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Compressive Strength of Dry Soil Crumbs

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Preface

The primary purpose of this investigation was to test the validity of a theoretical development relating the densities of compressed dry crumbs of soils to the pressures compressing them.

A secondary objective of the study was to evaluate the strengths of dry soil crumbs from a variety of different kinds of soils as a means of characterizing properties of the soils. In the process, strengths of dry crumbs from one kind of soil subjected to a history of different crops and cultural practices since 1888 (Sanborn Field) were evaluated.

A third objective was to investigate compressible pore space associated with bulk densities that affect the penetration and expansion of fleshy rooted crops. Investigation of this latter objective was stimulated by failure of sugar beet roots to expand in soils of certain experimental test plots.

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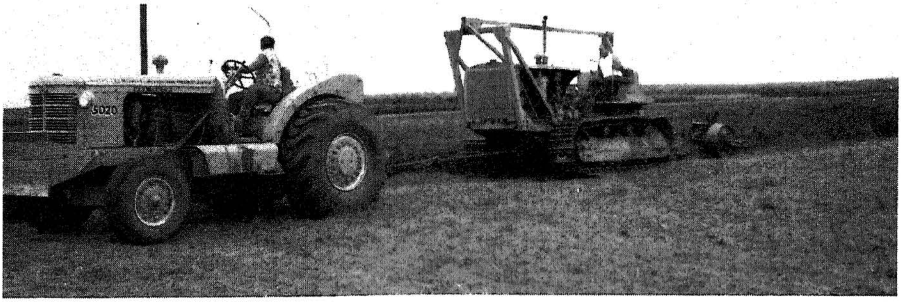
Another lesson from Sanborn Field.
Soil strength that sustains compressibility required by fleshy root crops.

Contents

Harvesting topped beets on soil lacking compressible pore space. The beets expanded above the soil.

Below: James A. Roth and G. E. Smith examine beets at Hati, Mo.



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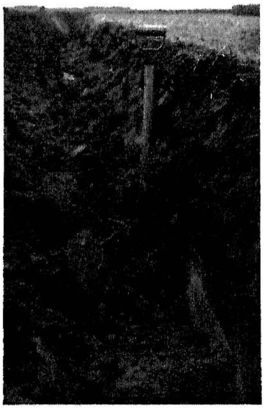
A 36 inch Moldboard plow pulled by tractors in Tandem.



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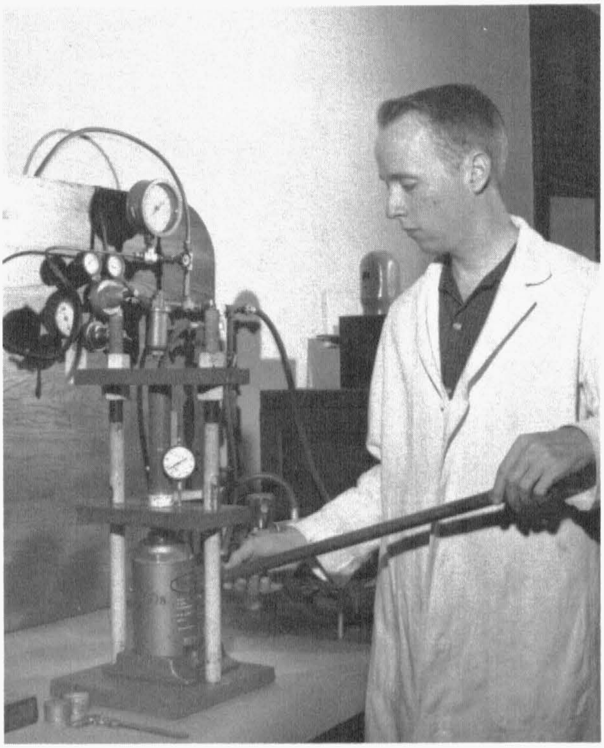
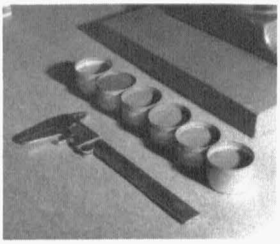


Left: C.B. Roth measuring compressible pore space in density samples not accommodate expanding sugar beets.

Below: Compressible pore space at 3 inch intervals. Bulk density = 1.7 gms/cc at 6 inch depth.



Below: Zonolite (expanded Mica) incorporated in soil (right) provided compressible pore space for beet roots.

THE COMPRESSIVE STRENGTH OF DRY SOIL CRUMBS.

SOIL TILTH: Tillage in many and variable forms has been an integral part of agriculture since its inception. The state of being tilled or "soil tilth" concerns the crumb structure of soil. The character of soil crumbs is determined by the nature of the soil, by the kind of tillage implement used and by the intensity with which it is used. The objective is a seed bed that later becomes a root bed. Soil tilth deteriorates under the impact of excessive water and traffic by cultural implements.

The stability of soil crumbs in water as measured by an aggregate analysis is indicative of the durability of crumb structure under the stress of excessive water supplied by rainfall or irrigation. A lack of stability results in crusting that impedes the emergence of seedlings and seals the surface of the soil retarding infiltration of water and exchange of air. For fleshy root crops as potatoes and sugar beets, a soil with a collapsed crumb structure upon drying resists compression. Potatoes distort in shape as they expand into cracks. Sugar beets expand above the ground where much is lost in topping for harvest.

Weak structured soils compact under the load of equipment used for tillage and harvesting forming traffic pans that restrict penetration of roots and water. Some tilled sandy soils settle together upon wetting then dry into hard intractable states that preclude expansion of fleshy roots and penetration of water after an irrigation.

Soil crumbs created by tillage exist in a spectrum of sizes. When dry these may be sieved into a common size for compressing different kinds of soil and the same kinds of soil with different cultural histories.

Crushing dry soil crumbs with increasing pressures breaks apart grains of sand and silt bound together with clay, humates and oxides of iron. It breaks apart compound crumbs of clay aggregates. And it fragments crumbs of clay created by tilling dry soils that were puddled or of a plastic consistency when plowed. Fragmented clay crumbs resemble shattered glass. Compound clay aggregates develop when fall plowed clays are exposed to alternate wetting and drying along with freezing and thawing through the winter months.

The densities of confined soil crumbs increase in response to applied pressures providing a physical measure of the strength of the crumbs and of the resistance of particles liberated by crushing to reorientations into closer packed configurations.

REQUIREMENT OF COMPRESSABLE PORESPACE FOR SUGAR BEETS

Expiration of federal controls on sugar production in the United States giving rise to reenactment of new allotments in the future suggested a need for information about the potential of producing sugar beets in Missouri. Investigations conducted from 1961 to 1967 with the shipment of two train loads of beets to Denver, Colorado for processing confirmed that the potential existed. Few new allotments were made, none for Missouri.

The sugar beet investigations involved experimental plots most of which were located on sandy to sandy loam alluvial soils of the Missouri and Mississippi River bottoms. Locations included Platte City in Platte, Missouri City in Clay, Henrietta in Ray, McBaine in Boone, Weldonspring in St. Charles, Sikeston in Scott, Portageville in New Madrid and Hati in Pemiscot Counties. A common problem that emerged was the hardening of the soil upon drying after rain or irrigation. The beets were forced to expand above the soil. Exposed tops accumulated salts that formed molasses rather than crystallizing as sucrose when processed. Losses from topping before harvest were excessive. Additionally, the settled sand after the first irrigation accepted water so slowly in later irrigations that water ran through the furrows all day leaving the soil dry beneath the plow sole.

Expansion of the beets above dense sandy and clay soils suggested that they required soils possessing compressible pore space. In confirmation of this, two bags of expanded hydrous mica, marketed commercially as Zonolite for home insulation, were incorporated into the soil at a rate of one part to ten of soil by volume. The new seeding of beets developed normally alongside beets that emerged from untreated soil.

Two consequences of the investigations involved attempts to (a) correct the physical conditions of the soil , and (b) to develop methods for evaluating the compressibility of soils. Some alluvial soils are deposited in layers laid down at different times of flooding. When a blanket of sand covers a desirable soil of silt loam texture within reach of a suitable plow, deep plowing may be considered. Evaluating soil compressibility provides a measure by which to guide modifications in cropping and cultural practices to improve the strength of crumbs and soil aggregates produced by tillage. Soils may be managed to fit the crop or crops may be selected to fit the soil.

DEEP PLOWING OF SANDY RIVER ALLUVIUM

Evaluation of the soil profile of the sandy alluvium of the Portageville Research Center revealed a black silt loam soil beneath twenty inches of sand. Former soils laid down in the wanderings and flooding of the Mississippi River were covered with a blanket of sand in which the sugar beets were grown.

Sand covering good farmland across the Missouri River from Glasgow, Missouri in the flood of 1951 was plowed under with a thirty six inch moldboard "Post" plow. The plow was leased and used to plow the range of plots growing sugar beets at Portageville. Versatile and Caterpillar tractors in tandem were required to pull it. The mixture of sand silt and clay that was exposed provided the needed tilth and stability of tilth that produced acceptable sugar beets.

RIDGE PLANTINGS OF FLESHY ROOT CROPS.

Sugar beets and potatoes, both Irish and sweet, require compressible pore space to expand in the soil..Lacking that and the feasibility of deep plowing to change the constitution of the soil one other remedy is that of planting on ridges. Ridge planting may not be suitable for saline soils. Capillary rise of water brings salts to the top of ridges where evaporation leaves concentrations that damage seedlings. Otherwise fleshy root crops expand horizontally by pushing the ridge aside.

Ridge plantings on heavy clay soils are advantageous in two ways. The ridge opens horizontally as expanding roots push it aside. Also the ridge rises above excess water in the furrows between ridges reducing the collapse of aggregates and crumbs of soil on the ridge. Flat seed beds prepared on clay and gumbo soils, when subjected to excessive amounts of rain, are compressed into intractable masses by removal of water as the soil dries. The sugar beets produced upon flat gumbo soil at the Weldonspring site expanded above the soil.

Compressible pore space of mineral soils is reflected by bulk densities provided suitable standards are available identifying the limit of density where compression ceases. Also ,for an individual soil, the difference between the density of a dried soil that settled under wet conditions and its limiting density of compression provide a measure of expandibility for a fleshy root crop.

BULK DENSITIES INDICATIVE OF SOIL COMPRESSABILITY.

Field bulk densities of soils were determined by pressing seamless steel, deep style one ounce ointment boxes into the soil. A three millimeter hole in the bottom for escape of air also provided a view of the soil to insure that it was not compressed in the process. The soil in the excavated box was shaved to a plane surface at the top of the box, covered and weighed before and after drying to establish the percentage by weight and bulk density of the dry soil.

Bulk densities of soils that did not accommodate expanding beets identified values associated with non compressible pore space. Although soil bulk density is an established measure of soil characteristics, there is a need for reference states of the spectrum of values defining the limits within which a specific soil operates. Some understanding of these limits is provided by considerations of open and close packed spheres in association with measured bulk densities of sandy soils under compression.

Beyond the performances of sandy alluvium of the sugar beet investigations, the crushing strength of dry suil crumbs from selected plots of Sanborn Field established in 1888 reflect the accumulated impact produced upon .the physical characteristics Of soil by different crops and cultural practices.

THEORETICAL DEVELOPMENTS

The compression of soils in response to applied pressures involves considerations of the crushing strengths of dry soil crumbs and of the reorientations of sand particles from open to more closely packed configurations. The theory for each of these phases will be considered separately.. Compression of soils involves changes in volumes. Volumes become more useful as a tool for characterizing the physical constitution of soil when they are transformed into bulk densities especially if a scale is provided for the spectrum of densities with an explanation of the conditions that create them.

A soil in a good state of tilth approaches that of a freshly prepared seed bed. It is characterized by a bulk density of about 1.3 grams per cubic centimeter and a total porosity near 50%. Compressible pore space is evident by depressions of foot prints and wheel tracks of farm equipment. Soils that settle together when wetted and dry into intractable surfaces lose that tilth, and exhibit densities near 1.5 gms./cc. Compact loamy sands at densities of 1.6 to 1.7 gms./cc. sustain pressures that exceed the expansibility of fleshy root crops and emergence of seedlings of many plants.

The Crushing of Dry Soil Crumbs.

A mass of dry soil crumbs when subjected to an applied pressure is compressed until the strength and arrangement of the crumbs will support the pressure. The pressure **P** supported will be proportional directly to-

1. The crushing strength **S** of the crumbs.
2. The fraction **F** of the initial volume V_i that is in a non-compressible form namely, V_f/V_i, where V_f denotes the volume of a fully compressed soil.
3. The volume V_c of compressed pores

and proportional inversely to the volume **Vr** of the compressible pores remaining in the system. Symbolically, $P = SF \frac{V_c}{V_r}$ ---(1).

The volume **Vs** of a soil at any stage of compression yields **Vc = Vi-Vs** and **Vr = Vs-Vf** from which $P = S \frac{Vf(Vi-Vs)}{Vi(Vs-Vf)}$.

The volume **V** of a unit mass of soil is, **V = 1/D.** Substituting the reciprocal of density for each volume yields, $P = S \frac{Ds-Di}{Df-Ds}$ and

$S = P \frac{Df-Ds}{Ds-Di}$ -----(2) from which $Df-Ds = S \frac{Ds-Di}{P}$.

During the crushing of dry soil crumbs, the parameters **Di, Df** and **S** are constant while **Ds** increases in values to support the added pressures. The change in value of the quantity **Df-Ds** is linear with respect to the change in value of **Ds.** Therefore the change in value of **(Ds-Di)/P** also is linear with respect to change in value of **Ds.** When **y = (Ds-Di)/P** and **x = Ds,** then **y = A-Bx.** And when **y =0, x = A/B ----(3)** which is the density **Df** at which crushing of crumbs is complete. It is, of a necessity, an extrapolation of the linear course of events operating earlier in the spectrum of compression.

With a value for the density **Df** of crushed crumbs established, a value for crumb strength **S** may be computed. Rewrite equation (2) as $S = \frac{Df-Ds}{(Ds-Di)/P}$. Equation (3) showed that **Df = A/B** when **y=0.** Also the quantity, **(Ds-Di)/P** of the denominator as **y = A-Bx** was shown to be **A-B Ds.** This permits writing $S = \frac{A/B-Ds}{A-B.Ds}$ Moving **B** outside the denominator gives $S = \frac{A/B-Ds}{B(A/B-Ds)}$ or **S=1/B ---(4).**

The volume of compressible pore space in a soil may be utilized as a parameter with which to express soil structure quantitatively. It is a characteristic involved in the expansion of fleshy root crops in soil. This is not a familiar parameter. It may be converted to more familiar terms by expressing results as bulk densities. Bulk densities of soils under field conditions are familiar units.

Particle densities of soils are integral components of bulk densities and of total pore space in terms of measured values of bulk densities. However they are not components of compressible pore space **Vp** as expressed by **Vp = Vi - Vf.** When initial and final volumes are expressed in terms of the reciprocals of their densities, **Vp = 1/Di - 1/Df.**

The initial density **Di** of an uncompressed sample of soil is subject to a direct determination. The fnal density **Df** is not so definite. As an extrapolation of soil densities under pressure, equation (3), the response of the density relation may be a composite of processes occurring simultaneously over the spectrum investigated. There is a reorientation of soil crumbs with the first increments of applied pressure. There follows a crushing of crumbs where increased densities per unit of pressure are linear with respect to density. Finally pressure moves liberated grains of sand and silt toward more dense configurations of packing.

Excluding values of densities that fall without the range of crumbs being crushed permits identifying the final density **Df** of crushed crumbs The reorientation of loose grains of sand and silt under increasing pressures involves a theoretical treatment that differs from that of crushing dry soil crumbs. Final densities of both occur at pressures that exceed by far that exerted by expanding fleshy root crops. The final densities are necessary as parameters along with initial densities and soil strength **S** to develop the functional relation of soil density to the pressure of compression. Equation (2) written as **SDs - SDi = PDf - PDi** and solved for **Ds** yields $\mathbf{Ds} = \dfrac{PDf + SDi}{P+S}$ for compressed dry crumbs. The comparable function for compressed grains of sand and silt to be developed later is $\mathbf{Ds} = \dfrac{\sqrt{P}\,Df + SDi}{\sqrt{P} + S}$. Crucial to the expansion of a fleshy root crop is the limiting pressure **P** that may approach that of the wilting point at 12 to 15 atmospheres. That pressure combines effects of both bulk density and crumb strength. Hence bulk density alone is not sufficient to define soil compressibility.

The Compression of Loose Grains of Sand.

A mass of loose grains of sand when subjected to pressure is compressed until the configuration of the particles will support the pressure. The change in configurations of particles occurs within a span of particle orientations between open and close packed arrangements. Defining the limits of open and close packed systems for various mixtures of particle sizes is beyond the scope of this development. Instead a model of open packed spheres of the same size will be constructed after which it will be converted to a close packed model.

Constructing a Model of Open Packed Spheres.

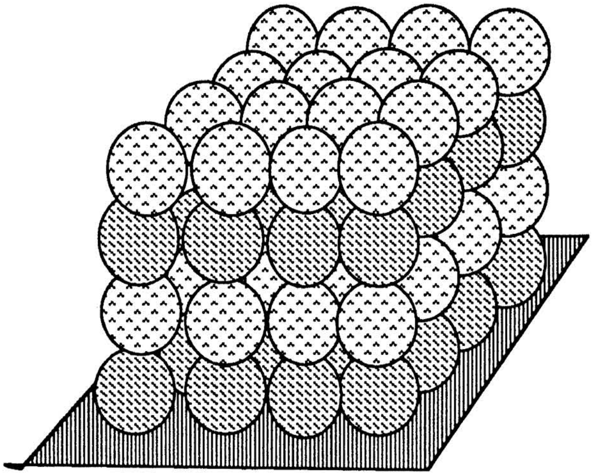
Initially prepare a grid of points located in positions that identify the corners of squares. Within each square place a sphere of diameter **D** equal to the distance **D** between the points of the grid. The sheet of spheres exhibits patterns of four spheres surrounding a space and four spaces surrounding each sphere. Within the boundaries of the sheet, the number of the spheres equals the number of spaces.

Prepare a second sheet of spheres like the first. Superimpose it upon the first with each sphere of the top sheet resting upon one in the bottom sheet. Likewise add additional sheets to the stack. The volume of each sphere is $\pi/6 * D^3$. It occupies the center of a cube of volume D^3. The fraction of the volume accommodating each sphere is **$\pi/6$ or 52.36%.** Each sphere in an isolated sheet is attached to neighboring spheres at four points of contact. Stacking adds another two,top and bottom, for a total of six per sphere in open packed systems. Crushing dry crumbs of uniform sized spheres in open packed systems requires breaking only six points of contact per sphere.

An average particle density of 2.65 gms./cc. characteristic of many mineral soils at 52.36% solid represents a bulk density of 1.39 as given by 2.65(0.5236). Only a fraction of the 47.64% pore space is compressible. Bulk densities of soils, after tillage.consist of dry crumbs containing internal pore space along with pore space surrounding the crumbs. This establishes a somewhat arbitrary minimum bulk density as low as 1.39(.5236)=0.73 gms./cc. for prepared seed beds prior to settling after rainfall.

CUBIC LATTICE OF SPHERES.

0PEN PACKED SPHERES, 52.36% SOLID, BULK DENSITY 1.39.



Eight spheres that form a cube in an open packed system surround a cavity that will accommodate a small sphere of diameter **0.5538D** and of volume **0.08893D³**. This volume added to that of a larger sphere produces **0.6123D³** or **61.23%** of solids at a particle density of **2.65** yields a bulk density of **1.62**. This bulk density is representative of that associated with sands and sandy loam soils. It also is found in finer textured soils at depths of two to three feet in the profile.

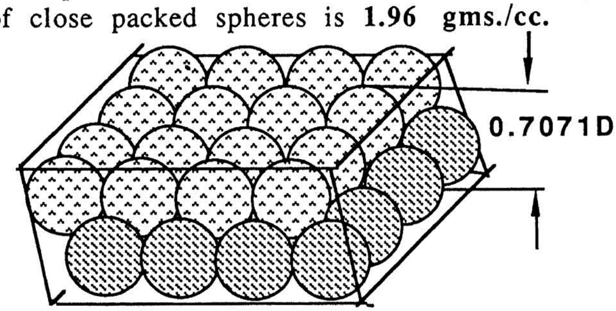
Note: In the model above, alternate sheets of spheres are identified by contrasting patterns that will prove useful when transforming a stacked open packed to a close packed configuration.

Constructing a Model of Close Packed Spheres.

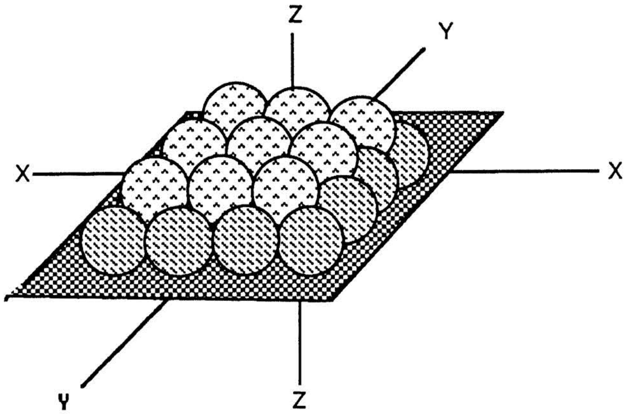
The tetrahedron and pyramid are familiar examples that illustrate close packing of spheres. Both may be represented by stacked cannon or bowling balls. The tetrahedron is a favorite of choice. But each is a different version of the same system. Evaluating the volume of solid in a tetrahedron requires time to exercise ones comprehension of geometry and trigonometry and to correct errors of computations. The pyramid provides a simpler approach. The configuration of spheres in a pyramid is achieved by a slight modification of their configuration in the cube of an open packed system.

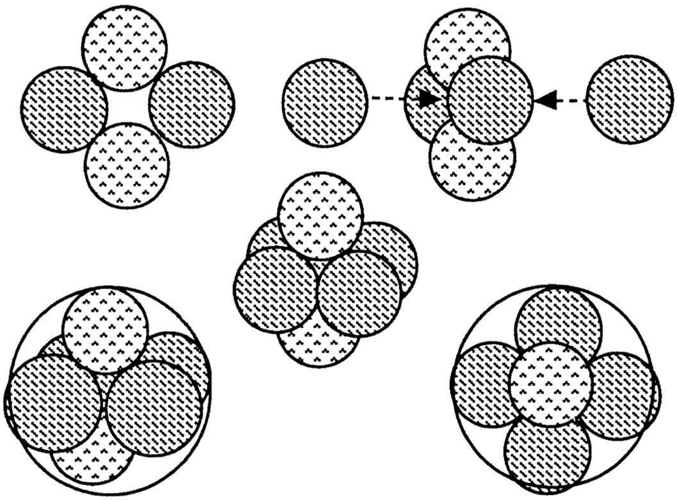
Initially prepare two sheets of spheres occupying the corners of squares. Superimpose one over the other producing a sheet of open packed cubes. For spheres of diameter **D** the centers of the spheres in the upper sheet are at an elevation of **D** units above the centers of the spheres in the lower sheet. Each sphere occupies **$0.5236D^3$** of the volume of the cube in which it is centered.

Move the upper sheet 45° With respect to the XY plane permitting spheres of the upper sheet to drop into the area surrounded by four spheres of the lower sheet. The collapse of the distance between centers of the two sheets does not change the volume of the solids in the two sheets. It does reduce the volume of space that they occupy. The distance between the centers of two spheres in contact is the diameter **D** of the spheres. The diagonal distance across the square formed by the centers of four spheres in contact is $\sqrt{2D^2}$ or **1.4142D.** Half of this distance, **0.7071D** represents the distance between the centers of the two sheets after shifting and collapse. Each sphere now occupies **0.5236/0.7071** = **74.05%** of the space that accommodates it. At **2.65 gms./cc.** the bulk density of close packed spheres is **1.96 gms./cc.**



Stacked sheets of spheres occupying positions at the corners of squares in the XY plane and the corners of cubes in XYZ coordinates collapse to a close packed system when alternate sheets are shifted **45°**. After shifting each sphere is bound to twelve neighboring spheres through twelve points of contact. Broken apart as octahedra, each of six spheres is bound to neighbors through four points of contact. The six as corners of three squares fill a larger sphere of diameter **2.4142D.** They occupy a spheroid as a miniature spherical domain. Spheroids associating in units of six create agglomerates of spheroids of decreasing strength and increasing amounts of collapsible pore space.





COMPRESSING CRUMBS OF DRY SOILS.

The object here is to derive an expression for the relationship between the bulk density **Ds** of a soil and the pressure **P** of the load it will support over the spectrum of densities from a recently tilled dry soil to the density limit of compression. The variable distribution of crumb sizes may be minimized by sieving to provide one to two millimeter dry crumbs.

Pressure applied to crumbs of soil crushes them. Pressure creates shearing forces that break the crumbs apart. Crumbs from dried clods of clay fragment much as glass shatters. Crumbs of clay aggregates created by differential expansion and contraction through exposure of plowed soil to freezing and thawing and to wetting and drying break apart to form smaller aggregates of the parent crumbs. A similar process occurs with crumbs of aggregates developed in soils permeated with roots of sod plants.

Crushed crumbs of soil support applied pressures much as concrete in vertical cylindrical columns support bearing loads. The force in the horizontal x, y, plane is minimal. The product of a compressed soil is a disc shaped planchet or cake in a matrix of finer materials. The densities of the cakes as a function of applied pressures are related directly to the pressures.

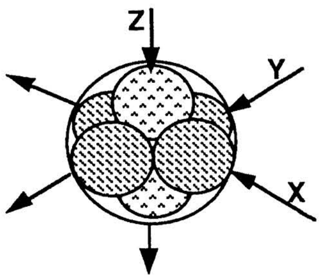
The first increment of pressure applied to crumbs of sand held together by weak cohesive forces tends to disrupt the structure There-after compression of loose grains of sand reorients the configuration of the arrangements of the particles. Particles flow from positions of low densities to positions of high densities, from positions of minimum numbers of contacts to positions of greater numbers of contacts between particles. Pressure ruptures contacts while creating new ones.

A metal plate resting on the surface of a container of sand transmits a load of compression, not as a pressure but as vectors of forces, distributed to individual particles contacted by the plate. Each particle in turn transmits the force to the particles supporting it. Spherical particles of equal diameters attain maximum densities in a close packed configuration with twelve points of contact per sphere. Six individual spheres in a close packed configuration constitute a miniature spherical domain characterized by equal forces in each of the three coordinate **x y z** axes.

The radial vector of force, $\mathbf{F_r}$, in any direction from the origin is the net result of the vectors of force in each of the three coordinate axes as expressed by:

$\mathbf{F_r}^2 = \mathbf{F_x}^2 + \mathbf{F_y}^2 + \mathbf{F_z}^2$. Solving, $\mathbf{F_r} = \sqrt{\mathbf{F_x}^2 + \mathbf{F_y}^2 + \mathbf{F_z}^2}$.

Squared values of force vectors correspond to pressures per unit area in each of the coordinate axes. As spheres with frictionless surfaces at points of contact, the respective values are equal. With friction between grains stabilizing the bulk density at each stage of compression, the radial vector of force $\mathbf{F_r} = \mathbf{f}(\sqrt{\mathbf{P}})$.



A sand system is characteristic of a liquid in a cylindrical vertical tower frequently seen in rural water districts. The sides of a one ounce seamless steel ointment box bulged outward when pressures approaching 1000 lbs./sq.in. were applied to the surface of sand filling the box. The bulging of the sides of the container reflects the vectors of forces operating in the horizontal planes of compressed grains of sand.

Spherical grains of sand posses rough surfaces covered with films or colloidal coatings, These create frictional forces that retard movement of grains subjected to unequal forces in the coordinate axes. A matrix of loose grains of sand exists as a static structure with all vectors of force in equilibrium. Each increment of pressure applied to the surface of the system injects a vector of force that overcomes the friction retaining a particle in a configuration of unequal forces. The particle moves in a direction that relieves the stress opposing the force. It moves from a less dense to a more dense environment. It participates in the process of creating a close packed from an open packed configuration of particles. The ultimate limit of packing brings each sphere into contact with twelve of its neighbors.

Compressing grains of sand unlike molecules of water requires introducing frictional components into each of the coordinate vectors of force. The frictional force accounts for each stage of compression associated with each increment of applied pressure.

Summary: Theoretical Developments.

1. **Two systems of compressibility were involved:**
   (a) The crushing of dry soil crumbs.
   (b) The compression of unbound grains of sand and silt.
   Both systems require a means of arriving at a value for the parameter **Df**, the final density of a fully compressed soil. Both systems perform differently with respect to the parameter **P** of applied pressure.

   Evaluating the parameter **Df** :
   From a series of measurements of bulk densities, **Ds** at various pressures, the function **y = A - Bx** where **y=(Ds-Di)/P** and **x=Ds** for dry crumbs and **y=(Ds-Di)/√P** and **x=Ds** for unbound grains extrapolate to zero where **Ds = Df.**

2. **Establishing the values of the parameter S for crushing strength of dry soil crumbs and for frictional strength of reorienting grains into denser packed configurations:**
   The easier crumbs are crushed or grains of soil are moved, the greater the value of **B** in the expression **y=A-Bx** used for evaluating **Df** where **1/B=S.** An explanation:
   By equation (2.), $S = \frac{D_f - D_s}{(D_s - D_i)/P \text{ or } \sqrt{P}}$. The denominator of the function is the quantity **y** of **y = A-Bx** and **x** is the density D_s. When **y=0,** $x=D_f$ and $D_f = A/B$. Substituting in (2.):,
   $S = \frac{A/B - D_s}{A - BD_s}$, which written as $S = \frac{A/B - D_s}{B(A/B - D_s)}$ becomes $\frac{1}{B}$ - - (4).
   If for convenience the pressure is scaled to provide workable numbers such as **0.01P** then **S = 100/B.** The square root function **√P** is acceptable without scaling..

3. **An expression that relates the bulk density D_s of a soil of strength S to the pressure P compressing it.**
   Equation (1) in the form, $\frac{S}{P} = \frac{D_f - D_s}{D_s - D_i}$, gives
   $SD_s - SD_i = PD_f - PD_s$,, and $PD_s + SD_s = PD_f + SD_i$, Solving,
   $D_s = \frac{PD_f + SD_i}{P+S}$ for crushing crumbs, and
   $D_s = \frac{\sqrt{P}D_f + SD_i}{\sqrt{P} + S}$, for compressing grains of sand and silt.

PROCEDURES EMPLOYED.

Collection and Preparation of Samples:

Approximately one pound of soil of a friable consistency was obtained from the surface plow layer. The soil was crumbled while moist and spread in a thin layer on a sheet of brown paper to dry. The dried soil was sieved saving the crumbs that passed a 2 mm. sieve and were retained on a 1 mm.. sieve.

Measurements of Bulk Densities:

The dry soil crumbs were poured into a tinned one ounce seamless steel ointment box 2.54 cm. deep and 3.77 cm. internal diameter. The box was tapped gently on the table top to settle the soil after which surplus soil was struck from the surface with the straight edge of a steel bladed spatula.The initial bulk density D_i of the soil was computed from D_i = gms./28.4 cc.. The bulk density of the soil, D_s = 2.54 D_i/cm. of depth at each stage of compression.

Compression of Soil:

The soil crumbs were compressed in two stages. The first stage applied pressures from 23 to 130 pounds per square inch by means of an air driven piston. The second stage applied pressures from 213 to 990 lbs./sq.in. by means of a hydraulic press. The stress upon the container at these higher pressures required a support consisting of a steel sleeve of 1.5 inch internal diameter. Otherwise the sides of the container bulged.

The net pressures applied at each determination were 23, 46,69, 92, 115 and 130 lbs./sq.in. by compressed air and 213, 390, 600, 810 and 990 lbs./sq.in by hydraulic pressure. Pressures were achieved by weights added to a balance pan suspended from the outer end of the handle to the hydraulic jack The pressures were calibrated with equipment designed for that purpose in the laboratories of the mechanical engineering department.

The depth of compression of the soil at each stage of compression was measured using a Starrett dial gauge attached to the plunger with the anvil of the gauge resting on the steel base supporting the container of soil. The dial gauge was calibrated to provide readings to one thousandth of an inch with an accuracy of one ten thousandth of an inch. Maximum compressible pore space when measured was achieved by compressing moist soil to the limit at which compression ceased.

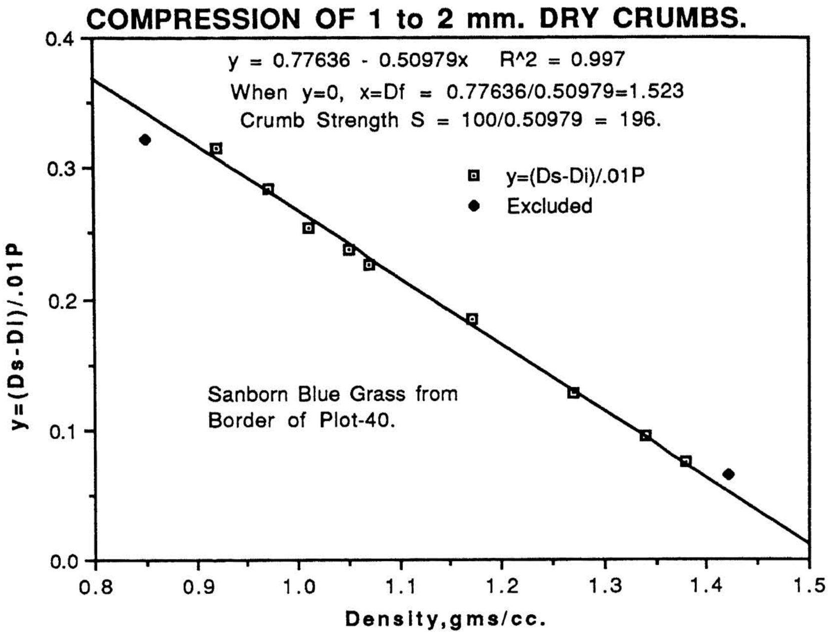
PERFORMANCES OF SOILS STUDIED

Reference Bench Marks.

The first question to be answered was the degree to which the results of crushing crumbs of soil agreed with the theoretical developments as set forth in the summary. For this purpose dry sieved crumbs were obtained from a blue grass sod adjacent to plot 40 of Sanborn Field. The field was established as a crop rotation and cultural practice experiment station project in 1888. The soil a uniform silt loam in texture except for a few concretions of iron and manganese passed a 300 mesh sieve after dispersing. Results of previous investigations established that soil aggregates from sod were water stable. In contrast to the performance of crushed crumbs from a long developed grass sod, dry crumbs of sandy alluvium from a field in wheat adjacent to the Missouri River were obtained during the month of April when wheat was in the early stages of spring growth before shoot elongation.. The first increment of applied pressure crushed the crumbs after which compression of the grains of sand involved reorientation of the particles.

Results of compression relating bulk densities to applied pressures ranging from 23 to 990 pounds per square inch provided satisfactory agreement with theory for each of the systems as set forth in part 3 of the summary. The results for the two systems served as a bench mark with which to judge the results obtained for soils many of which exhibited mixed performances of crumb crushing and reorientation of products of crushing. As an example of a soil characterized by a mixed performance, dry crumbs were obtained from continuous wheat plot 9 of Sanborn Field. In wheat since 1888 with no applied soil amendments and all crop residues removed, most of the soil organic matter was gone. Located on the watershed divide and with cover most of the year, the plow depth of soil was still above the clay of the subsoil. As a consequence the dry crumbs of soil crushed easily between the fingers and smoothed out to a floury consistency. The bulk density-compression relationship combined the two phenomena of crumb crushing and particle reorientation

Figures 1, 2, 3a and 3b portray the results obtained for the three systems using applied pressures. Each figure contains two graphs. The first establishes the parameters of the initial and final densities along with the strength of the crushed soil crumbs. The second graph relates the measured and computed bulk densities at each of the applied pressures.


COMPRESSION OF 1 to 2 mm. DRY CRUMBS.
y = 0.77636 - 0.50979x R^2 = 0.997
When y=0, x=Df = 0.77636/0.50979=1.523
Crumb Strength S = 100/0.50979 = 196.
y=(Ds-Di)/.01P
Excluded
Sanborn Blue Grass from
Border of Plot-40.
y=(Ds-Di)/.01P
0.0
0.1
0.2
0.3
0.4
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5
Density,gms/cc.

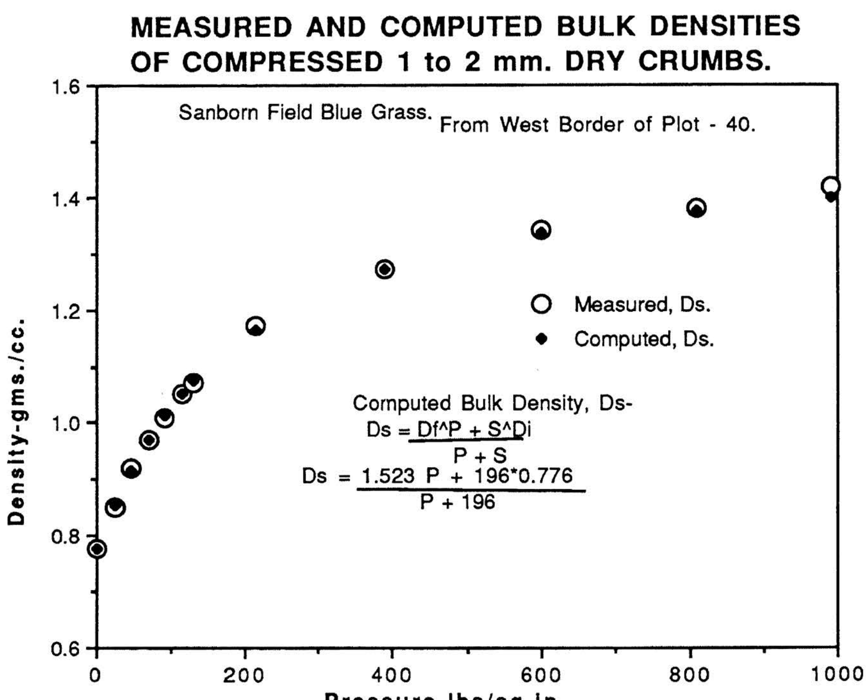
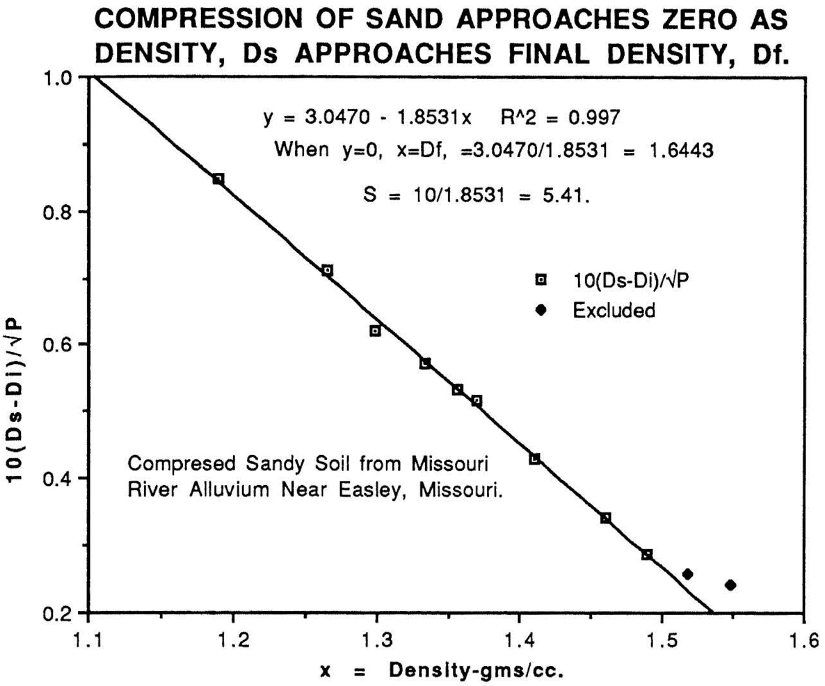

MEASURED AND COMPUTED BULK DENSITIES
OF COMPRESSED 1 to 2 mm. DRY CRUMBS.
Sanborn Field Blue Grass. From West Border of Plot - 40.
Measured, Ds.
Computed, Ds.
Computed Bulk Density, Ds-
Ds = Df^P + S^Di / P + S
Ds = 1.523 P + 196*0.776 / P + 196
Density-gms./cc.
0.6
0.8
1.0
1.2
1.4
1.6
0
200
400
600
800
1000
Pressure-lbs/sq.in

FIGURE-1.


COMPRESSION OF SAND APPROACHES ZERO AS DENSITY, Ds APPROACHES FINAL DENSITY, Df.
y = 3.0470 - 1.8531x R^2 = 0.997
When y=0, x=Df, =3.0470/1.8531 = 1.6443
S = 10/1.8531 = 5.41.
10(Ds-Di)/√P
Excluded
Compresed Sandy Soil from Missouri River Alluvium Near Easley, Missouri.
10(Ds-Di)/√P
x = Density-gms/cc.
1.0
0.8
0.6
0.4
0.2
1.1
1.2
1.3
1.4
1.5
1.6

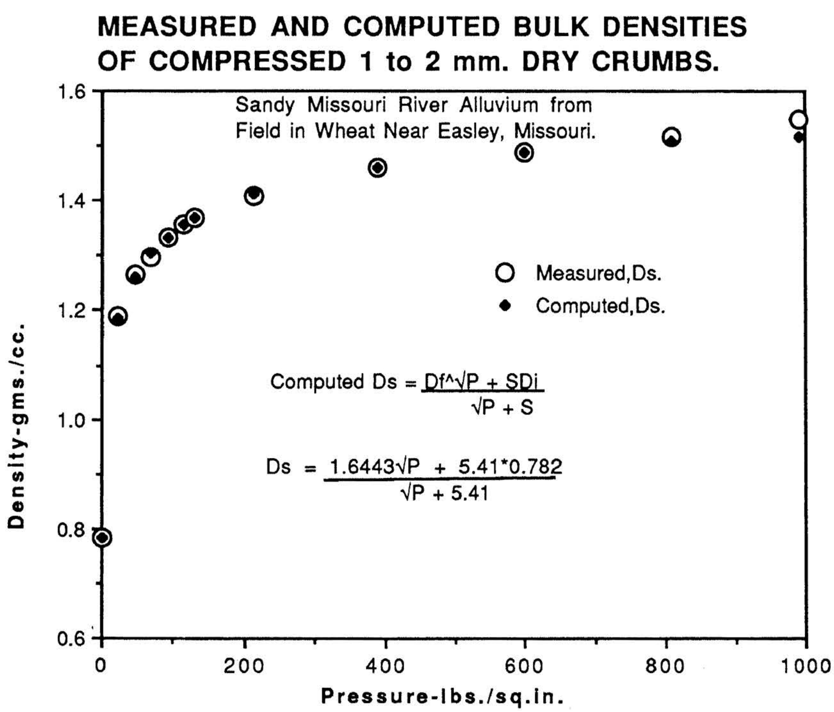
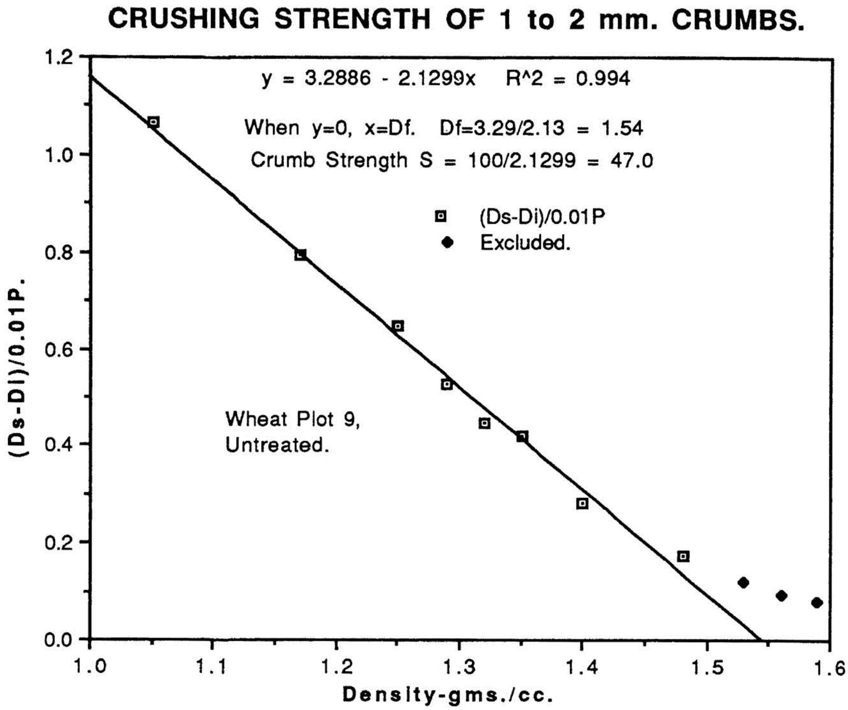

MEASURED AND COMPUTED BULK DENSITIES OF COMPRESSED 1 to 2 mm. DRY CRUMBS.
Sandy Missouri River Alluvium from Field in Wheat Near Easley, Missouri.
Measured,Ds.
Computed,Ds.
Computed Ds = Df^√P + SDi / √P + S
Ds = 1.6443√P + 5.41*0.782 / √P + 5.41
Density-gms./cc.
Pressure-lbs./sq.in.
1.6
1.4
1.2
1.0
0.8
0.6
0
200
400
600
800
1000

FIGURE-2.


CRUSHING STRENGTH OF 1 to 2 mm. CRUMBS.
y = 3.2886 - 2.1299x R^2 = 0.994
When y=0, x=Df. Df=3.29/2.13 = 1.54
Crumb Strength S = 100/2.1299 = 47.0
(Ds-Di)/0.01P
Excluded.
Wheat Plot 9,
Untreated.
(Ds-DI)/0.01P.
Density-gms./cc.
1.2
1.0
0.8
0.6
0.4
0.2
0.0
1.0
1.1
1.2
1.3
1.4
1.5
1.6

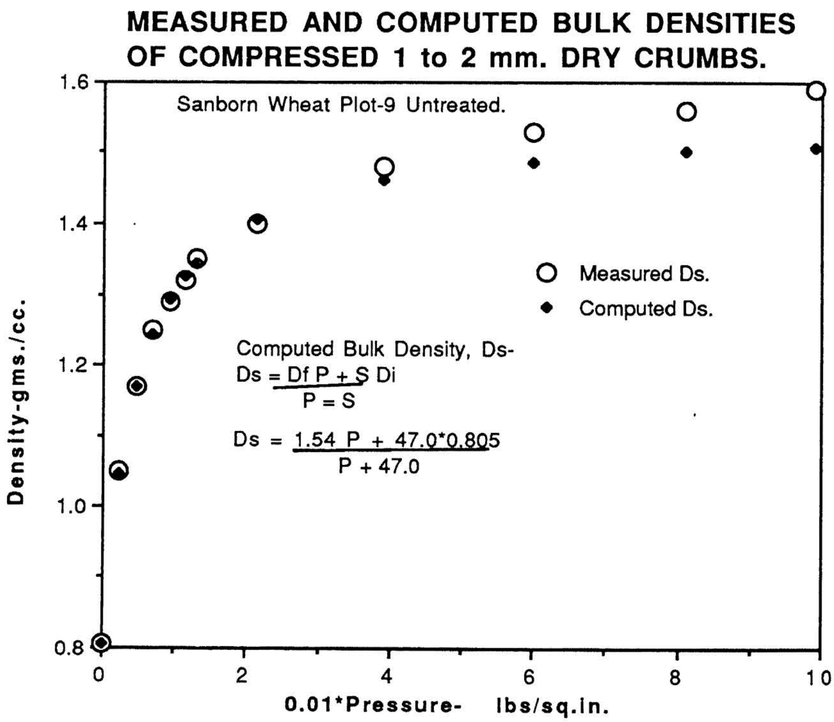
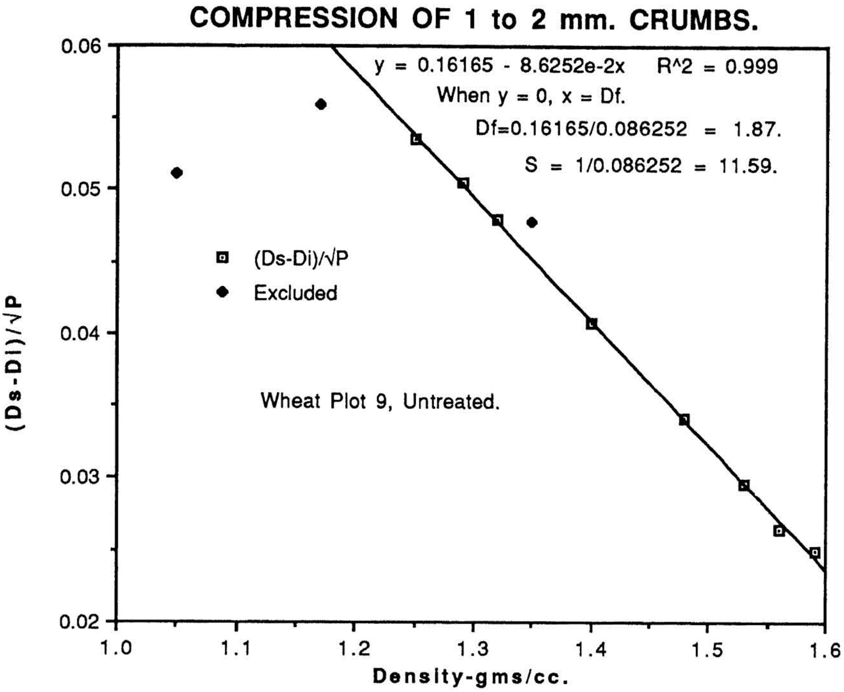

MEASURED AND COMPUTED BULK DENSITIES
OF COMPRESSED 1 to 2 mm. DRY CRUMBS.
Sanborn Wheat Plot-9 Untreated.
Measured Ds.
Computed Ds.
Computed Bulk Density, Ds-
Ds = Df P + S Di
P = S
Ds = 1.54 P + 47.0*0.805
P + 47.0
Density-gms./cc.
0.01*Pressure- lbs/sq.in.
1.6
1.4
1.2
1.0
0.8
0
2
4
6
8
10

FIGURE-3a.


COMPRESSION OF 1 to 2 mm. CRUMBS.
y = 0.16165 - 8.6252e-2x R^2 = 0.999
When y = 0, x = Df.
Df=0.16165/0.086252 = 1.87.
S = 1/0.086252 = 11.59.
(Ds-Di)/√P
Excluded
Wheat Plot 9, Untreated.
(Ds-Di)/√P
0.06
0.05
0.04
0.03
0.02
1.0
1.1
1.2
1.3
1.4
1.5
1.6
Density-gms/cc.

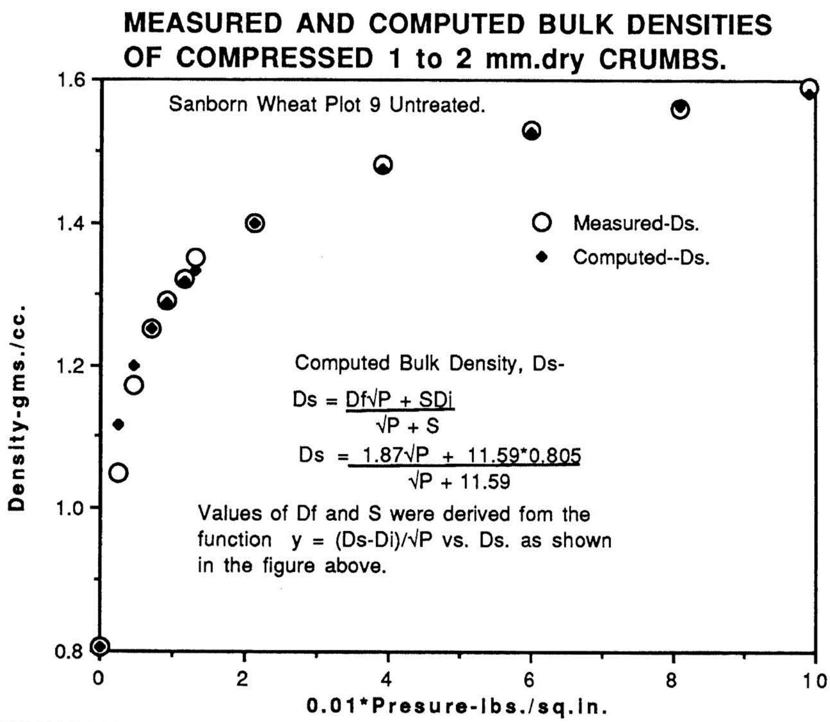

MEASURED AND COMPUTED BULK DENSITIES
OF COMPRESSED 1 to 2 mm.dry CRUMBS.
Sanborn Wheat Plot 9 Untreated.
Measured-Ds.
Computed--Ds.
Computed Bulk Density, Ds-
Ds = Df√P + SDi / √P + S
Ds = 1.87√P + 11.59*0.805 / √P + 11.59
Values of Df and S were derived fom the
function y = (Ds-Di)/√P vs. Ds. as shown
in the figure above.
Density-gms./cc.
1.6
1.4
1.2
1.0
0.8
0
2
4
6
8
10
0.01*Presure-lbs./sq.in.

FIGURE-3b.

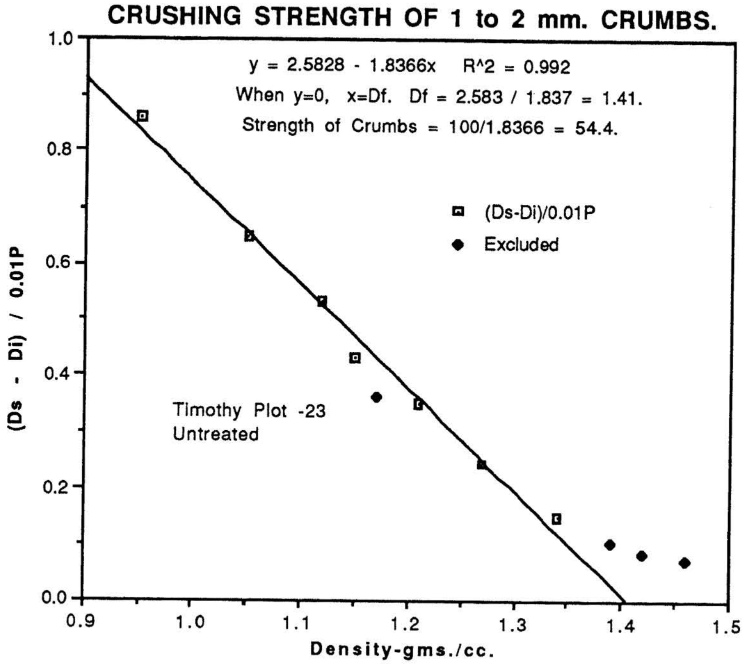
Figures 1 and 2 span a spectrum of compression from crumb strengths from 196 pounds per square inch down to frictional resistances between sand grains of 5.4 pounds per square inch. Weak structured soil, Figure 3a, exhibits properties of both. The crushing of crumbs with a strength of 47 lbs./sq.in. terminated at 200 lbs. pressure. Pressures exceeding 200 lbs. reoriented the grains of silt liberated from the crushed crumbs. Compression of the silt involving the square root of the pressures is presented in Figure 3b. The computed densities agreed with the measured values for pressures of 200 to 990 lbs./sq.in.

Estimated maximum bulk densities of the sod and the soil of the wheat plot were 1.52 and 1.54 respectively. Maximum density of the compressed river sand was estimated at 1.64 gms./cc. while that for the silt,Figure 3b, was 1.87 suggesting a greater distribution of particle sizes for the silt than for the water laid sand.

Except for a small deviation of the measured densities at 990 pounds pressure for both the compressed crumbs and the river sand the agreements of the computed values with the measured values supported the theoretical derivations. The 990 pound pressure applied to the surface area of 1.73 sq.in of the container amounted to a total force of 1700 pounds by the hydraulic press. It is reasonable that some distortion of the container occurred at this pressure.

The evidence obtained from the initial measurements was encouraging. It stimulated a desire to characterize properties of other soils to provide a better understanding of the physical performances of soils. The first soils studied were from selected plots of Sanborn Field. Various crop and cultural histories have impressed their effects upon the soils since 1888. Most changes in the soil are small over short periods of time. Only when accumulated over extended period do the effects of a system of soil management become great enough to reveal the consequences to the soil and to the land. Many initial successes are achieved at the expense of a destroyed resource.

Many chemical and physical properties of the soil and performances of crops have been catalogued over the years that investigations have been pursued on Sanborn Field. Measures of the strength of dry soil, crumbs and of the compressibility of the dry soil will add to the evidence from this field. Measurement will be made on other kinds of soil with extended properties after which soils of the sugar beet investigations will be studied. **Results for selected plots from Sanborn Field follow.**


CRUSHING STRENGTH OF 1 to 2 mm. CRUMBS.
y = 2.5828 - 1.8366x R^2 = 0.992
When y=0, x=Df. Df = 2.583 / 1.837 = 1.41.
Strength of Crumbs = 100/1.8366 = 54.4.
(Ds-Di)/0.01P
Excluded
Timothy Plot -23
Untreated
(Ds - Di) / 0.01P
Density-gms./cc.
1.0
0.8
0.6
0.4
0.2
0.0
0.9
1.0
1.1
1.2
1.3
1.4
1.5

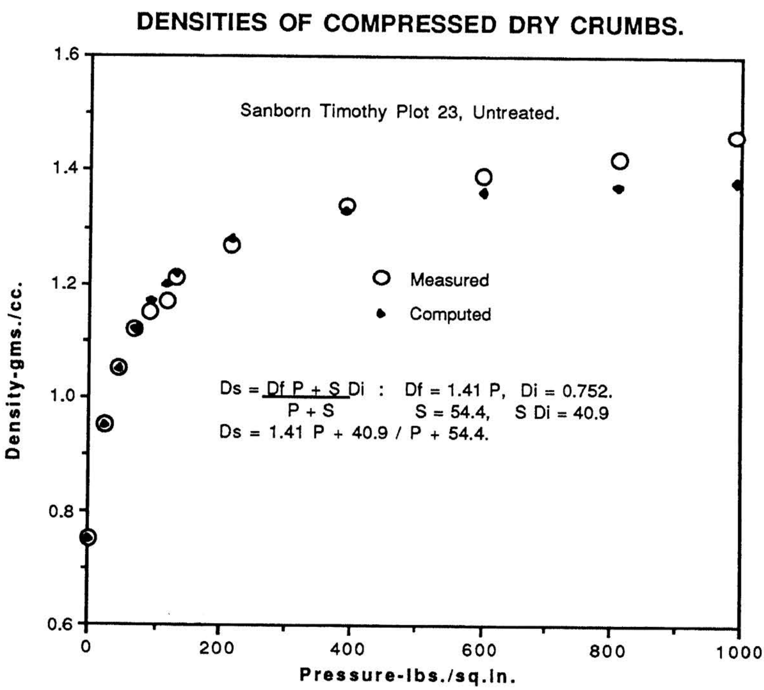
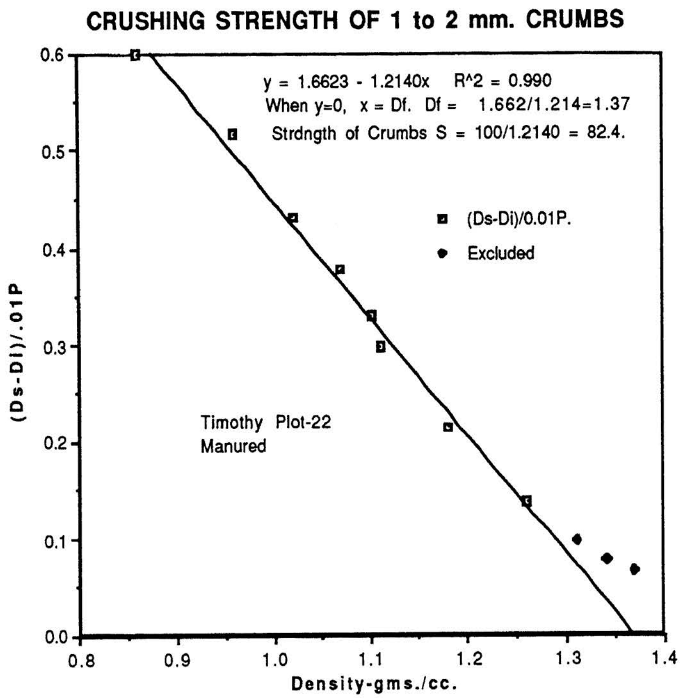

DENSITIES OF COMPRESSED DRY CRUMBS.
Sanborn Timothy Plot 23, Untreated.
Measured
Computed
Ds = Df P + S Di / P + S : Df = 1.41 P, Di = 0.752.
S = 54.4, S Di = 40.9
Ds = 1.41 P + 40.9 / P + 54.4.
Density-gms./cc.
Pressure-lbs./sq.in.
1.6
1.4
1.2
1.0
0.8
0.6
0
200
400
600
800
1000

FIGURE-4.


CRUSHING STRENGTH OF 1 to 2 mm. CRUMBS
y = 1.6623 - 1.2140x R^2 = 0.990
When y=0, x = Df. Df = 1.662/1.214=1.37
Strdngth of Crumbs S = 100/1.2140 = 82.4.
(Ds-Di)/0.01P.
Excluded
Timothy Plot-22
Manured
(Ds-Di)/.01P
Density-gms./cc.
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.8
0.9
1.0
1.1
1.2
1.3
1.4

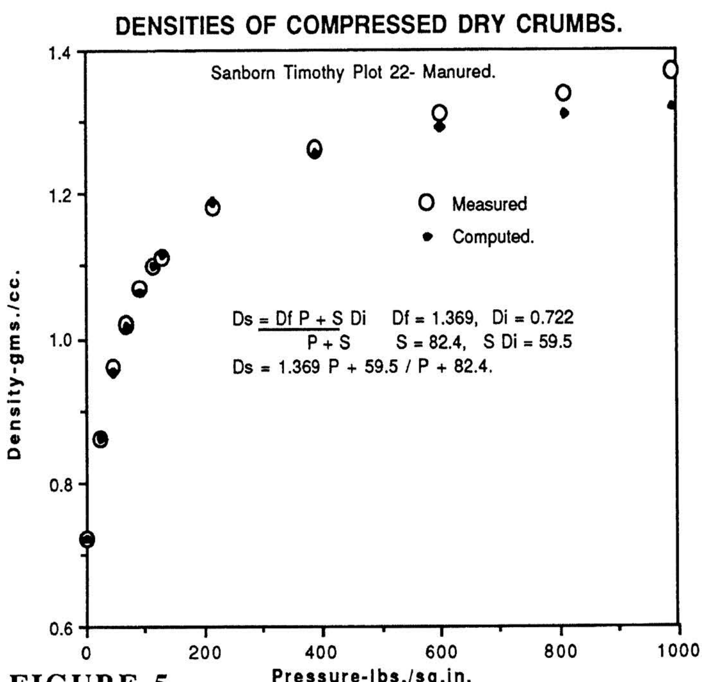
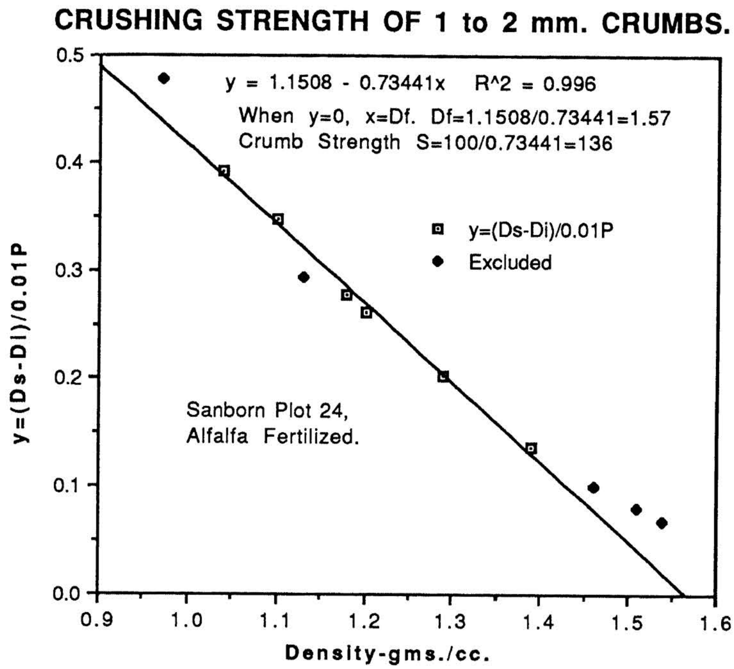

DENSITIES OF COMPRESSED DRY CRUMBS.
Sanborn Timothy Plot 22- Manured.
Measured
Computed.
Ds = Df P + S Di / P + S
Df = 1.369, Di = 0.722
S = 82.4, S Di = 59.5
Ds = 1.369 P + 59.5 / P + 82.4.
Density-gms./cc.
Pressure-lbs./sq.in.
0.6
0.8
1.0
1.2
1.4
0
200
400
600
800
1000

FIGURE-5.


CRUSHING STRENGTH OF 1 to 2 mm. CRUMBS.
y = 1.1508 - 0.73441x R^2 = 0.996
When y=0, x=Df. Df=1.1508/0.73441=1.57
Crumb Strength S=100/0.73441=136
y=(Ds-Di)/0.01P
Excluded
Sanborn Plot 24,
Alfalfa Fertilized.
y=(Ds-DI)/0.01P
Density-gms./cc.
0.0
0.1
0.2
0.3
0.4
0.5
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6

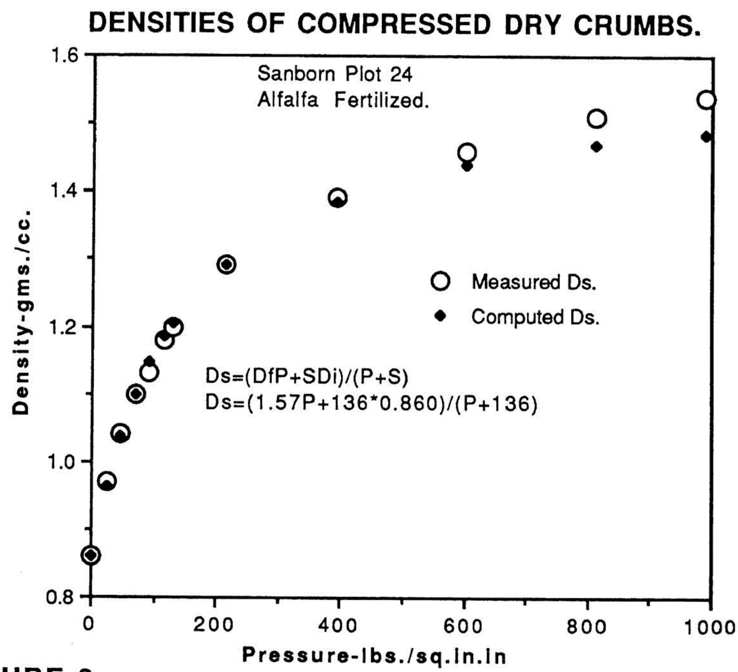
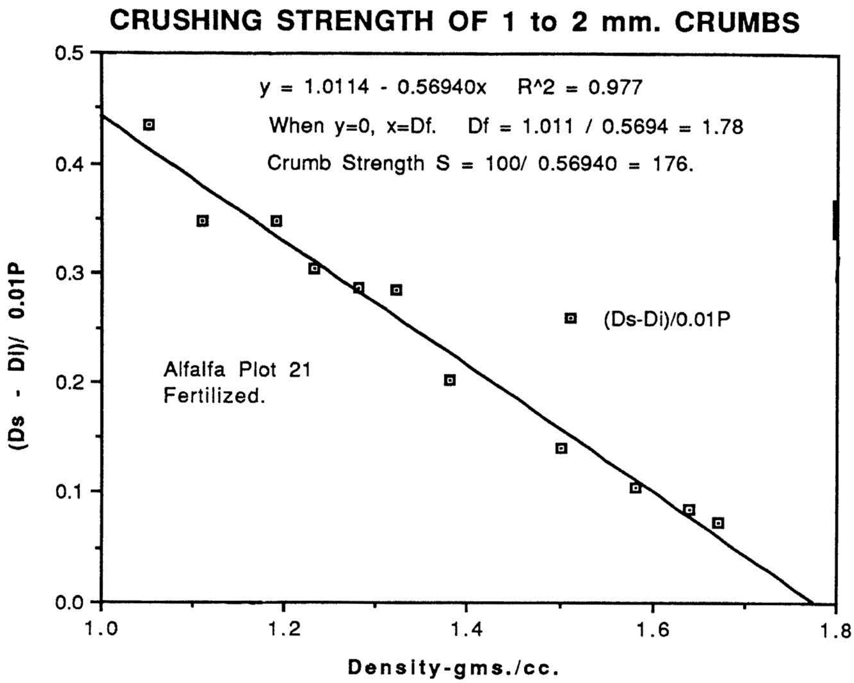

DENSITIES OF COMPRESSED DRY CRUMBS.
Sanborn Plot 24
Alfalfa Fertilized.
Measured Ds.
Computed Ds.
Ds=(DfP+SDi)/(P+S)
Ds=(1.57P+136*0.860)/(P+136)
Density-gms./cc.
Pressure-lbs./sq.in.In
0.8
1.0
1.2
1.4
1.6
0
200
400
600
800
1000

FIGURE-6.


CRUSHING STRENGTH OF 1 to 2 mm. CRUMBS
y = 1.0114 - 0.56940x R^2 = 0.977
When y=0, x=Df. Df = 1.011 / 0.5694 = 1.78
Crumb Strength S = 100/ 0.56940 = 176.
(Ds-Di)/0.01P
Alfalfa Plot 21
Fertilized.
(Ds - Di)/ 0.01P
Density-gms./cc.
0.0
0.1
0.2
0.3
0.4
0.5
1.0
1.2
1.4
1.6
1.8

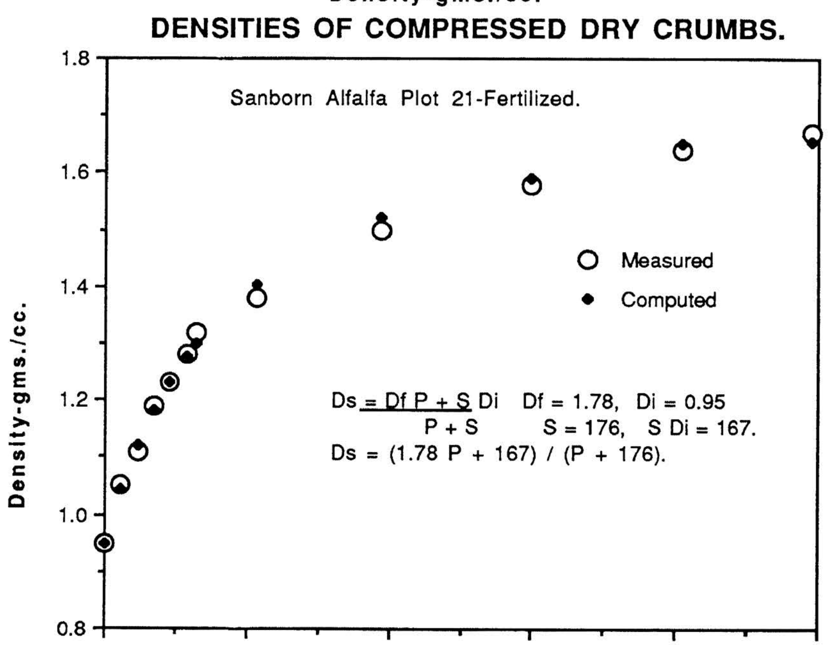
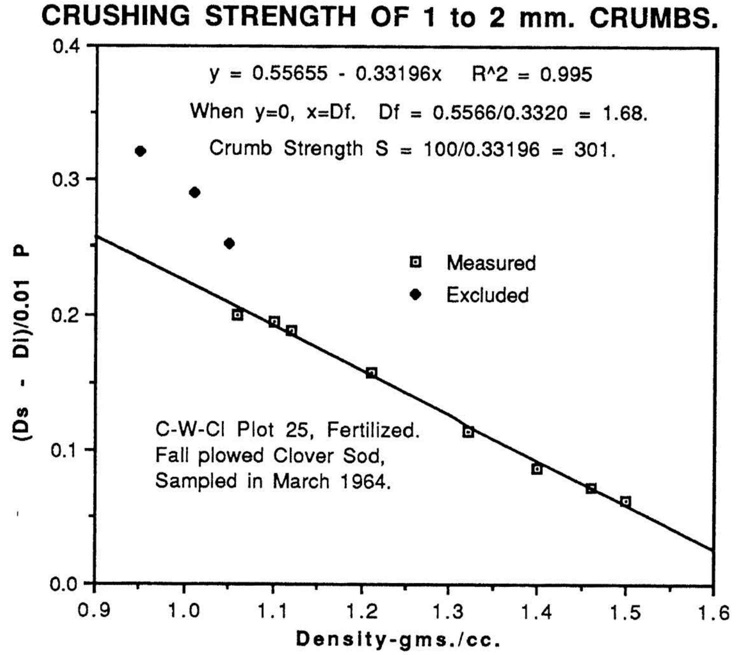

DENSITIES OF COMPRESSED DRY CRUMBS.
Sanborn Alfalfa Plot 21-Fertilized.
Measured
Computed
Ds = Df P + S Di / P + S Df = 1.78, Di = 0.95
S = 176, S Di = 167.
Ds = (1.78 P + 167) / (P + 176).
Density-gms./cc.
Pressure-lbs./sq.in.
0.8
1.0
1.2
1.4
1.6
1.8
0
200
400
600
800
1000

FIGURE-7.


CRUSHING STRENGTH OF 1 to 2 mm. CRUMBS.
y = 0.55655 - 0.33196x R^2 = 0.995
When y=0, x=Df. Df = 0.5566/0.3320 = 1.68.
Crumb Strength S = 100/0.33196 = 301.
Measured
Excluded
C-W-Cl Plot 25, Fertilized.
Fall plowed Clover Sod,
Sampled in March 1964.
(Ds - Di)/0.01 P
Density-gms./cc.
0.0
0.1
0.2
0.3
0.4
0.9
1.0
1.1
1.2
1.3
1.4
1.5
1.6

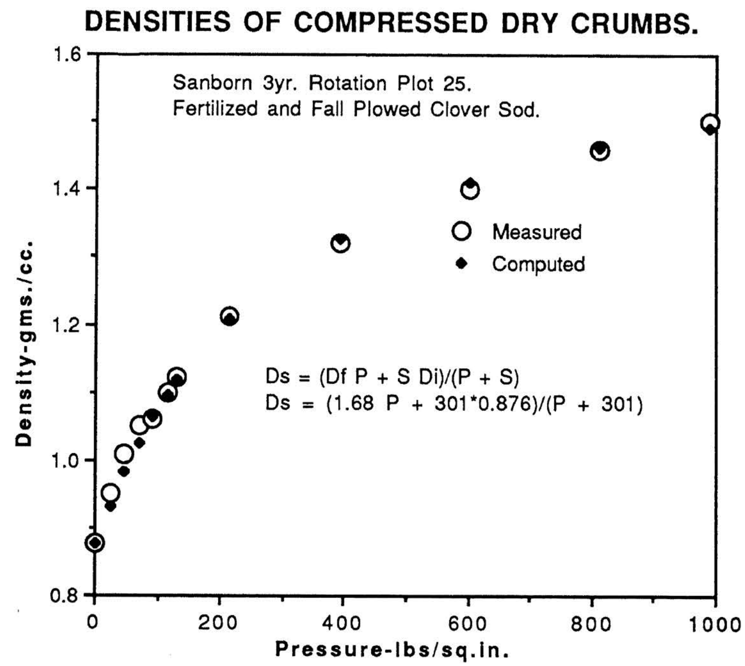
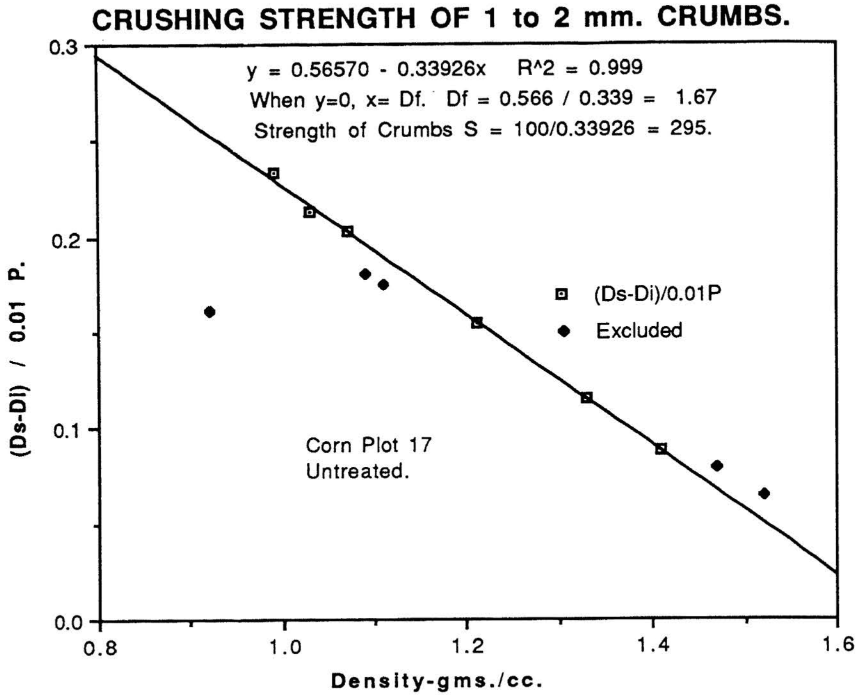

DENSITIES OF COMPRESSED DRY CRUMBS.
Sanborn 3yr. Rotation Plot 25.
Fertilized and Fall Plowed Clover Sod.
Measured
Computed
Ds = (Df P + S Di)/(P + S)
Ds = (1.68 P + 301*0.876)/(P + 301)
Density-gms./cc.
Pressure-lbs/sq.in.
0.8
1.0
1.2
1.4
1.6
0
200
400
600
800
1000

FIGURE-8.


CRUSHING STRENGTH OF 1 to 2 mm. CRUMBS.
y = 0.56570 - 0.33926x R^2 = 0.999
When y=0, x= Df. Df = 0.566 / 0.339 = 1.67
Strength of Crumbs S = 100/0.33926 = 295.
(Ds-Di)/0.01P
Excluded
Corn Plot 17
Untreated.
(Ds-Di) / 0.01 P.
0.0
0.1
0.2
0.3
0.8
1.0
1.2
1.4
1.6
Density-gms./cc.

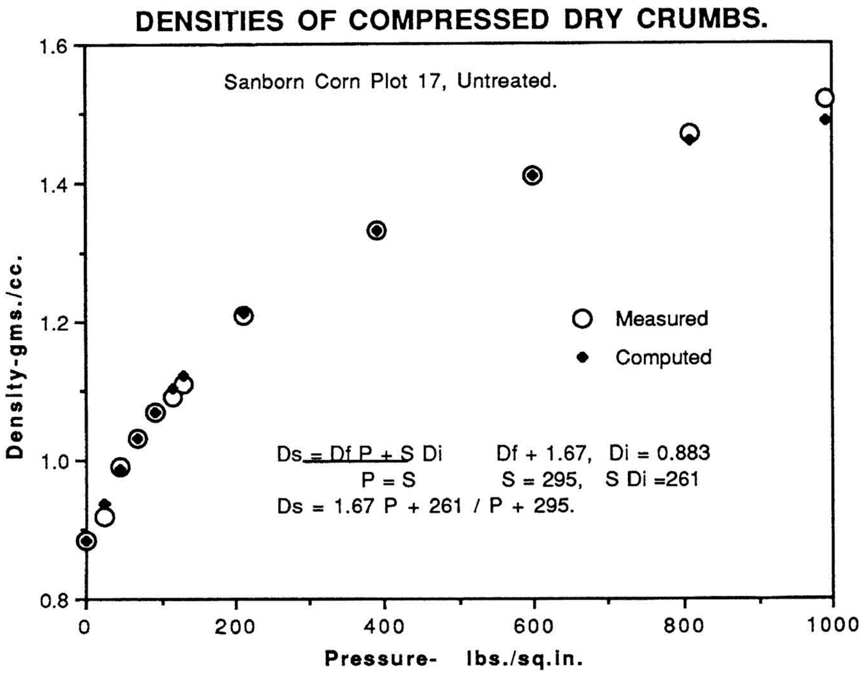

DENSITIES OF COMPRESSED DRY CRUMBS.
Sanborn Corn Plot 17, Untreated.
Measured
Computed
Ds = Df P + S Di / P = S
Df + 1.67, Di = 0.883
S = 295, S Di =261
Ds = 1.67 P + 261 / P + 295.
Density-gms./cc.
0.8
1.0
1.2
1.4
1.6
0
200
400
600
800
1000
Pressure- lbs./sq.in.

FIGURE-9.

Interpretations of Results from Sanborn Field.

Figures 4 and 5 present results from continuous timothy plot 23 untreated, and manured plot 22. Crumb strengths were 54 and 82 lbs./sq.in. respectively. Limiting densities of 1.4 gms./cc. and equal pressures of 390 lbs./sq. in. delineating the transition from crushing crumbs to orienting of grains indicate minor effects of added manure.

Figures 6 and 7 compare results for crushed crumbs from plots 24 and 21 in alfalfa since 1950. Brome grass seeded with alfalfa on plot 21 never provided a substantial component of the vegetation subject to the frequent harvests of alfalfa. Differences between the soils of the two plots revealed by the crushing of crumbs included maximum densities of 1.78 and 1.57 for plots 21 and 24 respectively and crushing sprectums of pressures of 990 and 390 lbs./sq.in. for each.

Both plots 24 and 21 were cropped to wheat with annual applications of 6 tons of manure for the first 50 years after the field was established in 1888. Average yields of wheat were 19.5 bu./ac. for each plot after 25 yrs. 200 lbs./ac. of acid phosphate (0-16-0) was applied to seedings of wheat on plot 21 for the second 25 years giving an average yield of 21 bu./ac. compared with 16 from untreated plot 24. The fully fertilized alfalfa introduced in 1950 after 20 years averaged 4.8 tons per acre from pot 21 compared to 3.9 t./ac. from 24.

A mechanical analysis of the centennial sampling of plots of Sanborn Field indicated percentage silt contents of 79.6 and 77.2 for plots 21 and 24. Fine silt in the soil from plot 21 was 130% of the coarse. That from plot 24 was 94%. The fine silt filling the pores of the coarse silt would account for the bulk density of 1.78 gms./cc. for plot 21 compared to 1.57 for plot 24. Loss of fine silt by erosion from plot 24 during the 25 years of cropping to unfertilized wheat may account for the differences that exist today.

Figures 8 and 9 presenting results for plots 25 and 17 with widely different histories exhibit similar characteristics of the crushed crumbs. Plot 25 in a rotation of corn, wheat and clover with six tons of manure applied annually until 1938 followed by five tons on corn since 1939 and this accompanied with full fertilization since 1950 was fall plowed out of clover sod prior to sampling dry soil crumbs the following March. Plot 17 in continuous corn without treatment since 1888 was fall plowed and sampled the following spring . The plow first reached the subsoil by 1940. By 1960 the plow depth was clay over most of the plot.

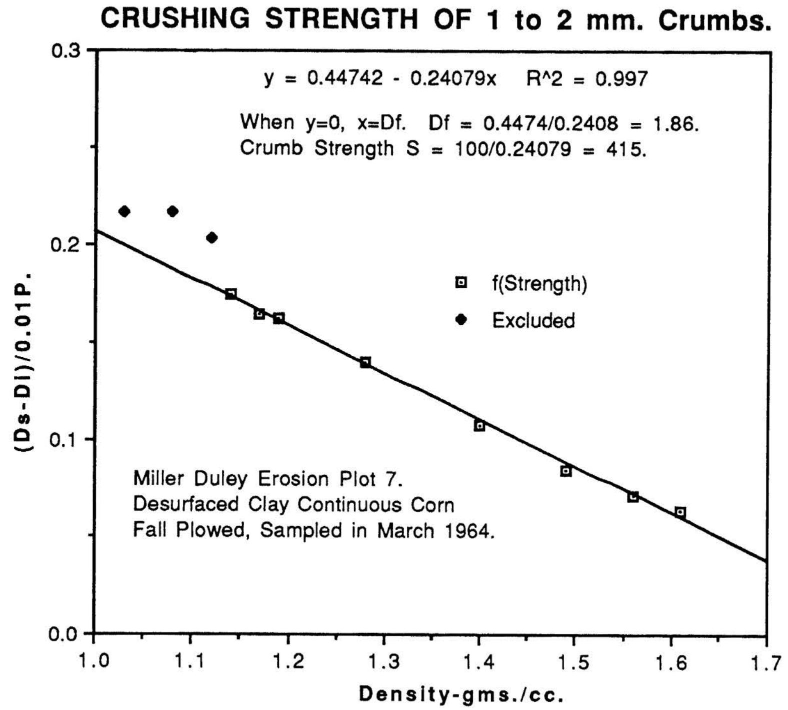
The final densities of the crushed soil were 1.68 for the clover sod, 1.67 for the clay. Crushing strengths were 301 and 295 lbs./sq.in. for the respective plots. The spectrum of crushing attained 990 lbs. for crumbs from sod and 810 lbs. for crumbs from clay subsoil. Their physical characteristics were much the same.

Figures 1 through 9 complete the measurements of soils from selected plots of Sanborn Field. The values obtained do provide a set of bench marks for future studies. Also the results emphasize the role of colloidal constituents in soils. Continuous cropping to wheat without organic returns to the soil left plot 9 with a structureless mass of silt much like waterlaid river sand Fig. 2, 3a and 3b. Corn and cotton cropping have left many sandy alluvial soils depleted of organic binding agents. Clay of subsoil exposed by erosion substituted for physical properties of organic substances in tilled surface soil of plot 17. However it does not provide the needed drainage and aeration of the deeper root environment, nor does clay substitute for benefits of biological properties associated with organic matter.

CHARACTERIZATIONS OF MISCELLANEOUS SOILS.

Three soils differing in properties from the silt loam texture of soil on Sanborn field were studied. The first, Fig. 10, was a glacial deposit of sandy clay exposed by desurfacing the original Miller-Duley soil erosion plots in 1941. Plot 7 in continuous corn that was fully fertilized was fall plowed to create a desirable physical structure and sampled before tillage the following spring. The second, Fig. 11, was an organic muck soil from the "old field" near Advance ,Missouri in the Mississippi Delta. The third soil Fig. 12 was a sample of Houston black clay from Texas. A fourth miscellaneous soil a river laid sand from near Easley, Missouri was used in establishing the compression function for reorienting discrete particles of sand and silt, Fig 2..

Crumbs of clay from erosion plot 7 exhibited a crushing pressure of 415 lbs./sq.in. up to a density of 1.9 gms./cc. Organic muck crushed at 199 lbs./sq.in. up to a density of 1.1 gms./cc. Houston black clay required 115 lbs./sq.in. of pressure to settle the crumbs before crushing started.. The crushing strength of the crumbs was 766 lbs,/sq.in. attained up to a maximum density of 1.8 gms./cc.


CRUSHING STRENGTH OF 1 to 2 mm. Crumbs.
y = 0.44742 - 0.24079x R^2 = 0.997
When y=0, x=Df. Df = 0.4474/0.2408 = 1.86.
Crumb Strength S = 100/0.24079 = 415.
f(Strength)
Excluded
Miller Duley Erosion Plot 7.
Desurfaced Clay Continuous Corn
Fall Plowed, Sampled in March 1964.
(Ds-Di)/0.01P.
0.0
0.1
0.2
0.3
1.0
1.1
1.2
1.3
1.4
1.5
1.6
1.7
Density-gms./cc.

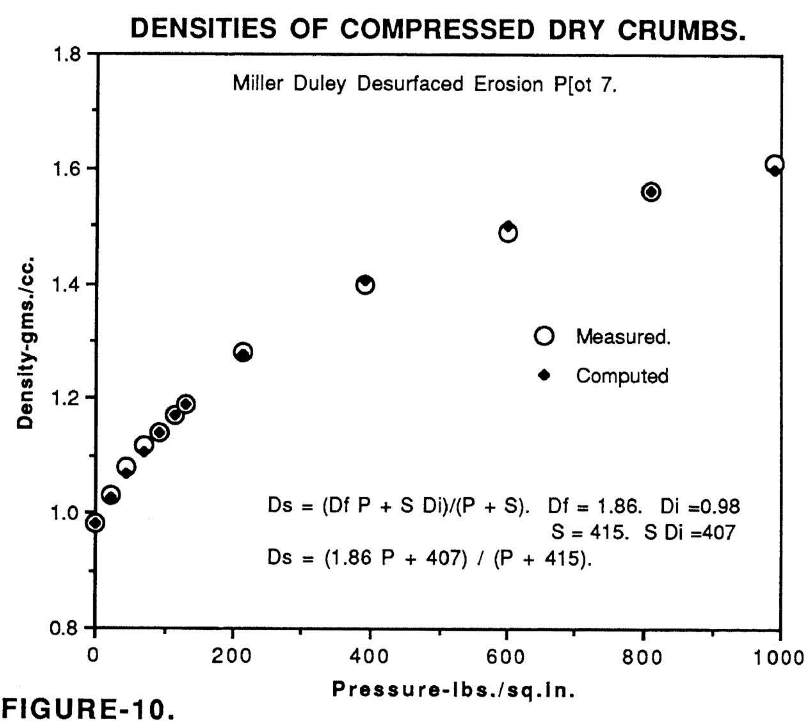
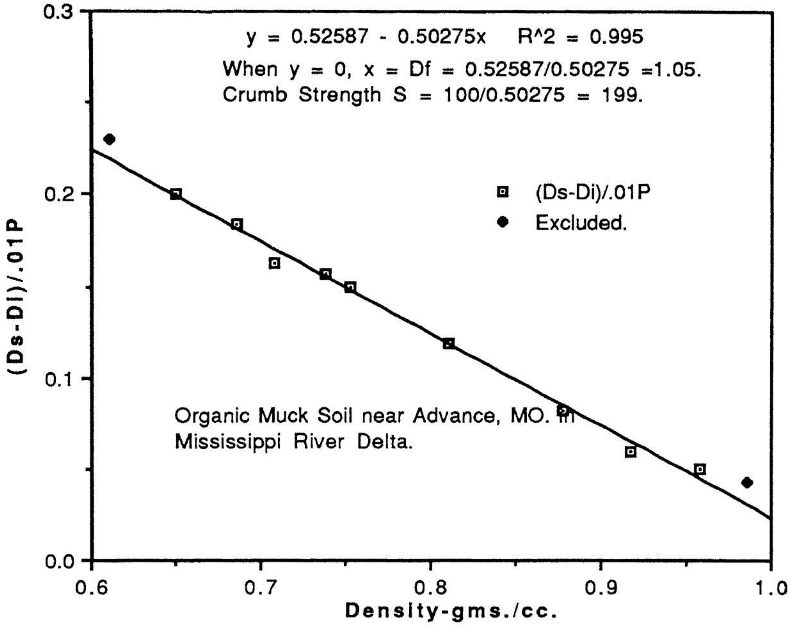

DENSITIES OF COMPRESSED DRY CRUMBS.
Miller Duley Desurfaced Erosion P[ot 7.
Measured.
Computed
Ds = (Df P + S Di)/(P + S). Df = 1.86. Di =0.98
S = 415. S Di =407
Ds = (1.86 P + 407) / (P + 415).
Density-gms./cc.
0.8
1.0
1.2
1.4
1.6
1.8
0
200
400
600
800
1000
Pressure-lbs./sq.in.

FIGURE-10.

COMPRESSION OF 1 to 2 mm. CRUMBS.



DENSITIES OF COMPRESSED DRY CRUMBS.

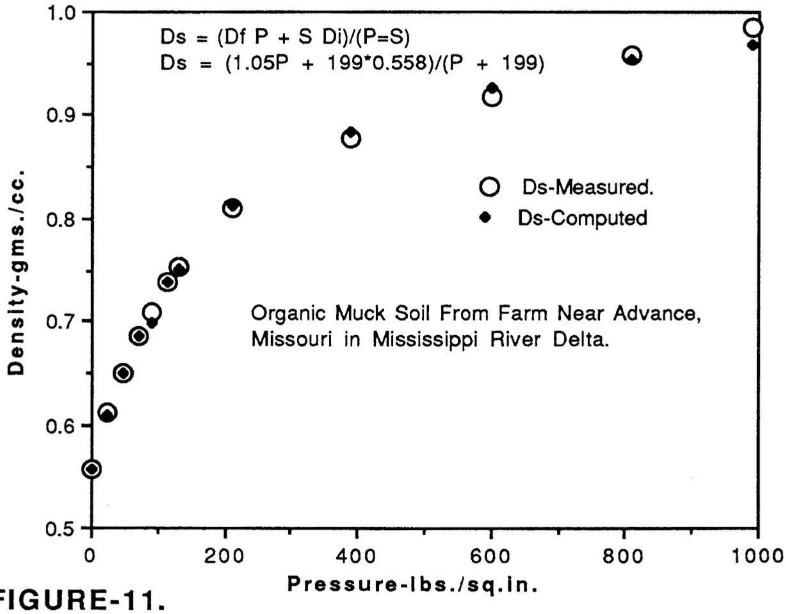
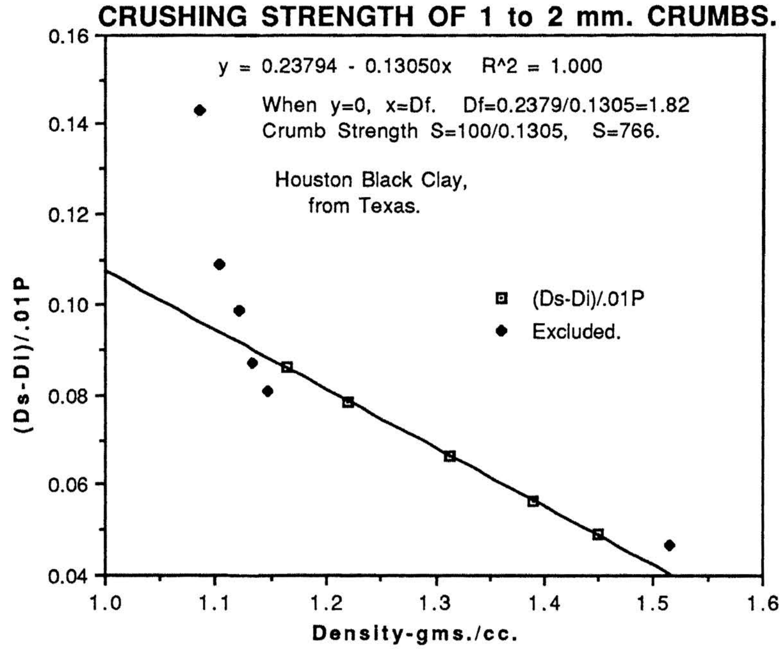


FIGURE-11.


CRUSHING STRENGTH OF 1 to 2 mm. CRUMBS.
y = 0.23794 - 0.13050x R^2 = 1.000
When y=0, x=Df. Df=0.2379/0.1305=1.82
Crumb Strength S=100/0.1305, S=766.
Houston Black Clay, from Texas.
(Ds-Di)/.01P
Excluded.
(Ds-Di)/.01P
Density-gms./cc.
0.16
0.14
0.12
0.10
0.08
0.06
0.04
1.0
1.1
1.2
1.3
1.4
1.5
1.6

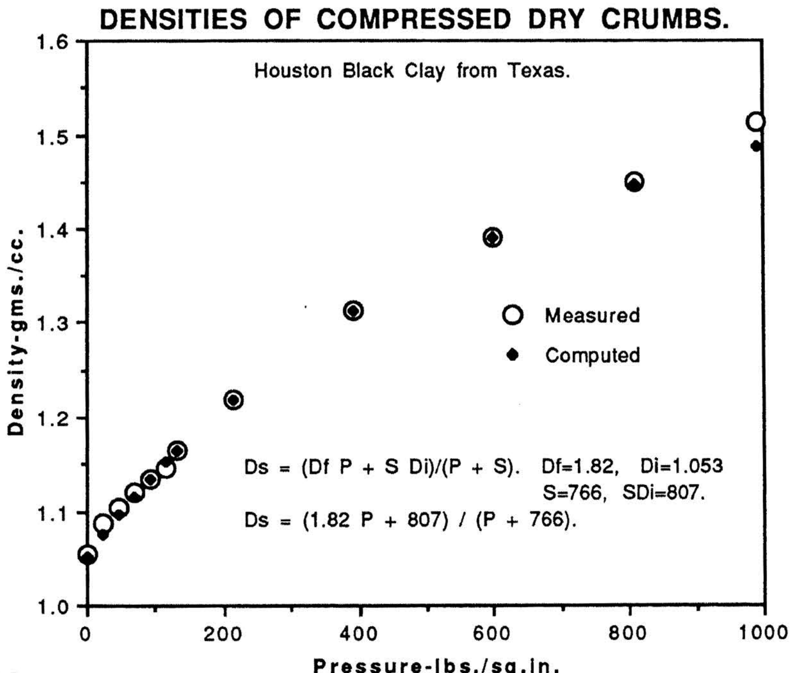

DENSITIES OF COMPRESSED DRY CRUMBS.
Houston Black Clay from Texas.
Measured
Computed
Ds = (Df P + S Di)/(P + S). Df=1.82, Di=1.053
S=766, SDi=807.
Ds = (1.82 P + 807) / (P + 766).
Density-gms./cc.
Pressure-lbs./sq.in.
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0
200
400
600
800
1000

FIGURE-12.

Densities for Compressed Sandy Loam Field Soil of Missouri River Alluvium Near McBaine, Missouri.

The soil, a highly productive cropped soil, produced good sugar beets. The soil structure developed by tillage was stable through the growing season of the beets permitting them to expand in the soil. A field sample was procured on April 21 by pressing a one ounce ointment boxe into the plow layer after scraping off the top inch of exposed surface. The soil was air dried in the container and compressed. Densities expressed on an oven dry basis are presented in figure 13.

A pressure of 213 lbs./sq.in. approximates that of the wilting point as an estimate of the compressible pore space that would accommodate an expanding root. The initial density of 1.315 gms./cc. corresponds to 37.4 gms. in the 28.4 cc. container. The volume occupied by the soil at 213 lbs. pressure was 25.8 cc. giving 2.6 cc. or 9.2% reduction in volume by compression at the wilting point. Compressible pore space within the capacity of a beet root to expand is essential in dry soils that have been wetted thoroughly by rainfall or irrigation. Density increased exponentially with cracking followed by crushing of soil crumbs..

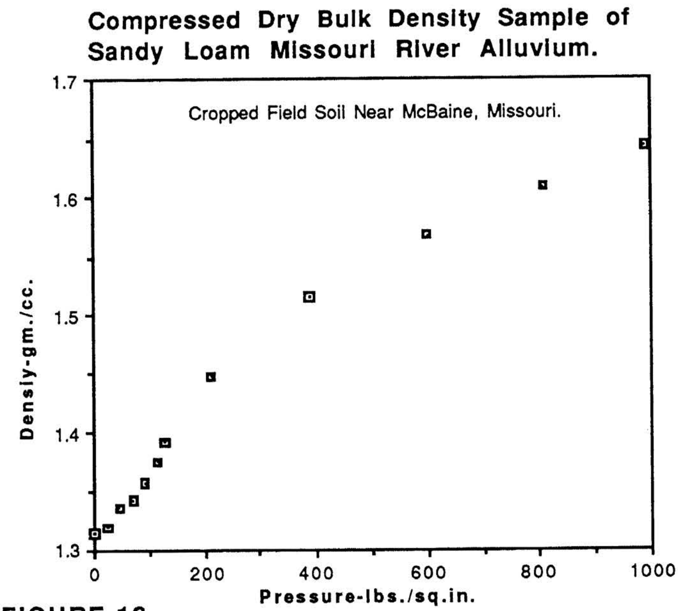


FIGURE-13.

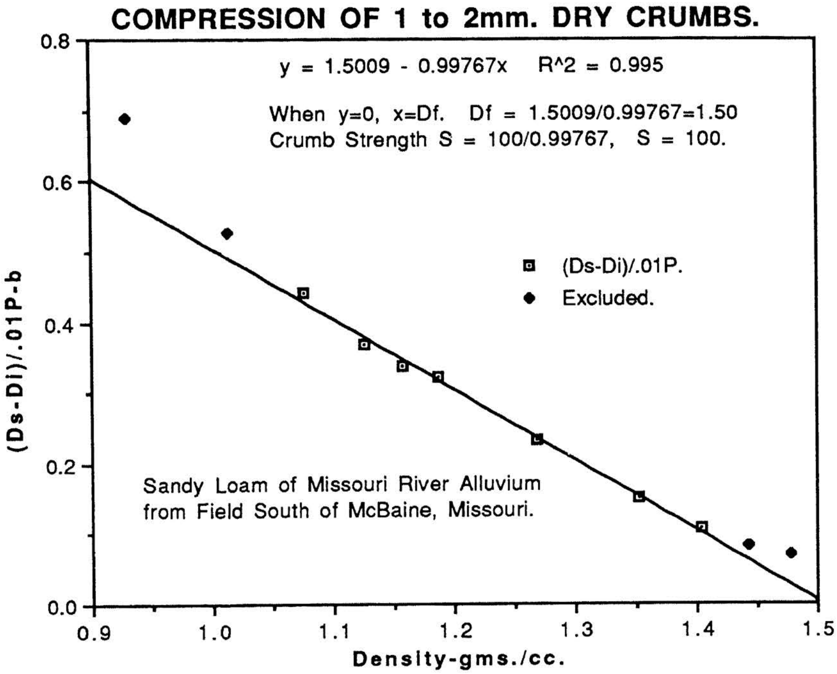
Two Stages of Compression-Cracking and Crushing.

The results in figure 13 reveal two stages of compression. Initially the dry sample of soil was a solidified mass as much of it is after a wetted soil dries in place. After applied pressure produces the first crack in the dry mass of soil, addiional incriments of pressure produce increasing numbers of cracks while the density rises exponentially. The rate of rise increases attaining a maximum at a flex point after which it declines as it approaches some final limiting density Df. The first stage of compression is that of cracking fragments. Beyond the flex point the second stage of compression is that of crushing crumbs. The force required to break a soil initially by tillage is the force that expanding beet roots must accomplish if they are to expand in the soil. An initial bulk density of 1.4 gms./cc. may imply a greater breaking strength or an inadequate amount of compressible pore space for fleshy root crops.

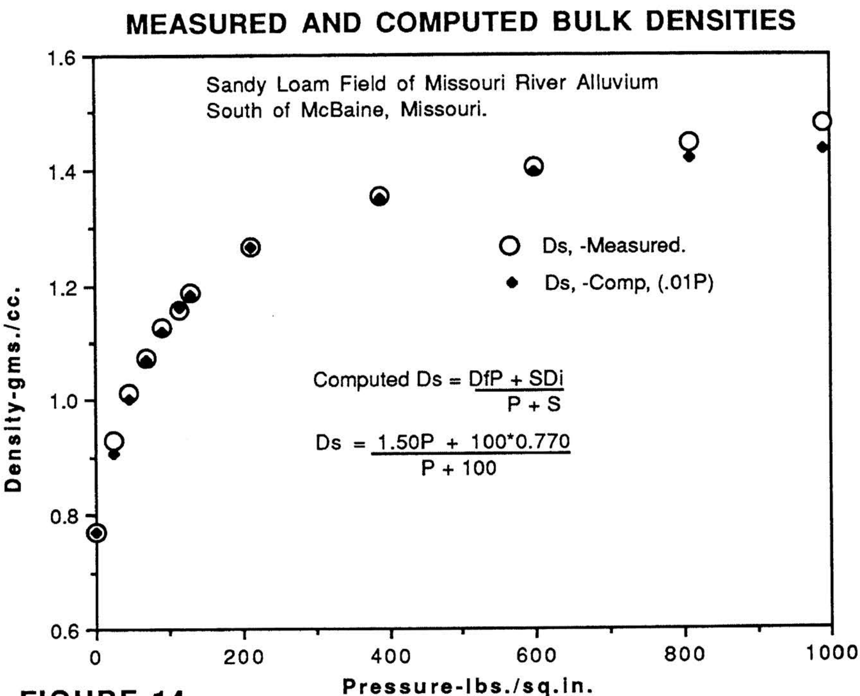
Crushing dry crumbs of soil provides a measure of crumb strength. The duration of crushing before compaction develops is indicative of amounts of compressible pore space. If crumb strength is associated with the strength of dispersed clay that has dried to cement a mass of sand grains into a solid, then high bulk densities and small amounts of compressible pore space result in beets that expand above the sail. If that strength is associated with water stable organic compounds that cement grains of sand into crumbs, or coat aggregates of clay and silt, the stable soil tilth, low bulk densities and large amounts of compressible pore space favor beets that expand in the soil..

DENSITIES OF COMPRESSED 1 to 2 mm. DRY CRUMBS FOR McBAINE RIVER ALLUVIUM OF FIGURE-13.

Compressed dry crumbs of the sandy loam soil as presented in the upper graph of figure 14 yielded an estimate of the final density of crushing **Df=1.5 gms./cc.** and a crushing strength **S = 100 lbs./sq.in.** With the initial parameter **Di=0.77 gms./cc.** the computed densities agreed satisfactorily with the measured values up to a pressure of 600 lbs./sq.in. Crushing of crumbs completed, the pressures reoriented individual grains into a more dense degree of packing.



COMPRESSION OF 1 to 2mm. DRY CRUMBS.
y = 1.5009 - 0.99767x R^2 = 0.995
When y=0, x=Df. Df = 1.5009/0.99767=1.50
Crumb Strength S = 100/0.99767, S = 100.
(Ds-Di)/.01P.
Excluded.
Sandy Loam of Missouri River Alluvium
from Field South of McBaine, Missouri.
(Ds-Di)/.01P-b
Density-gms./cc.
0.0
0.2
0.4
0.6
0.8
0.9
1.0
1.1
1.2
1.3
1.4
1.5



MEASURED AND COMPUTED BULK DENSITIES
Sandy Loam Field of Missouri River Alluvium
South of McBaine, Missouri.
Ds, -Measured.
Ds, -Comp, (.01P)
Computed Ds = DfP + SDi / P + S
Ds = 1.50P + 100*0.770 / P + 100
Density-gms./cc.
Pressure-lbs./sq.in.
0.6
0.8
1.0
1.2
1.4
1.6
0
200
400
600
800
1000

FIGURE-14..

DELTA RESEARCH CENTER, PORTAGEVILLE, MISSOURI.

BULK DENSITIES AND COMPRESSIBLE PORE SPACE OF SOILS ON RANGE-J IN SUGAR BEETS, SAMPLED JUNE 14, 1964.

Pit No. 1. Between Beet Rows, 20 feet West of Roadway.

Sample Depth inches.	Bulk Density gms./cc.	Compressible Pore Space,%.	Soil Texture.
1.5	1.57	20.4	Brown
5.0	1.74	13.3	Loamy
8.0	1.71	13.2	Sand.
13.5	1.61	14.4	'Same'
17.0	1.48	22.5	Black Silt Loam.

Pit NO. 2. Roadway Adjacent to Beets of Pit No. 1

1.5	1.65	19.7	Brown
4.5	1.67	16.9	Loamy
10.0	1.57	19.6	Sand.
17.0	1.42	25.7	Black
23.5	1.49	28.4	Silt
32.0	1.55	26.9	Loam.

Pit No. 3. Sugar Beets 300 feet West of Roadway

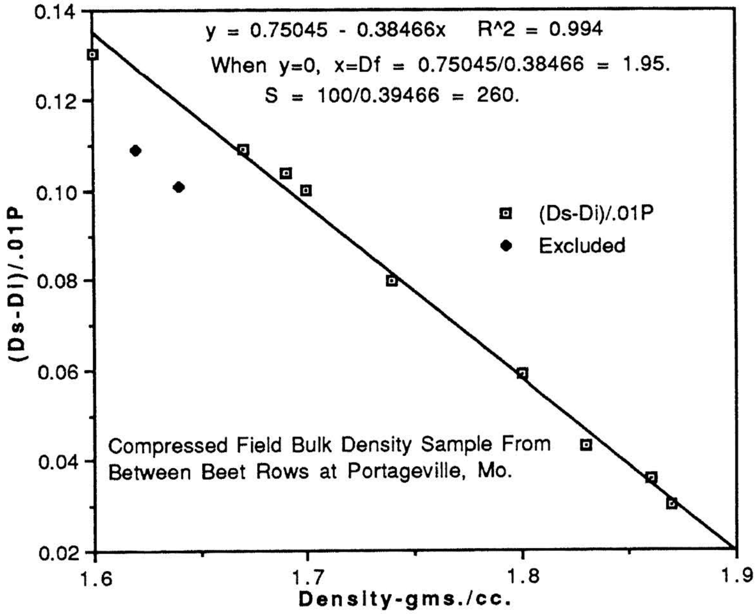
1.5	1.60	22.7	Brown
5.5	1.73	21.0	Loamy
11.5	1.58	20.9	Sand.

Pit No. 4. Cotton West of Pit No.3

1.5	1.50	28.9	Brown
7.5	1.55	27.9	Sandy Loam.

Beets expanded above the soil surface at bulk densities of 1.6 to 1.7 gms./cc. with compressible pore spaces of 13 to 14% by volume. Densities of 1.4 to 1.5 gms./cc. were associated with compressible pore spaces that exceeded 20%. However the strengths of the loamy sands when dry, figure 15, did not permit beets to expand in the soil. Of the sixteen samples obtained from the four pits all were compressed in the field moist condition. After compression the soils were ovendried and weighed. Bulk densities before compression ranged from 1.42 to 1.74 gms./cc. After compression all were from 1.88 to 2.15 gms./cc. Compression of soils in the moist condition not only destroys natural aggregates. It also compresses clay and colloidal coatings of primary minerals.

COMPRESSED BULK DENSITIES OF SUGAR BEET SOIL AT DELTA RESEARCH CENTER.



MEASURED AND COMPUTED DENSITIES OF COMPRESSED FIELD BULK DENSITY SAMPLE.

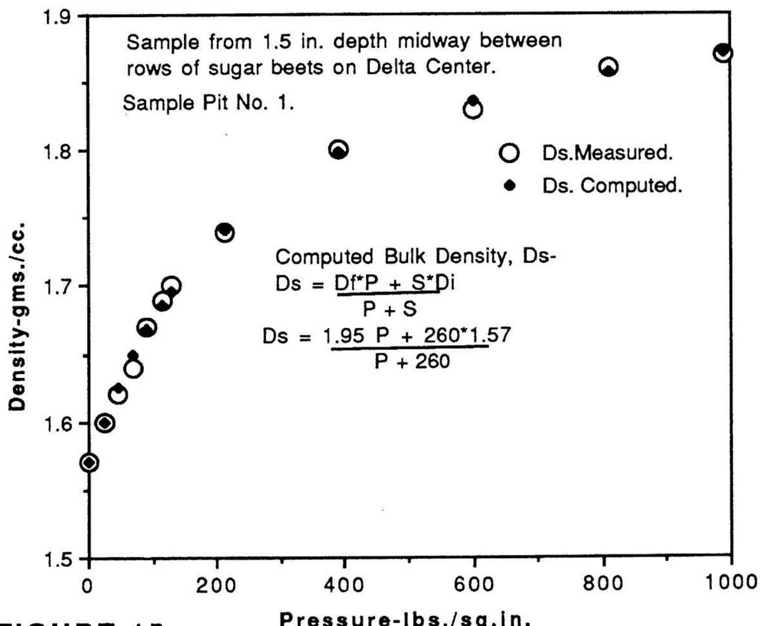


FIGURE-15.

SUMMARY AND CONCLUSIONS.

Establishing Values of the Parameters Di, Df and S for Dry Crumbs and Loose Grains of Sand.

A mass of dry soil crumbs exists at an initial bulk density **Di** before application of a pressure load. Crumbs crushed by an applied load increase in density until the density **Ds** will support the load. Increase in density per pound of applied pressure, **(Ds-Di)/P,** is a linear function of the density. **Ds** ceases at a final density **Df.** Thereafter individual mineral particles, the products of crushed crumbs, support additional pressure loads by reorienting into more closely packed configuration. The internal radial vector of pressure operating to move particles to a closer degree of packing is a function of the square root of the applied pressure operating in the coordinate axes, namely, **√P.** Soil density of loose particles increases with increasing pressures approaching a maximum density **Dm** at which changing configurations of particles ceases.

The compression functions **(Ds-Di)/P = A-BDs** for crushing crumbs and **(Ds-Di)/√P = A-BDs** for compacting individual grains extrapolate to zero as densities approach **Df or Dm,** Solving, **Df or Dm = A/B** according to which of the two processes is operating. The quantity **B** of the relationship expresses the rate at which density increases as a consequence of compression. The rate is rapid when **B** is large and crumb strength is weak. The rate is slow when **B** is small and crumbs are strong. The reciprocal **1/B** expresses crumb strength in pounds per square inch. Pressures scaled to units of **0.01P** used to operate with smaller numbers require appropriate corrections, namely, **S=100/B** for crumb strength.

Validity of the Concepts Relating Bulk densities to Compression of Soils by Applied Pressures.

Compression of dry soil crumbs produced by applied pressures as expressed by bulk density in relation to pressure involves parameters, **Di,Df and S** from which

$$Ds = \frac{DfP+SDi}{P+S} \text{ and for loose grains, } Ds = \frac{Df\sqrt{P}+SDi}{\sqrt{P}+S}.$$

Computed densities compared with measured values for a variety of soils and cultural conditions gave satisfactory agreement suggesting that the parameters were valid measures for characterizing the properties of agricultural soils. A summary of results presented in figures 1 to 15 follows.

PARAMETERS CHARACTERIZING THE SOILS OF THIS STUDY.

Soil, Crop or Cultural History. -	Di gms./cc.	Df gms./cc.	S lbs/in.^{2}
Sanborn Field Established in 1888 on Silt Loam Soil..			
Blue Grass Sod of Plot Border.	0.776	1.52	196
Plot 9 Wheat Continuous-N.T.	0.805	1.54	47
Silt After Crushing.	0.805	1.87	12
-17 Corn Cont. Eroded to Clay.	0.883	1.67	295
-21 Alfalfa-Brome,Fertilized	0.950	1.78	176
-24 Alfalfa, Fertilized	0.860	1.57	136
-Timothy,Manured.	0.722	1.37	82
-Timothy,Untreated	0.752	1.41	54
-25 Corn,Wh.Cl. Fall Plowed	0.876	1.68	304
Miscellaneous Soils			
-7 Miller-Duley Eroded Clay.	0.980	1.86	415
Sandy Alluvium, Easley, Mo.(√P)	0.782	1.64	5.4
Muck,Advance,Mo. Miss. Delta.	0.558	1.05	199
Houston Black Clay, Texas	1.053	1.82	766
Sandy Loam, McBaine, Mo.	0.770	1.50	100
Loamy Sand, Portageville,Mo.	1.570	1.95	260

Conclusions- Crushing dry crumbs of soil provides an undeveloped source of information about the character of arable soils as they are tilled in the dry condition and as dry soils influence the expansion of developing plant roots. Historically, soils change under crop and cultural practices, sometimes for better, many times for worse. The weak crumbs of soil from plot 9 on Sanborn field associated with the loss of soil organic matter under continuous cropping to wheat agree with observations of an earlier era when the burning of straw after harvest was investigated. In contrast, the strength of crumbs from plot 25 in a three year rotation of corn, wheat and clover since 1888 and fall plowed out of clover sod was the greatest of the soils investigated on the field.

Organic residues returned to the soil provide the source of energy essential to the life of the soil. Without them the future will be a land of burned out soils.

SUGAR BEET TESTS IN MISSOURI, 1961-1967.

Beginning in 1961, test plots of sugar beets were grown on farm fields from North West to South East Missouri to determine whether or not sugar beets could be produced commercially in Missouri. The purpose was to establish potentials for yields and sucrose contents with attention to fertilizer requirements, disease and insect problems and cultural practice requirements. The tests were supported by the Great Western and Holley Sugar Companies.

Compaction of loamy sand alluvial soils, recognized as a problem by cotton and vegetable producers for which remedial measures had not been investigated, surfaced as a serious limitation to sugar beet production. Soil compaction on the sugar beet test plots at the Delta Research Center were responsible for the limited studies reported in this bulletin.

Tests of sugar beet production in Missouri were terminated when it was learned that to obtain an allotment a processing facility would be required. Producers were not interested in financing such a facility. No formal reports of sugar beet production tests were published. However, the best documentation of the work is provided by the following items that appeared in the Missouri Ruralist Farm Magazine.

Sugar Beet Development Moves Ahead in Missouri.
August 12, 1961.- Pages 14 and 15.

A Year of Progress.
December 23, 1961- Pages 4 and 14.

Missouri Can Grow Sugar Beets, by Cordell Tindall.
January 27, 1962 - Page 18.

Goal of Sugar Controls to Insure Steady Prices, by Tom A. Murphy
March 10, 1962 - Pages 44 and 46.

Good Yields Reported in Sugar Beet Tests. by Cordell Tindall.
April 13, 1963 - Pages 10 and 11.

Delta Center Research Reviewed at Field Day, by Richard Lee.
September 26, 1964 - Pages 14 and 15.