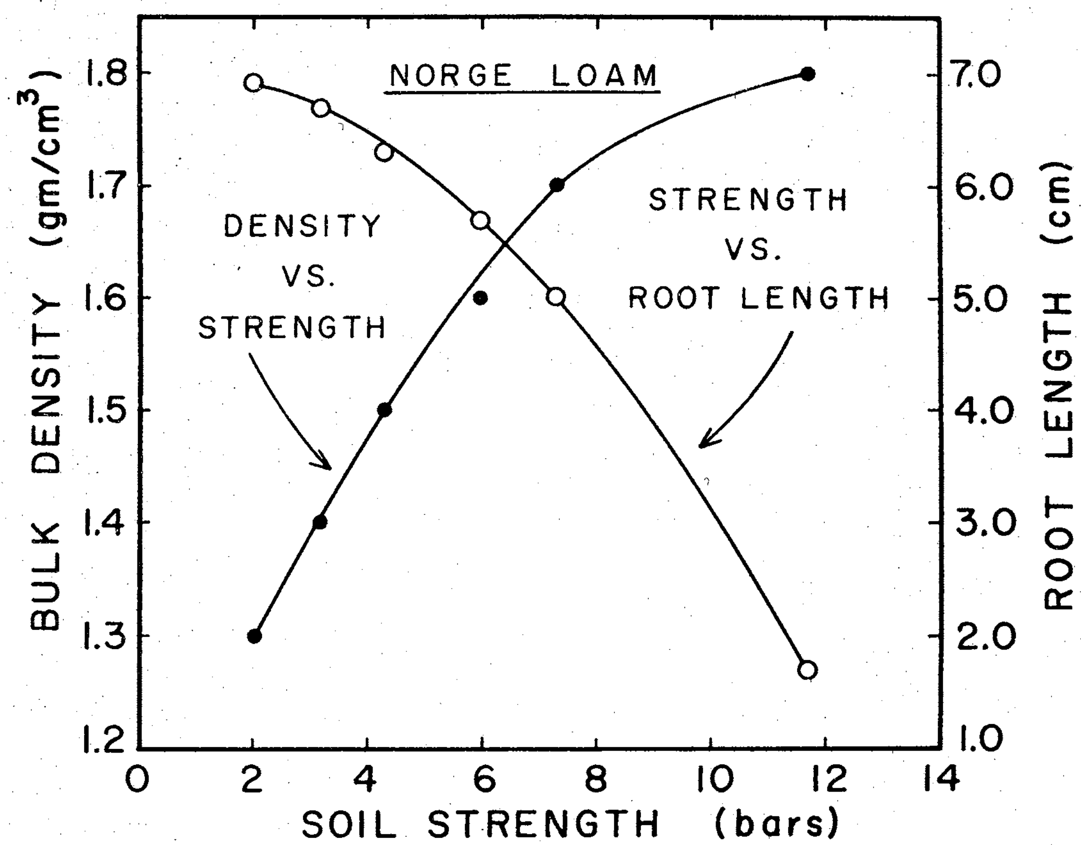

Figure 8. Soil Strength Versus Bulk Density, and Average Root Length 51 Hours After Planting Versus Soil Strength. Soil strength measurements were made at -0.2 bar soil-water pressure.

increase as bulk density increases and the soil strength increases becoming greater as bulk density increases. The average cotton root length 51 hours after planting versus soil strength is also plotted on Figure 8. Root length decreases rapidly as soil strength increases. This illustrates that even though root growth continued at these soil strength values, root length was drastically affected.

CHAPTER V

SUMMARY AND CONCLUSIONS

The importance of a metal to soil sliding action and soil-water content at the time of force application was studied. Also studied were: the effect of a sliding action as compared to the same compactive effort applied only as a vertical force on soil strength, the effect of drying on soil strength, and root elongation as affected by soil strength.

The major conclusions drawn from the above study using a Norge loam were:

1.) If the soil-water content is variable and resultant pressure constant, soil strength and bulk density produced by sliding forces are inversely related. However, if the resultant pressure is variable and the soil-water content constant, soil strength and bulk density developed are directly related.

2.) Soil strengths developed from sliding forces were greater than soil strength developed from vertical static forces of equal magnitude.

3.) Soil compacted with a sliding force at a water content of 0.144 gm/gm developed high strength values upon drying. These strengths were much greater than those obtained when the soil was compacted at the corresponding water contents.

4.) Compaction at 0.112 gm/gm soil-water content caused only a slight decrease in total soil porosity. Compaction at 0.17 gm/gm soil-water content decreased the total soil porosity, but increased the number of smaller pores.

5.) Large reductions in root length occurred as soil strength increased.

This study has shown the importance of considering the source of compactive effort in compaction studies. Efforts should be made to use a tillage type sliding action when studying soil properties.

Soil strength should be considered a property affecting root elongation and distribution in most soils, and not as a limiting factor occurring only in unusual soils.

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VITA

Loyd Raymond Stone

Candidate for the Degree of

Master of Science

Thesis: SOIL STRENGTH AND BULK DENSITY CONDITIONS FOLLOWING AN IMPOSED METAL TO SOIL SLIDING ACTION

Major Field: Agronomy

Biographical:

Personal Data: Born in Prague, Oklahoma, January 6, 1945, the son of Ralph and Alma Stone.

Education: Graduated from Paden High School, Paden, Oklahoma, in May, 1963; attended Murray State College, Tishomingo, Oklahoma, from 1963 to 1965; received the Bachelor of Science degree, with a major in Agronomy, from Oklahoma State University, Stillwater, Oklahoma, in May, 1967; completed the requirements for the Master of Science degree at Oklahoma State University in May, 1969, with a major in Agronomy.

Professional Experience: Half-time graduate research assistant, Department of Agronomy, Oklahoma State University, 1967-1969.