ROLE OF PHYSICAL PROPERTIES OF CLAYS IN SOIL SCIENCE

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ABSTRACT

The physical properties of clay are of extreme importance in soil science. Plant growth, and hence crop production, within any environmental condition is largely controlled by soil structure which results from reactions involving clay. The active clay material in soil, particularly in combination with small amounts of organic matter, exerts a tremendous effect on soil properties. This effect may be on structure (the arrangement of soil particles), or on consistence (the response of the soil to mechanical manipulation). Where structure is favorable soil grains are clumped together into effectively larger aggregates so that soils have a more open arrangement and water and air can move freely and roots function normally. Where structure is unfavorable, soils tend to be heavy and impervious, and both the physical and chemical properties of the soil become unfavorable for plant growth. Soils which are low in clay, such as sands and silts, exhibit a rather narrow range over which physical properties can change and may be unfavorable for plants, being droughty and lacking in fertility. Structure of soil may change through action of natural forces, management practices, or cropping systems, and it is of great importance that we understand how structure affects plants, and how it is formed and stabilized by reactions involving clay.

Combination of clay with relatively small amounts of certain organic compounds greatly changes the physical properties of the system and the nature of the combination and the mechanics of the soil structure-forming process are but little understood. Such changes greatly affect soil consistence and soil-water relationships as well as soil structure. The problem is made difficult since the results of any particular combination or change in clay characteristics must be interpreted not in terms of the clay system alone but in light of the resultant effect on the complex and dynamic system which constitutes a soil. Solution of such problems, however, may be of great importance to our future ability to produce food and fiber abundantly and efficiently from our limited soil resource.

INTRODUCTION

Clay is involved in almost every reaction in soils which affects plant growth. Both chemical and physical properties of soils are controlled to a very large degree by properties of clay, and an understanding of clay properties is essential if we are to arrive at a full understanding of soil plant relationships.

Soil scientists have in the past placed most emphasis on chemical properties of soils; increasing interest is now being shown in physical properties and reactions as well. Poor physical conditions such as tight impervious layers, crusts, or over-all high density and unfavorable porosity cause soils to be quite unsatisfactory for plant growth. This of course has long been known, but in recent years an increasing amount of interest has been shown in studying such conditions and in attempting to arrive at an understanding of how and why physical conditions affect plant growth. Such characteristics as soil temperature, soil aeration, soil consistance, and soil-water relationships and their effects on plant growth are now being studied intensively. In some cases plant growth has been shown to be severely limited because of physical conditions and addition of fertilizers has had little or no effect in improving yields on such soils. These conditions result almost entirely from reactions involving clay. At the same time most of the favorable conditions occurring in soils are also associated with clay so that it is important to understand how clay enters into and controls soil properties if high and efficient

levels of production of food and fiber are to be maintained.

In soil science we are primarily concerned with determining and controlling those factors which affect plant growth. The physical properties of soil control the supply of water and air (and to a certain extent, nutrients) to the plant roots and also modify the environment in which roots grow and function. Since roots grow in spaces between soil particles or granules, and water and air are supplied to the root by movement through these pore spaces, soil porosity is an extremely important characteristic. When porosity is favorable water and air can move freely and plant roots find a favorable environment. Where pores are small, strong capillary forces tend to keep them filled with water so that air cannot diffuse freely. Obviously, where pores are discontinuous or sealed off at the surface free movement of water and air would be restricted.

The physical characteristics of the soil are largely controlled by reactions in which clay plays a leading part. Clay is the active part of the soil both chemically and physically. In a soil where content of clay is low and sands or silts predominate most of the pores will be large and continuous so that water and air may move freely. In this case porosity may be favorable, but chemical properties would be unfavorable, as nutrient supplying capacity would be low. Where clays are more abundant and the chemical properties are more favorable, physical characteristics of the soil may be either good or poor depending upon the arrangements of the soil particles. The final environment in which the plant grows is the resultant of the balance of all forces acting on and within the soil. In soil physics, studies of clay must always be made with the objective of arriving at an understanding of how the clay properties will affect the whole soil complex. Many chemical properties and reactions of clays can best be studied on separated clay samples, since sand and silt are comparatively inert and act only as diluents to the more active clay. Studies of the physical properties of pure clays, however, although of extreme significance in other phases of clay technology, are of only limited value to soil physics. There are two reasons for this: (1) in soil, clay is always mixed with other materials such as sands and silts and these materials strongly affect physical characteristics; (2) physical and chemical characteristics of clay are greatly changed by absorption or combination with certain types of organic compounds which exist in soils. Because of this we are interested in clay as it exists in soils and controls soil properties, rather than clay as a separate material.

SOIL STRUCTURE

The physical characteristics of a soil which have the greatest influence on the growth of plants are those associated with soil structure. Soil structure can change as a result of either time or management. The range of soil characteristics associated with soil structure, in fact structure itself, is controlled largely by clay.

Definition. Soil structure has been defined in many ways (Baver 48). The simplest definition is that soil

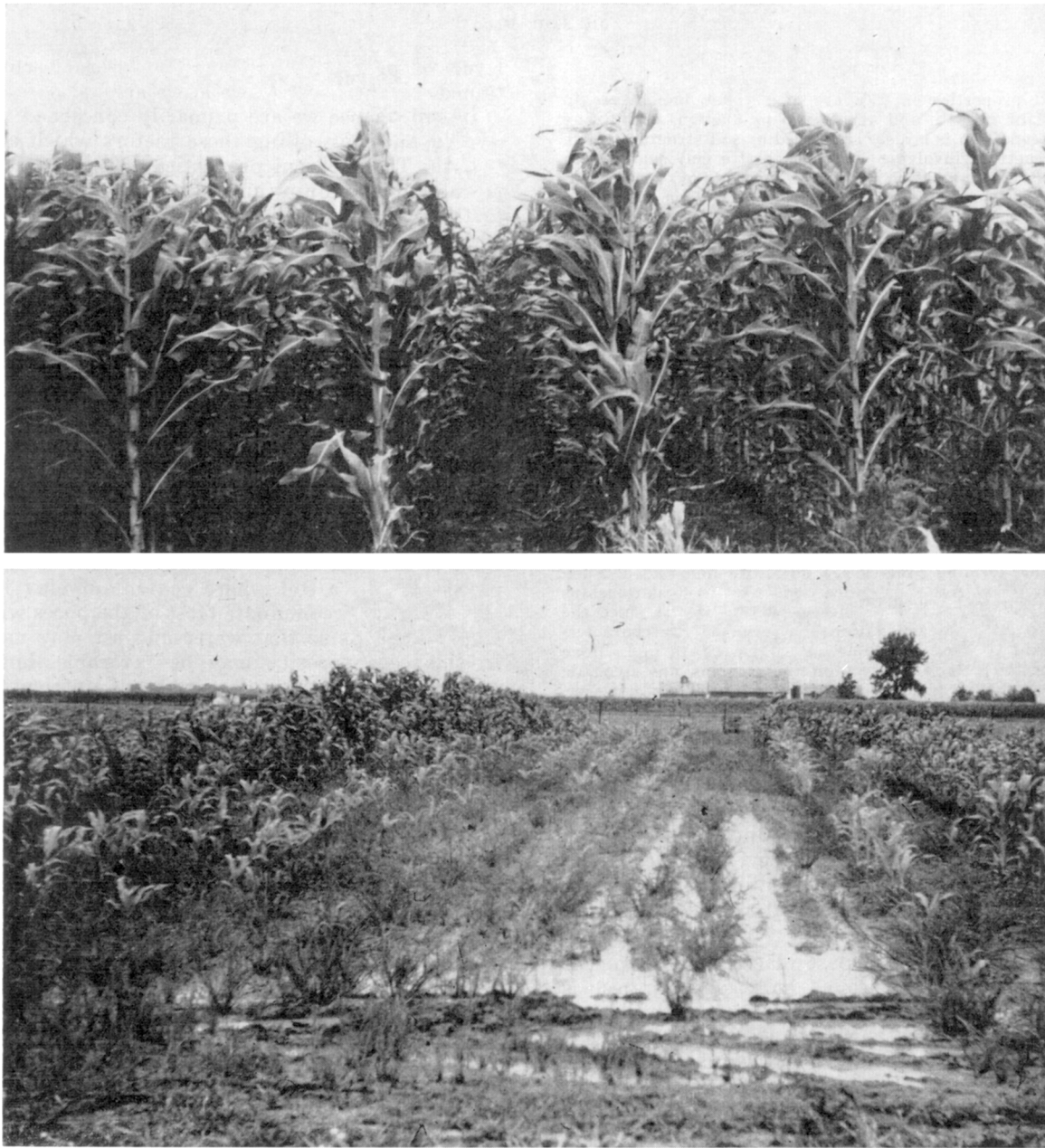* Professor of Agronomy and Soil Physics, Agricultural and Mechanical College of Texas, College Station, Texas.

FIGURE 1.   Adjacent corn plots on Paulding clay, July, 1949, showing effect of soil structure on crop growth. *Top,* corn on plot grown in crop rotation in which soil structure improves. *Bottom,* corn grown continuously; structure has deteriorated; water is standing as a result of inadequate porosity for water and air movement; poor soil structure has definitely resulted in seriously reduced crop production.

structure is the arrangement of soil particles. Such a general definition may be adequate for strictly classification purposes, but in terms of plant growth the stability of the structural arrangement and the over-all volume relationship of the structure need to be specified. Other writers have used a different definition in which structure is defined as the extent to which soil is aggregated (Anonymous 1938; Nikiforoff 1941; Zakharov 1927). An aggregate is a cluster of soil particles held together more or less loosely but with sufficient strength so that it behaves in the soil as a unit. The forces holding particles together are stronger within the aggregates than the forces between the aggregates. An aggregate of

agricultural significance is usually taken to be between a quarter of a millimeter and five millimeters in diameter and to have at least a moderate degree of stability even when saturated. When a soil is aggregated the clay particles no longer act as individuals but cause the sand and silt grains to be held together in larger units: This causes an increase in the proportion of larger pores in the soil, thus improving movement of water and air.

In some soils with proper management, stable aggregates of ideal size have developed and it has been found that as the soil becomes more thoroughly aggregated it becomes more productive (where other factors are favorable). Where aggregates are quite stable and exist as

discrete units of characteristic shape and size, a determination of the proportion of the total soil combined into these aggregates can be used, to a large extent, as an index of the characteristics of the pore space. In such soil a fair degree of correlation has been found between the degree of aggregation and crop yields or productivity (Alderfer and Merkle 1944; Baver 1948; Olmstead 1947; Page and Willard 1947). In many soils, however, the aggregates may differ greatly in size, shape, or stability and quite different volume-pore space relationships may result, depending upon how the aggregates themselves are arranged in the soil mass. In such cases determination of the amount of aggregation may be of limited value and give little indication of the volume relationships in the whole soil, since these may be subject to sudden change. In these soils, determination of aggregation [1] may be of limited value in describing the environment in which plants grow, since the over-all structure of the soil is necessarily destroyed in the separation and measurement of the aggregates (Robinson and Page 1951).

Soil Porosity. The important characteristic of soil structure is porosity. It is important to know: (1) the proportion of soil volume existing as pores, (2) the size of these pores, and (3) their configuration and whether they are connected into channels or exist as pockets in the soil. Porosity in the soil may be of two kinds—textural and structural.

Textural porosity is that porosity associated with the primary mineral grains in the soil and can be inferred from a mechanical analysis. Where sands or silts predominate the geometry can be calculated fairly well assuming cubes or spheres and closest packing (Dallavalle 1948). In these cases soils usually have an excessive proportion of large pores, and too little water-holding capacity, so that they tend to be droughty and low in fertility (because of absence of clay). In contrast to this, when appreciable amounts of clay are present and the clays are not aggregated, the pores between the larger grains may be filled with dispersed clay so that the soil pore space is preponderantly in the very fine capillary range. Such soils are practically impermeable to water or air and are quite unsatisfactory for growth of plants.

Under more favorable conditions the clay particles may combine with one another and the silt and sand grains, causing them to be clumped together into aggregates so that the porosity is quite different than in a soil where each particle acts individually. The favorable porosity (because of the increased proportion of larger pores) associated with aggregation is called structural porosity. This will of course change as structure changes. Where structural porosity is favorable the soil will usually have sufficient clay to hold water and nutrients, yet at the same time will have a high proportion of larger pores. Under this condition excess water can drain readily from the soil, air will diffuse freely into the soil and roots can develop normally. Soils having this more favorable arrangement of their particles are said to have good structure. Characteristics of such soils, the transformations of structure with time or with different cultural treatments, and the influence of various structures on

crop production all constitute a major area of study in soil physics. There are large gaps in our knowledge of how soil structure is formed, but it is known that the reactions are almost all associated with the properties of clay; in fact, clay is essential for formation and maintenance of favorable structure in soils.

Importance of Soil Structure to Plants. That soil structure is of extreme importance to plant growth has been amply attested by much research and many published reports (Baver 1949; Page and Bodman 1951; Russell 1950).[2] Figure 1 shows an example of how completely crop production may be limited by soil structure. Figure 2 shows restricted root growth resulting from very poor structure in the lower layers of the soil. In this case only a small fraction of the total soil volume is available to the roots for absorption of nutrients or water. Our knowledge of these important physical factors however, is still largely in the beginning stage, partly because of the complexity of soil-plant relationships and partly because there has not been adequate realization of the importance of the physical factors in plant growth and crop production.

Good soil structure has a profound effect upon plant growth in at least three ways:

First, because of favorable porosity associated with good soil structure, roots find a favorable environment and can penetrate and spread through the soil readily. Where structure is unfavorable roots may be restricted to growth in only a small part of the soil. Thus but little soil is contacted and water and nutrients available to the plant are limited even though the bulk of the soil contains water and nutrients in what would appear to be normal amounts.

Second, for normal growth and function roots need a continued supply of oxygen. This is supplied primarily by free diffusion through open soil pores and channels into the root zone. If soil pores remain saturated or are not continuous to the surface, oxygen will not be supplied to the roots at the required rate. Roots deprived of

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[1] Degree of aggregation is determined by sieving after moderately severe mechanical treatments. Sieving is usually done under water to measure stability when wet, but dry sieving is sometimes used.

[2] The publications in this field are too numerous to list. The references given are to recent survey articles which adequately review the literature and present current thinking on the subject.
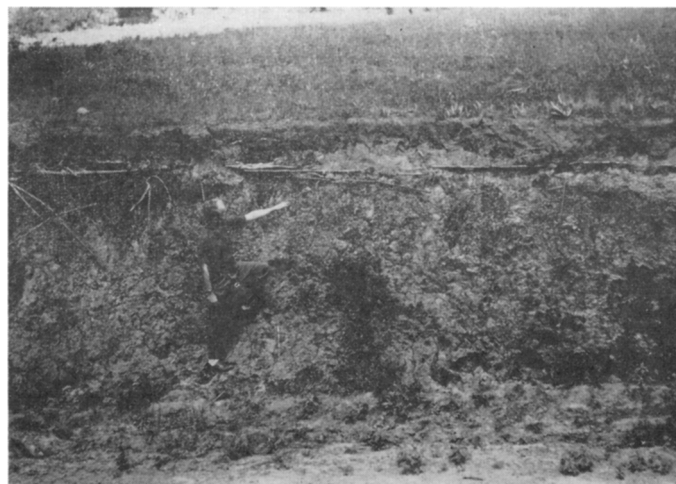

FIGURE 2. Tree roots exposed in road cut near College Station, Texas. Roots have extended horizontally, rather than penetrate tight, less porous subsoil.

oxygen stop functioning and are unable to assimilate water or nutrients at required rates regardless of how abundantly these essentials may be supplied (Page and Bodman 1951). Wherever tight layers or crusts occur in soils free movement of water and air into the soil may be hampered so that normal supplies are not made available to the plants (Winters and Simonson 1951). Under conditions of poor aeration plants frequently show symptoms of deficiencies of nutrients or of water. The usual practice in such cases has been to add more fertilizer or more water, either of which would increase the difficulty. The correct solution in this case would be to improve soil structure.

Third, soils having good structure usually allow free drainage of excess water. This not only favors diffusion of necessary oxygen and permits free root growth but modifies heat capacity and conductivity so that soils remain more nearly at the optimum temperature. Water has a much higher heat capacity than other constituents in soils; poorly drained soils remain wet and cold in the spring.

Formation of Structure. Since most of the factors which control plant growth are intimately associated with physical characteristics of the soil, soil structure is of prime importance. In many cases unfavorable soil structure limits or restricts plant growth and response to application of fertilizers. Since soil structure has such a profound effect on crop production, it is important that a sound basis for understanding the mechanics of structure formation be developed. Both genesis and stabilization of structure are important, and in both of these clay plays the primary role.

Various theories have been proposed to explain the processes by which soil structure develops. The earlier attempts at an explanation pictured the soil particles as being held together by cementation with the amorphous oxides and hydrous oxides of iron and aluminum which were then considered to be the materials of clays. These were thought to surround the larger soil grains and hold them together by cementation. With the introduction of the concept of the crystallinity of clays and advances in knowledge of their colloidal properties, the way has been opened for a fuller understanding of the role of clay in soil structures.

The mechanisms which have been proposed to explain formation of aggregates in the soil are: (1) Direct effect of living microbes and fungi to bind soil particles together (Martin 1946; Martin and Waksman 1940; McCalla 1947; Olmstead 1947; Peele and Beale 1942), (2) Encapsulating or cementing action of gelatinous organic material, gums, resins, and waxes which occur quite commonly in the soil (Martin 1945; McCalla 1945; Sideri 1936) and (3) Action of clay particles themselves to cohere and enclose or even bridge between larger grains (Peterson 1945; McHenry and Russell 1944; Russell 1934). There is good evidence that each of these types of binding may contribute to formation of aggregates in different soils and it is probable that they all operate either singly or in combination to different degrees in different soils.

Where numbers and activity of micro-organisms are high the first mechanism is undoubtedly of importance, but this is usually short lived (McHenry and Russell

1944) and either of the other two processes would have to operate to give the stable, long-lived structural units commonly found in many soils.

The second type of process in which gelatinous or resinous compounds enclose and bind soil particles is an attractive and rather obvious explanation. The significance of this type of process has not been established, but available evidence does not strongly support it. Such compounds are quite resistant to microbiological attack and do accumulate in the soil, but careful examination does not reveal the capsules or matrix of organic matter one would expect. Even with the electron microscope no evidence was found (Kroth and Page 1947) of coatings or capsules on microaggregates.

The third mechanism, in which clay plays the primary role, now appears to be by far the most important. Under certain conditions cohesive forces between clay particles may be very great, leading even to solidification. This last condition would obviously be unfavorable for agriculture but the same types of forces between clay particles appear to be involved in producing desirable structure in agricultural soils as are active in solidification of puddled soils.

There are three ways in which clay particles in soil are thought to be held together: (1) by linkages of water dipoles or bridging with divalent absorbed cations (Russell 1934; Hénin 1937; Peterson 1945, 1946; Sideri 1936); (2) by bridging or tying together with certain types of polar long chain organic molecules (Kroth and Page 1947; Martin 1945; McCalla 1947; Myers 1937); (3) by cross bridging and sharing of intercrystalline ionic forces and interactions of exchangeable cations between oriented clay plates (Hauser and leBeau 1938; Hénin 1937; Sideri 1936).

It is quite likely that the first of these is of importance under moist conditions and probably accounts for some of the resistance to dispersion observed in some soils. It is difficult to see, however, how such a mechanism could operate over the dry part of the moisture range or account for the coherence of dry soil granules. Such a mechanism may be active in causing or at least affecting orientation of adjacent clay particles as they are dried out.

The second mechanism in which polar, probably long-chain, organic compounds hold clays together may prove to be of great significance and certainly needs to be thoroughly investigated. There is evidence to show that many such compounds can be strongly adsorbed by clays. It appears logical that they could serve as cementing or binding agents to hold soil particles together either by hydrogen bonding or direct bridging. It is known that different compounds vary tremendously in the degree to which they are held by clays and likewise that the clays differ in the force with which polar compounds are adsorbed (Bradley 1945; Gieseking 1939; MacEwan 1946). Many such compounds are held very tightly and it has been reported that certain clay-organic complexes are resistant to redispersion or crushing after drying (Gieseking 1949). Recently synthetic long-chain polymers have been introduced for use in stabilizing soil structure. These have produced very striking results on certain types of clay soils and much interest is being shown in these materials not only for practical use, but

for research on soil structure as well. The mechanism by which these materials stabilize soil aggregates has not been determined. Such a study should prove valuable in helping to reveal the nature of the combination between clay and similar active organic compounds and their effects on physical properties of the clay. It would be of considerable importance to determine whether similar compounds occurred naturally during the process of decomposition of organic matter in the soil or whether the mechanism operating under natural conditions was of a completely different kind.

Most of the work on adsorption of polar organic compounds which has been done emphasizes the probable role of such compounds as cementing agents to bind clay particles together. Very frequent reference is made in soils literature to the cementing action of organic materials and it is quite well agreed that the active portion is probably polar. It appears that this aspect of the problem although important may have received disproportionate emphasis. The strongest cohesive forces operating in the soil are probably those existing between clay particles themselves where a high degree of orientation or contact exists between adjacent clay particles. Direct cementation undoubtedly is of importance in formation of desirable structure in soils which are initially loose or have single-grained structure. In most cases, however, agricultural soils tend toward a high degree of orientation of clay particles (as a result of improper tillage and compaction). The mechanisms by which such compacted soil masses can be brought back into a more desirable open or porous structure are thus of more immediate interest and should be studied intensively. According to this view adsorption of polar organic molecules is of interest not so much because it might bring about a direct cementation but because such absorbed molecules would greatly modify the surface properties of the individual clay particles.

Looking at the problem from the viewpoint expressed in the preceding paragraph it can be seen that the third type of mechanism in which clay itself is the primary cementing material can, under certain conditions, give rise to extremely strong forces which could account for all the binding observed in soils containing clays. These forces are at their maximum when the clay particles are in closest contact and preferred orientation, so that the number of points of contact as well as the area of contact are both large. Puddling of soils or clays favors such orientation and the pieces resulting after puddled clays are dried are very strong and coherent. Crumbs resulting from drying of dispersed soils are usually much stronger than those from flocculated clays since in flocs the tendency is for random orientation.

In most agricultural soils which have not been mismanaged the clay particles will not yet have been strongly oriented. Natural structure may still be favorable and the total cohesive force may not be high. With a more nearly random orientation the number and area of points of contact would be at a minimum. Further, if, as is usually the case, water dipoles as well as active organic molecules are adsorbed on the free clay surfaces, the magnitude of any further cohesive forces which could become effective between clay particles will be even further reduced. Apparently the same types of bonds would be involved at existing points of contact as in puddled soils. However with part of the surface energy directed toward adsorption and orientation of water and organic molecules and with these molecules serving as a protective layer over free surfaces of the particles, any further expression of these forces would be markedly reduced. Thus these materials would act to stabilize existing structure partly through cementation and partly through modification of surface properties of the clay particles. Swelling has been shown to cause breakdown of aggregates under certain conditions. Many polar organic compounds when adsorbed greatly reduce the swelling tendency of clays. Presumably this is brought about because these compounds are adsorbed by the same forces which attract water dipoles. They are however much more tightly held. It should be emphasized that relatively small amounts of active organic material exert a tremendous influence on swelling, cohesion and other physical characteristics of clays. There is need for intensified research in this field.

Clays, of course, differ in their surface activity and ability to adsorb or orient water and organic molecules and this is reflected in soil properties. They differ also in the magnitude of cohesive forces which would be exhibited even under complete orientation and contact. Adsorbed cations play an important role as well, presumably dependent upon the degree of hydration of the adsorbed cation and whether they cause dispersion or flocculation of the colloidal clay. It appears that soils which are predominantly kaolinitic may not exhibit as strong cohesive forces upon drying as are exhibited by soils that are predominantly montmorillonitic. It would be unsafe to generalize, however, since too little is known at the present time of the characteristics of the clay minerals in large numbers of soils. With either mineral type granules formed by drying from highly hydrated monovalent systems are less resistant to rehydration and dispersion than are those from soils saturated with slightly hydrated cations.

Formation of Aggregates. In light of these considerations the following seems to best explain how aggregates are formed and stabilized in agricultural soils. Aggregates result primarily from the action of natural agencies or any process by which parts of the soil are caused to clump together and separate from adjacent masses of soil. If soils are initially dispersed (as in alkali soils), flocculation is essential for aggregate formation; if they are partially puddled or solid, fragmentation into smaller units is the first essential. Separation of parts of the soil mass may result because of: (a) action of small animals, particularly earthworms, (b) tillage processes, (c) pressures and differential drying caused by freezing, (d) compression of roots, (e) localized shrinkage caused by removal of water by roots or evaporation. Roots appear to be tremendously important, acting to separate and compress small clumps of soil, cause shrinking and cracking due to desiccation near the root, and make conditions favorable for activity of microorganisms at the surfaces of these units. Alternate wetting and drying causes cracks or cleavage planes to develop, as a result of differential swelling and shrinking. Freezing causes extreme localized desiccation and localized pressures, again tending to cause the soil to break up into rather

small fragments or crumbs. When this occurs forces within the crumb which cause clay particles to cohere are stronger than these between clay particles of adjacent crumbs. These units tend to exist separately in the soil until forced back into intimate contact with neighboring groups. The size and shape of the masses which are thus caused to form in the soil are extremely important but little is known of the factors governing the characteristics of the aggregates resulting, nor of the specific role of the different clay minerals. Figure 3 shows differences in size and character of aggregates produced on the same soil under different cropping systems. The characteristics of the pore spaces in the soil obviously depend upon the shape, size, and arrangement of aggregates. It has been suggested that kaolinitic clays tend to produce platy aggregates in contrast to the blocky aggregates produced from montmorillonitic clays, but not enough is known of the specific effects of these minerals to generalize at this time.

Stabilization of Structure. Structural units once formed in the soil would readily disappear and recombine with others in the soil if not stabilized. This is thought to be the chief role of organic matter and one whose importance cannot be overemphasized. As was pointed out above, certain types of compounds and active groupings on organic compounds have been shown to be strongly adsorbed on clay colloids. The forces involved differ with the different compounds and different kinds of clay, as well as the adsorbed inorganic cations which are already present. Some compounds appear to be adsorbed as cations, others as anions, and others as molecules; the binding capacities as molecules do not appear to be related to either anion or cation adsorptive capacities.

Strong adsorption of active organic molecules on clay surfaces would have a profound effect in modifying the forces between clay particles which cause the particles to cohere. Those particles within the aggregate where a degree of orientation and close contact had already occurred would be less affected than those on the outer surfaces where clay surfaces would be exposed and available for adsorption. With outer surfaces essentially saturated or occupied with the active organic compounds, but little residual force would be left which could act to cause coherence between clay particles of adjacent aggregates. In this situation the requirements for aggregates would have been met, namely, stronger cohesive forces between particles within the aggregate than between aggregates and the unit would exist in the soil as a separate entity. Such a unit would tend to be stable even when wet if organic molecules were so strongly absorbed that further hydration or swelling and consequent weakening of bonds between clay particles did not occur, or if the compounds themselves tended to hold adjacent clay particles together through cross linkage or mutual adsorption. Apparently both mechanisms are of importance and it is probable that they operate concurrently. Figure 4 shows the extent to which absorbed organic matter can affect stability of aggregates.

Polar organic compounds may be thought of as playing two important roles in soil structure: (1) weakening the potentially strong cohesive bonds between clay particles, thus permitting formation into aggregates, and
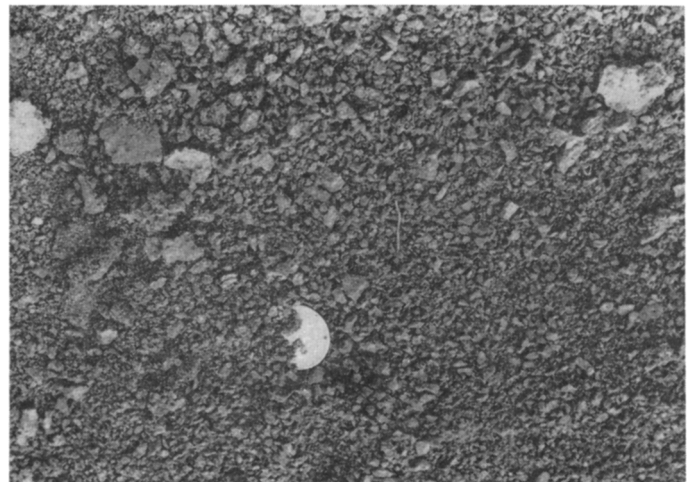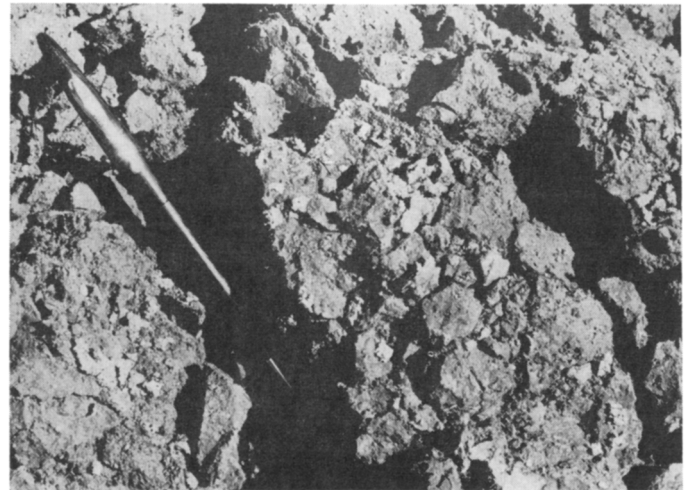

FIGURE 3. Aggregates produced on the same soil under different cropping conditions; all photos are same scale—objects are pencil, in the top and middle photos, and dime in the lower photo. Cropping systems were: *top*, continuous corn; *middle*, corn, oats-alfalfa; *bottom*, corn, oats, alfalfa. Paulding clay, Ohio.

(2) linking clay particles together through mutual adsorption of such compounds by two or more clay particles. There is insufficient evidence available to indicate which of these two functions is the more important. It is almost certain however that both actions may occur concurrently in stabilizing soil structure.

Recent findings indicate that a very important, if not the most important, role in soil structure is played by the polyuronides and polysaccharides. These types of compounds are not only abundant in soils exhibiting good structure but they are also strongly adsorbed by clays. Much interest is being shown in this problem and electrophoresis and infra-red adsorption techniques are being applied in the identification and characterization of the organic compounds active in producing soil structure.

It seems apparent that adsorption of polar organic molecules on clays is an essential for structure formation. This is based on the fact that soils low in clay show little improvement in structure upon addition of organic materials which would otherwise be effective when clay is present.

Recent work with synthetic soil additives mentioned above has shown that these highly polymerized straight-chain compounds are extremely tightly held by clays. They do not appear to be replaced by ordinary exchange and are quite resistant to microbial attack. The extent to
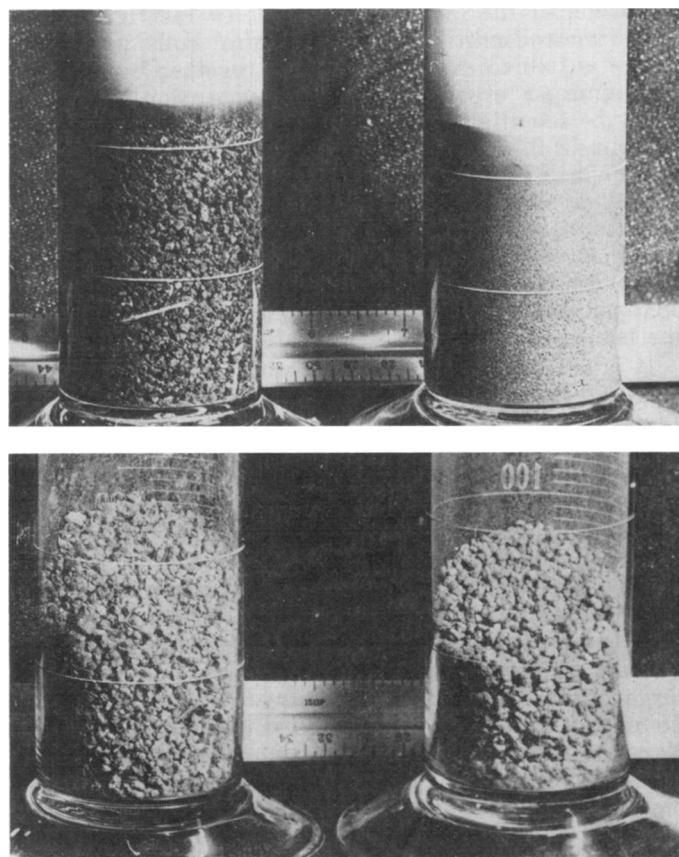

FIGURE 4. Aggregates screened (air dry) from soil in plots shown in figure 1 before (*bottom*) and after (*top*) adding water, show extreme difference in stability. The amount and kind of clay are the same in the two samples; presumably the only difference is in the adsorbed organic matter.

which they are adsorbed varies roughly with the adsorptive capacity of the clay and the adsorption may be either anion or cation adsorption depending upon how the molecule dissociates. It is significant that these materials will not create good structure but act instead to stabilize whatever structure is present when the material is applied. If the soil can be prepared into favorable sized aggregates or fragments the materials do an effective job of stabilizing the aggregates so that they do not tend to run back together upon further wetting. If structure is poor at time of application the material acts to stabilize that condition and may be of little or no benefit. Enough work has been done to show that different types of clay respond quite differently to these materials, but further work is needed to elucidate the mechanism by which the stabilizing effects are produced.

It has been shown that many organic compounds when adsorbed on clays are still subject to attack by micro-organisms. As would be expected this results in loss of their stabilizing effect on soil structure and striking changes can occur in a short time if decomposition of fresh supplies of organic matter does not continue to supply new polar compounds for adsorption. Most of the changes in soil structure which are observed in the field can be explained on the basis of changes in the nature or amount of adsorbed organic compounds and the activity of micro-organisms.

One special type of soil-structure change needs special mention. Saline and alkali soils are normally low in organic matter and the structural changes which occur can best be understood from the standpoint of flocculation. Saline soils normally have an excess of calcium or magnesium or sometimes sodium ions which act to keep the colloids effectively flocculated. Such soils usually are thoroughly desiccated from time to time so that floccules are quite stable although the cohesive forces are not exhibited strongly enough to cause solidification. Crumbs resulting from drying of flocs are not highly oriented and the number of points of contact and total area of contact are not large. Such soils usually remain permeable and present no physical problem, although chemically they may be quite unfavorable for plant growth. If, however, the excess salts are leached out and sodium predominates on the exchange positions the colloids are *readily dispersed and the former random orientation is lost*. Depending somewhat upon the type of clay, the soil swells, becomes plastic, and usually is quite impermeable to water. If desiccation occurs the soil solidifies into a hard intractable mass but readily redisperses and seals off again upon wetting. Correction for this condition can be had by replacing the sodium with calcium so as to again produce flocculation. Earlier literature stressed the importance of flocculation in soil structure on all soils, but it has been found that colloids in most all non-alkali soils tend to be flocculated. Both Ca^{++} and H^+ ions produce flocculation and further, adsorption of most polar organic molecules causes complete flocculation. It is now considered that most soil clays are already flocculated and that changes occurring in soil structure are not primarily changes in degree of flocculation, but rather in degree of expression of cohesive forces between already flocculated clay particles.

It should be re-emphasized that clays are essential in structure formation and that the primary role of organic

matter is in modifying the physical properties of the clay. Since the mechanism involves an adsorption process, only very small amounts of the active compounds may be involved at any one time, but the effect on clay and hence on soil properties is tremendous. The amount and composition of the organic materials in the soil at any one time are dependent upon activity of micro-organisms so that physical properties of the clay organic matter system may change rather rapidly. During decomposition the micro-organisms themselves exert a direct effect, usually favorable, on structure but the effects produced through adsorption of the compounds produced are thought to be much the most significant. The specific organic compounds which combine with and modify the characteristics of the clay are not yet known but their importance is tremendous and studies of the nature of these compounds and the clay-organic matter combination should prove to be very fruitful.

Swelling and Plasticity. Major emphasis has been placed on the role of clays in soil structure. This approach was chosen because soil structure is of first importance as far as plant growth is concerned and it is through soil structure that the various materials·in soil affect agriculture. Clay plays the major role in soil structure even when present in comparatively small amounts. When clay is a major component of soils its characteristics may predominate and the soil will then exhibit many properties of the clay. Structure is still of prime importance to plant growth but such soils may also exhibit marked tendencies to swell or be plastic. These properties are exhibited in practically all soils containing appreciable amounts of clay to a degree depending upon the amounts and properties of clay present and upon the adsorbed cations or organic compounds.

Swelling is an extremely important soil characteristic, but one that has received comparatively little study. Since swelling of clays is discussed in another paper in this symposium the mechanics of swelling will not be discussed in detail here, but it is important to indicate a few ways in which swelling is of significance in soil science. Soils which swell usually swell rather slowly, and probably only reach maximum swelling of the whole soil profile during the winter or early spring months when the soil is saturated for long periods of time. During the growing season excess water drains away and such soils are usually characterized by cracks, which in some cases are very deep and very large. Most such soils are heavy clays, and it is probable that agriculture could not be practiced on these soils if they did not crack, since the cracks serve to ventilate the soil and facilitate water and air movement into what would otherwise be a tight, solid mass, quite unsuitable for plant growth. It appears that most soils do not swell to any great extent during the growing season of plants, although there may be some localized swelling. An example of the latter is swelling and sealing of the soil surface which sometimes occurs during excessively long periods of flood irrigation, or where intense rains coupled with poor surface drainage cause water to stand on the soil for several days. In general it does not appear that swelling has a very significant direct effect on plant growth since conditions are not favorable for swelling to occur during most of the growing period. Shrinkage and formation of

cracks is, however, of considerable direct importance. Swelling and shrinking of soils influence formation or destruction of favorable structure in the soil. Swelling in some soils helps to cause destruction of aggregates since the tendency is for adjacent aggregates to be forced together strongly so that they rejoin and lose their identity. On the other hand shrinkage favors formation of aggregates from large masses of soil initially in poor structure. Swelling of soils also is of great importance in engineering as well as agriculture, for it may cause destruction or damage of building foundations, bridges, roads, etc.

It has usually been inferred that swelling soils are composed primarily of clays having an expanding lattice and that the swelling can be accounted for on the basis of the increased volume resulting from expansion of the lattice. It has in fact been suggested that swelling characteristics in soils indicate that expanding lattice type of clay predominates. It appears that this is an over-simplification. Most explanations of swelling show that swelling is a result of adsorption and orientation of water molecules on the surfaces of the individual particles. The property of an expanding lattice is usually associated with clays which have a very high affinity for water and exhibit high surface activity, but the volume increase occurring during swelling and the quantity of water involved are usually much greater than could be accounted for by water associated with expansion of the lattice alone. It is in fact likely that under most conditions in agricultural soils where the lattice is free to expand (not held together by "fixed" potassium or organic molecules) expansion would already be essentially complete. There is no known direct experimental verification of this assumption but there is abundant evidence that montmorillonites will expand to 20Å or more at relative humidities above 90 percent. Soils at a moisture content even somewhat below the point at which plants will wilt and die are in equilibrium with an atmosphere in the soil pores of more than 98.5 percent relative humidity, so that one would expect the lattices to be rather completely expanded.

It is surprising that so little work has been done on swelling in soils. Probably the most important direct effect of swelling is the effect on water infiltration or entry into soil under conditions of saturation as prevail during irrigation. The almost universal finding in measurements of infiltration rates is that with many soils high initial infiltration rates soon change to low rates or the soil becomes completely impervious. Serious reduction of rate of infiltration usually occurs (where it occurs at all) within a time which will be of practical significance during heavy irrigations or high rainfall.

Work has been reported (McCalla 1947) showing that large organic molecules and many polar organic compounds are strongly adsorbed by highly hydrophyllic clays, and that such adsorption interferes with further adsorption of water. This, of course, markedly reduces swelling. Recent work with synthetic soil additives indicates a similar action. These findings suggest the possibility of effectively reducing the tendency of certain soils to swell by treatment with additives or active organic matter, and help explain some of the results observed on soil structure when such materials are adsorbed on the clay. Much work is needed on the me-

chanics of the swelling reaction, not alone on pure clays and in systems having commercial importance, but in soils as well, and the exact role of swelling in genesis or breakdown of soil structure needs to be determined.

Much that has been said concerning swelling could also be said concerning plasticity. Plasticity of soils is entirely a property of clay; soils containing less than 20 percent of material smaller than 5 microns in effective diameter do not exhibit plasticity. Although plasticity has a considerable effect on soil mechanics or tillage of soil, it does not affect plant growth or plants directly. The importance of plasticity lies in its effect on soil structure. The usually accepted, and apparently adequate, interpretation of the phenomenon of plasticity in soils is that after sufficient stress has been applied to overcome the cohesive forces between clay particles, viscous flow occurs, favored by lubrication by water between clay sheets. For plasticity, clay must constitute a continuous phase serving to lubricate movement of other mineral grains within the soil. At the moisture range over which plastic flow occurs sufficient water is present at all points of contact to weaken cohesive forces between clay particles thus permitting ready reorientation and alignment of particles during flow. If soils are manipulated or tilled at a moisture content at which these conditions will be met structure will be destroyed and clays will be oriented so that upon drying the most favorable condition for maximum expression of cohesive forces will be produced. In most cases this leads to hard, intractable clods which are difficult to handle or get back into favorable condition for growth of plants. As would be expected, organic matter is extremely important in modifying plasticity of clays, apparently having two roles in soils: (1) because of its bulk and absorptive capacity, organic matter absorbs water and insulates or coats soil granules so that the clays do not become plastic until quite a high moisture content is reached (thus permitting plowing at higher moisture contents); (2) by virtue of direct adsorption, polar organic molecules modify cohesive forces or bind clay particles together so that they are not so free to move and thus are less plastic.

Again, these reactions have not been studied in detail and need to be thoroughly investigated. In most cases the effectiveness of any favorable structural condition in the soil will depend upon the resistance of the structural units to breakdown by swelling or as a result of tilling. Too often tilling is done at excessively high moisture levels and with too great intensity so that there is a strong tendency toward breakdown of structure and orientation and consolidation of clay particles. In the last analysis, the changes which occur naturally or during tillage and which are so extremely important to crop production, are changes in the arrangement of the colloidal clay particles. The arrangement is greatly affected by interactions of surface and cohesive forces of the clay particles and hence can only be understood on the basis of knowledge of the colloidal properties and reactions of the clay.

CONCLUSION

It has been the purpose of this discussion to show how clay affects physical properties of soil and how such properties are important to the growth of plants. It is evident that clay is of vital significance in controlling the physical properties of soils and that intensified studies of colloidal properties and adsorption reactions of clays in soils are needed.

It might appear at first glance that studies of surface properties of clays and nature of the adsorption reactions which occur on soil clays would be chiefly of academic interest; but it is hoped that this discussion has shown that such studies have an immediate and important practical value as well. Much that is done at the present time in the way of tillage, or management of soil tilth is an art and as such is dictated largely by whim, fad, or custom. It seems quite apparent that if these operations, which are so vital to our economy and well being, are to be put on a sound scientific basis, studies of the colloidal properties of soil clays and the effects of adsorption of organic compounds on these properties must be carried forward to the point where a clear picture can be obtained.

Little mention has been made in this discussion of how specific types of clay minerals contribute to the physical properties of soils. This was done partly because it was not felt that enough good information was available for a sufficiently wide range of soils to permit generalizations, but mainly because of the strong conviction that identification of clay minerals is of much less importance for these purposes than characterization. In many cases traces of polar organic molecules when adsorbed have profoundly changed expression of physical characteristics of clay in soils. There is no intent to imply that identification is of little importance; rather what is meant is that identification, without characterization and study of the combinations in which clay is found in the soil, may be quite inadequate to explain soil properties.

Soil-plant relationships are extremely complex, but at the same time very challenging. The benefits to be gained by increased knowledge in this important field of study justify the best efforts of colloid chemists, clay mineralogists, plant physiologists, and soil scientists. The best techniques developed in these fields should be applied to solution of soil problems: it is hoped that this can be done so that soil management can be put on a truly scientific basis.

DISCUSSION

T. F. Buehrer:

Regarding the use of polymethacrylates and other correctives for impermeable soil conditioning, we have some work going on, testing various Kriliums put out by Monsanto Chemical Company: CRD 186, the Ca-saturated Krilium; CRD 189, the Na-saturated form; and several others. Bradley, MacEwan, and others have shown that such ions can be adsorbed between the layers of montmorillonite. Gieseking has done a great deal of work on the adsorption of substituted organic ammonium groups on montmorillonite and other clays. I understand that the polyanions are adsorbed on kaolinite and the polycations into montmorillonitic and beidellitic clays. I wonder if there might be some discussion on the operation of these polyanions and polycations.

J. E. Gieseking:

We think these amino compounds are adsorbed as exchangeable cations or, in many cases, as very difficultly exchangeable cations. There are so many of the Krilium-like compounds, that we have not had a chance to find out very much about them. In general, these materials are hydrolyzed polyacrylonitriles, which means that they must have many carboxyl groups on the molecules—if we might be permitted to call them molecules. The amino compounds

are large cations and the Krilium-like molecules are large anions. They are polymers, and we have indications that about 100 units of acrylonitrile polymerize to give the Krilium-like materials. I think that the Krilium-like molecules are adsorbed by hydrogen bonding in a manner similar to the situation described by Bradley.

J. B. Page:

The people from Monsanto Chemical Company have worked with adsorption of the polyacrylonitriles and find no variations in the basal spacing of montmorillonites. It should be noted that an issue of Soil Science [vol. 73, No. 6, June 1952] is devoted to these materials.

T. F. Buehrer:

Gieseking and Ensminger showed that when such things as gelatin and other large molecules are adsorbed by montmorillonite, the exchange capacity is greatly reduced (Gieseking 1949).

J. E. Gieseking:

In polymerizing, the molecules must be very highly branched, and I suspect that they would not be able to get into the variable spacings in the montmorillonite. We have done a little work which indicates that they do not get in at all. However, this work on base exchange has not been applied to Krilium. Krilium-like material should have an exchange capacity of its own. It should not greatly affect the base-exchange capacity of the clay except to increase it slightly.

E. B. Kinter:

In practice, Krilium is not ordinarily added in large enough quantities to contribute much to affect the base-exchange capacity of clay soils or to affect all of the clay particles, internally or externally.

F. N. Hveem:

What is the relative efficiency of Krilium-like materials in producing aggregates or flocculation in comparison with other materials?

J. B. Page:

The chief action of these materials is in stabilizing rather than producing aggregates. Most experiments have shown a tremendous increase in stability with these materials as compared with lime or large quantities of organic matter.

Irving Goldberg:

Preliminary studies in our laboratory have shown that the addition of 0.1 percent of a Krilium-type compound to a highly expansive clay soil is approximately equivalent, in reducing swelling pressure and increasing stability, to the addition of 2 percent calcium hydroxide $(Ca(OH)_2)$. This improvement, however, was not particularly impressive when compared with additions of higher percentages of calcium hydroxide. No higher percentages of the Krilium-type compound were investigated.

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