THE EFFECT OF CLAY ON THE HARDNESS OF A CLAY-SAND AGGREGATE

by

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TABLE OF CONTENTS

INTRODUCTION

The surface of the earth is underlain by very large areas of sand that are often intermixed with very small percentages of clay. The aggregation of these two materials produces a soil that does not react like either of its components. From an agricultural standpoint, these soils may be productive but tilth is very difficult except within a very narrow range of moisture content. These soils are also highly susceptible to drought. The engineer experiences even greater difficulty in working with these soils. When saturated they appear to be a fluid and as hard as concrete when dry.

In a previous study Ibanga (1) reported that large areas of his homeland, Nigeria, are underlain by soils that fall within this classification. During the wet season travel on dirt roads is forbidden since the travelers would sink into the mud and become stranded, and Dr. O. W. Bidwell (2) states that essentially all intracity commerce comes to a halt until the dry season begins. During the dry season the soil becomes so hard that it must be blasted with dynamite for earth moving projects.

These soils exist elsewhere in the world also as per example at Kansas State University's Sandyland experimental farm at Saint John, Kansas. The soil conditions at Saint John are not so severe as in Nigeria, but tillage of the soil is very difficult except at specific moisture content.

Since much work has been done on these soils by the agronomists and the agricultural benefits could be easily recognized,

this study was made in cooperation with the Agronomy Department at Kansas State University. To further this cooperation, and to promote the immediate application of the findings, testing procedures common to agronomy were used in the study. This also had an advantage of acquainting the author with both engineering and agronomy testing procedures.

PURPOSE AND SCOPE

The specific purposes of this report are:

1. Identify the mechanism that renders these soils subject to such a hard and unworkable consistency.

2. Discover and recommend a workable solution for treatment of these soils to produce a tillable soil profile, if possible.

This thesis is a continuation of work started by I. I. Ibanga, completed during the 1973-74 school year at Kansas State University with the Department of Agronomy. Mr. Ibanga is at present working to improve the agricultural production of Nigeria.

The study consisted of fabricating some 200 briquettes of various sand-clay mixtures in the soil mechanics laboratory at Kansas State University. The modulus of rupture of the specimens was determined by a method described by Richards (3) and Reeve (4). The results were analyzed and compared to determine the effects of very low clay content on the modulus of rupture of sand-clay mixtures.

THIS BOOK CONTAINS NUMEROUS PAGES WITH DIAGRAMS THAT ARE CROOKED COMPARED TO THE REST OF THE INFORMATION ON THE PAGE.

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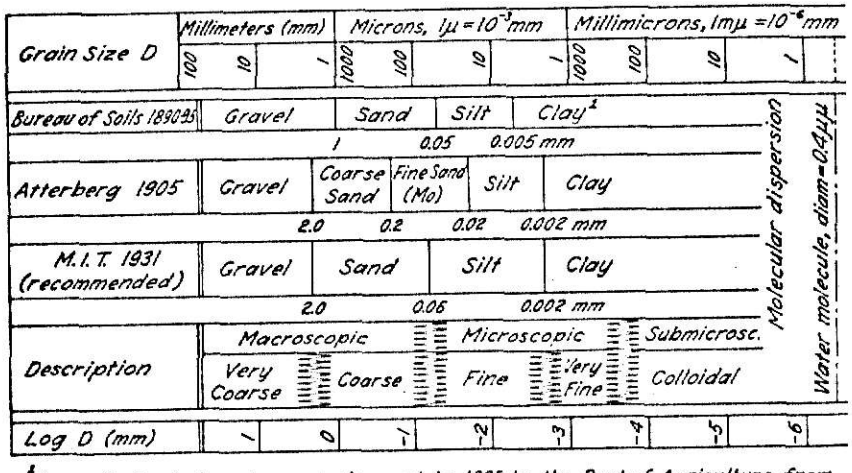
LITERATURE REVIEW

The physical characteristics of soil are measured by the engineer for the most part by test methods defined by the American Society for Testing Materials (5) and outlined in detail in Lambe (6). The simplest and most often used of these tests are the gradation and Atterberg limits tests which are used for classification.

Classification

Most of the early attempts at soil classification systems were based on the grain size characteristics, but the results of these systems have been consistently disappointing. The behavior of a soil is dependent on many other variables such as mineralogy, grain shape, and surface texture of the particles. In almost all soil classification systems the particle sizes are divided into three fractions: sand, silt, and clay. The definition of these sizes by various authors are shown in Fig. 1 taken from Terzaghi and Peck (7).



[1]Upper limit of clay size was changed in 1935 by the Dept of Agriculture from 0.005 mm to 0.002 mm. However, some engineering organizations still adhere to the original value of 0.005 mm.

Fig. 1 - Particle Size Range

The classification of soil materials by the agronomists is shown in Fig. 2.

Figure 2 (2) shows the triangular guide for classification used by agronomists and the U. S. Department of Agriculture.

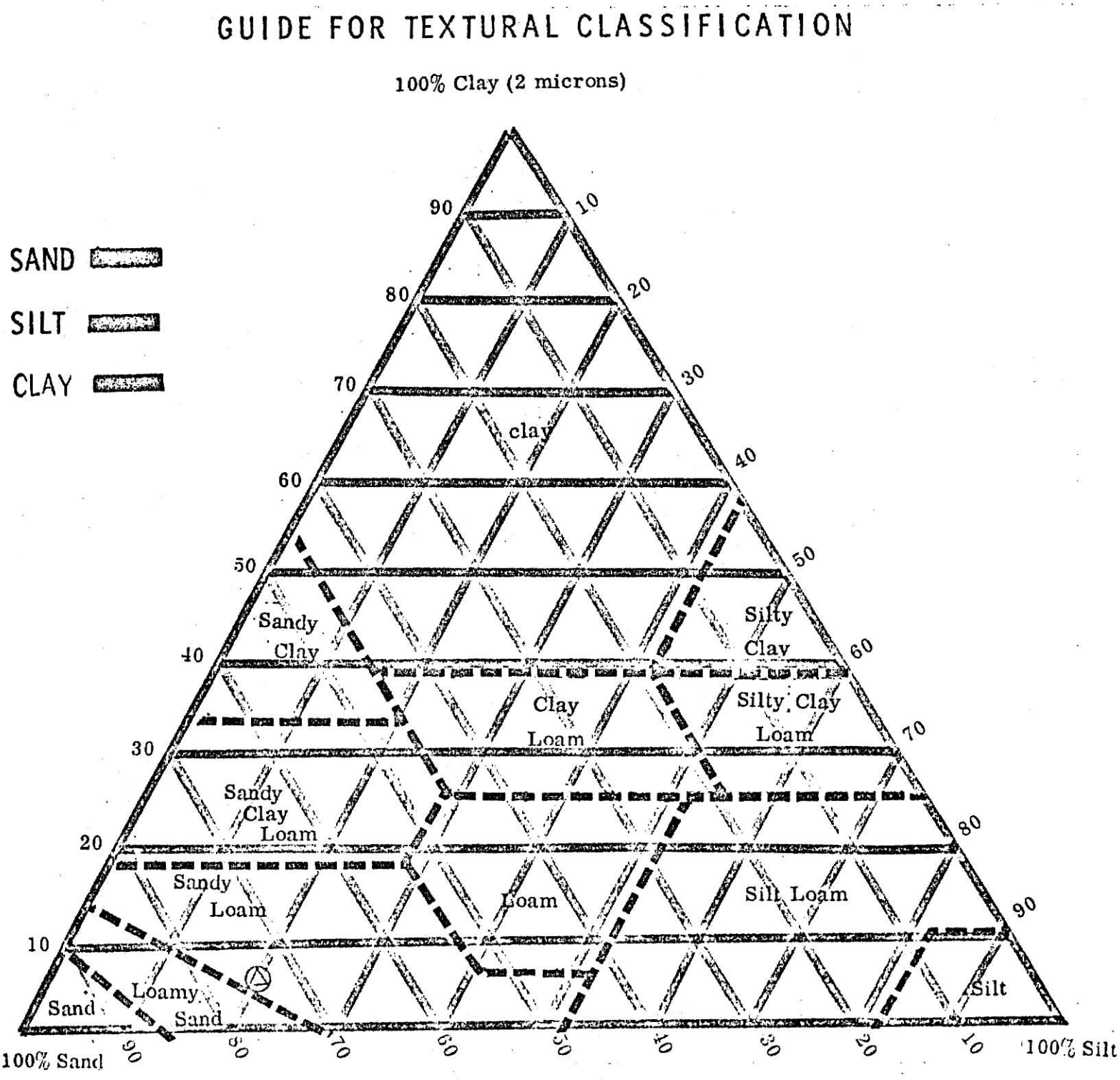


Fig. 2 - U.S.D.A. Textural Classification

There are three classification systems in current usage by engineers: AASHTO (8), FAA (9), and Unified (10). These are based upon the gradation, liquid limit, and plastic index of the soil. Each of these classification systems divide the soil into a relatively small number of groups. Within each, the individual members will have similar engineering properties.

The strength or hardness of the soil can be measured in terms of the modulus of rupture, the compressive strength, or in terms of shear strength in some type of confined compression. The engineer commonly uses the unconfined compression test for the cohesive soils and the direct or triaxial shear test for mixed and granular soils. The hardness of the soil is measured by a modulus of rupture test as described by Richards (3) and Reeve (4) which consists of breaking a small briquette of dried soil by three point loading similar to that used in concrete modulus of rupture tests.

By the use of these classification systems the engineer has been able to accumulate a large amount of data concerning the performance of each of the soil classes when used for engineering construction. On the other hand, the agronomist has been able to relate the modulus of rupture of the soil to the soil tilth, thus making it a useful tool for the farmer.

Since this report was a continuation of the Ibanga thesis and it is directed toward solving an agricultural problem, the modulus of rupture test was used to determine the hardness of the soil.

Mineralogy

In the past, neither the agronomist nor the engineer have considered the mineralogy of the soil deposits. Minerals are defined by Marshall (11) as a naturally occuring chemical element or compound formed by a geological process. The granular soils consist of equidimensional mineral grains.

The primary source of the soil materials is the chemical weathering of granite. Granite is a coarse-grained igneous rock dominated by light-colored minerals, consisting of about 50 percent orthoclase, 25 percent quartz and the balance plagioclase feldspars, and ferromagnesian silicates (12).

The primary by-product of the decomposition of granite is clay minerals derived primarily from the feldspars. Feldspar is an aluminosilicate and makes up nearly 54 percent of the minerals that are found in the earth's crust according to Stokes and Judson (12). The three basic feldspars are listed in Table 1. Their differences derive from their dominant positive ion.

Diagnostic Positive Ion	*Name*	*Symbol*	*Descriptive Name*		*Formula**
K^+	Orthoclase	Or	Potassic feldspar		$K(AlSi_3O_8)$
Na^+	Albite	Ab	Sodic feldspar	plagioclase	$Na(AlSi_3O_8)$
Ca^{+2}	Anorthite	An	Calcic feldspar	feldspars	$Ca(Al_2Si_2O_8)$

*In these formulas, the symbols *inside* the parentheses indicate the tetrahedra. The symbols *outside* the parentheses indicate the diagnostic ions—that is, the ions that are worked in among the tetrahedra.

Table 1 - Characteristics of the Three Basic Feldspars

Aluminum silicate, derived from the chemical breakdown of the original feldspar combines with water to form hydrous aluminum silicate, which is the basis for another group of silicate minerals; the clays.

In the decomposition of orthoclase two substances are essential, carbon dioxide and water. Since carbon dioxide is extremely soluble in water, it unites with rain water and water in the soil to form a weak acid H_2CO_3; carbonic acid. When orthoclase comes in contact with water, several products are formed as shown by the following equation (12):

2 parts orthoclase	carbonic acid	water	clay	potassium carbonate	silica

$$2K(Al\ Si_3\ O_8) + H_2CO_3 + H_2O = Al_2\ Si_2\ O_5(OH)_4 + K_2CO_3 + 4\ Si\ O_2$$

In this reaction, the hydrogen ion formed from the water forces the weaker potassium out of the orthoclase, disrupting its crystal structure. Then the hydrogen ion combines with the aluminum silicate to form the new clay mineral. A second product of the original orthoclase crystal is a soluble salt, potassium carbonate, which is formed when the potassium ejected from the orthoclase combined with the carbonate ion of the carbonic acid. The third product, silica, is formed by the silicone and oxygen that are left over after the hydrogen has been combined with the aluminum silicate to form the clay mineral.

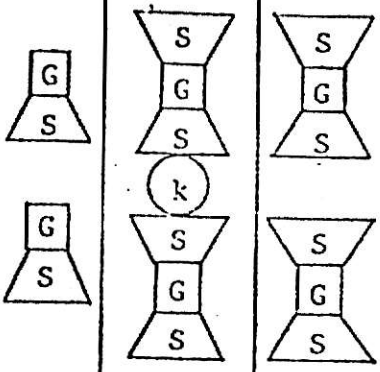
The word clay comes from the anglo-saxon word, claeg, derived from the Latin word, Glus, meaning glue which points out the sticky, cohesive properties of the material. The

individual clay particle is a colloid in the classical sense in that its behavior is controlled by its surface electrical charges according to Gromko (13). The clay minerals are plate-like crystals with near perfect basal cleavage similar to the micas. The sheets are composed of various layers of silica tetrahedra and aluminum (gibbsite) and magnesium (brucite) octahedra. To understand the reaction of clay, it is necessary to understand the forces derived from the surface charges and those derived from the external environment in which the clay plate exists.

The clay "plates" carry net electrical surface charges because of isomorphous substitution occurring within the mineral lattice and broken bonds at the edges of the sheet. These net electrical charges are balanced by exchangeable ions at the surfaces of the minerals.

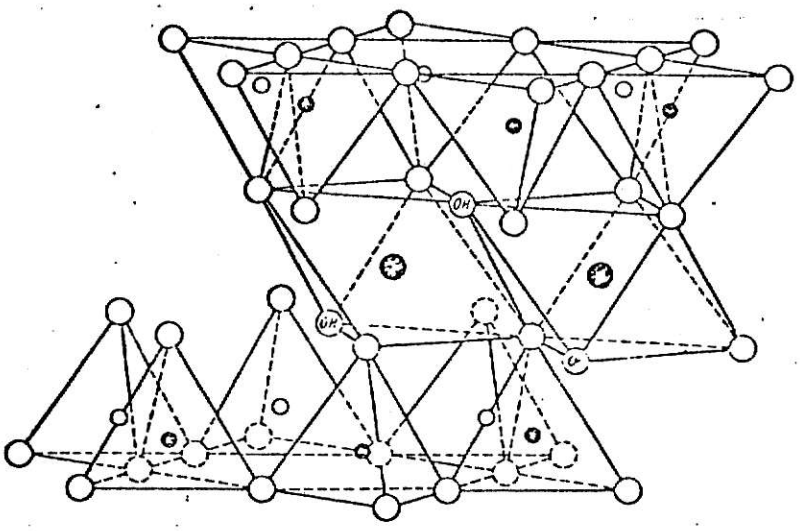
The three major types of clays that occur in nature are kaolinite, illite and montmorillonite. Diagrams representing the structure and some of the properties of these clays are listed in Fig. 3 taken from Gromko (13).

Montmorillonite is termed a hydrophillic clay in that it will very readily attract and hold water due to the net negative surface charge on the clay plates. The thickness of the water on the face of the clay plate varies with the water available. This causes the expansion for which montmorillonite clays are so infamous. Figure 4 taken from Peck, Hanson and Thornburn (14) shows the structure of

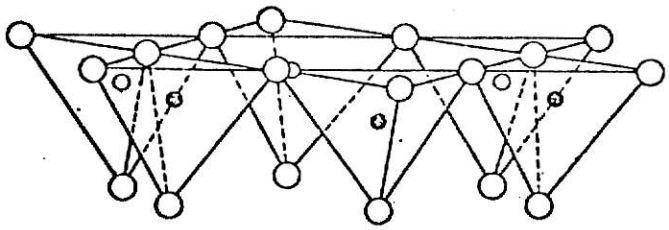
Property (1)	Mineral		
	Kaolinite (2)	Illite (3)	Montmorillonite (4)
Schematic structure*			
Particle thickness	0.5μ-2μ	0.003μ-0.1μ	9.5 Å
Particle diameter, in microns	0.5μ-4μ	0.5μ-10μ	0.5μ-10μ
Specific (Ref. 37) surface, in *sp* meters per gram	5-30	65-100	600-800
Cation exchange (Ref. 18) capacity, in milliequivalents per 100 g of clay	3-15	10-40	80-150
Maximum swelling (Ref. 7), as a percentage, for surcharge load, in tons per square foot			
0.1	Negligible	350	1,500
0.2	Negligible	150	350

*G = Gibbsite sheet; S = Silica sheet; k = Potassium ion.

Fig. 3 - Structure and Properties of the Clay Minerals



Exchangable cations
nH_2O



○ Oxygens (OH) Hydroxyls ⊛ Aluminum, iron, magnesium
○ and ⊕ Silicon, occasionally aluminum

Fig. 4

montmorillonite. Figure 5 taken from Lambe (15) shows the water layer between two montmorillonite plates.

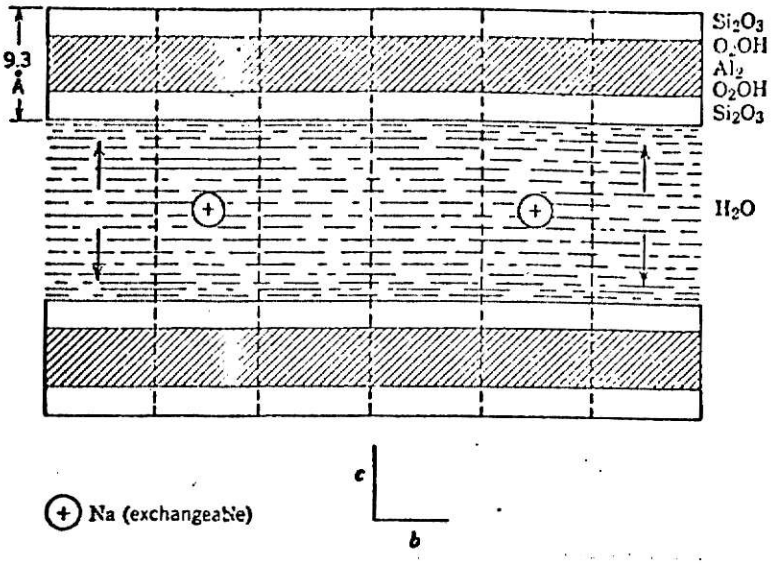


Fig. 5

The electrical polarization of the water extends outward for a distance of approximately 400 A^o (Ref. 15) from the surface of the clay plate. Closer to the surface, the water becomes ever more tightly bound to the clay surface by the electrostatic forces. The 10 A^o of water nearest to the clay plate has been a subject of great discussion as to its behavior but essentially the water is so tightly bound to the clay surface that it is actually stiffer than steel. The molecules beyond 10 A^o are readily given off at temperatures that are normally

experienced in the soil. As these molecules of water are removed by drying from between the clay plates the plates draw closer together and their net surface charges act as a repelling force upon each other and they try to maintain their distance from one another. Figure 6 taken from Lambe and Whitman (16) shows the forces necessary to compress two montmorillonite plates together.

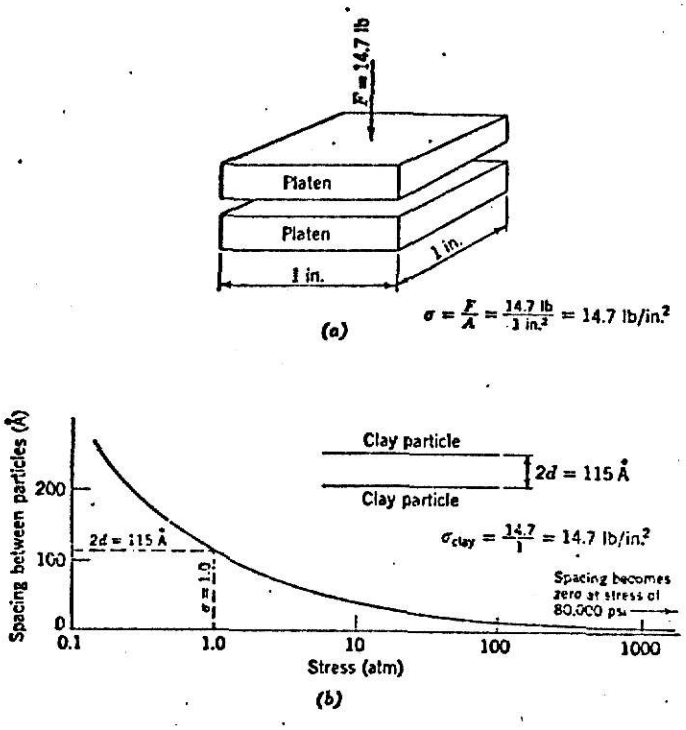


Fig. 6

The relationship between the montmorillonite structure and its double layer or expanding layer of water molecules was first shown by Hofman, Endell and Wilm in 1933, as reported by Herrin and Michell (17). Based on their work, Marshall in

1935 (17) showed that water molecules could effect the placement of an exchangeable cations in the interlayer spaces of montmorillonite. This theory is the basis of lime stabilization. Over recent years engineers have had excellent success in the treating of expansive soils by lime stabilization. The addition of lime to a plastic soil causes the soil to become friable and to attain a silt-like condition. This is due to either or both of the following conditions. First is the cation exchange reaction where the strong, positively charged calcium ions from the lime replace the weaker metallic ions on the surface of the clay particles surface. Second is the crowding of the additional calcium cations onto the surface of the clay. The calcium ions therefore dominate the surfaces of the clay plates. Because the bond between any two clay particles is dependant upon the charge and size of the ions, the domination of the divalent calcium ions attract the soil particles together. This lowers the plasticity of the soil and it becomes friable. Herrin and Mitchell (17) report that between 1% and 10% lime by weight is needed to modify or stabilize a clay but not usually less than 3%. The percentage of lime required to achieve the maximum reduction of plasticity in the clay is termed the lime retention point (18). Pinto, Davidson and Laguros (18) showed this point by means of the graph in Fig. 7 (18). The point where further addition of lime does not increase the rate of flocculation is the lime retention point.

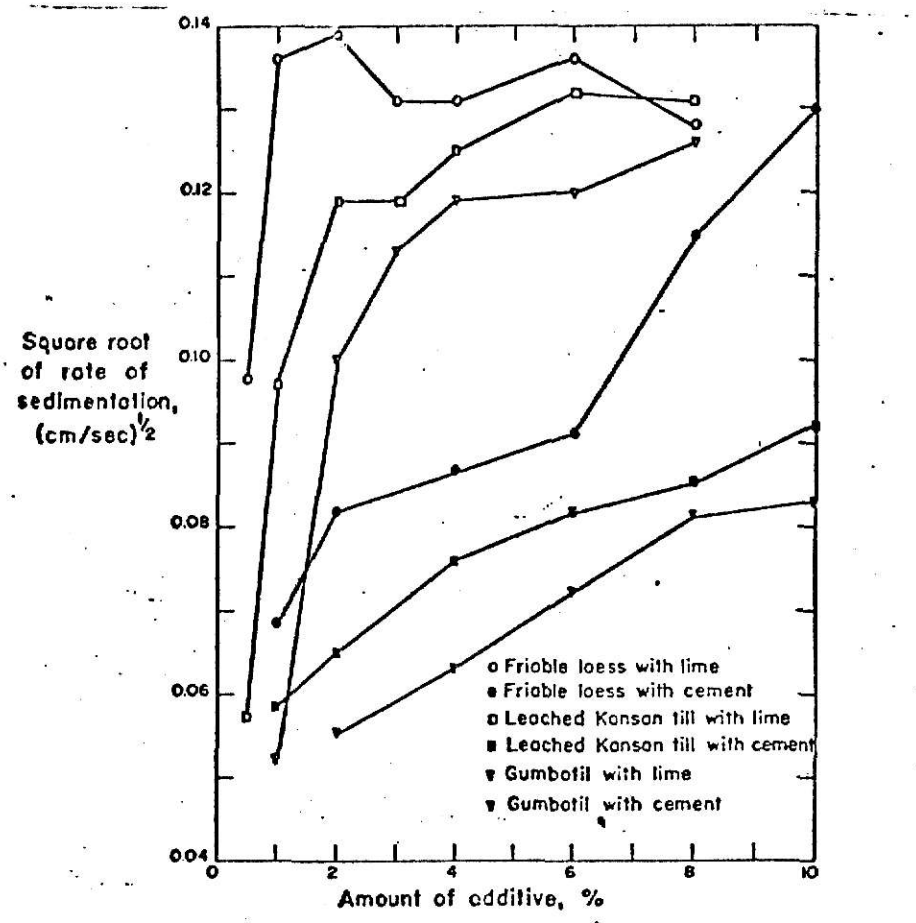


Fig. 7

Strength of Soil

The strength of soil was first described fully and accurately by Coulomb (7) who found the strength to be dependent upon one component called the cohesion and another called friction. These properties are for the most part independent of each other. The frictional component was found to be further dependent upon the normal force on the shear plane or in equational form:

Shearing resistance = cohesion + normal force x tan ϕs
where ϕs = angle of static friction

Terzaghi further modified the formula in 1941 (19) to limit the normal force on the shear plane to the intergranular or effective stress thereby recognizing that excessive pore water pressure can exist and adds nothing to the shearing resistance of soil.

In natural soil deposits the effects of a cohesional component in the soil is many times compounded by a phenomena called apparent cohesion. Apparent cohesion results from the tensional forces in menisci of water at the contact points between the mineral grains. Apparent cohesion cannot exist in saturated soil since there can be no menisci. As the soil dries the menisci become smaller and smaller and the binding force increases as the menisci decreases.

The mixed clay-sand soils have extremely complicated strength components which are a function of cohesion, apparent cohesion, friction, and effective stress.

Design of Experiment

The effects of clay content on the dry modulus of rupture of soils was determined by moulding specimens from a poorly graded (Ottawa) sand and a well graded sand from the Sandyland Experimental Farm at St. John, Kansas.

The samples were taken in early December when the soil profile was still moist and fairly friable. The soil was taken from the top 6" of the soil profile in the Carwile soil series as shown in Fig. 8. This was used as a section of irrigated farm land.

SANDYLAND EXPERIMENT FIELD

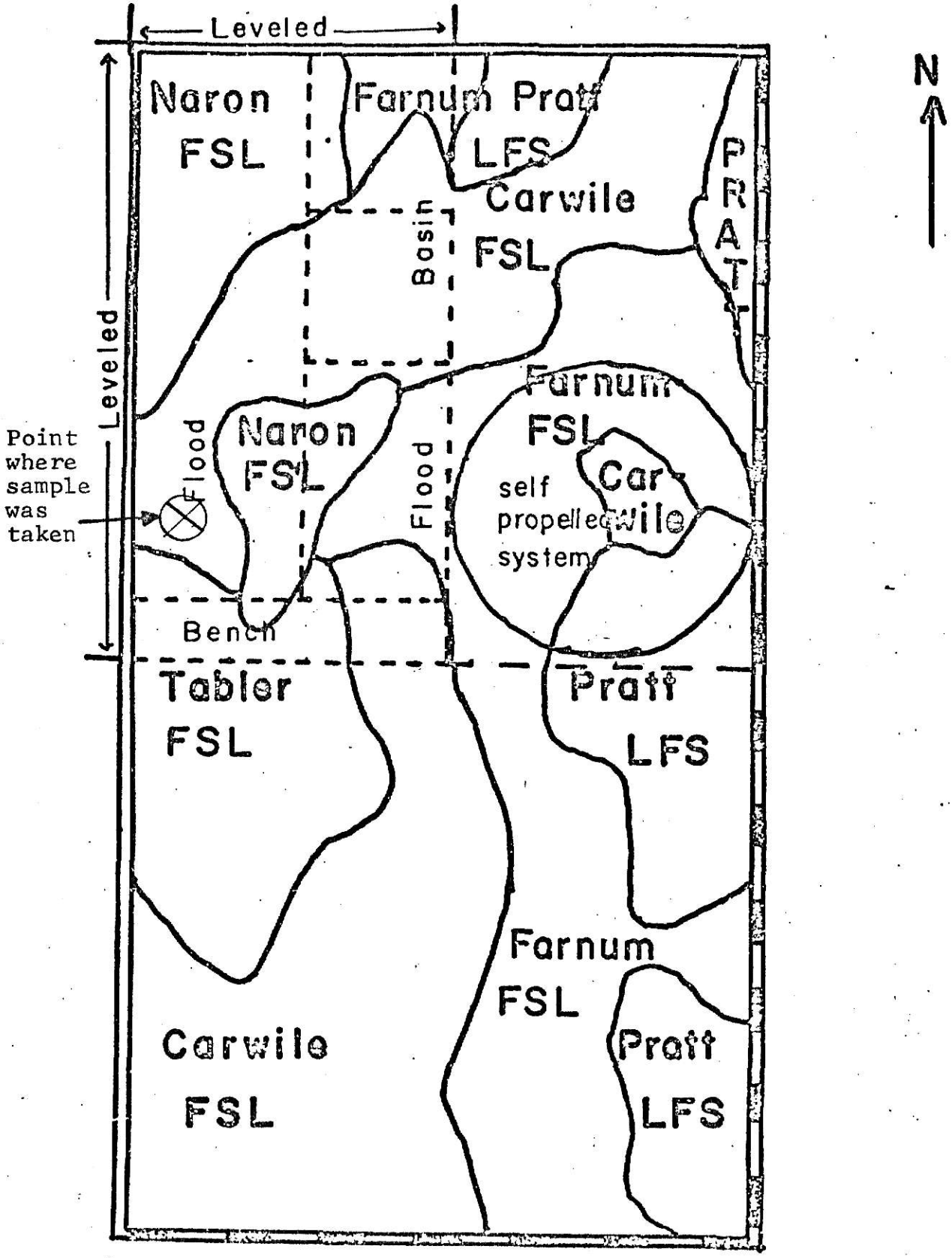


Fig. 8

The test used as the basis for comparison of the soil samples for this study was the modulus of rupture test as described by Richards (3) and Reeve (4).

A series of soil samples was produced as follows:

1) Ottawa sand plus bentonite in one percent increments varying from 2% to 15% bentonite by weight. Twelve samples of each series were produced and the best ten structurally were kept for modulus of rupture testing.

2) Natural soil from the Saint John agricultural farm plus bentonite starting at its natural 5% clay content and increasing the clay content with the bentonite in 2% increments by weight to 17% clay content. Three samples of each series were produced for modulus of rupture testing.

3) Natural soil from the Saint John Agricultural farm at 5% clay content plus 2 to 10% hydrated lime. These specimens were tested by wetting and drying to determine the durability of the stabilization process. Modulus of rupture testing was not possible since the specimens would not cohere after stabilization.

To observe the intergranular cementation mechanism, photomicrographs were taken of the Ottawa sand and bentonite specimens and of the natural soil and the natural soil and bentonite specimens.

The modulus of rupture test consists of forming soil briquets and allowing them to dry. These briquets are then placed on an apparatus that places them in flexure. The measured force required to break the briquet is its flexural strength or modulus of rupture.

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The briquets were formed in molds with inside dimensions of 7 cm. by 3.5 cm. by 0.95 cm. as shown in Fig. 9. Several methods for lubricating the molds were tried and silicone spray was found to be the most successful lubricant. It prevented the soil from bonding to the molds and yet did not pollute the soil samples as did oil or grease lubricants. The soil was moistened to a saturated level and was then troweled into the molds and the surface struck level. The molds were then placed in a drying oven at 90°C for a period of 24 hours. After drying, the briquets were removed from the molds and allowed to cool before they were tested.

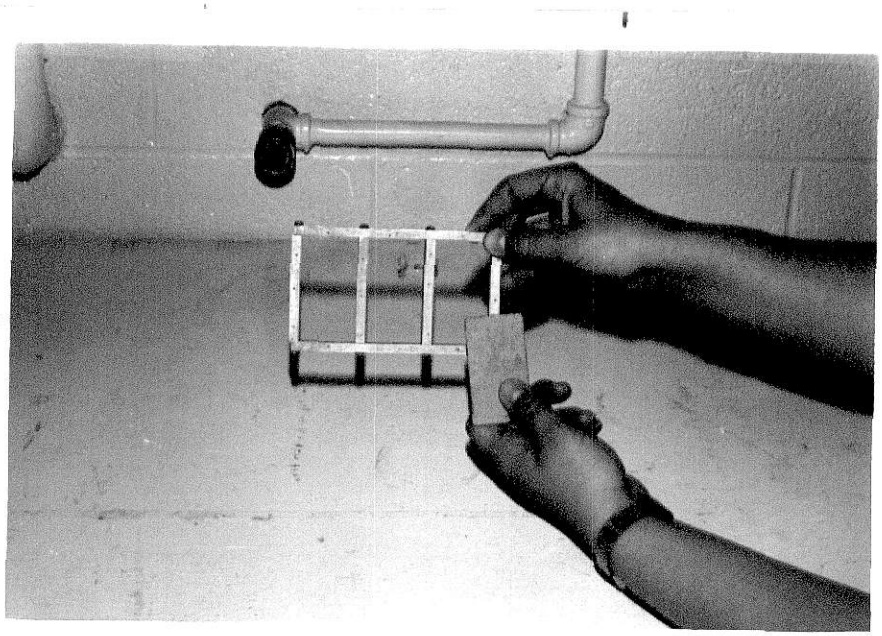


Fig. 9

Reeve (4) describes the apparatus used for rupturing the briquets as the briquet-support and knife-edge assembly. A diagram of this device is shown in Fig. 10.

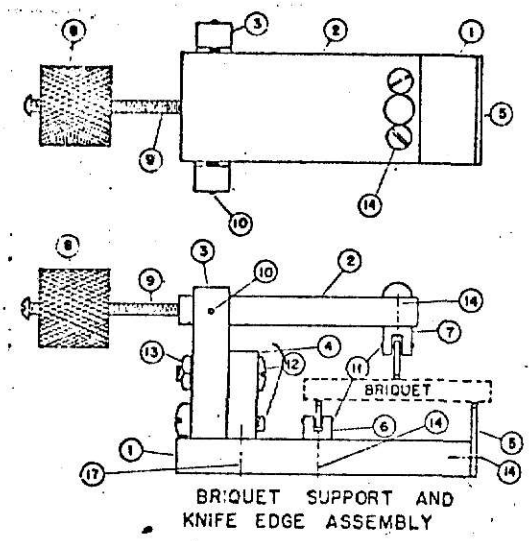


Fig. 10

It consists of two parallel bars 5 cm. apart that support the sample and a third overlying bar, centrally located and parallel with respect to the supporting bars, that supplies the breaking force. The bar above and one below are self-aligning to accommodate to any slight lack of parallelism in the lines of bearing of the sample. The edges of the bars in contact with the briquet were coated with a strip of rubber to distribute the breaking force rather than concentrating it at a few points of contact with projecting soil grains. A picture of the assembled device is shown in Fig. 11.

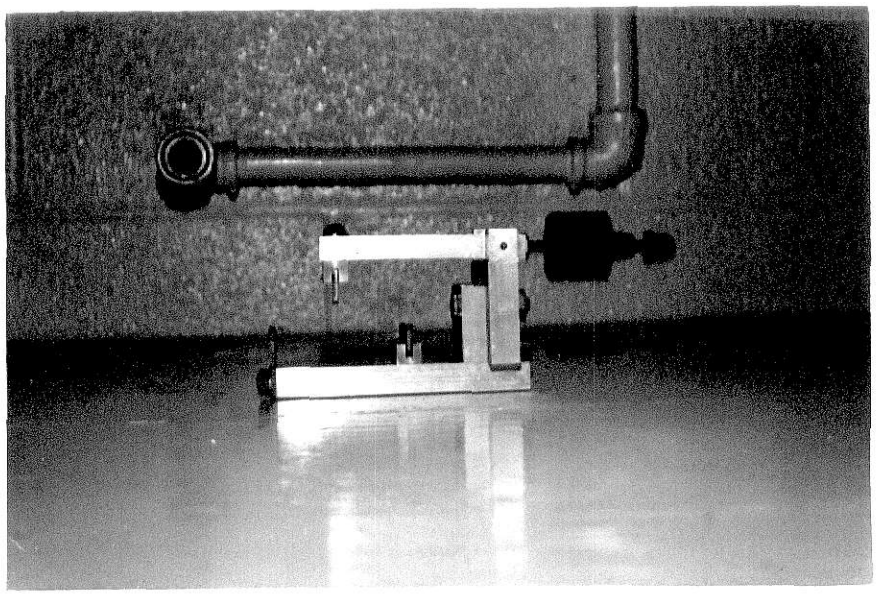


Fig. 11

Figure 12 shows the apparatus with a soil briquet mounted upon the knife-edged supports.

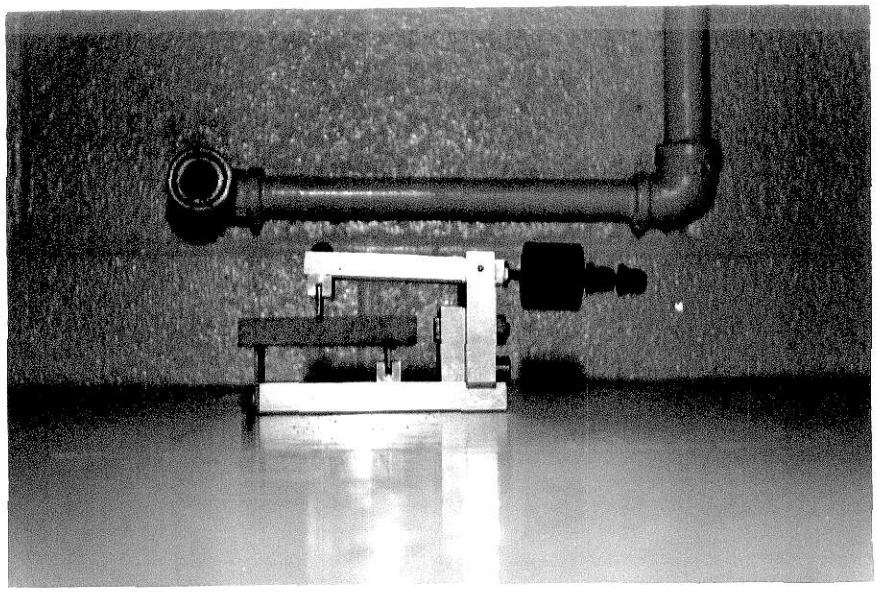


Fig. 12

Figure 13 shows the same briquet after it has been loaded to failure.

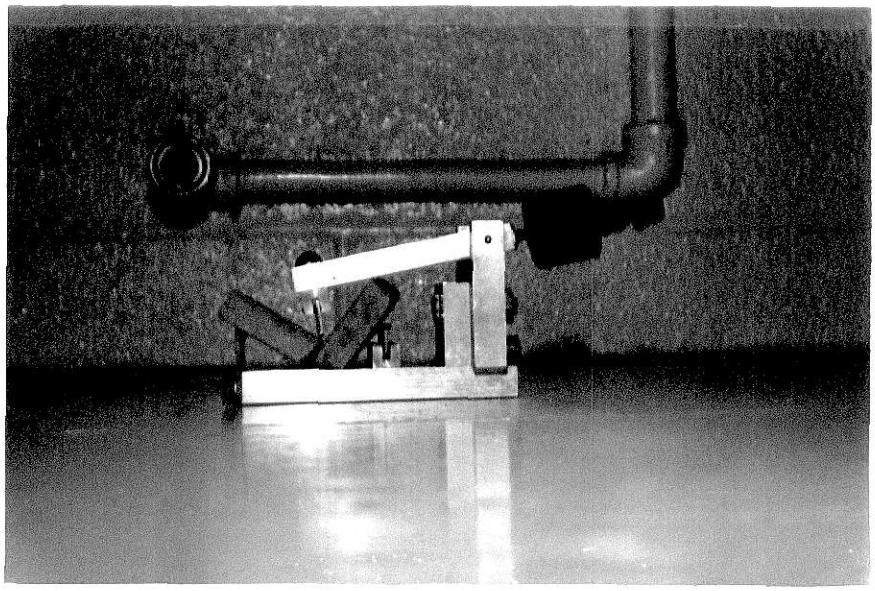


Fig. 13

The briquet-breaking apparatus is mounted on the platform of a beam balance. Upward motion of the upper bar is constrained by a cross frame that is anchored externally and located above the balance platform. The briquet is broken by upward motion of the two lower bars, which are supported by the platform of the balance. The load on the beam balance is slowly increased until the briquet fails. This load, to the nearest tenth of a pound, was used as the rupture strength of the specimen.

Figure 14 shows the full assembly with briquet mounted on apparatus and ready to be loaded.

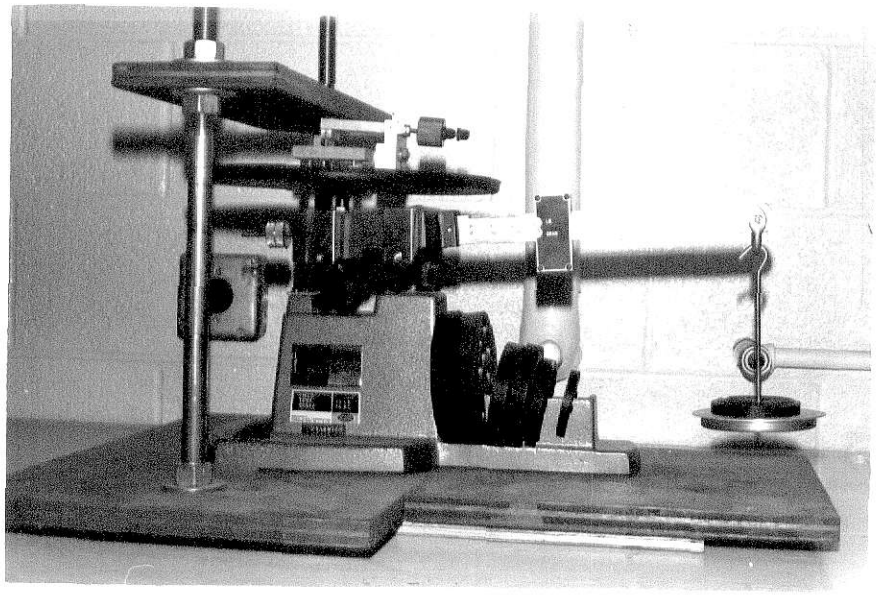


Fig. 14

Figure 15 shows the point at which failure of the briquet has occurred. The reading on the scale at the point of rupture is read as the rupture strength.

A sieve analysis and hydrometer analysis was run on the Sandyland Farm's soil.

The remainder of the artificial aggregate was bentonite, which is an almost pure Montmorillonite clay mineral.

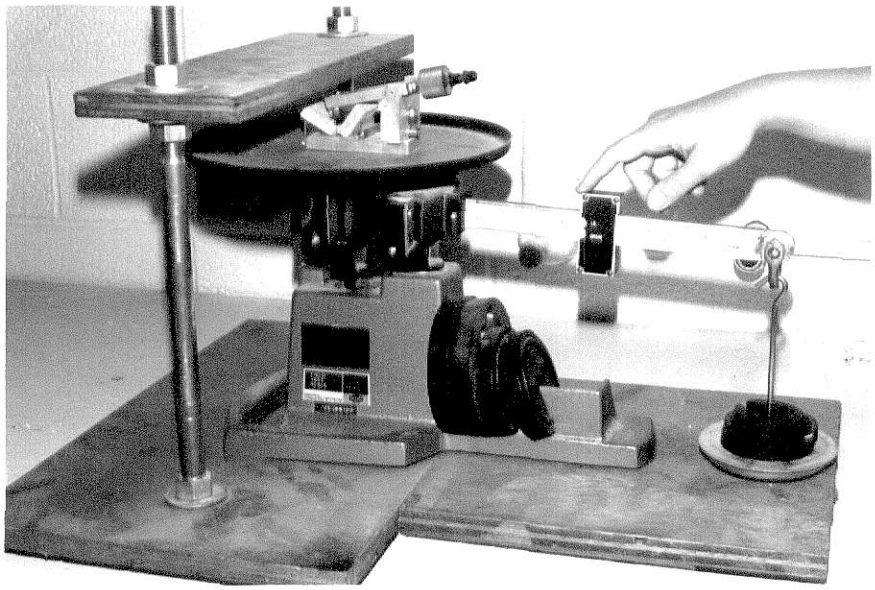
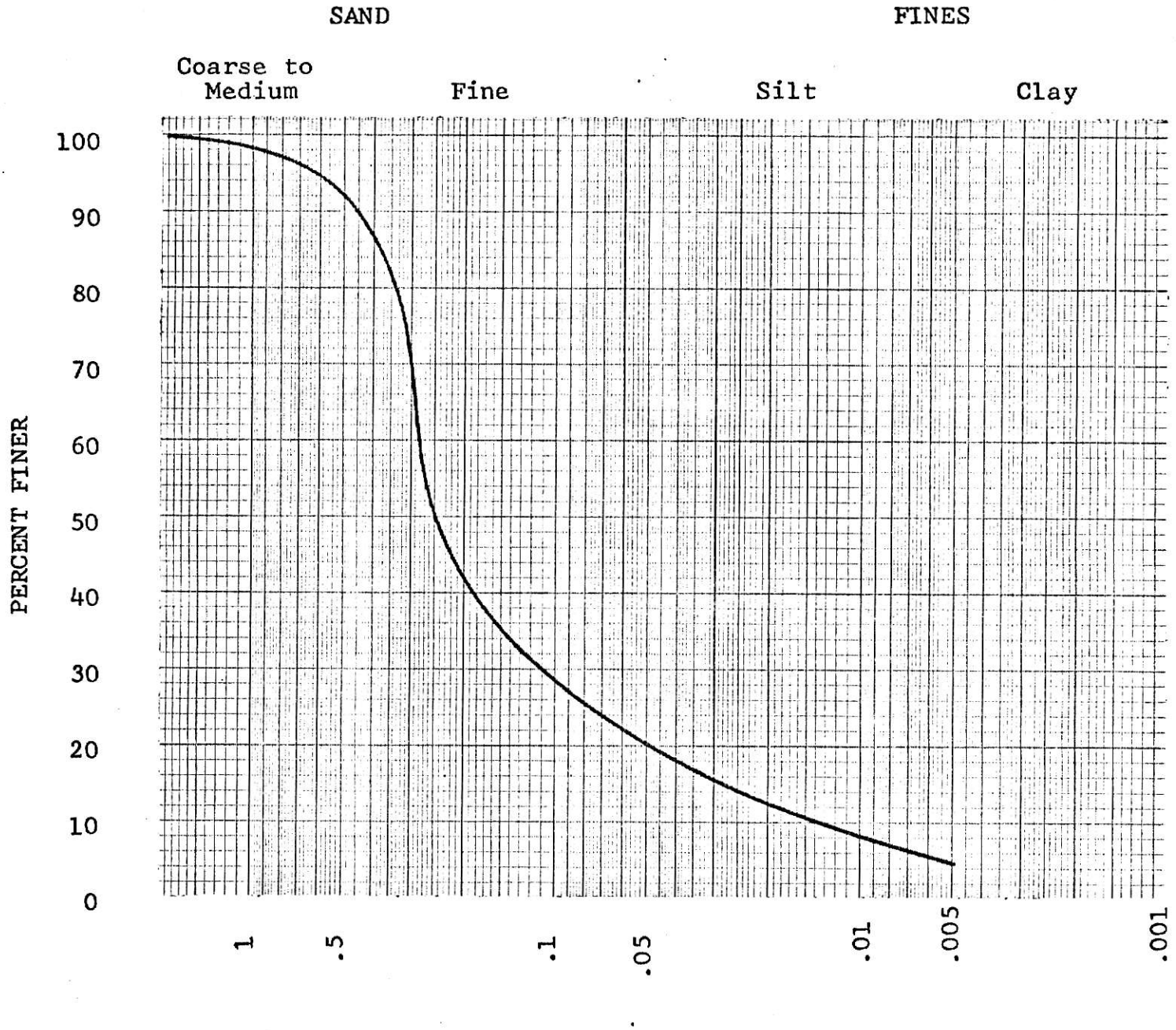


Fig. 15

Presentation of Data

The Sandyland Farm soil sample was first subjected to hydrometer and sieve analysis to determine the grain size curve, as shown on the following page in Fig. 16.

Using the engineering definition of clay particle size as 0.005 mm or smaller, the grain size curve shows the aggregate to be 5% clay, 20% silt and 75% sand by weight.



GRAIN DIAMETER, mm

Fig. 16

This gives the resulting triangular agronomist's chart in Fig. 17.

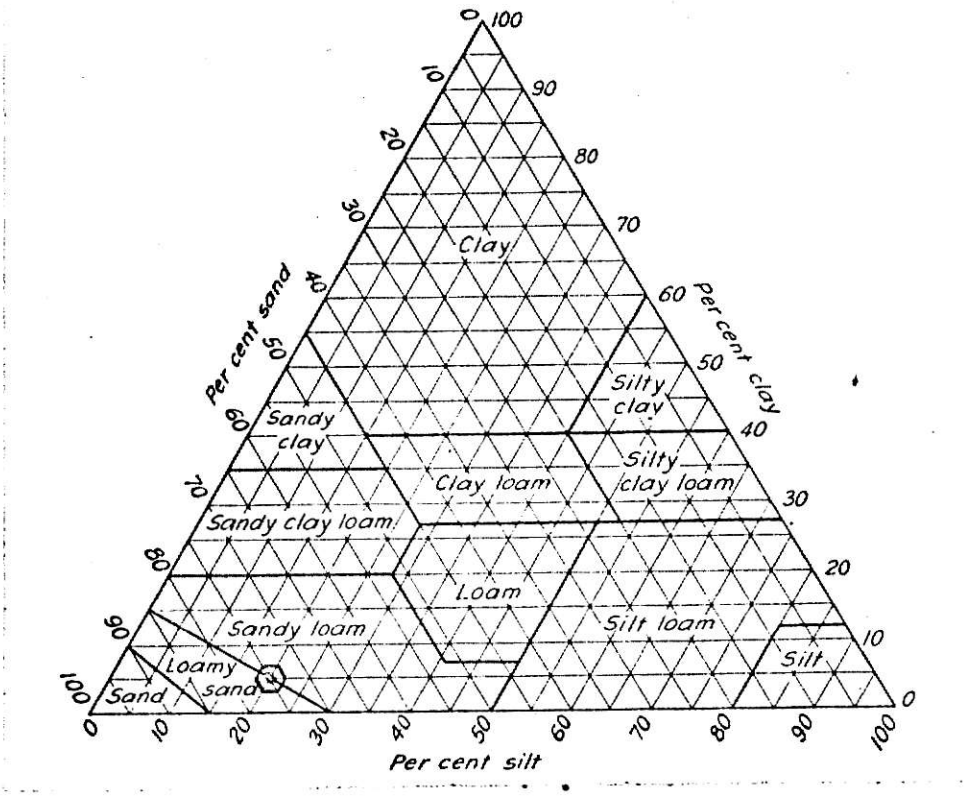


Fig. 17

The synthetic soil briquets were the next to be produced. Twelve samples of each series from 2% clay and 98% sand to 15% clay and 85% sand by increments of 1% were produced. The ten samples of each series that appeared the best structurally were tested for their rupture of modulus. The average force required to break the briquets in each series is listed in the following table:

% Clay (by total weight)	Average Rupture Strength (lbs.)
2	3.5
3	4.0
4	4.7
5	4.9
6	5.8
7	5.9
8	5.8
9	5.5
10	5.4
11	5.1
12	5.2
13	5.0
14	4.5
15	4.0

Figure 18 shows the plot of rupture modulus versus percent clay.

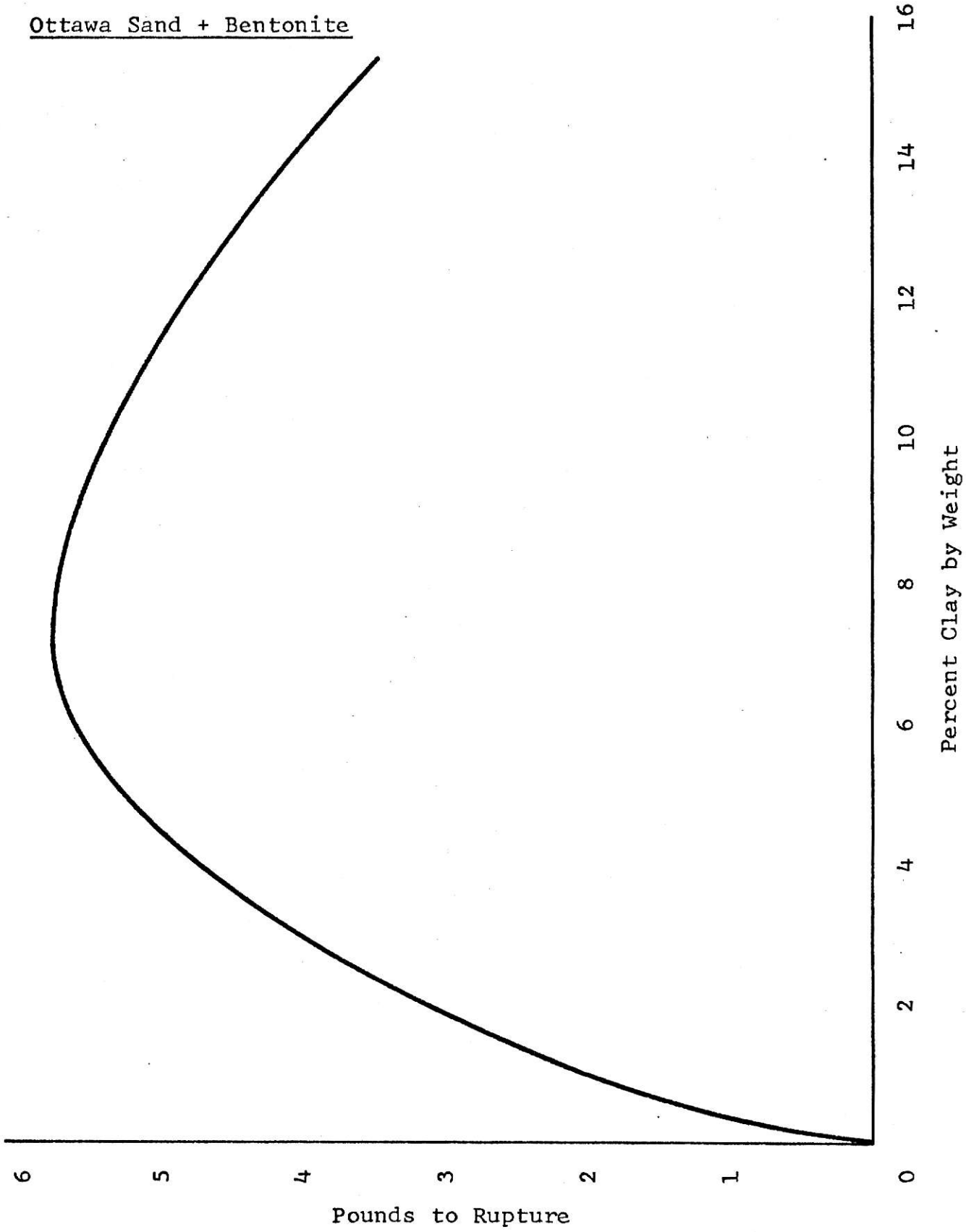

Ottawa Sand + Bentonite
Percent Clay by Weight
0
2
4
6
8
10
12
14
16
Pounds to Rupture
6
5
4
3
2
1

Fig. 18

The natural soil was formed into molds similar to the synthetic soil and was dried and tested for flexural strength. The clay content of the natural soil was increased from its natural 5% clay content to 17% clay content in 2% increments by the addition of bentonite. Three samples of each series were produced and each was tested for flexural strength. The results of these averages are tabulated below.

% Clay (by total weight)	Average Rupture Strength (lb.)
5%	6.5
7%	8.0
9%	10.0
11%	10.3
13%	9.7
15%	8.8
17%	8.1

The results are shown in Fig. 19 comparing the natural soil versus % clay and Ottawa sand versus % clay.

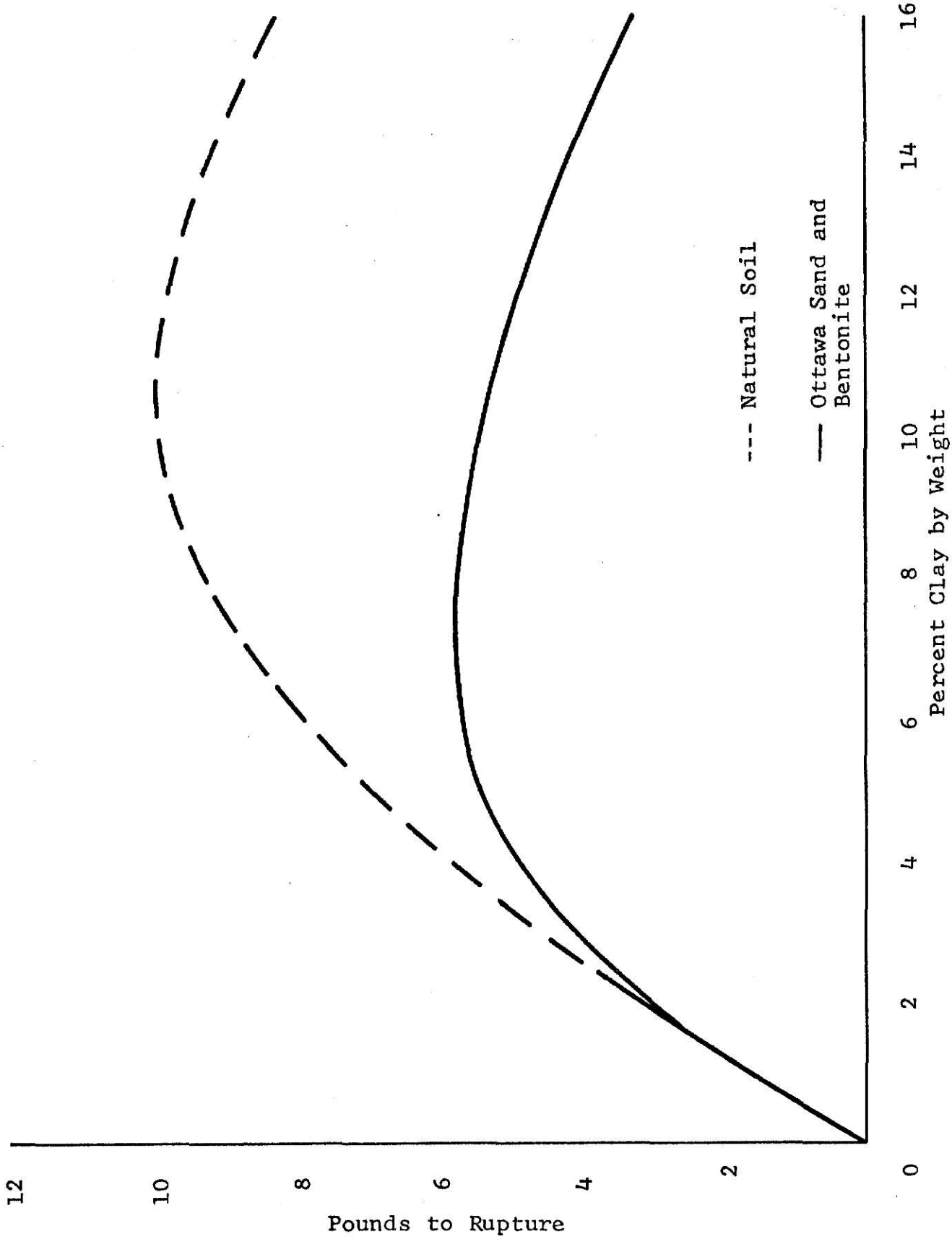

Pounds to Rupture
12
10
8
6
4
2
0
2
4
6
8
10
12
14
16
Percent Clay by Weight
--- Natural Soil
— Ottawa Sand and Bentonite

Fig. 19

The final experiment run was that of lime stabilization. Hydrated lime was added to the natural soil at 2%, 4%, 8% and 10% of the 5% clay content. That is .1%, .2%, .4% and .5% of the total weight of the sample of lime was added. The result was that the 0.5% of the total weight in lime successfully stabilized the clay constituant. The resulting soil was of a loamy texture. The clay had been reduced to a silt-like consistency and no longer bonded the sand grains together. Repeated wettings and dryings of the stabilized soil did not effect any change as the soil remained extremely friable.

Specimens were prepared of 5% bentonite with 95% Ottawa sand and 10% bentonite with 90% Ottawa sand for the scanning electron microscope. The Ottawa sand was specially sieved and thoroughly washed to produce as close to one grain size as possible. While viewing through the electron microscope special attention was focused on the points of contact between the grains of sand. Figures 20, 21, 22 and 23 show the photographs taken of these specimens.

Samples of the natural soil were then prepared for viewing on the electron microscope. As before, points of contact between grains of sand were given special attention.

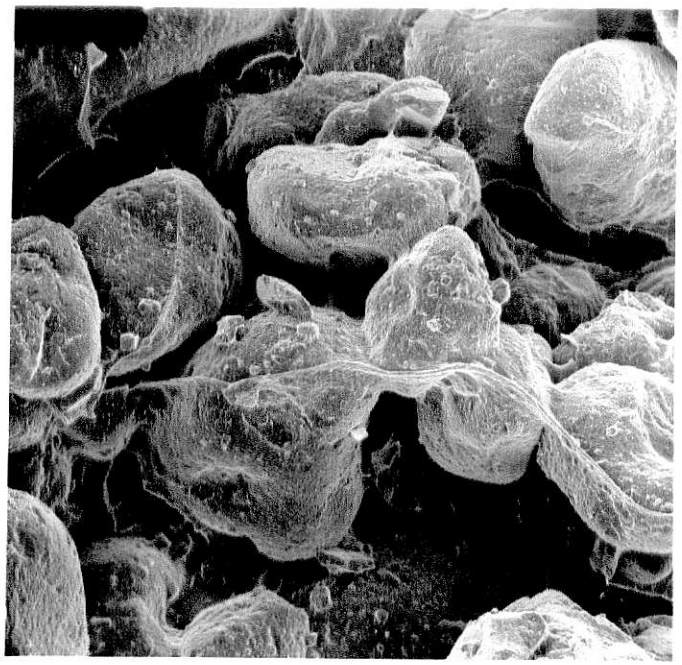


Fig. 20 - 5% bentonite and 95% Ottawa sand x 60.4 magnification

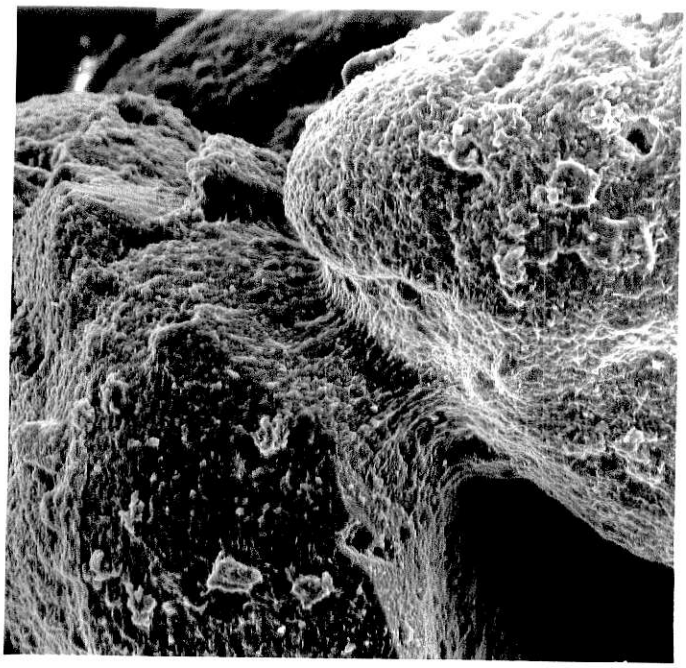


Fig. 21 - 5% bentonite + 95% Ottawa sand x 302 magnification

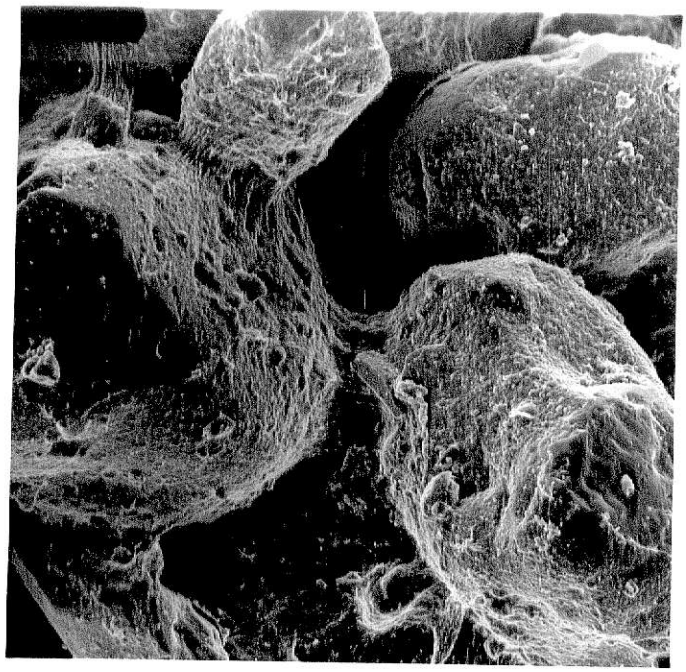


Fig. 22 - 10% bentonite + 90% Ottawa sand x 154 magnification

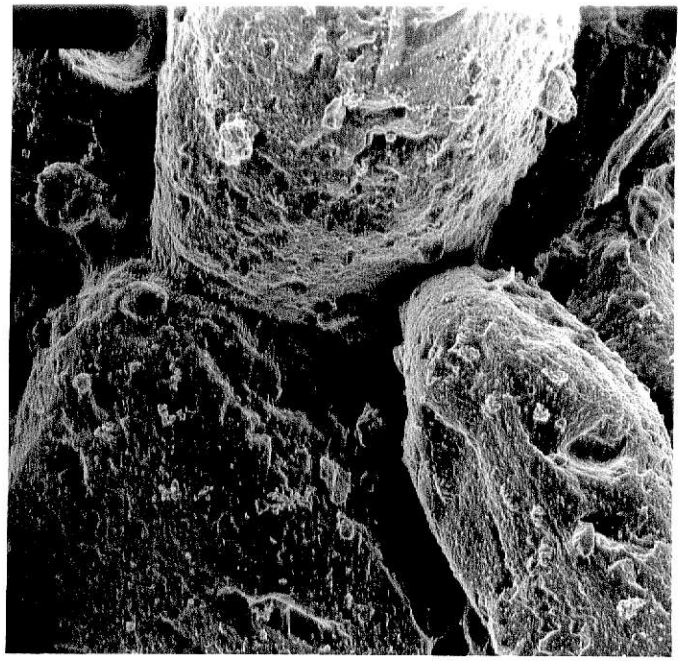


Fig. 23 - 10% bentonite + 90% Ottawa sand x 121.6 magnification

Figures 24 through 31 show the photographs taken of these specimens.

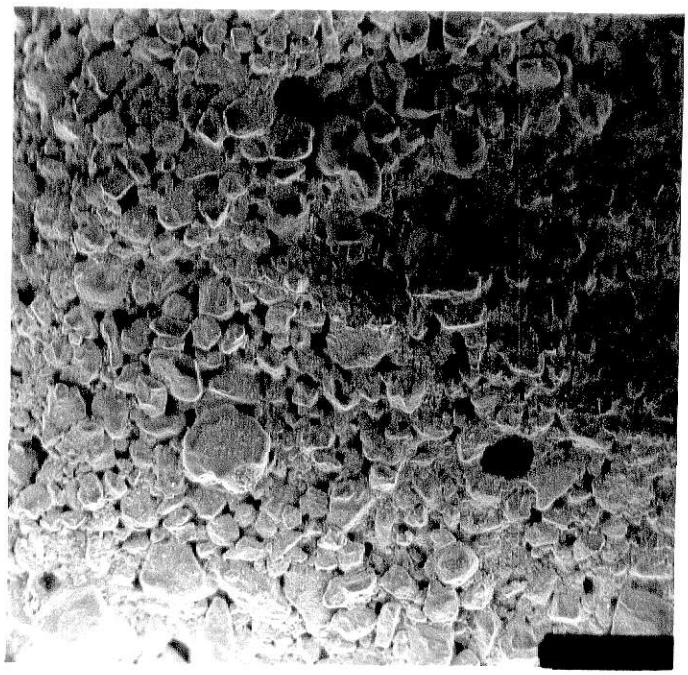


Fig. 24

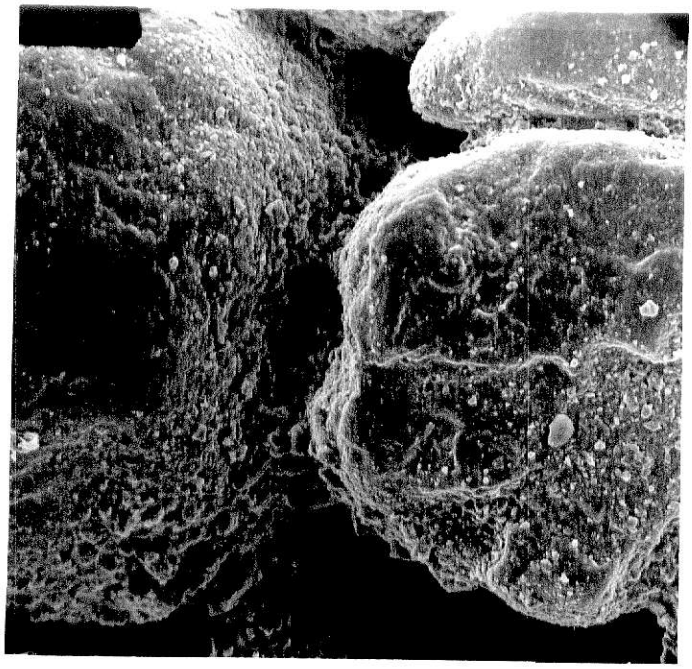


Fig. 25

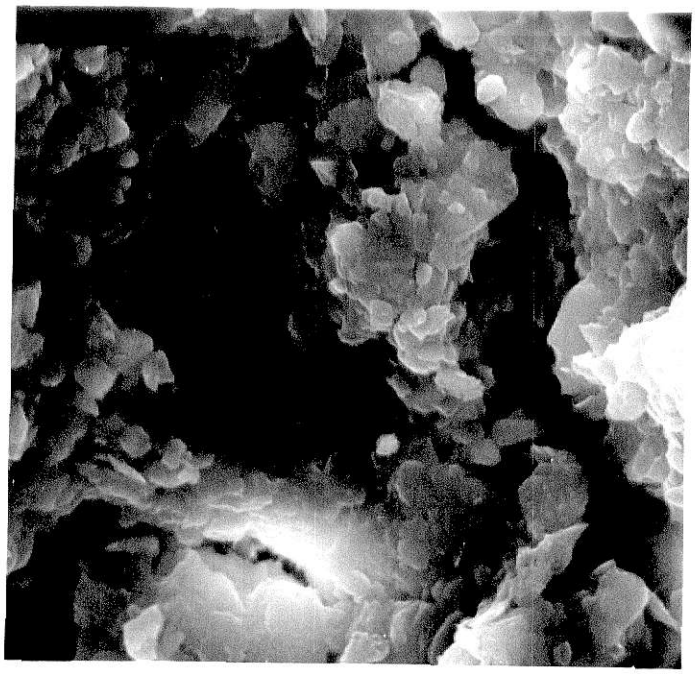


Fig. 26

Fig. 27

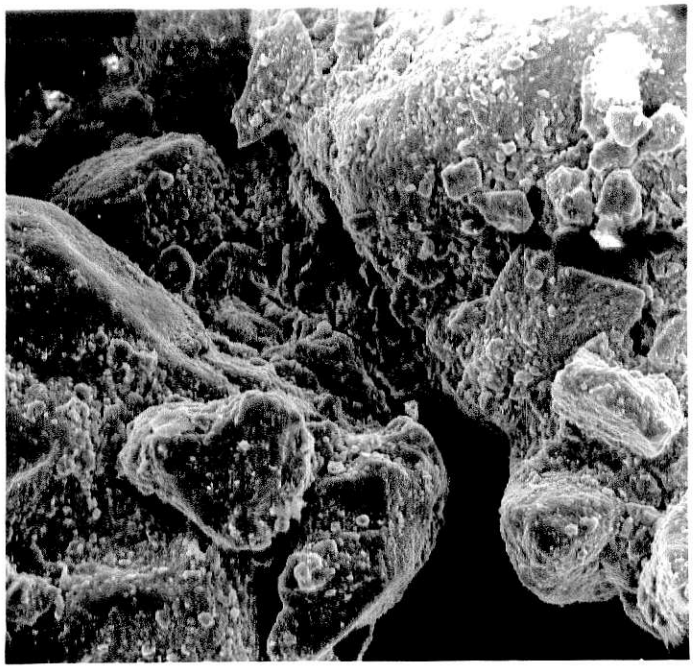


Fig. 28

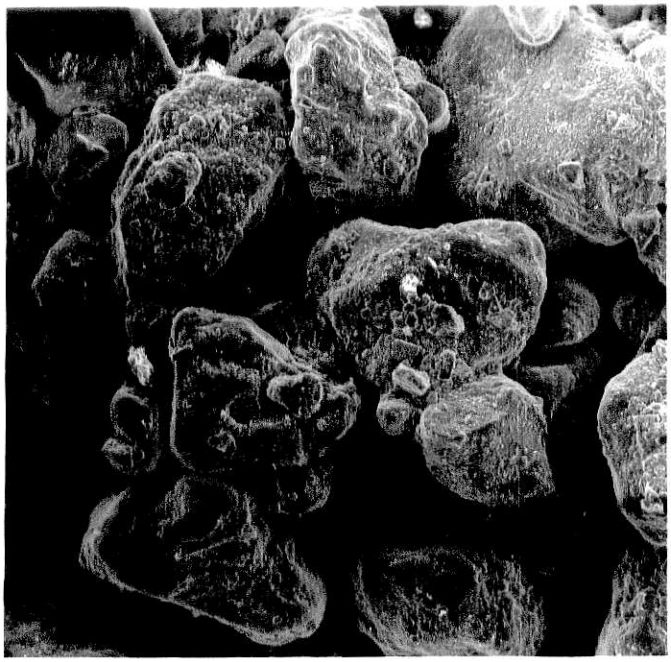


Fig. 29

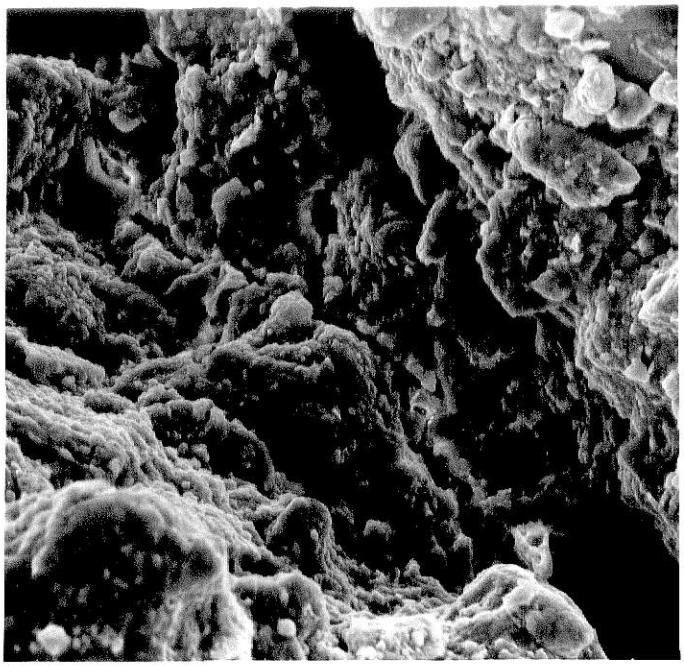


Fig. 30

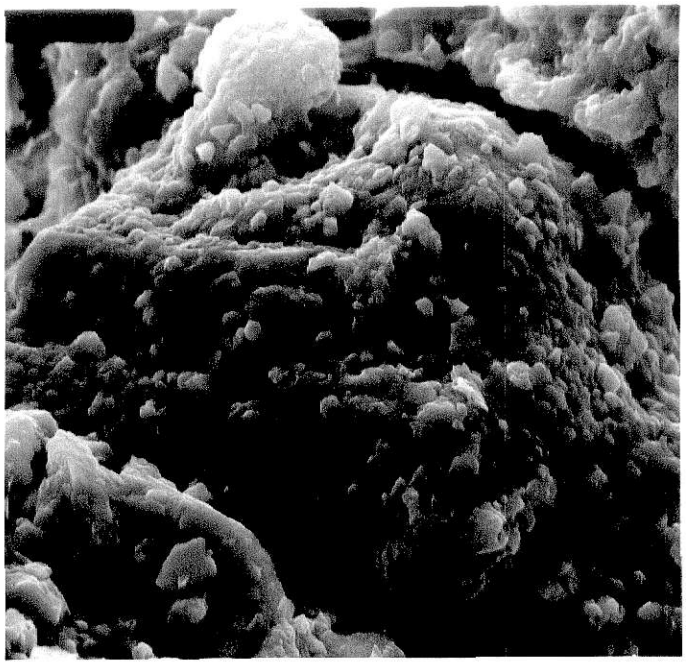


Fig. 31

DISCUSSION OF RESULTS

The first objective of this report was to identify the mechanism employed that renders these soils to such a hard and unworkable consistence. The best way to actually observe this mechanism is in the photographs from the electron microscope. Figure 21 shows a photograph of 5% bentonite and 95% Ottawa sand at x302 magnification. The two particles shown are bound together at the points of contact by the bentonite. Figure 21 shows the voids to be relatively free from large amounts of clay. Figures 22 and 23 are of 10% bentonite and 90% Ottawa sand. They show the same situation as with the smaller amount of clay but the particles have more clay between them and in the voids. Also the particles do not tend to be in as close contact with one another.

These observations explain the reason for the shape of the curves in Fig. 19. The hardness of the soil aggregate increases with higher percentages of clay since the clay supplies the bonding strength to the soil.

At approximately 7% clay content the curve peaks out and the "hardness" of the aggregate goes down with additional percentages of clay added. Up to approximately 7% clay content in the Ottawa sand and bentonite mixture, the clay adds to the strength by bonding the sand grains at the points of contact. Above 7% the additional clay actually displaces the sand grains and moves them further apart from one another. This is not nearly as strong or stable a configuration as the grains at a closer spacing.

The reason the clay forms at the points of contact is important to consider. As explained previously, moist sand displays a cohesion even though it is a cohesionless material. This is due to the water which forms menisci at the points of contact of the grains of sand. The surface tension of the water actually bonds the grains of sand together with what is termed apparent cohesion.

As the water forms menisci at the points of contact of the grains of sand the clay is carried into this position by the water. When the soil is saturated the montmorillonitic clay is actually suspended in the voids of the sand particles. As the soil dries out, the water gradually forms menisci at the points of contact and the clay goes with the water. When the water is gone, the clay remains where it was left, at the contact points of the sand particles. Figure 21 shows this very well.

The same principle applies to the natural soil. This is a much better graded aggregate and the particles are not rounded but angular. For this reason the curve of the natural soil in Fig. 19 reaches a higher maximum strength than does the synthetic aggregate and has a higher optimum clay content. Figures 24 through 31 show the natural soil and the conditions described exist here also.

The second objective of this report was to recommend a workable solution for treatment of these soils to produce a tillable soil profile. If the clay could be rendered cohesionless then it could not cement the sand grains together. This can be accomplished by lime stabilization of the clay percentage of the aggregate.

The stabilization of expansive clay is usually done with from 3% to 10% lime by total weight of the clay. Since the aggregate we were working with contained only 5% clay by weight, it was found that 10% lime of the 5% clay or 0.5% lime of the total weight successfully stabilized the clay part of the aggregate. The resulting soil was of a loamy texture. This is because the stabilized clay was no longer cohesive but was reduced to a silt-like consistency. Repeated wetting and drying of the stabilized soil did not affect any change as the soil remained extremely friable. The stabilization is a non-reversible process.

CONCLUSIONS

The soils are rendered to their hard consistency by the cementing together of the sand grains by the montmorillonitic clay at the contact points. These clays are positioned at the contact points by the forming of menisci at these points by water when the soils are drying. There is an optimum percentage of clay to the hardening of these soils above which the clay spreads the sand grains further apart and weakens the fabric of the aggregate. The tilth of the soil can be improved by using lime stabilization.

The group of soils consisting of primarily sand and a small percentage of montmorillonitic clay can be effectively treated to produce a friable soil profile by the use of lime stabilization.

SUGGESTIONS FOR FUTURE STUDY

There are most certainly many soils around the world that exhibit these same characteristics. For one, the Nigerian soils spoken of earlier have the same characteristics. It would be most desirable to obtain these soils and run the same series of tests on them that were run on the Sandyland farm soils.

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THE EFFECT OF CLAY ON THE HARDNESS OF A CLAY-SAND AGGREGATE

by

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B.S., University of Kansas, 1971

AN ABSTRACT OF A MASTER'S THESIS

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ABSTRACT

Cohesionless soils with small amounts of clay present are often difficult to till in agriculture and to use in engineering construction. This study found that there is an optimum percentage of clay which produces the most severe deleterious effects and that this optimum varies in different sands. The optimum percentage was found to vary from 7% clay in Ottawa sand to 11% in a natural Kaw River sand.

The mechanism for these effects was found by scanning electron microscope studies to be caused by cementation of the contact points of the sand grains by the clay.

The deleterious nature of these clay-sand mixtures was found to be greatly lessened by the addition of lime oxide in the study.