1961

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Recommended Citation

Tamboli, Prabhakar Mahadeo, "The influence of bulk density and aggregate size on soil moisture retention " (1961). *Retrospective Theses and Dissertations*. 2449.
https://lib.dr.iastate.edu/rtd/2449

TAMBOLI, Prabhakar Mahadeo, 1929–
THE INFLUENCE OF BULK DENSITY AND
AGGREGATE SIZE ON SOIL MOISTURE
RETENTION.

Iowa State University of Science and Technology
Ph.D., 1961
Agriculture, general

University Microfilms, Inc., Ann Arbor, Michigan

THE INFLUENCE OF BULK DENSITY AND AGGREGATE SIZE ON SOIL MOISTURE RETENTION

by

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A Dissertation Submitted to the
Graduate Faculty in Partial Fulfillment of
The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Soil Management

Approved:

Signature was redacted for privacy.

In Charge of Major Work

Signature was redacted for privacy.

Head of Major Department

Signature was redacted for privacy.

Dean of Graduate College

Iowa State University
Of Science and Technology
Ames, Iowa

1961

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I. INTRODUCTION

Through the manipulation of soil by tillage the bulk density of the soil is changed, and the aggregate size and arrangement is altered. These changes influence the void-solid relationship and they in turn affect the consistency of the soil and its capacity to conduct and retain water, air and heat as pointed out by Richards and Wadleigh (76).

The importance of the soil-water relationships with regard to plant growth has been recognized for a long time. Directly soil-water relationships affect the adequacy of moisture supply for the growth of the plant. Indirectly, the soil's content of moisture influences plant growth through its effects on other properties of the soil which in turn condition plant growth. For example, the mechanical properties of the soil are greatly changed by the amount of moisture in the soil; gaseous diffusion in soil depends on the critical moisture content as shown by Taylor (88); likewise, the thermal properties of soils are materially affected by the soil moisture content.

Soil compaction can modify to a marked degree a number of plant growth factors. Conventional tillage systems and use of heavy machinery often result in excessive packing of soil which reduces the capacity and conductivity of water and air and consequently the available moisture supply. The minimum tillage systems, on the other hand, frequently create a low degree of packing which results in high air contents at field capacity but relatively low available moisture storage capacity per volume of soil. Lutz (51) pointed out that the most suitable compactness is that bulk density at which the soil pore size distribution results in the proper amount of water and air for plant growth. Similar views are shared by Jamison and Domby (40). A study of the literature shows that the effects of various levels of soil packing on plant growth are usually attributed to lack of aeration and/or impedence to root growth. However, there is a surprisingly lack of data regarding the effects of size, packing and arrangement of soil aggregates on the soil moisture status per se.

It is expected that the differences in packing and aggregate size and arrangement will influence: a) the moisture content per volume of soil, b) the soil moisture retention characteristics, and c) the moisture conductivity from soil to plant. The objective of the present investigation is to study the effect of various levels of packing and of aggregate size on the soil moisture retention. It is considered that this information will serve as a useful guide in planning future tillage research programs.

II. REVIEW OF LITERATURE

A. Effect of Tillage and Management Practices on Some of the Soil Physical Properties

It has been recognized by soil scientists that various tillage and management practices affect the soil physical properties. Alterations in bulk density due to tillage and due to freezing and thawing cycles have been reported by Alderfer and Merkle (2), and Domby and Kohnke (23) respectively. The former authors stated that the bulk density of the soil is a good criterion of field aggregation. Their results indicate that the bulk density of forested soils was low but it increased as the structure became destroyed by poor management practices. Domby and Kohnke (23) recognized that remarkable changes in bulk density of surface 1 inch of soil are produced by alternate freezing and thawing cycles. They reported that the increase in bulk density of mulched as well as bare soil was from 1.15 g. per cc. in September to 1.35 g. per cc. the following spring with a loss of about half of the volume of pores drained at a tension of 50 cm. of water. The changes in bulk density due to these cycles offer an expanation, in part, as to why soils loosened in summer become dense again during the following winter. It may be also visualized that changes are brought about in aggregate size distribution through tillage and management practices. Olmstead (61) calculated that about 80 percent of the initial aggregation in the surface tilled zone of the Great Plains of United States was lost in a period of two to three decades after the soils were broken from sod.

Since bulk density is an index of packing of soil separates, and bulk density in conjunction with aggregate size decides the pore geometry in a soil system, the changes in these two properties, as brought about by various tillage and management practices, have far reaching consequences with respect to: 1) soil compaction (impedence to roots), 2) soil pore space distribution (aeration) and 3) the soil moisture status (retention and conduction).

1. Soil compaction (impedence to roots)

High levels of soil packing are known to cause compaction problems. Valuable information regarding the effects of tillage implements, etc. on the formation of soil horizons of high bulk density is given by Brind (11) and Raney *et al.* (73). Comprehensive reviews of the literature on the effect of soil compaction on growth and yield of crops are given by Jensen (43) and Phillips (70). It is not intended to go into the details of this aspect in this review.

2. Soil pore space distribution (aeration)

The void-solid ratios are often changed due to tillage and consequently the pore space distribution is changed. Valasoff (91) reported that pore volume changes among soils due to various management practices are quite appreciable. A comprehensive review of this subject is given by Russell (81) and hence will not be repeated here.

3. Soil moisture status (retention and conduction)

The changes in pore space distribution are accompanied by changes in the soil moisture status of soil due to the rearrangement of capillary and noncapillary pores. Dreibelbis and Post (24) reported that the changes in the total pore volume bring about variations in the water holding capacity of soils. Gliemroth (32) calculated the moisture content on the volume basis and concluded that the water holding capacity of soils with pore volumes greater than 45 percent decreases with increasing porosity. Apparently according to his calculations, with increasing total pore volume of more than 45 percent, the total volume of small (capillary) pores will decrease. Thus, beyond certain limits, increasing the air capacity will decrease the available water capacity. Jamison (39), however, found that under field conditions, aggregate stabilization increased the rate of infiltration of water resulting in greater storage of water in the profile. These observations were further confirmed by experimental data of Diebold (22). He was studying the effect of tillage practices upon intake rates and runoff. His results show that when the bulk density was low (1.17 g. per cc.), the infiltration rate was 4.7 inches per hour; but when the bulk density was high

(1.49 g. per cc.), the infiltration rate was reduced to only 1.2 inches per hour.

That variations in the bulk density can have a great effect on the soil moisture status was shown by Heinonen (36). A high correlation between bulk density and available water capacity was obtained by him for Finish top soils. He suggested that if the humus content and the bulk density of a given soil are known, it is possible to calculate the effect of unit change in bulk density and humus content on the available water capacity of a given mass of top soil by the following equation:

$$Y = b_1 x_1 + b_2 x_2 + b_3 x_3 + b_4 x_4 + a,$$

where Y is available water capacity by percent by volume, a and b are constants and x_1, x_2, x_3 and x_4 are humus percent, clay percent, silt percent and bulk density respectively. He also found that larger the amount of water stable aggregates in a soil group, the greater is the effect of bulk density on available water capacity.

While studying soil moisture availability, the relation between the amount of water in the soil and forces with which it is held is of vital importance. Richards and Wadleigh (76) have indicated that the moisture held by more than 15 bars is not available to plants and the upper limit of water storage against gravity is about 0.33 bar. Thus plant available water is held between 0.33 and 15 bars. The same thing was pointed out by Jamison et al. (40).

As plant roots absorb water, soil moisture tension increases in the immediate vicinity of the roots. This gives rise to a moisture gradient which initiates moisture flow. From a purely physico-chemical viewpoint, a plant should show the same growth responses in soils as it does in an osmotic solution of equal stress, if all other variables were held constant. In practice, however, this is not so. The failure of this similarity could be due, in part, to the transmissibility of water in unsaturated soils. Gingrich and Russell (31) studied this problem and concluded that the water transmission characteristics of soil are believed to affect the root growth and are more pronounced in the range of 1 to 3 bars tension.

A considerable amount of diverse opinion has been evolved concerning the moisture availability within specified energy ranges. The argument as to whether soil moisture is equally available at all points between 0.33 and 15 bars tension, or whether availability decreases with increasing tension has been reviewed by Richards and Wadleigh (76). The most common explanation for reported differences has been based upon an analysis of the shape of moisture energy relation curves. Peters (64) offered a good explanation to this problem. In his studies, he set up a soil moisture variable in such a manner that separated the effect of the moisture tension component from the moisture content component upon plant growth and water absorption. He concluded that uptake of water by roots is a function of the specific moisture content as well as the soil moisture tension. The data presented show that the uptake of water and elongation of corn roots was decreased as the moisture tension increased; that the uptake of water and root elongation decreased as the moisture content per unit tension decreased. He suggested a mathematical relationship that the radius of soil from which plant roots must extract its water is directly proportional to the amount of water absorbed and inversely proportional to the slope of the moisture characteristic curve. Thus the study of the moisture characteristic curves is of great importance in the investigation of plant root and soil moisture relationships.

In the field of soil structure, attempts have been made to define soil structure and the moisture relationships in terms of the stability of aggregates. Such studies have been reported by Feng _et al_. (27), Garey (29) and Mazurak (55), on synthetic aggregates and natural aggregates. However, there is very little information over the complete range of aggregate size and concerning the effect of particle and aggregate sizes on the soil moisture availability. Wittmuss and Mazurak (96) undertook such a study. They determined the physical and chemical properties of a range aggregates from 4760 to 18.5 microns in size and compared them with the physical properties of a complete range of primary particles. The physical effects of aggregation were attributed by them to the differences between the physical properties of aggregates and ultimate particles for a given size fraction. They found that there was a definite trend for the smaller sized aggregates to retain less moisture at a given tension than did the larger sized ones. Their data show that for aggregates of diameter 4760 to 2380 micron the tension of maximum moisture release was 0.000 to 0.005 atmosphere while for aggregates of 74 to 34 micron it was 0.08 to 0.17 atmosphere. This increased tension was directly related to the size of the pores among the particles within aggregates. Such studies have a great potential in explaining fundamental relations between soil structure and moisture status.

In the course of the discussion of soil moisture status as affected by tillage and management practices, it is pertinent to discuss: a) the contact between soil solution and plant roots, b) ion absorption by plant roots and c) seed germination, because the soil moisture status can greatly influence these factors.

a. Contact between soil solution and plant roots

Miller and Mazurak (57) have observed that the area of root solution contact and aeration, as determined by moisture tension and pore size, appear to be the dominent factors affecting plant growth. They grew sunflower in 20 compacted soil separates ranging in diameter from 4760 to 2.31 microns and having pores of diameter between 529 to 2.23 microns. Two moisture levels were used, 20 cm. of water tension and the moisture content at the flex point on the moisture retention curve. Their results show that the maximum growth of sunflower occurred at 20 cm. water tension from separates between 52.3 and 210 microns in diameter, i.e., pores with mean diameter of 17.7 to 43.5 microns. The optimum growth of sunflower at the flex point moisture was obtained on separates between 13.1 to 9.25 microns in diameter whose pores were about 4 microns in diameter. Their data support the hypothesis that the maximum growth rate of sunflower at both moisture levels was determined by the influence of pore size upon aeration and the area of root solution contact. The greater the area of root solution contact the more favorable was the growth of roots and shoots, provided aeration was not limiting.

b. Ion absorption by plant roots Although considerable attention has been paid to the study of the response to plants to moisture and aeration, there is a lack of information on the dependency of ion absorption upon the moisture content in the soil. Danielson and Russell (19) studied the ion absorption by roots as influenced by moisture and aeration. By studying the Rb86 uptake in corn, they concluded that Rb uptake decreases rapidly with initial increase in soil moisture tension (up to 3 bars). The ion uptake from soil is nearly a straight line function of soil moisture content. Their results can be explained on the basis that the thickness of moisture films connecting the absorbing roots may control the ion concentration at the root surface. They hypothesized that reduced uptake was due to the reduction in the diffusion rate of ion species as the moisture content was decreased. Peters and Russell (66) carried this work further and found that the reduction in ion uptake is more closely related to the reduced concentration of ion species than to the reduced diffusion to plant roots. Another possible explanation for the reduced uptake could be that increased tension or reduced moisture content has a large effect on the rate of growth of plant roots, this reduced growth rate in turn reduces the ability of roots for ion absorption.

Mederski and Wilson (56) also observed that the variation in soil moisture was concomitant with the variation in ion absorption by corn roots. They hypothesised: a) at low moisture contents, the continuity of the moisture film is broken and ion transfer from soil to root is impared; b) as the thickness of moisture film decreases, solvent properties of water also decreases; c) at low moisture content, the amplitude of the cationic swarm surroundings soil particles is decreased.

c. Seed germination It is commonly observed that the emergence of many seedlings is greatly influenced by the physical condition of soil. Hanks and Thorp (34) reviewed the work on this aspect and conducted an experiment to study the emergence of wheat seedlings in three different textured soils with different combinations of soil moisture, bulk density, oxygen diffusion rate and crust strength. They reported that the ultimate seedling emergence, in general, was nearly the same when the moisture content was maintained between the field capacity and the wilting percent provided other factors for maximum seedling emergence were not limiting. The rate of seedling emergence was, however, related directly to the moisture content. Their data show that bulk density was related indirectly to seedling emergence in that any changes in bulk density bring about changes in oxygen diffusion rate and crust strength. Crust strength as measured by modulus of rupture, apparently limited seedling emergence in the drier end of the available moisture range.

Many of the relationships between environmental conditions and germination of seed are not thoroughly understood. Suput (87) suggested that there is some minimum soil moisture content for satisfactory germination and the early growth of a crop. He, however, did not specify any limits. Hunter and Erickson (37) have established some definite relationships between germination and soil moisture tension. According to their results, for good germination at 25° C. a soil must have a moisture tension of not more than 12.5 bars for corn kernels, 7.9 bars for rice kernels, 6.6 bars for soybean kernels and 3.5 bars for sugar beets. Wiersma (94) recently has reviewed the literature in great detail concerning soil environmental conditions and seed and root development.

The growth rate of plants as an index of soil moisture availability has been used by some workers. Blair et al. (7) reported that the time rate of stem elongation of sunflower was markedly reduced before one-half of the available water was depleted. Gingrich and Russell (30) found that increases in soil moisture tension from 1 through 12 bars brought about progressively smaller increases in the radicle elongation, fresh weight, dry weight, and seedling hydration. Growth properties were most sensitive in the range between 1 and 3 bars tension. At low moisture stress, oxygen concentration of the root atmosphere needed to be above 10.5 percent for maximum growth.

Flocker and Nielson (28) used the growth of tomato plants as a criterion for determining the effect of soil moisture on growth processes. They used two soil types and compressed them to five levels of bulk densities. In one part of the experiment, the air space was maintained at about 15 percent by regulating the soil water content and/or the suction at pre-calculated levels. In another part of the experiment, the soil suction was maintained at about 0.5 bar while the air content was varied. They concluded that the decrease in yield of tomatoes corresponding to an increase in the bulk density at nearly a constant air space may be attributed to increasing soil suction. If the mean soil suction was maintained at about 0.7 to 1.0 bar, the fresh weight yield was independent of bulk density provided the air space was not limiting. At 14 percent air space, the fresh weight was dependent only on soil suction. Thus they tried to evaluate the moisture supply, mechanical impedence and aeration separately and then studied their interaction.

In summary it may be said that although one of the basic objects of tillage is to create the desired tilth around the seed (*i.e.*, most favorable physical condition of soil) yet very little is known concerning the quantitative specifications of tilth. It is now an established fact that different tillage practices produce different types of seed beds, depending upon the soil type as shown by Haynes *et al*. (35), upon the climatic condition and the soil type according to Bower *et al*. (9), Browning *et al*. (13, 14) and on the type of tillage practices as shown by Ackerson (1) and Peterson (67). Therefore, as pointed out by Yoder (99), Page *et al*. (63) and Jamison *et al*. (42), there is a tremendous need to investigate further the significance of soil structure as related to problems of tilth.

B. Principles of Soil Aggregation

In order to understand the retention and conduction of moisture in soil as influenced by aggregate size, it is necessary to consider the causes and mechanics of formation of aggregates.

In the early work on aggregation, flocculation in dilute suspension was the basic concept of granulation and aggregate formation, but as early as 1936, Bradfield (10) found that granulation consists of flocculation plus the cementing or binding together of flocculated particles. Three main factors are thought to be responsible for this binding action: a) cations, b) soil colloids, and c) organic matter.

1. Factors involved in binding soil particles

a. Cations Calcium is known to be a flocculating agent while sodium is a deflocculating agent. For a long time it was considered that exchangeable calcium has a binding effect. In 1935 Baver (3) undertook a statistical analysis of 77 different soils of the United States of America and showed that there was no significant correlation between the amount of exchangeable calcium and granulation. Peterson (69), however, suggested that liming and addition of organic matter may cause stable granulation of soils through calcium linkage between certain polyuronides and clay particles. In view of the present day knowledge it may be concluded that exchangeable calcium has an indirect effect on aggregate formation, *i.e.*, it affects the production and decomposition of organic matter (4).

b. Soil colloids This material has a great cementation effect in aggregate formation. In the soil, the colloidal material exists in three forms--namely, as clay particles, irreversible or slowly reversible inorganic colloids like the oxides of iron and aluminum, and organic colloids. Baver (3) has reported that cementation effects of clay were more pronounced with smaller aggregates (.05 mm.). Russell (78) presented a theory of the mechanism of aggregate formation. He suggested that it takes place in three steps, first the hydrated cations give rise to orientation of water molecules, then chains of oriented dipole molecule are formed in the vicinity of soil particles, and finally these chains are then linked as the dehydration takes place. He postulated that the dipole water molecules hold calcium ions and clay particles together by directing negative ends towards the calcium ion and the positive ends towards the clay surface. This theory of Russell (78) is criticized because of its weakness of placing too much emphasis upon cations as the connecting link between particles.

Sideri (83) visualized that oriented absorption of disc shaped clay particles onto the sand surface and subsequent dehydration into an almost irreversible state may be the basis for stable aggregate formation.

Since water is considered to be the bond between the oriented particles, dessication contracts the chain of water molecules and brings the particles together. Complete dehydration effects a union of clay micelles through oxygen linkages, as water is driven off from the OH groupings in the surface (5). Thus it is apparent that the cohesive forces between oriented clay particles are extremely important in aggregate formation. That the type of clay minerals have a bearing on aggregate formation was brought out by Peterson (68). He measured the relative capacity of kaolinite and montmorillonite to form water stable aggregates under the influence of cyclic wetting and drying. He found kaolinite was very inert as a binding agent. Montmorillonite formed gel-like globules which varied in resistance to dispersion in water.

There is some experimental evidence to suggest that irreversibility of colloidal iron and aluminum hydroxide is an important factor in the production of stable aggregates in certain soils (5).

c. Organic matter It is a commonly accepted fact that organic matter works as a granulating agent in the soil. That organic matter is useful in the formation of relatively large stable aggregates was pointed out by Baver (3) who found a very high correlation between organic matter and aggregation in soils containing less than 25 percent clay. Various attempts have been made in the past to explain the exact nature of organic matter effects on granulation. Williams (95) explained that the tenacity of the binding forces of aggregates was due to the saturation of aggregates with ulmic acid which is a secretion of anaerobic bacteria during decomposition of roots of plants. When divalent cations are associated with ulmic acid, a water stable cement is supposedly produced. It is not understood why Williams (95) did not take into account humic, aprocrenic, and other acids which are also present in soil.

Sideri (83) considered that humus is adsorbed by clay through the process of the orientation of organic molecules on the surface of clay particles. This adsorption is irreversible upon dehydration.

Myers' (59) data show that the polar adsorption of organic and inorganic colloidal materials may offer an explanation of the union between the two. The humic compounds are polar and are therefore, capable of being oriented. They are only slightly ionized compounds and the carboxyl ends are positive. Soil colloids, on the other hand, possess electrical properties and therefore, serve as orienting material. Soil colloids are electro-negative and attract towards their surface the positive ends of the organic compounds. This polar adsorption results in a close packing of organic colloids on the surface of inorganic colloids. Then the dehydration of the adsorbed humus results in a stable union between the organic and inorganic materials.

Kubiena (48) suggested that there is gradual dissolution of the humus in slightly alkaline solutions. This alkali soluble humic material serves as a coating and binding agent when the process of dehydration is complete. This theory is good for explaining the formation of aggregates in chernozen soils (5).

Certain polysaccharides formed during the decomposition of organic residues by microbial activity may serve as a cementing agent as was pointed out by Martin (52, 53). Kroth and Page (47) worked on natural and synthetic aggregates and on incubation studies in which fresh and composted organic matter were incorporated with soil. They found that all aggregating agents were uniformly distributed throughout the aggregates. They thought that polar substances resulting from decomposition of fresh organic matter were most effective in aggregating cultivated soils. More resistant humus, fats, waxes and resins were found to be effective as well. They suggested a need for additional research so that good management can insure a constant supply of polar active materials in order to keep a given soil in optimum physical condition.

Robinson and Page (77) while studying aggregate stability found that organic matter associated with the clay fraction and presumably adsorbed on the surfaces of clay particles is the fraction most effective in aggregate stabilization.

Page (62) gave the following remarks about the role of organic matter in soil aggregation:

> It is generally agreed that organic matter plays a key role in the soil aggregation and most of the workers have apparently concluded that the main effect is cementing. But very little direct evidence can be found in the literature concerning the mechanism of cementing action of organic matter. Some workers proposed that organic matter cause soil aggregation through co-precipitation or flocculation with clay colloids. Others have suggested that organic matter serves to water proof the soil thus preventing further breakdown of already formed aggregates. There has been some study concerning the nature of the organic compounds involved in the production and stabilization of aggregation. A lignin-protein complex was once thought to be the important constituent, however, the fact that such complexes are subject to further microbial attack raises some doubts as to their importance in producing long time stable aggregates.

Therefore, although the exact nature of the organic matter effect is not completely understood, the majority of the evidence points to some type of oriented adsorption or complex linkage of organic molecules with clay particles that is stabilized by subsequent dehydration.

2. Natural agencies involved in aggregate formation

Even though the nature of flocculation and cementing agents in soils is somewhat understood, there is no clear picture concerning the processes of aggregate formation under natural conditions. The activity of root systems appears to be very important, acting to separate and compress small clumps of the soil, causing shrinkage and cracking due to dessication near the root, and making conditions favorable for activity of micro-organisms at the surface of these units. Page (62) pointed out that although it has been demonstrated in laboratory experiments that aggregation increases in almost direct proportion to the number and activities of micro-organisms, it is difficult to use these results to explain the field situation. He suggests that it is rare that the sources of energy are as abundant in the field as are provided in the laboratory. Furthermore, the level of aggregation soon diminishes sharply as the energy sources are utilized and the number of micro-organisms is decreased.

Periodic changes in moisture and temperature are considered to be processes responsible for aggregate formation. Alternate wetting and drying causes cracks or cleavage planes to develop due to differential swelling and shrinkage. Freezing causes localized pressure and makes the soil break up into rather small crumbs. Tiulin (90) considered that pressure and co-agulation aid in aggregation. According to him, pressure produces more intimate contact between particles so that the cementing influences of water films are rendered more effective. Baver (5) has given a detailed review of literature concerning the role of the natural agencies in the process of aggregation.

Page (62) visualized the formation of aggregates in nature as follows:

> Aggregates result primarily from the action of natural agencies by which parts of the soil are caused to clump together and separate from adjacent masses of soil. There are two kinds of processes involved (a) building up of aggregates from dispersed materials and (b) breaking down of large coherent masses into favorable sized aggregates. The second process is more important because most soils become more dense and compact with continuous farming, and the large masses are broken down through (a) the action of small animals like earthworms, (b) the tillage practices, (c) pressure and differential drying caused by freezing, (d) compression due to roots and (e) localized shrinkage caused by the removal of water by roots or evaporation.

3. Structure of soil aggregates

Recently Emerson (26) has reported a study on the structure of soil crumbs. According to his concept, the hypothesis of organic matter forming inter-crystalline complexes is untenable. From his previous work, he has concluded that the clay crystals in soil crumbs formed by drying are oriented. Flakes of oriented calcium saturated clay do not disperse in distilled water unless mechanically disturbed. He defined a Clay-Domain as a group of clay crystals having suitable exchangeable cations which are oriented and sufficiently close together for the group to behave in water as a single unit. Emerson (26) thinks that the process of soil drying by roots may be enough to bring the clay aggregates together sufficiently close so as to form a domain. He hypothesized that organic matter and soil conditioners stabilize soil crumbs by increasing the strength of quartz-clay bond. The carboxylated polymer form bonds with quartz surfaces in addition to bonding clay crystals together. As per his model of a soil crumb, several clay domains are linked to each quartz particle. The types of bonds could be (a) between quartz-organic matter-quartz, (b) between quartz-organic matter-domain, (c) between domain-organic matter-domain and (d) between domain-domain-edge faces. He advances two evidences in favor of his concept. First that the crystalline water uptake by the clay in the soil crumbs and swelling of crumbs are unchanged by the presence of a polymer. Second, that no alterations in the spatial distribution of crumbs constituents is required to accommodate the polymer. This implies that the pore size distribution is also unchanged by the presence of the polymer. In support of this statement, he quotes data of Jamison and Kroth (41), Peters et al. (65) and Wittmuss and Mazurak (96). The first authors found similar moisture retention curves for grass land and cultivated soil. The other authors found that the soil moisture retention curves were the same for soils treated with soil conditioners and the untreated soils. The limitations of the model proposed by Emerson (26) are that it applies only to the soil crumbs in which the clay domains are free to take up their inter-crystalline water. Secondly, it does not apply to crumbs in which clay is purely kaolinite.

In conclusion it may be said that the fundamental process of aggregate formation is at best but little understood. It is recognized that the shape, size, configuration and stability of aggregates govern the porosity of the soil system and consequently the physical and chemical environment in which the plant roots grow. Thus there is an acute need for further investigation into this problem in order to understand the differences between the properties of one aggregate system and another.

III. METHOD OF PROCEDURE

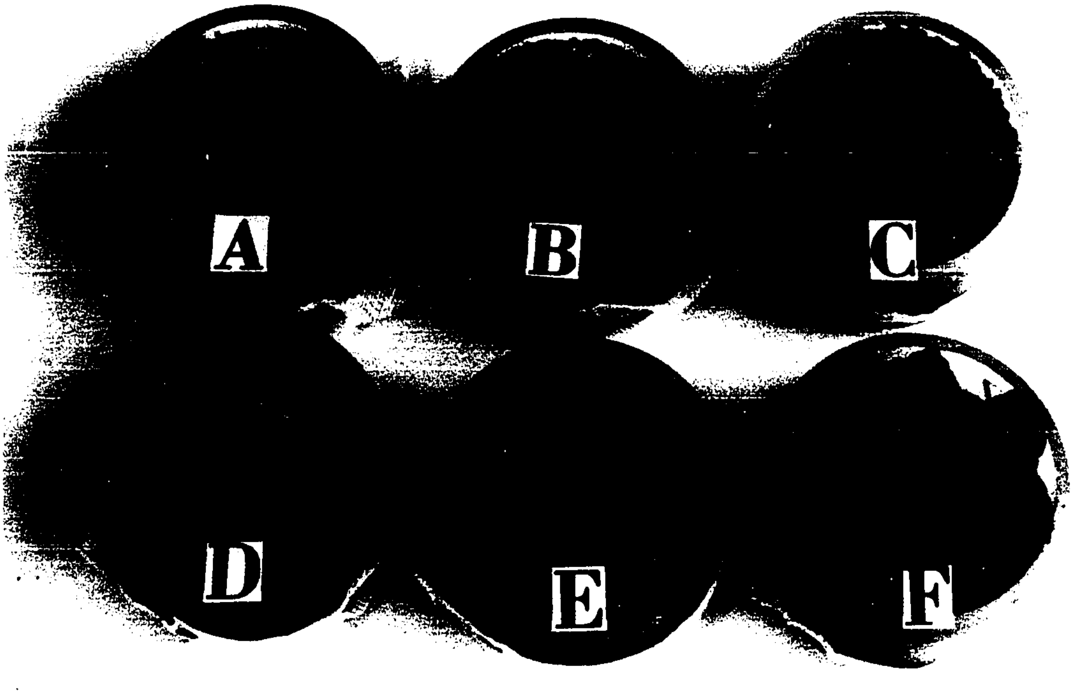
A. Collection of the Soil Samples

Bulk samples from the surface 0 to 9 inches of Nicollet silt loam were randomly collected from a field at the Agronomy Farm at Ames, Iowa. The samples were taken from plots X, 2, 10 and L of block IV of the fertilizer experiment number I on corn.

B. Preparation of the Samples

The larger clods in the bulk sample of soil were broken by hand and the mass of soil was air dried. Repeated lots of approximately 500 g. samples of air dried soil were agitated by hand on a 2.0 mm. sieve for about 3 to 4 minutes. Subsequently the material passing through this sieve was further separated into smaller fractions to obtain aggregates of 1.0 and 0.5 mm. in diameter. For obtaining aggregates larger than 2.0 mm. in diameter, a set of four sieves, (namely, 9.5, 5.0, 3.0 and 2.0 mm. openings) was used. Dry sieving was done by screening approximately 500 g. samples each time and agitating for about 3 to 4 minutes. Soil aggregates remaining on sieves of 9.5 mm., 5.0 mm., 3.0 mm., 2.0 mm., 1.0 mm. and 0.5 mm. were separated from the entire lot of surface samples (Figure 1).

Figure 1. The six aggregate sizes used in the study: (A) $> 0.5 <$ 1.0 mm., (B) $> 1.0 <$ 2.0 mm., (C) $> 2.0 <$ 3.0 mm., (D) $> 3.0 <$ 5.0 mm., (E) $> 5.0 <$ 9.5 mm., (F) > 9.5 mm. $<$ 12.0 mm.


A
B
C
D
E
F

C. Determination of Properties of Soil Aggregates

The particle size distribution of all six aggregate sizes was determined by the Pipette method as described by Kirkham (45). The results are reported in percent silt (between 20-50 microns), percent clay (less than 2 microns) and percent sand (greater than 50 microns).

The organic carbon content of each aggregate size was determined by the method described by Tinsley (89), i.e., digesting the soil with potassium dichromate and sulphuric acid and titrating the excess of acid with ferrous ammonium sulphate.

The total surface area was determined by the procedure of Bower and Gschwend (8). The aggregates of 0.5 mm., 1.0 mm. and 3.0 mm. diameter sizes were ground to pass through a 60 mesh sieve and then treated with hydrogen peroxide to remove organic matter. The weight of vacuum dried unheated soil was determined by drying in a vacuum 2.10 g. of the prepared sample over phosphorous pentoxide in an evacuated dessicator, until (about 5 to 6 hours) a constant weight was obtained. The weight of ethylene glycol retained by a heated soil was determined by heating the prepared sample in a muffle furnace at 600 ± 15°C. for two hours. One ml. of ethylene glycol was then added to the soil. The excess of ethylene glycol was removed by drying in vacuum until the loss in weight per hour interval was less than three to four percent of the weight of the ethylene glycol remaining on the soil. The following relation was used to calculate the total surface area.

Total surface area in sq. meter per g. =

$$\frac{\text{wt. of ethylene glycol retained by heated soil (g.)}}{\text{wt. of vacuum dried unheated soil (g.)} \times 0.00031}.$$

The factor 0.00031 is derived from the assumption that 3.1×10^{-4} g. of ethylene glycol are required for the formation of a mono-molecular layer of 1 sq. meter of a surface (8).

The apparent bulk density of individual aggregates was determined by the method of Chepil (15). A test tube of 50 ml. capacity and about six inches in height was filled with aggregates. The test tube was tapped on the table 20 times before obtaining the weight of its contents. The contents of the tube were then weighed and the bulk density of aggregates was calculated using the following relation as used by Chepil (15).

The apparent density of the soil aggregate =

$$\left(\frac{\text{bulk density of bed of aggregates of some sieve grade}}{\text{bulk density of oven dry quartz sand of any sieve grade}}\right) \times \text{(real density of quartz grain)}.$$

Chepil (15) used aggregates of quartz sand and gravel of various sieve grades and found that their bulk density varies between 1.59 and 1.48 g. per cc. for various sieve grades. He considers that an average figure of 1.53 can be used as a constant value for any sieve grade of quartz sand. He also found that the real density of quartz sand is constant and is 2.65

for various particle sizes.

D. Determination of Moisture Retention by Various Aggregate Sizes

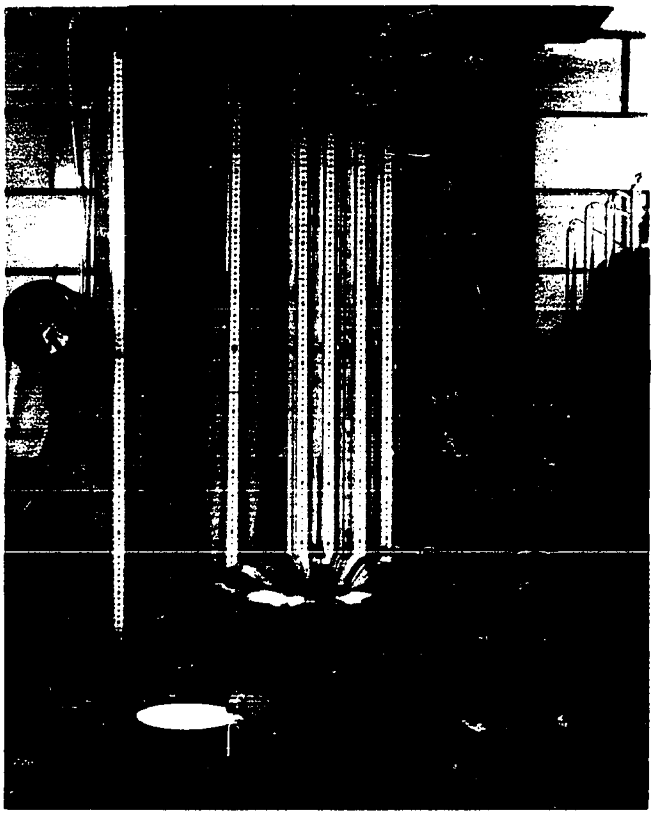
The pressure plate apparatus described by Richards (75) (Figure 2) was used for determining the moisture retention of 9.5, 5.0, 3.0, 2.0, 1.0 and 0.5 mm. diameter aggregates at tensions between 0.10 and 1.0 bar. Each aggregate size sample was poured into the sample retaining rings which were resting on the pressure plate. These were brass rings, 44 mm. in diameter and 22 mm. in height. The aggregates while in the ring were saturated with water overnight and pressure was applied to the system the next morning. For each aggregate size, the moisture retention determinations were made in triplicate at tension levels of 0.10, 0.20, 0.33, 0.50 and 1.0 bar. However, the triplicate samples were all placed in the same pressure unit at the same time. The amount of moisture retained was determined, after equilibrium was reached in about 98 hours, in the usual manner by oven drying the samples at 105° C. for 24 hours. The results are expressed in percent moisture on a dry weight basis. The bulk density of each sample was used for converting the results to a volume basis.

For determining moisture retention by aggregates at tension between 2 and 15 bars, the pressure membrane apparatus of Richards (76) was used (Figure 3). The samples were kept

Figure 2. (a) Pressure plate apparatus containing aggregates in the rings

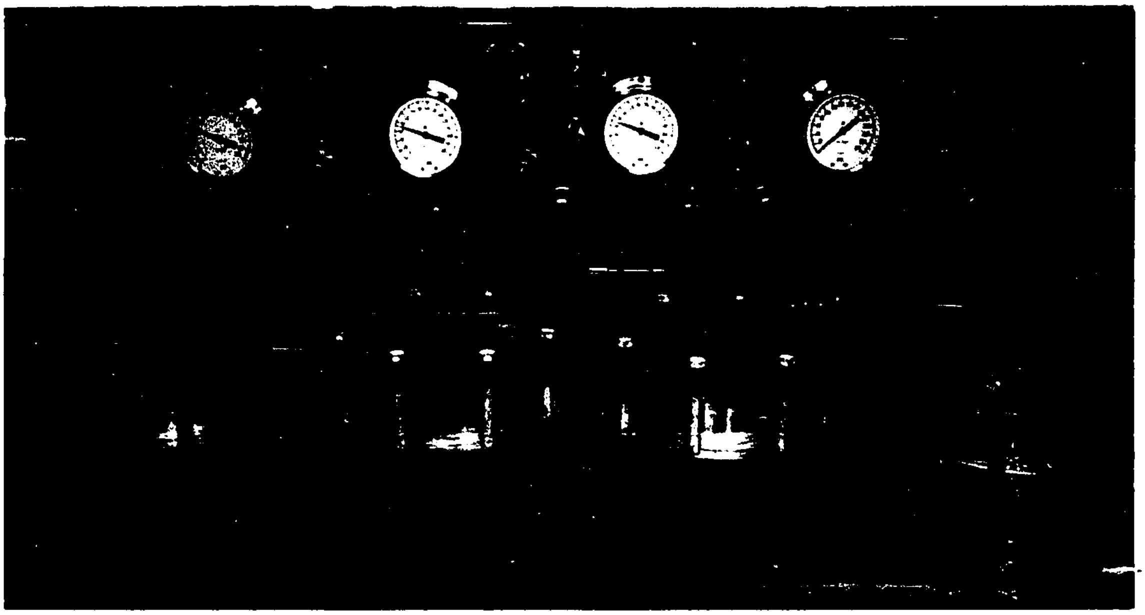
(b) The pressure plate apparatus in use

a



b

Figure 3. The pressure membrane apparatus in use



and wetted in the same manner except that the sample retaining rings were of plastic and were 58 mm. in diameter and 10 mm. in height. In this case the tensions used were 2, 3, 5, 10 and 15 bars and the time required for reaching equilibrium was 108 hours.

E. Determination of Moisture Retention by Three Aggregate Sizes at Three Levels of Packing

From the study of the moisture retention data of the aggregates ranging between 0.5 mm. and 9.5 mm., it was found that the aggregates of diameter of 0.5 mm. retained less moisture than those of 2.0 mm., 3.0 mm., 5.0 mm. and 9.5 mm. diameter. There was practically no difference in the moisture retention by the latter four aggregates. Therefore, aggregates of 0.5 mm., 1.0 mm. and 3.0 mm. diameter were chosen for further study. Three levels of packing were selected for studying the effect of packing on moisture retention:

a) Loose packing, having a bulk density of 0.95 g. per cc. This level was chosen because it could be obtained without any destruction of the natural aggregates.

b) Medium level of packing, having a bulk density of 1.15 g. per cc. This level was selected because it commonly occurs in the field.

c) Higher level of packing, having a bulk density of

1.36 g. per cc. This level was arbitrarily chosen because packing to a greater bulk density resulted in the destruction of more than 60 percent of the original aggregates.

To obtain the same levels of bulk densities (*i.e.*, .95, 1.15 and 1.36 g. per cc.) at each time, the quantity of soil to be contained in the volume of the ring was calculated. Plexiglas (acrylic plastic) rings of 50 mm. in diameter and 30 mm. in height were used as sample retaining rings. The bulk density of 0.95 g. per cc. was obtained by gently pouring the soil aggregates into the ring with no packing. For obtaining a bulk density of 1.15 g. per cc., packing of soil aggregates was done by hand with a plexiglas plunger. To obtain a bulk density of 1.36 g. per cc. use of hydraulic press was made in addition to packing by hand with a plexiglas plunger. A pressure of approximately 50 to 60 pounds per sq. inch was applied to successive layers until the desired amount of soil was contained in the ring. The determination of moisture retention for nine combinations (*i.e.*, 3 levels of bulk density and 3 aggregate sizes) were made in triplicate. However, the triplicate samples were all placed in the same pressure unit at the same time. It was observed that the aggregates were relatively less destroyed if wetted under partial vacuum as compared to wetting under atmospheric pressure. Thus the samples were wetted under a partial vacuum of about 1.0 cm of mercury as suggested by Mazurak (55).

For tensions of 0.10, 0.20, 0.33, 0.50 and 1.0 bar, the pressure plate apparatus of Richards (75) was used and for tensions of 3.0, 5.0 and 15.0 bars, Richards (74) pressure membrane apparatus was used. The moisture content was determined as described in Section D and expressed on a weight and a volume basis.

F. Determination of the Extent of Destruction Caused to the Aggregates by Packing and Wetting

1. Krilium treatment

The aggregates were partially evacuated and then wetted with a solution of krilium (Vinyl Acetate Maleic Acid copolymer) so that the concentration of the additive in the dry aggregates was 0.15. These aggregates were then air dried.

2. Packing and dry sieving

Natural aggregates and krilium treated aggregates were packed in the plexiglas rings to three levels of bulk densities (as mentioned in Section E above) and then dry sieved. The quantity of material passing through the respective size of the sieve was reported as destroyed. The percent destruction of the original aggregates was calculated from the total weight of the aggregates in the ring after packing and before sieving.

3. Packing followed by wetting under atmospheric pressure and under partial vacuum

Natural aggregates and krilium treated aggregates were packed in plexiglas rings to three levels of bulk densities as above and then wetted under atmospheric pressure and under partial vacuum. After air drying, they were dry sieved and the percent destruction was calculated as in Section 2 above.

G. Statistical Analysis

In the determination of moisture retention by various aggregates, it was expected that the error involved would not be the same in the lower range of tension as in the higher range. In order to test homogeneity of variance, Bartlett's test described by Snedecor (85) was applied. The chi-square for the sum of each tension was calculated. It was found that there was nonhomogeneity of variance at the different tension levels. Therefore, a pooled error was not used in the analysis of variance for testing the significance of aggregate sizes, instead a separate analysis of variance for each tension level was carried out. Since the triplicate determinations on each aggregate size were all made in the same pressure unit at the same time, they were not used as replications in the statistical analysis.

For splitting the degrees of freedom into linear, quadratic and cubic effects, a set of coefficients was derived because the aggregate sizes were not equally spaced. For testing of all comparisons among means, procedure described by Tukey and modified by Snedecor (85) was used. This was made by computing the difference D, which is significant at 5 percent level, and then comparing it with the mean values of moisture retained by the different aggregate sizes. For the purpose of statistical analysis, data on moisture retention by five aggregate sizes were used.

IV. RESULTS AND DISCUSSION

The relationship between gravimetric percent moisture, aggregate size and moisture tension is shown in Figures 4 and 5. In both the figures the gravimetric percent moisture is plotted as the dependent variable. In Figure 4 aggregate size is plotted as the independent variable whereas moisture tension is plotted as the independent variable in Figure 5.

The analysis of variance and comparison of mean values of the gravimetric percent moisture retained by various sized aggregates is presented in Appendix A. The data in Figure 4 show that at all tensions, except at 10.0 and 15.0 bars, the 0.5 mm. aggregates retained significantly less moisture than the larger aggregates. Between tensions of 0.10 and 1.0 bars, the gravimetric percent moisture retained by various sized aggregates was in the following order: $0.5 < 1.0 < 2.0 \cong 3.0 \cong 5.0$ mm. Between tensions of 1.0 and 5 bars the percent moisture retained was in the following order: $0.5 < 1.0 \cong 2.0 \cong 3.0 \cong 5.0$ mm. At tensions of 10 and 15 bars, differences in moisture retention by various sized aggregates were essentially the same. The differences in soil moisture retention among 2.0, 3.0 and 5.0 mm. aggregates generally were not significant. Analysis for the linear, quadratic cubic effects of the gravimetric percent moisture retained by all aggregate sizes studied is presented in Appendix A. This analysis and data presented in Figure 4 show that the

Figure 4. The relationship between gravimetric percent moisture and aggregate size

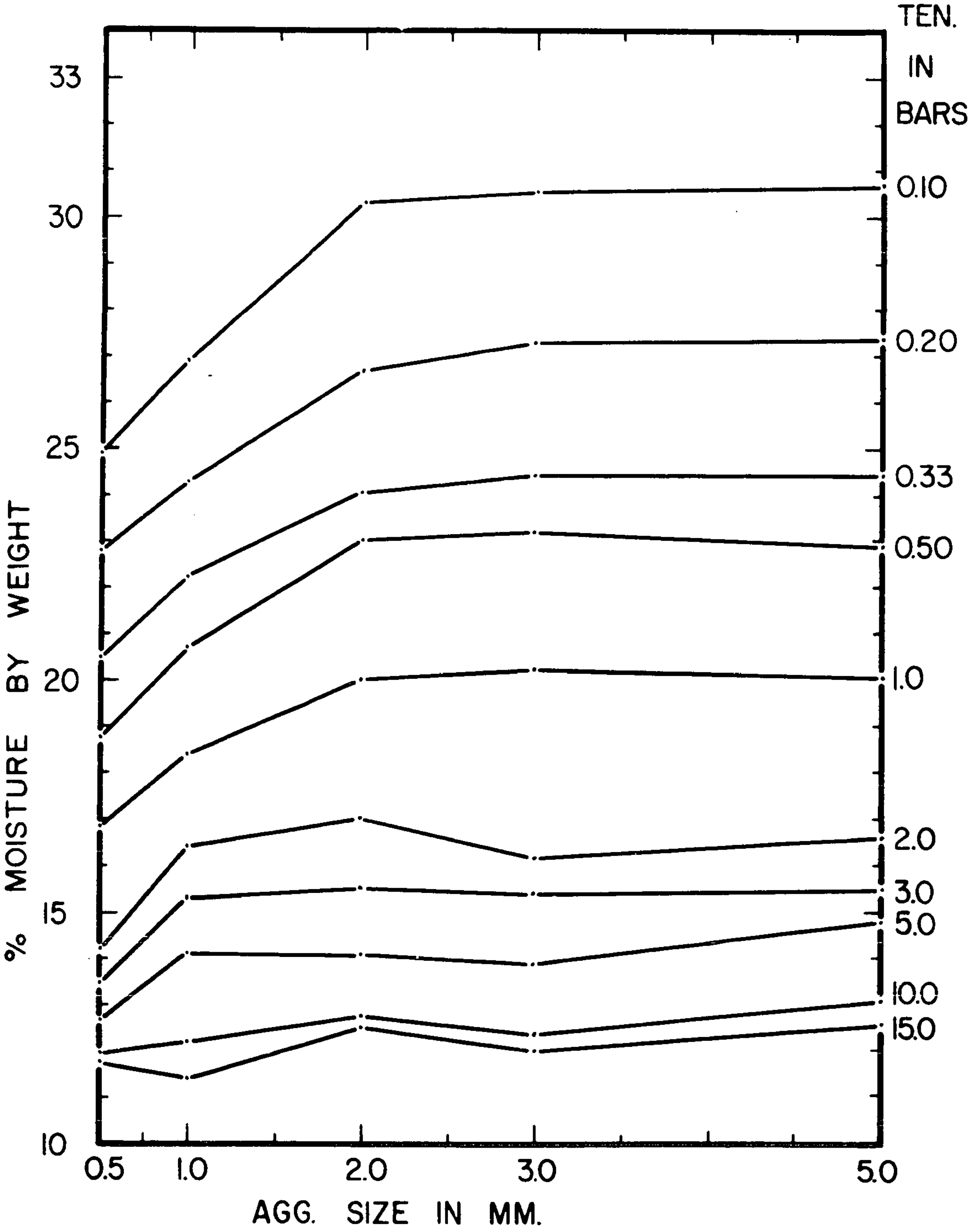
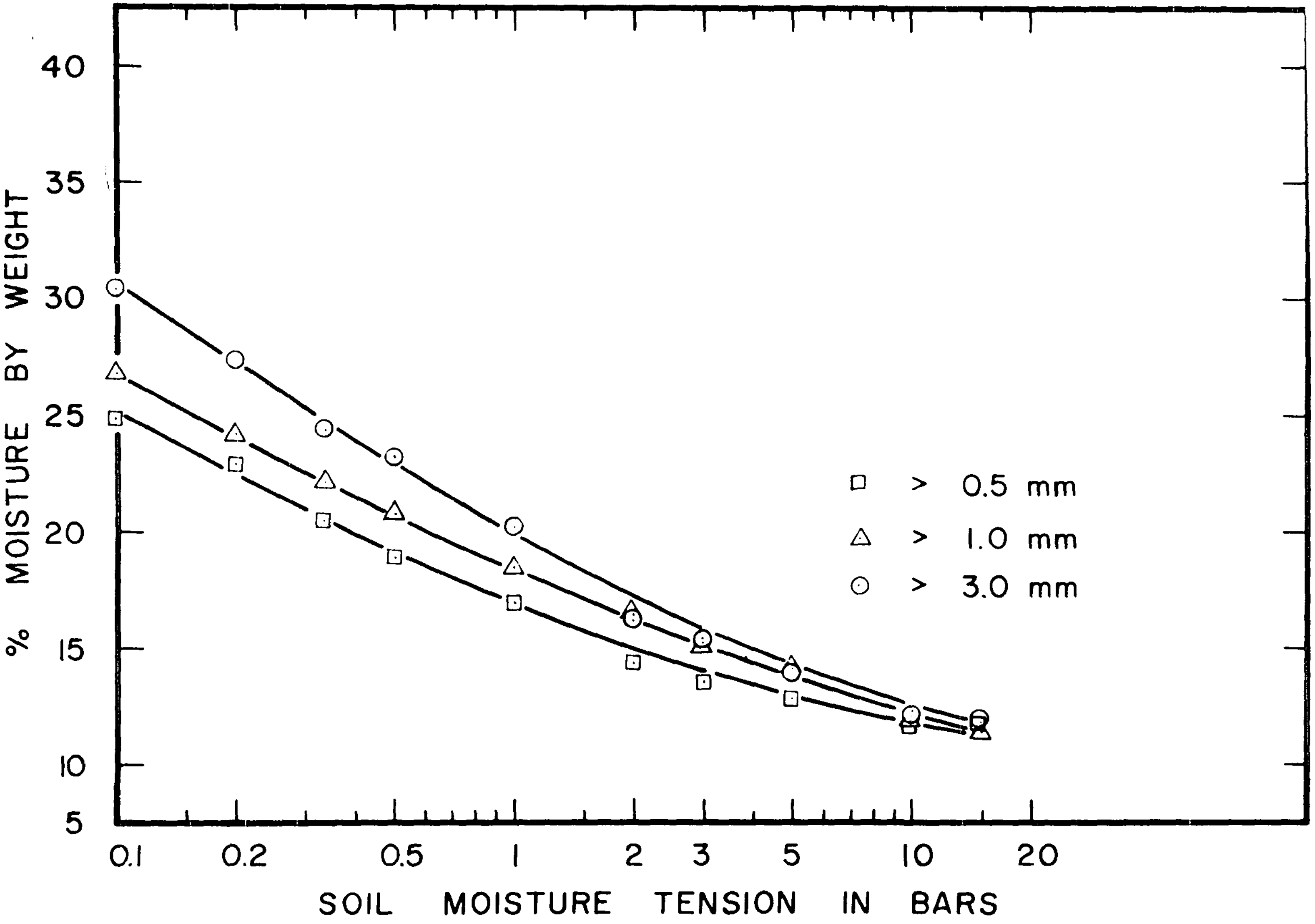

TEN.
IN
BARS
0.10
0.20
0.33
0.50
1.0
2.0
3.0
5.0
10.0
15.0
33
30
25
20
15
10
% MOISTURE BY WEIGHT
0.5
1.0
2.0
3.0
5.0
AGG. SIZE IN MM.

Figure 5. The relationship between gravimetric percent moisture and soil moisture tension (data for 2.0, 5.0 and 9.5 mm. aggregates are not plotted because the points closely correspond to the points for the 3.0 mm. curve)


% MOISTURE BY WEIGHT
40
35
30
25
20
15
10
5
0.1
0.2
0.5
1
2
3
5
10
20
SOIL MOISTURE TENSION IN BARS
□ > 0.5 mm
△ > 1.0 mm
○ > 3.0 mm

relationship between the aggregate size and moisture retention is primarily of a quadratic nature up to 1.0 bar. At tensions greater than 1.0 bar, this relationship tends to become cubic.

It is seen from Figure 5 that as soil moisture tension increases, differences in the moisture retention progressively decrease. In other words, the effect of soil moisture tension is more pronounced in the range of 0.10 to 1.0 bar than in the range of 2.0 to 15.0 bars. This may be because in the lower tension range, moisture retention is dominated by the size and shape of the pores in the soil system; whereas the moisture retained at higher tension values is dominated by surface adsorption effects.

It has been shown by Heinonen (36), and Jamison and Kroth (41) that changes in any of the textural components of a soil will tend to affect its soil moisture retentivity. Therefore, to be sure that the observed differences in the moisture retained by the aggregates of various sizes were not due to any variation in the textural component, the particle size distribution was determined for each of the aggregate sizes and is presented in Table 1.

Since a considerable variation within the textural grades (sand, silt, clay) could occur between the various sized aggregates, the determination of the total surface area of the 0.5, 1.0 and 3.0 mm. aggregates was made as a measure of uniformity of particle sizes. The data in Table 1 show that

Table 1. Particle size distribution, organic carbon content, total surface area and apparent bulk density of various sized aggregates

Aggregate size in mm.	Particle size distribution silt % 20-50μ	clay % < 2μ	sand % > 50μ	Organic carbon %	Total surface area m. sq. per g.	App. bulk density g. per cc.
0.5	36.1	22.6	41.5	1.6	34.8	1.55
1.0	35.9	22.4	41.7	1.6	34.3	1.41
2.0	36.0	22.2	41.9	1.4	--	1.39
3.0	36.0	23.2	40.8	1.4	34.4	1.38
5.0	36.8	23.2	40.5	1.3	--	--
9.5	36.6	23.2	40.2	1.3	--	--

the total surface area of the particles in the aggregates of three sizes is almost the same.

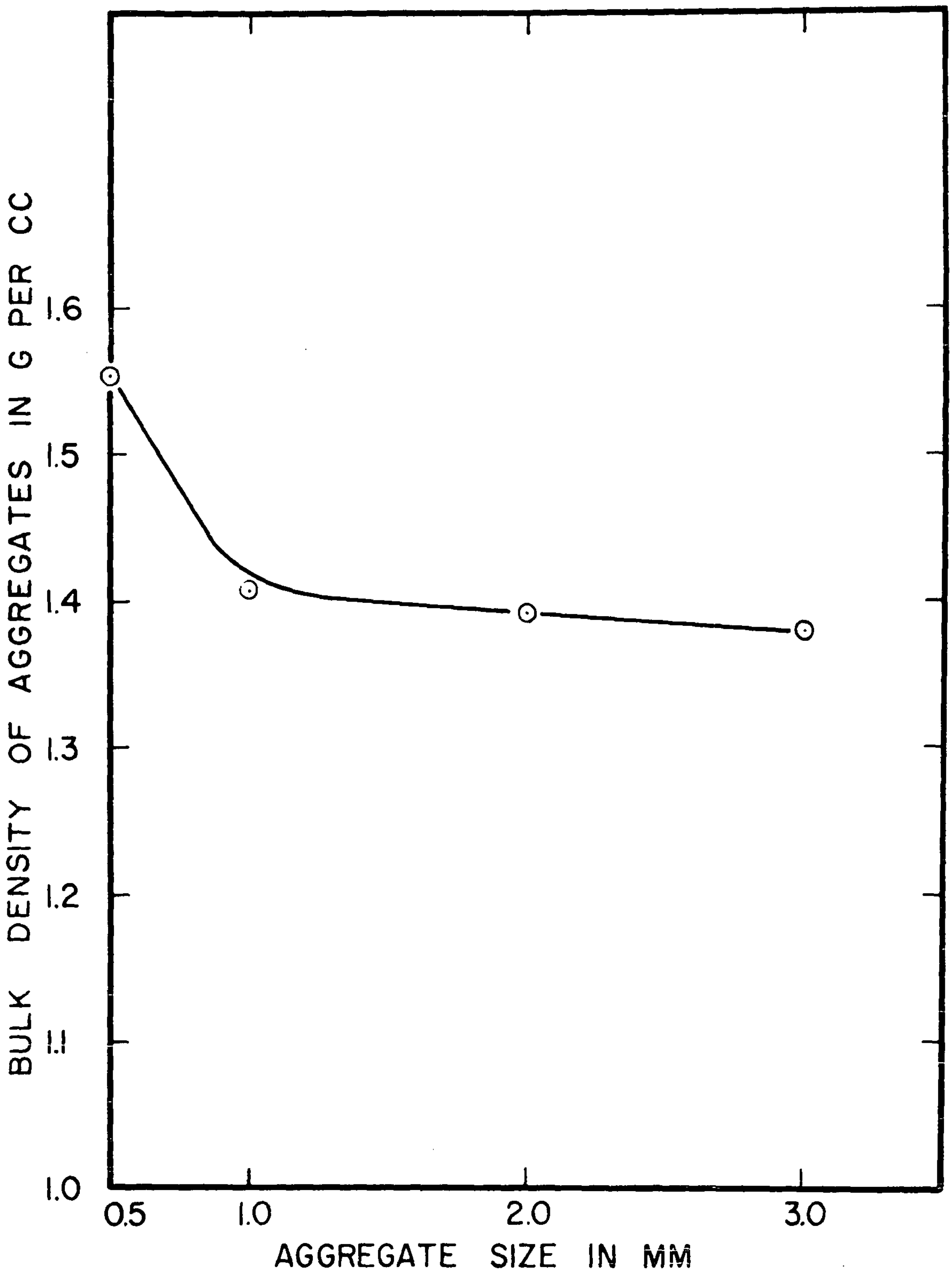
Percent organic carbon of various sized aggregates is also presented in Table 1. The data show that as the aggregate size increases from 0.5 to 9.5 mm., the organic carbon content decreases. Organic matter has been reported to be present on the external surface of the aggregates as a thin coating (52, 53). Since the smaller sized aggregates have higher external surface area, this may explain why the quantity of organic matter is greater in the 0.5 mm. aggregates than the 9.5 mm. aggregates. Higher contents of organic matter are usually associated with higher water holding capacities but in the present study a reverse trend is observed.

Thus the differences in the moisture retention by the aggregates of various sizes cannot be ascribed to increases in organic matter content.

The values for apparent bulk density of individual aggregates of various sizes are presented in Figure 6. It is observed that as aggregate size increases from the 0.5 to 3.0 mm., the apparent bulk density decreases from 1.55 to 1.38 g. per cc.

It is therefore concluded that the reason for the greater moisture retention by 3.0 mm. aggregates as compared to 0.5 mm. is that the 3.0 mm. aggregates have a greater internal porosity. These results are in agreement with those reported by Wittmus and Mazurak (96). Hagin (33) found that coarsely aggregated soils (having aggregates of 2.0 mm. and larger) produced better plant growth than did the finely aggregated soils (having aggregates of 0.5 mm. in diameter). He suggested that the total porosity of soil was not changed by the variation in the aggregate size, but the ratio of capillary to non-capillary porosity was greatly influenced. According to his hypothesis, the retarded plant growth in the finely aggregated soil was due to the presence of a smaller volume of non-capillary pores which in turn reduced the supply of oxygen and nutrients to plant roots. He, however, did not mention the factor of moisture availability to plant roots in soils of different sized aggregates. It has been shown that

Figure 6. Bulk density of aggregates of various sizes


BULK DENSITY OF AGGREGATES IN G PER CC
1.0
1.1
1.2
1.3
1.4
1.5
1.6
0.5
1.0
2.0
3.0
AGGREGATE SIZE IN MM

the availability of moisture to plants depends on the specific moisture content as well as on the soil moisture tension (64). The results of the present study show that at a given tension, the 0.5 mm. aggregates retained less moisture than did the 3.0 mm. aggregates. Therefore, the retarded plant growth, as reported by Hagin (33), in the finely aggregated soil could have been due to the reduced moisture supply to plant roots.

Variations in the intra-aggregate porosity can be related to Emerson's (26) concept of "The Structure of Soil Crumbs" as described in the review of the literature. According to him, soil organic matter and soil conditioners stabilize the soil aggregates by increasing the strength of the quartz-clay bonds within the aggregates. The intra-aggregate pore space exists between the two quartz grains. Thus it is possible to visualize that 0.5 mm. aggregates composed of a few primary aggregate units (i.e., smallest individual unit of a aggregate) possess less intra-aggregate pore space and a higher ratio of solids to voids than the 3.0 mm. aggregates.

Because significant differences in moisture retention due to aggregate size were found, an additional study of the effect of packing the various sized aggregates on moisture tension was made. Before undertaking such an experiment, a study of the destruction of natural soil aggregates due to packing and due to wetting under various conditions was initiated. The results are shown in Figure 7 which illustrates that the destruction of aggregates increased as the bulk density increased from 0.95 to 1.36 g. per cc. Packing of aggregates to a bulk density of 1.36 g. per cc. resulted in the destruction of 58 percent of the original aggregates. The 0.5, 1.0 and 3.0 mm. aggregates were treated with krilium in an attempt to increase their stability. The data presented in Figure 7, however, show that the differences in extent of destruction of the aggregates between untreated and krilium treated was not appreciable. One of the primary factors in the break down of the aggregates during wetting is the pressure exerted by the trapped air inside the aggregates (55). Therefore, wetting under atmospheric pressure and under partial vacuum was done after the aggregates were packed to three levels of bulk densities. Results in Figure 7 show that at all levels of packing, wetting under partial vacuum caused less destruction than did wetting under atmospheric pressure. Similar results were reported by Mazurak (55). Therefore in the following study, natural aggregates, without krilium treatment, were wetted under partial vacuum before the soil moisture retention was determined.

The relationship between the gravimetric percent moisture, aggregate size, bulk density and moisture tension are shown in Figures 8, 9, and 10. In all the figures gravimetric percent moisture is plotted as the dependent variable. In Figure 8

Figure 7. Percent destruction caused to the natural aggregates and krilium treated aggregates when packed to three levels of bulk densities and when wetted under atmospheric pressure and under partial vacuum

A) Packing and dry sieving

B) Packing followed by wetting under atmospheric pressure and then dry sieving

C) Packing followed by wetting under partial pressure and then dry sieving

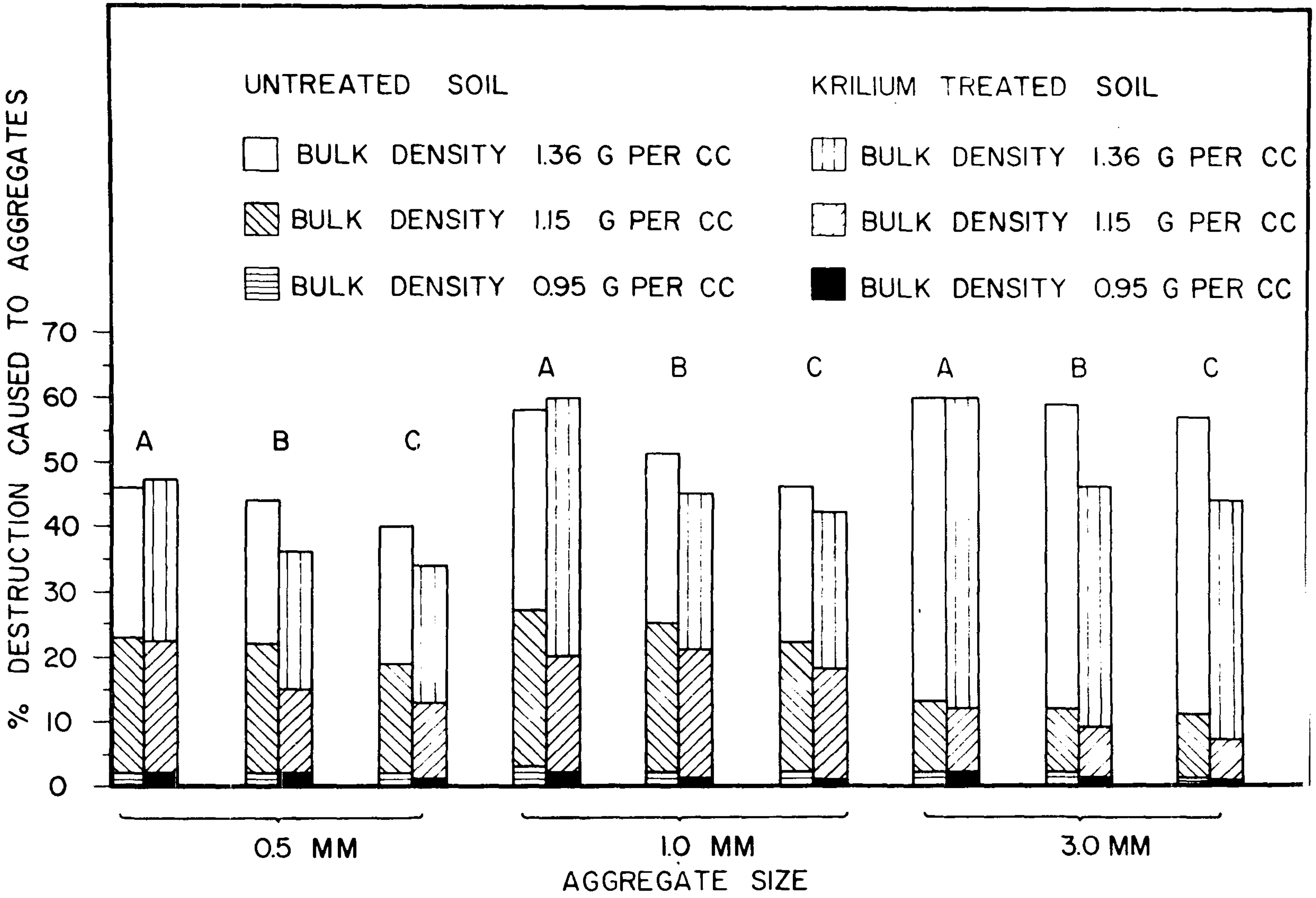

UNTREATED SOIL
BULK DENSITY 1.36 G PER CC
BULK DENSITY 1.15 G PER CC
BULK DENSITY 0.95 G PER CC
KRILIUM TREATED SOIL
BULK DENSITY 1.36 G PER CC
BULK DENSITY 1.15 G PER CC
BULK DENSITY 0.95 G PER CC
% DESTRUCTION CAUSED TO AGGREGATES
0
10
20
30
40
50
60
70
A
B
C
A
B
C
A
B
C
0.5 MM
1.0 MM
3.0 MM
AGGREGATE SIZE

Figure 8. The relationship between the gravimetric percent moisture retained and aggregate size; families of curves representing tension levels are shown for each bulk density

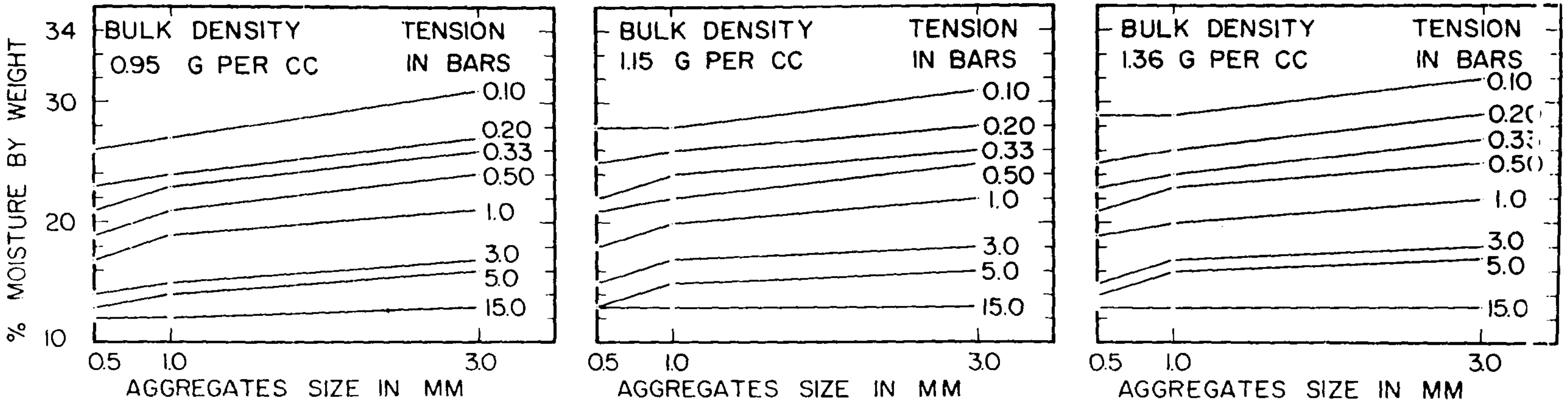

% MOISTURE BY WEIGHT
34
30
20
10
BULK DENSITY 0.95 G PER CC
BULK DENSITY 1.15 G PER CC
BULK DENSITY 1.36 G PER CC
TENSION IN BARS
0.10
0.20
0.33
0.50
1.0
3.0
5.0
15.0
0.5
1.0
3.0
AGGREGATES SIZE IN MM

Figure 9. The relationship between the gravimetric percent moisture retained and bulk density; families of curves for three bulk densities are shown for each tension level

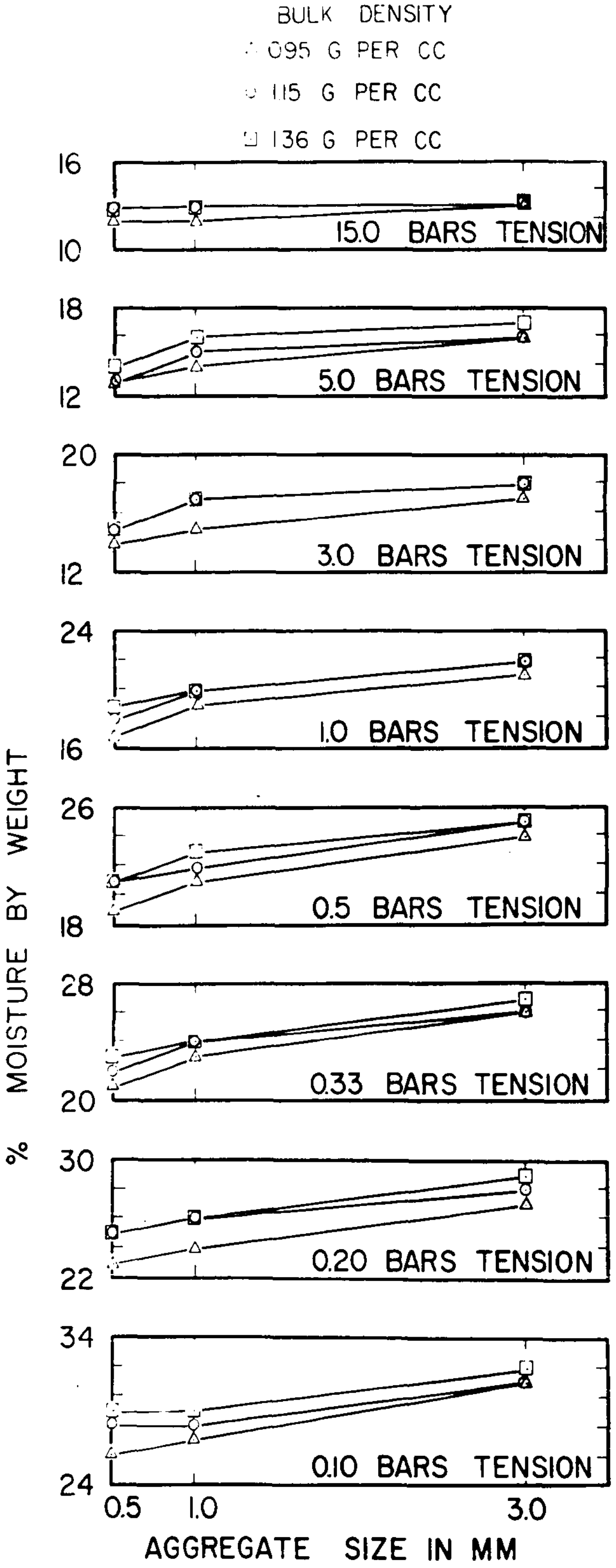
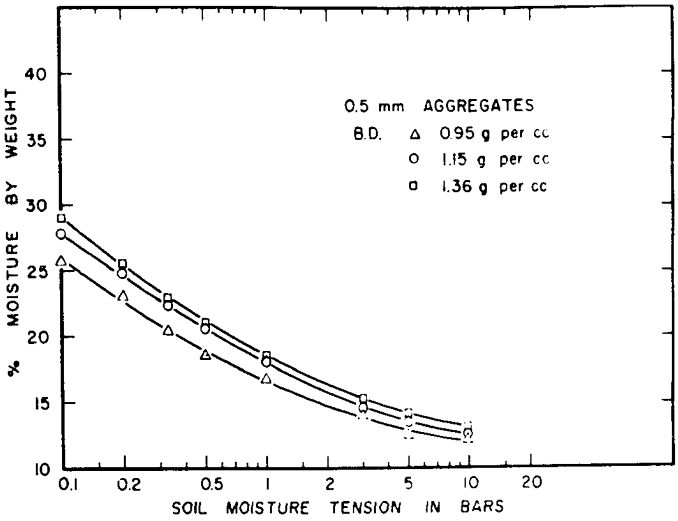
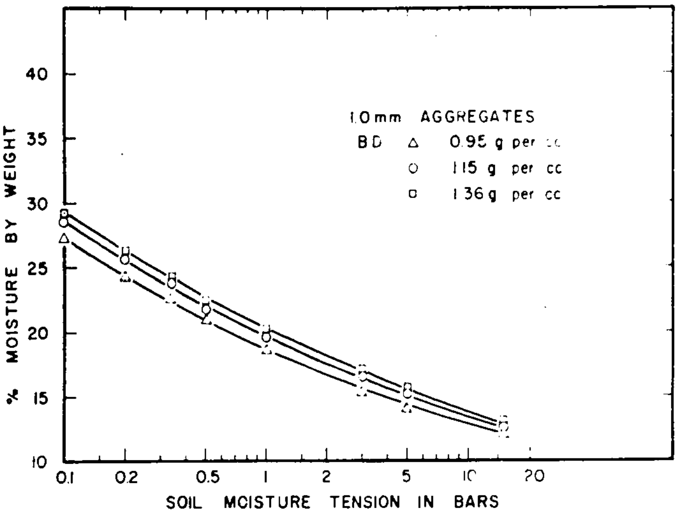
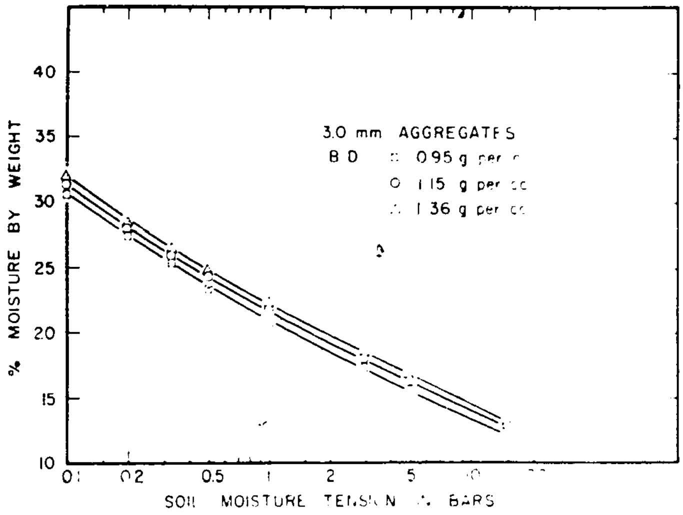

BULK DENSITY
△ 0.95 G PER CC
○ 1.15 G PER CC
□ 1.36 G PER CC
% MOISTURE BY WEIGHT
16
10
15.0 BARS TENSION
18
12
5.0 BARS TENSION
20
12
3.0 BARS TENSION
24
16
1.0 BARS TENSION
26
18
0.5 BARS TENSION
28
20
0.33 BARS TENSION
30
22
0.20 BARS TENSION
34
24
0.10 BARS TENSION
0.5
1.0
3.0
AGGREGATE SIZE IN MM

Figure 10. The relationship between gravimetric percent moisture retained and soil moisture tension; families of curves for all bulk densities are presented for aggregate size


0.5 mm AGGREGATES
B.D. △ 0.95 g per cc
○ 1.15 g per cc
□ 1.36 g per cc
% MOISTURE BY WEIGHT
10
15
20
25
30
35
40
0.1
0.2
0.5
1
2
5
10
20
SOIL MOISTURE TENSION IN BARS


1.0 mm AGGREGATES
B D △ 0.95 g per cc
○ 1.15 g per cc
□ 1.36 g per cc
% MOISTURE BY WEIGHT
10
15
20
25
30
35
40
0.1
0.2
0.5
1
2
5
10
20
SOIL MOISTURE TENSION IN BARS


3.0 mm AGGREGATES
B D 0.95 g per cc
○ 1.15 g per cc
1.36 g per cc
% MOISTURE BY WEIGHT
10
15
20
25
30
35
40
0.1
0.2
0.5
1
2
5
SOIL MOISTURE TENSION IN BARS

the aggregate size is plotted as the independent variable and families of curves representing tension levels are given for each bulk density. Figure 9 presents the aggregate size as the independent variable and families of curves for three bulk densities are plotted for each tension. Moisture tension is plotted as the independent variable in Figure 10 and families of curves for all bulk densities are presented for each aggregate size. The analysis of variance and comparison of mean values of the gravimetric percent moisture retained by the aggregates of three sizes at three levels of packing are reported in Appendix B.

The data presented in Figures 8 and 9 show that at any given bulk density and at any given tension (up to 5.0 bars) the moisture retained by the aggregates is in the following order: 0.5 mm $<$ 1.0 mm. $<$ 3.0 mm. The moisture retained at any given tension (up to 5.0 bars) and by any given aggregate size is in the following order: 0.95 $<$ 1.15 $\leq$ 1.36 g. per cc. bulk density. The interaction between the aggregate size and bulk density is also significant.

Figure 10 shows that as the soil moisture tension increases, the differences in percent moisture retained by the aggregates of three sizes at three levels of packings progressively decrease.

The relationship between the volumetric percent moisture retained, aggregate size, bulk density and moisture tension are presented in Figures 11, 12 and 13. In these three figures the volumetric percent moisture retained is plotted as the dependent variable. In Figure 11 the aggregate size is plotted as independent variable and families of curves representing the tension levels are given for each bulk density. Figure 12 presents the aggregate size as the independent variable and families of curves for three bulk densities are plotted for each tension. Moisture tension is plotted as the independent variable in Figure 13 and families of curves for three bulk densities are presented for each aggregate size. The analysis of variance and comparison of mean values of the volumetric percent moisture retained by the aggregates of three sizes at three levels of packing are reported in Appendix C.

The data presented in Figures 11 and 12 show that at any given bulk density and at any given tension (up to 5.0 bars) the moisture retained by the aggregates is in the following order: 0.5 mm $<$ 1.0 mm. $<$ 3.0 mm. The moisture retained at any given tension (up to 5.0 bars) and by any given aggregate size is in the following order: 0.95 $<$ 1.15 $<$ 1.36 g. per cc. bulk density. The interaction between the aggregate size and bulk density is also significant.

Figure 13 shows that as the soil moisture tension increases, the differences in percent moisture retained by the aggregates of three sizes at three levels of packing progres-

Figure 11. The relationship between the volumetric percent moisture retained and aggregate size; families of curves representing tension levels are shown for each bulk density

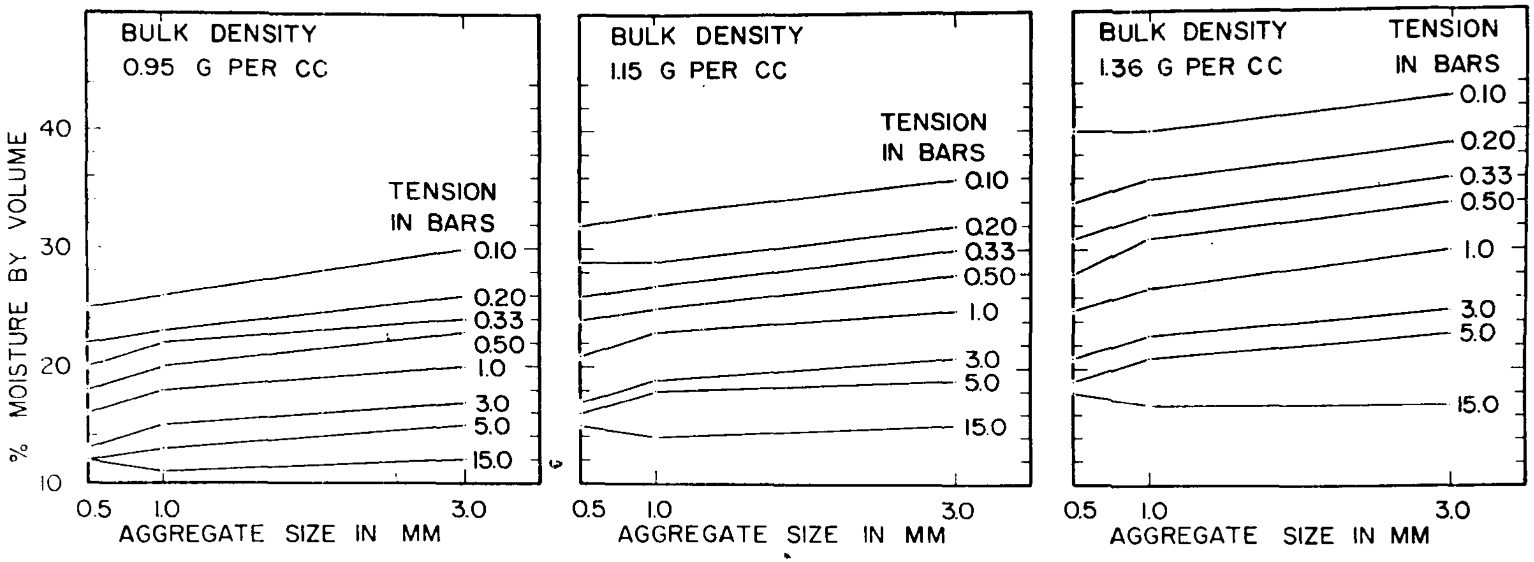

BULK DENSITY 0.95 G PER CC
TENSION IN BARS
0.10
0.20
0.33
0.50
1.0
3.0
5.0
15.0
% MOISTURE BY VOLUME
10
20
30
40
0.5
1.0
3.0
AGGREGATE SIZE IN MM
BULK DENSITY 1.15 G PER CC
TENSION IN BARS
0.10
0.20
0.33
0.50
1.0
3.0
5.0
15.0
0.5
1.0
3.0
AGGREGATE SIZE IN MM
BULK DENSITY 1.36 G PER CC
TENSION IN BARS
0.10
0.20
0.33
0.50
1.0
3.0
5.0
15.0
0.5
1.0
3.0
AGGREGATE SIZE IN MM

Figure 12. The relationship between the volumetric percent moisture retained and bulk density; families of curves for three bulk densities are shown for each tension level

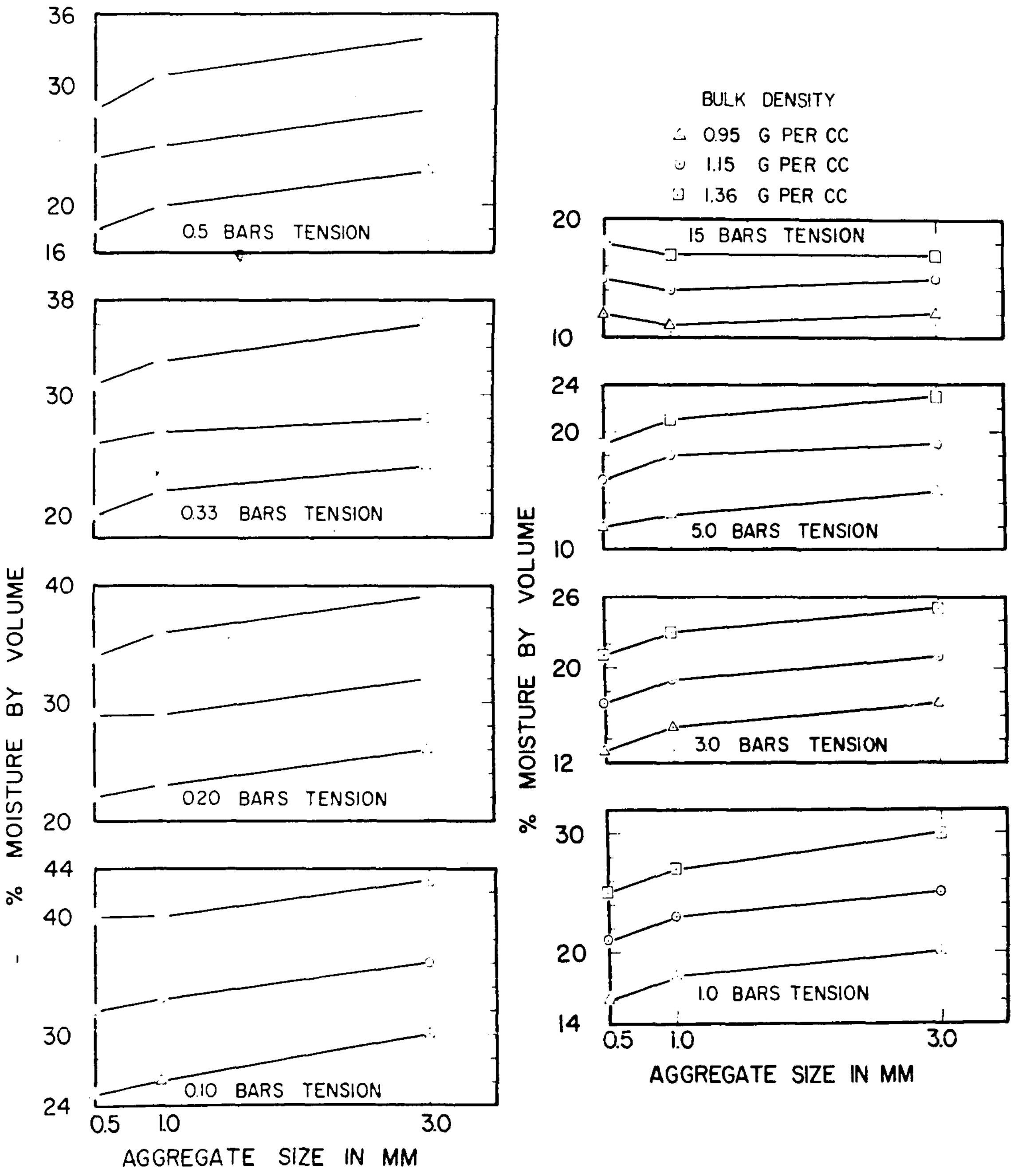
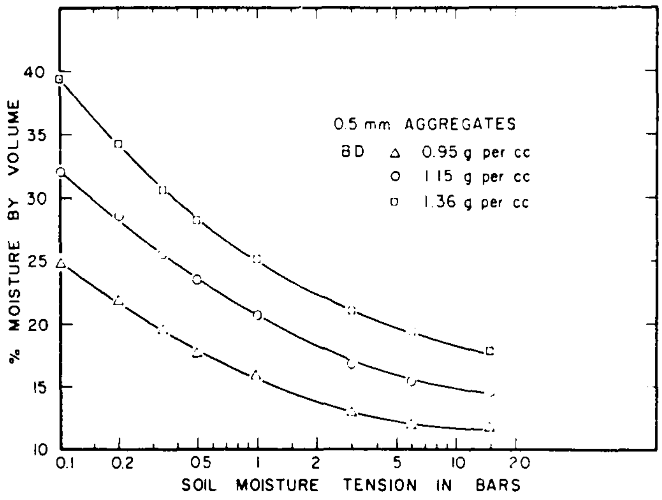
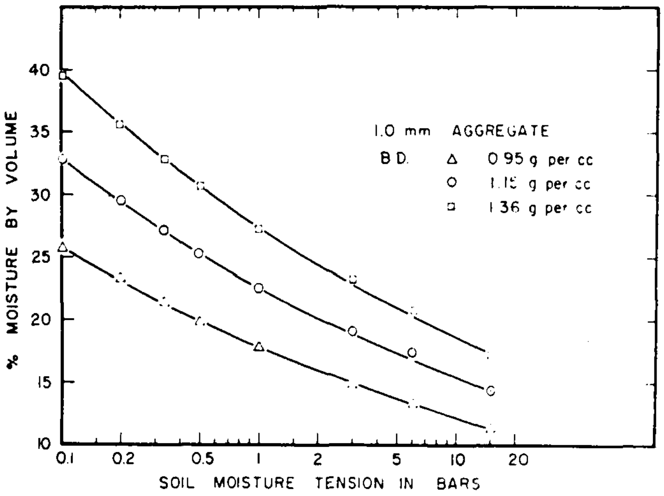
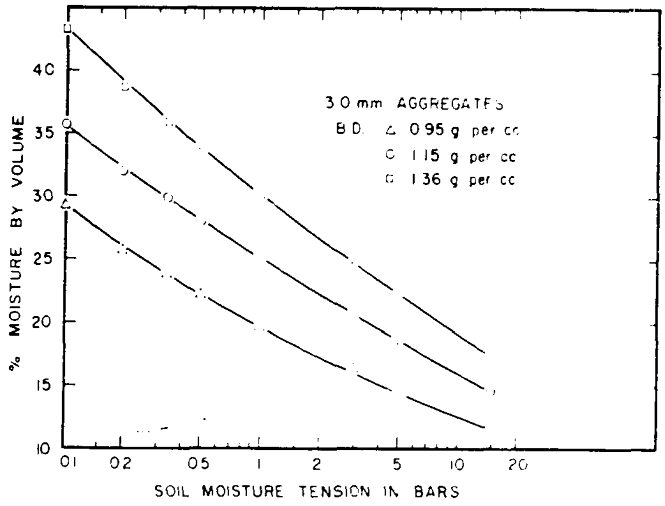

BULK DENSITY
△ 0.95 G PER CC
○ 1.15 G PER CC
□ 1.36 G PER CC
% MOISTURE BY VOLUME
0.5 BARS TENSION
36
30
20
16
0.33 BARS TENSION
38
30
20
0.20 BARS TENSION
40
30
20
0.10 BARS TENSION
44
40
30
24
0.5
1.0
3.0
AGGREGATE SIZE IN MM
15 BARS TENSION
20
10
5.0 BARS TENSION
24
20
10
3.0 BARS TENSION
26
20
12
1.0 BARS TENSION
30
20
14
0.5
1.0
3.0
AGGREGATE SIZE IN MM

Figure 13. The relationship between volumetric percent moisture retained and soil moisture tension; families of curves for all bulk densities are presented for aggregate size


0.5 mm AGGREGATES
BD △ 0.95 g per cc
○ 1.15 g per cc
□ 1.36 g per cc
% MOISTURE BY VOLUME
40
35
30
25
20
15
10
0.1
0.2
0.5
1
2
5
10
20
SOIL MOISTURE TENSION IN BARS


1.0 mm AGGREGATE
B.D. △ 0.95 g per cc
○ 1.15 g per cc
□ 1.36 g per cc
% MOISTURE BY VOLUME
40
35
30
25
20
15
10
0.1
0.2
0.5
1
2
5
10
20
SOIL MOISTURE TENSION IN BARS


3.0 mm AGGREGATES
B.D. △ 0.95 g per cc
○ 1.15 g per cc
□ 1.36 g per cc
% MOISTURE BY VOLUME
40
35
30
25
20
15
10
0.1
0.2
0.5
1
2
5
10
20
SOIL MOISTURE TENSION IN BARS

sively decrease.

Therefore, it is concluded that within the ranges studied, moisture retention increases as the aggregate size increases and also as bulk density increases. The effect of aggregate size on soil moisture retention has been previously discussed. The effect of bulk density on moisture retention can be ascribed to two causes. Firstly, the weight of aggregates is more in a given volume of soil at a higher level of bulk density than at a lower level. Therefore more surface area and greater intra-aggregate pore space is available for retention of moisture in the soil packed to higher level than to a lower level. Secondly, changes in bulk density affect moisture retention due to the differences in the pore size distribution. With increased bulk density, the aggregates are packed more closely and hence the pores between aggregates are smaller than at lower bulk densities.

Soil moisture characteristic curves have been used in interpreting the pore size distribution within a soil.

Childs (16) pointed out that the soil moisture characteristic curves are analogous to the mechanical analysis of soils, the former concerns the pore size distribution while the latter concerns the particle size distribution.

The following relation is used to calculate the diameter of pores.

$$P = \frac{2\sigma}{r} = -dgh. \text{ dynes per sq. cm.} \qquad (1)$$

Equation 1 can be rewritten in the following form.

$$2r = \frac{4\sigma}{dgh} \qquad (2)$$

Where σ is the surface tension of water,

r is the radius of curvature of a simple hemispherical interface which is in equilibrium with the more complex air water interfaces of the porous system,

d is the density of water,

g is the acceleration due to gravity,

h is the vertical distance of the point from a reference level at which the pressure is zero,

$2r$ is often referred to as D (effective pore diameter) and is the upper limiting diameter of pores which can remain full of water when a tension of h cm. is applied to the water in the wet soil.

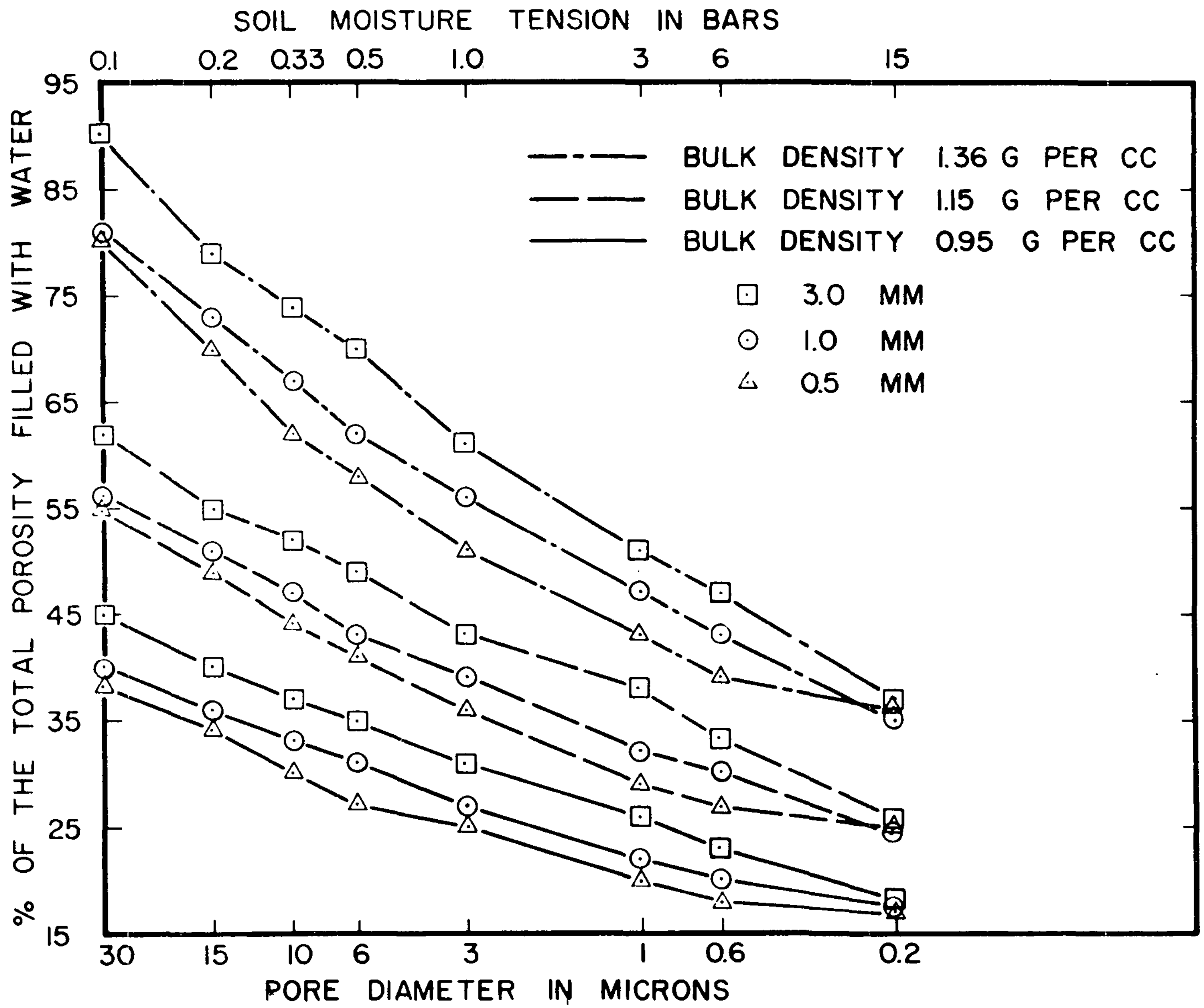
According to this relation, the pores into which the interface may retreat via channels of diameters greater than 2r will, at this tension be emptied of all water. But pores into which the interface cannot retreat except through the channels of diameters smaller than 2r will remain full of water. Thus, as the soil moisture tension increases, the moisture content progressively decreases as a result of successive emptying of pores of smaller and smaller diameter. The shape of the whole characteristic curves, therefore, shows the distribution of different effective pore sizes. While Equation 2 gives a good approximation of pore size distribution in soils, Russell (78) has pointed out that Equation 2 only holds strictly for pores in which an air-water interface exists. Consequently in the desorption process some of the voids may remain filled with water at tensions significantly higher than would be calculated from Equation 2.

Smith and Browning (84), however, found that pore size distribution and the volume of soil pores filled with water are the real keys in understanding many soil moisture relations. Childs and George (17) pointed out that the water occupied void space together with the solid surface is the seat of physico-chemical activity which largely determines the gross physical properties of soil. Miller and Mazurak (57) have shown that the area of root solution contact and the volume of air-filled voids as calculated from moisture tension curves are dominant factors affecting plant growth. Mederski and Wilson (56) hypothesized that at low moisture content and/or at high moisture tension, the continuity of the moisture film is broken and ion transfer from the soil to root is impaired; as the thickness of the moisture film decreases, the solvent properties of water decreases; and at low moisture content, the size of the cationic swarm surrounding the soil particles is decreased.

In view of the above discussion, the pore distribution within three aggregate sizes at three levels of packing was calculated and is presented in Figure 14. The data show that when the soil system has a bulk density of 0.95 g. per cc. and the aggregate sizes are 0.5, 1.0 and 3.0 mm., the pores of 30 microns or less in diameter are 38, 40 and 45 percent of the total pore space respectively. At a bulk density of 1.36 g. per cc., 81, 81 and 89 percent of the total pores are of 30 microns or less in diameter when the aggregate sizes are 0.5, 1.0 and 3.0 mm. respectively. Thus at the same level of packing the larger sized aggregate have more pores of a given diameter than the smaller sized aggregates. When the soil system is composed of 0.5 mm. aggregates the volume of pores of 30 microns or less in diameter is 25, 32 and 40 percent of the total soil volume for bulk density of 0.95, 1.15 and 1.36 g. per cc. respectively. It must be pointed out that because of the destruction of the aggregates due to packing the average aggregate diameter was somewhat less than indicated above, particularly at the higher bulk density.

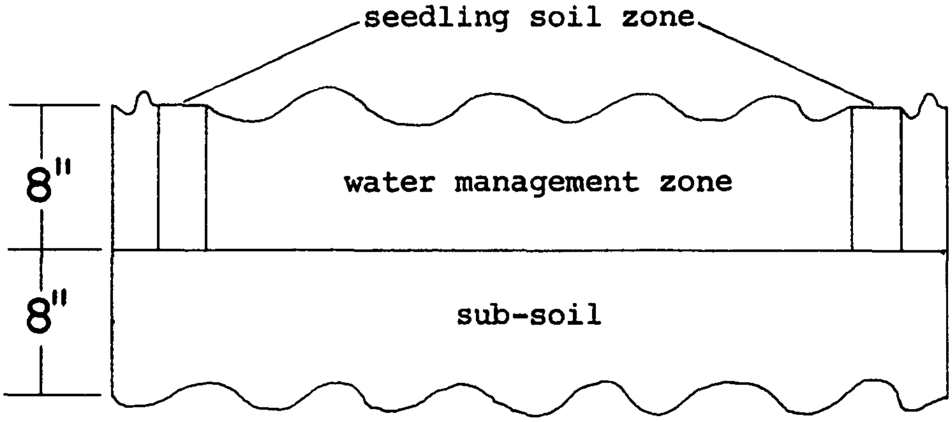
Frequently the data on moisture retention characteristics obtained on the disturbed and ground soil samples (< 1.0 mm.) in conjunction with the bulk density values are used to calculate the water holding capacity in inches per foot of soil. These data are then used in the estimation of available storage capacity of soil and in evaluating irrigation needs. The results of present study have shown that variation in aggre-

Figure 14. Pore size distribution as affected by aggregate size and bulk density (total porosity at bulk densities of 0.95, 1.15 and 1.36 g. per cc. are 65, 58 and 49 percent respectively)


SOIL MOISTURE TENSION IN BARS
0.1
0.2
0.33
0.5
1.0
3
6
15
95
85
75
65
55
45
35
25
15
% OF THE TOTAL POROSITY FILLED WITH WATER
BULK DENSITY 1.36 G PER CC
BULK DENSITY 1.15 G PER CC
BULK DENSITY 0.95 G PER CC
□ 3.0 MM
○ 1.0 MM
△ 0.5 MM
30
15
10
6
3
1
0.6
0.2
PORE DIAMETER IN MICRONS

gate size and bulk density have an appreciable effect on the soil moisture retention. Thus pointing out that large errors in estimation of moisture retention in the field are possible if ground samples are used instead of samples of undisturbed soil structure.

Differences in soil moisture retention characteristics certainly have a bearing on the conduction and availability of moisture to plant roots or germinating seeds. The results of the present study show that soil moisture retention characteristics are influenced by aggregate size and state of packing. Therefore this information gives a better understanding of the effects of tillage on moisture relationship and plant growth since manipulation of soil brings about changes in aggregate size and state of packing. For example, in preparation of land for planting to row crops such as corn or soybeans, soil zones are prepared to meet two basic needs namely: a) the zone around the seed and seedling root prepared for the establishment of the crop, and b) the interrow zone prepared for the management of water-soil relationships. This is shown in the diagram on the following page. In the conventional tillage system for corn in the North Central States (U. S. A.), the soil physical condition in the two zones (upper 8 inches) are essentially the same. In minimum, mulch, ridge and listing systems of tillage, the two zones are quite different. To illustrate the application of



the results of the present investigation, let us consider a hypothetical case of an ideal minimum tillage system. In order to calculate differences between the moisture content (expressed in inches of water per 8 inches of soil) at saturation and the moisture content equilibrium at a given tension, the following two assumption were made:

a) The water management zone has a bulk density of 0.95 g. per cc.; the seedling soil zone has a bulk density of 1.15 g. per cc.; and the sub-soil has a bulk density of 1.36 g. per cc.

b) The mean diameter of aggregates in the water management zone is 3.0 mm.; in the seedling soil zone is 1.0 mm., and in the sub-soil is 0.5 mm.

The first assumption is not too far from reality, since the assumed bulk densities in the respective soil zones are frequently met in the field. The second assumption is arbitrary but the values are used to illustrate the relative magnitudes of what could occur in the field. Based on these two assumptions the following calculations were made using the data presented in Figure 13 and are shown in Table 2. These calculations show the relative additional moisture storage capacity (S) and air volume (Av.) in the three different zones of the upper 16 inches of soil. In the spring season during periods of considerable rainfall (when the soil moisture tension is about 0.10 bar) the water management zone has an additional storage capacity of 2.8 inches and adequate air volume (Av.). The seedling soil zone has less additional moisture storage (S) and less air volume (Av.) than the water management zone. In the sub-soil, however, the storage of moisture (S) is reduced to only 0.7 inches and the percent air volume (Av.) reaches the critical level.

Calculations for 0.33 and 15 bars tensions show what would happen under drier soil conditions. It is seen that the air volume is not limiting in any of the zones. The additional moisture storage (S) in the water management zone is considerable and thus is available for temporary storage of water during intense rains. This is a primary reason why runoff from plots of low bulk density (minimum tillage) has been less during intense rain than from plots with a moderate bulk density (conventional tillage).[1]

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[1] Larson, W. E., Ames, Iowa. Tillage specifications. Private communication. 1961.

Table 2. Calculation of differences in moisture content at saturation and equilibrium moisture content at a given tension[a]

Depth in inches	Tension	
	0.10 bar	
	Water management zone	Seedling soil zone
8	B. D. = 0.95 g. per cc.	B. D. = 1.15 g. per cc.
	Agg. = 3.0 mm.	Agg. = 1.0 mm.
	Mv. = 30.0 percent	Mv. = 33.0 percent
	Av. = 35.0 percent	Av. = 25.0 percent
	S. = 2.8 inches	S. = 1.9 inches
	Sub-soil	
8	B. D. = 1.36 g. per cc.	
	Agg. = 0.5 mm.	
	Mv. = 40.0 percent	
	Av. = 9.0 percent	
	S. = 0.7 inches	
	0.33 bar	
	Water management zone	Seedling soil zone
8	B. D. = 0.95 g. per cc.	B. D. = 1.15 g. per cc.
	Agg. = 3.0 mm.	Agg. = 1.0 mm.
	Mv. = 24.0 percent	Mv. = 27.0 percent
	Av. = 41.0 percent	Av. = 31.0 percent
	S. = 3.2 inches	S. = 2.4 inches
	Sub-soil	
8	B. D. = 1.36 g. per cc.	
	Agg. = 0.5 mm.	
	Mv. = 18.0 percent	
	Av. = 31.0 percent	
	S. = 1.4 inches	

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[a] In this table, B. D. = bulk density, Agg. = aggregate size, Mv. = volumetric percent moisture, Av. = air volume percent, and S. = difference in moisture content (expressed as inches of water per 8 inches of soil) between the moisture content at saturation and the equilibrium moisture content at a given tension.

Table 2. (Continued)

Depth in inches	Tension	
	15.0 bar	
	Water management zone	Seedling soil zone
8	B. D. = 0.95 g. per cc. Agg. = 3.0 mm. Mv. = 12.0 percent Av. = 53.0 percent S. = 4.2 inches	B. D. = 1.15 g. per cc. Agg. = 1.0 mm. Mv. = 14.0 percent Av. = 44.0 percent S. = 3.5 inches
	Sub-soil	
8	B. D. = 1.36 g. per cc. Agg. = 0.5 mm. Mv. = 18.0 percent Av. = 31.0 percent S. = 2.4 inches	

V. SUMMARY AND CONCLUSIONS

Manipulation of a soil by tillage implements influence the bulk density and aggregate size. This study was therefore concerned with the effect of aggregate size and bulk density on moisture retention characteristics.

Bulk soil samples from the surface 0 to 9 inches of Nicollet silt loam were randomly collected from a field at the Agronomy Farm, Ames, Iowa. The soil aggregates used in the study were (A) $> 0.5 < 1.0$ mm., (B) $> 1.0 < 2.0$ mm., (C) $> 2.0 < 3.0$ mm., (D) $> 3.0 < 5.0$ mm., (E) $> 5.0 < 9.5$ mm., (F) $> 9.5 < 12.0$ mm. in diameter. In order to study the effect of bulk density and the inter-relationships of aggregate size and bulk density on soil moisture retention, levels of bulk densities of 0.95, 1.15 and 1.36 g. per cc. and aggregate sizes of 0.5, 1.0, and 3.0 mm. were selected.

A pressure plate apparatus was used for determining the moisture retention by various sized aggregates and at various bulk densities, between 0.10 and 1.0 bar tensions. For tensions between 2.0 and 15.0 bars, a pressure membrane apparatus was used.

The particle size distribution, organic carbon content, total surface area and apparent bulk density of the aggregates were determined.

On the basis of the results of this study it is concluded that:

(1) Between tensions of 0.10 and 1.0 bar, the gravimetric (oven dry) percent moisture retained by various sized aggregates was in the following order:

$0.5 < 1.0 < 2.0 \cong 3.0 \cong 5.0 \cong 9.5$ mm.

(2) Between tensions of 1.0 and 5 bars, the gravimetric percent moisture retained was in the following order:

$0.5 < 1.0 \cong 2.0 \cong 3.0 \cong 5.0 \cong 9.5$ mm.

(3) At tensions of 10 and 15 bars, the moisture retained by aggregates of various sizes was essentially the same.

(4) The gravimetric percent moisture retained at tensions up to 5.0 bars, at three levels of bulk densities was in the following order:

$0.95 < 1.15 \leq 1.36$ g. per cc.

(5) The volumetric percent moisture retained at tensions up to 5.0 bars, and at three levels of bulk densities was in the following order:

$0.95 < 1.15 < 1.36$ g. per cc.

(6) The interaction between aggregate size and bulk density was found significant at almost all tensions.

(7) The effect of soil moisture tension on the percent moisture retained by various sized aggregates at various levels of bulk densities was more pronounced in the range of 0.10 to 1.0 bar than in the range of 2.0 to 15.0 bars.

In the smaller aggregate size range, water retention was directly related to the aggregate size and inversely related to the apparent bulk density of the aggregates. It is, therefore, suggested that the differences in moisture retention by aggregates of various sizes are due to variation in the intra-aggregate porosity.

The differences in the moisture retention at various levels of bulk densities are considered to be due to two factors. Firstly, the weight of aggregates is more in a given volume of soil at a higher level of bulk density than at a lower level. Thus greater intra-aggregate pore space is available for retention of moisture and there is more surface area of aggregates in the soil packed to a higher level than a lower level, particularly at higher tensions. Secondly, changes in bulk density affect moisture retention due to the differences in inter-aggregate pore size.

When the soil system has a bulk density of 0.95 g. per cc. and the aggregate sizes are 0.5, 1.0 and 3.0 mm. the pores of 30 microns or less in diameter are 38, 40 and 45 percent of the total pore space respectively. At a bulk density of 1.36 g. per cc. 81, 81 and 89 percent of the total pores are of 30 microns or less in diameter when the aggregates are 0.5, 1.0 and 3.0 mm. respectively. Thus at the same levels of packing, the percentage of total pores of a given diameter is higher in the larger sized aggregates than the smaller sized ones.

Similarly, when the soil system is composed of 0.5 mm. aggregates, the volume of pores of 30 microns or less in diameter is 25, 26 and 40 percent of the total soil volume for bulk density of 0.95, 1.15 and 1.36 g. per cc. respectively. The results of this study have shown that variation in aggregate size and bulk density have an appreciable effect on soil moisture retention. Thus pointing out that large errors in estimation of moisture retention in the field are possible if ground soil samples are used instead of samples of undisturbed soil structure.

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VII. ACKNOWLEDGEMENTS

The author wishes to express sincere appreciation and thanks to Dr. W. E. Larson for his stimulating counsel and help during this investigation.

A special note of appreciation is given to Dr. M. Amemiya for his valuable suggestions; to Dr. F. B. Cady for help in statistical analysis.

Appreciation is also expressed to the Soil Physics graduate section and to the staff members of the Iowa State University Department of Agronomy who, in various ways, contributed to this study.

The author is highly obliged to the Rockefeller Foundation for the financial assistance offered during the entire period of graduate study at Ames, Iowa.

The author is also thankful to his wife and parents for the inspiration offered by them during the period of graduate program.

VIII. APPENDIX A

Table 3. The relationship between gravimetric percent moisture, aggregate size and soil moisture tension

Agg. size in mm.	Gravimetric percent moisture retained[a] Soil moisture tension in bars									
	0.10	0.20	0.33	0.50	1.0	2.0	3.0	5.0	10.0	15.0
0.5	25.0	22.8	20.5	18.8	16.9	14.3	13.5	12.7	12.0	11.9
1.0	26.9	24.3	22.2	20.7	18.4	16.5	15.3	14.1	12.2	11.5
2.0	30.3	26.7	24.0	23.0	20.0	17.0	15.5	14.1	12.8	12.6
3.0	30.5	27.3	24.4	23.2	20.2	16.2	15.4	14.0	12.4	12.1
5.0	30.7	27.3	24.4	22.9	20.1	16.6	15.5	14.8	13.1	12.6
9.5	29.8	27.3	--	22.8	20.1	16.5	--	--	13.8	--

[a] Each value in the table is an average of three determinations.

Table 4. Test for homogeniety of variance and calculation of chi-square (from data presented in Table 3)

Source tension in bars	d.f.	M.S.S.	Log. M.S.S.
0.10	10	0.10575	1.0241
0.20	10	0.42138	1.6246
0.33	10	0.04752	2.6769
0.50	10	0.05501	2.7405
1.00	10	0.12726	1.1045
2.00	10	0.12060	1.0813
3.00	10	0.07796	2.8918
5.00	10	0.03031	2.4815
10.00	10	0.10811	1.0338
15.00	10	0.01717	2.2347

Calculated $X^2 = 53.67$, Tabular $X^2 = 23.59$, d.f. = 9.

Table 5. Analysis of variance of the gravimetric percent moisture retained by aggregates of various sizes at each of the tension levels (from the data presented in Table 3)

Soil moisture tension in bars	Source of of variation	d.f.	M.S.S.	Calculated F
0.10	Agg. size	4	20.3	
	Error	10	0.13	153.6*
0.20	Agg. size	4	12.1	
	Error	10	0.43	28.2*
0.33	Agg. size	4	9.2	
	Error	10	0.05	187.0*
0.50	Agg. size	4	11.2	
	Error	10	0.06	196.0*
1.0	Agg. size	4	6.5	
	Error	10	0.13	50.1*
2.0	Agg. size	4	2.7	
	Error	10	0.12	6.1*
3.0	Agg. size	4	2.2	
	Error	10	0.08	28.2*
5.0	Agg. size	4	1.8	
	Error	10	0.03	57.1*
10.0	Agg. size	4	0.6	
	Error	10	0.11	5.5**
15.0	Agg. size	4	0.75	
	Error	10	0.01	106.4*

*Significant at 1 percent level, Tabular F(0.01) = 6.0.

**Significant at 5 percent level, Tabular F(0.005) = 3.5.

Table 6. Comparison of mean values of gravimetric percent moisture retained by various sized aggregates at each tension level (from the data presented in Table 3)

Soil moisture tension in bars	Gravimetric percent moisture retained arranged in descending order					
	Agg. 5	Agg. 3	Agg. 2	Agg 1	Agg 0.5	D[a]
0.10	30.7	30.5	30.3	26.9	25.0	1.0
0.20	27.3	27.3	26.7	24.3	22.8	1.8
0.33	24.4	24.4	24.0	22.2	20.5	0.6
0.50	Agg. 3 23.2	Agg. 2 23.0	Agg. 5 22.9	20.7	18.8	0.6
1.0	Agg. 3 20.2	Agg. 5 20.1	Agg. 2 20.0	18.4	16.9	1.0
2.0	Agg. 2 17.0	Agg. 5 16.6	Agg. 1 16.5	Agg. 3 16.2	14.3	1.8
3.0	Agg. 2 15.5	Agg. 5 15.5	Agg. 3 15.4	Agg. 1 15.3	13.5	0.8
5.0	Agg. 5 14.8	Agg. 2 14.1	Agg. 1 14.1	Agg. 3 14.0	12.7	0.5
10.0	Agg. 5 13.1	Agg. 2 12.8	Agg. 3 12.4	Agg. 1 12.2	12.0	0.9
15.0	Agg. 5 12.6	Agg. 2 12.6	Agg. 3 12.1	Agg. 0.5 11.9	Agg. 1 11.5	0.2

[a] D = significant difference at 5 percent level, Agg. 5 = 5.0 mm. aggregates, Agg. 3 = 3.0 mm. aggregates, Agg. 2 = 2.0 mm. aggregates, Agg. 1 = 1.0 mm. aggregates, and Agg. 0.5 = 0.5 mm. aggregates.

Table 7. Analysis for the linear, quadratic and cubic effects for the gravimetric percent moisture retained (from data presented in Table 3)

Soil moisture tension in bars	Source of variation	d.f.	M.S.S.	Calculated F
0.10	linear	1	54.9	422.3*
	quad.	1	24.5	188.5*
	cubic	1	1.2	9.2**
	error	10	0.13	
0.20	linear	1	34.2	79.5*
	quad.	1	13.8	32.1*
	cubic	1	0.2	0.5
	error	10	0.43	
0.33	linear	1	24.4	488.0*
	quad.	1	12.7	254.0*
	cubic	1	1.0	20.0*
	error	10	0.05	
0.50	linear	1	25.2	420.0*
	quad.	1	19.0	316.7*
	cubic	1	0.7	11.7*
	error	10	0.06	
1.0	linear	1	15.5	119.2*
	quad.	1	9.9	76.2*
	cubic	1	0.5	3.8
	error	10	0.13	
2.0	linear	1	3.6	8.2**
	quad.	1	4.2	9.5**
	cubic	1	5.3	12.0*
	error	10	0.44	
3.0	linear	1	3.1	38.8*
	quad.	1	3.0	37.5*
	cubic	1	1.9	23.8*
	error	10	0.08	
5.0	linear	1	4.6	153.3*
	quad.	1	0.3	10.0*
	cubic	1	1.9	63.3*
	error	10	0.03	

*Significant at 1 percent level, Tabular F(0.01) = 10.0.

**Significant at 5 percent level, Tabular F(0.005) = 5.0.

Table 7. (Continued)

Soil moisture tension in bars	Source of variation	d.f.	M.S.S.	Calculated F
10.0	linear	1	1.8	16.4*
	quad.	1	0.02	0.18
	cubic	1	0.5	5.0**
	error	10	0.11	
15.0	linear	1	1.5	214.3*
	quad.	1	0.07	10.0*
	cubic	1	0.04	6.0*
	error	10	0.007	

IX. APPENDIX B

Table 8. The relationship between the gravimetric percent moisture retained, aggregate size, bulk density, and soil moisture tension

Soil moisture tension in bars	Gravimetric percent moisture[a]		
	0.5 mm.	1.0 mm.	3.0 mm.
Bulk density of 0.95 g. per cc.			
0.10	25.9	27.2	30.6
0.20	23.0	24.3	27.3
0.33	20.6	22.6	25.5
0.50	18.5	20.9	23.7
1.00	16.8	18.7	20.9
3.00	13.5	15.3	17.4
5.00	12.5	14.0	15.6
15.00	12.2	12.0	12.5
Bulk density of 1.15 g. per cc.			
0.10	27.8	28.4	31.1
0.20	24.8	25.6	27.8
0.33	22.2	23.6	26.0
0.50	20.5	21.8	24.5
1.00	18.1	19.6	21.8
3.00	14.5	16.5	18.0
5.00	13.4	15.2	16.4
15.00	12.6	12.5	12.7
Bulk density of 1.36 g. per cc.			
0.10	29.0	29.1	31.9
0.20	25.3	26.2	28.5
0.33	22.5	24.1	26.5
0.50	20.8	22.5	25.1
1.00	18.5	20.1	22.1
3.00	15.4	17.0	18.4
5.00	14.3	15.6	16.8
15.00	13.0	12.7	12.8

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[a] Each value in the table is an average of three determinations.

Table 9. Analysis of variance of the gravimetric percent moisture retained by three aggregate sizes at three levels of packing at each of the soil moisture tension levels (from the data presented in Table 8)

Soil moisture tension in bars	Source of variation	d.f.	M.S.S.	Calculated F
0.10	Agg. size	2	33.5	7606.9*
	bulk density	2	10.22	2321.9*
	Agg. x b.d.	4	0.7	151.7*
	error	18	0.004	
0.20	Agg. size	2	29.3	1636.4*
	bulk density	2	7.5	419.5*
	Agg. x b.d.	4	0.4	21.0*
	error	18	0.02	
0.33	Agg. size	2	41.5	1487.3*
	bulk density	2	5.3	188.2*
	Agg. x b.d.	4	0.3	9.0*
	error	18	0.03	
0.50	Agg. size	2	45.8	189.9*
	bulk density	2	7.5	307.9*
	Agg. x b.d.	4	0.3	13.8*
	error	18	0.02	
1.0	Agg. size	2	32.3	2184.8*
	bulk density	2	4.8	321.6*
	Agg. x b.d.	4	0.1	4.8*
	error	18	0.01	
3.0	Agg. size	2	27.0	4154.8*
	bulk density	2	5.3	818.7*
	Agg. x b.d.	4	0.2	34.8*
	error	18	0.007	
5.0	Agg. size	2	18.6	3146.8*
	bulk density	2	5.4	907.9*
	Agg. x b.d.	4	0.09	14.9*
	error	18	0.006	
15.0	Agg. size	2	0.2	46.5*
	bulk density	2	0.8	206.1*
	Agg. x b.d.	4	0.1	16.7*
	error	18	0.003	

*Significant at 1 percent level, Tabular $F_{2.18}(.01) = 6.0$, Tabular $F_{4.18}(.01) = 4.6$.

Table 10. Comparison of mean values of gravimetric percent moisture retained by three aggregates, at three levels of packing at each of the soil moisture tension levels (from the data presented in Table 8)

Tension in bars	Agg. 3.0 mm.	Agg. 1.0 mm.	Agg. 0.5 mm.	D[a]	Bulk density 1.36	Bulk density 1.15	Bulk density 0.95
0.10	31.2	28.2	27.6	0.1	30.0	29.1	27.9
0.20	27.9	25.4	24.4	0.2	26.7	26.1	24.9
0.33	26.0	23.4	21.7	0.2	24.4	23.9	22.9
0.50	24.4	21.8	19.9	0.2	22.8	22.3	21.0
1.00	21.6	19.5	17.8	0.2	20.2	19.8	18.8
3.00	17.9	16.3	14.5	0.1	16.9	16.3	15.4
5.00	16.3	14.9	13.4	0.1	15.6	15.0	14.0
15.00	12.7	12.4	12.6	0.1	12.8	12.6	12.3

[a] D is the significant difference at 5 percent level.

X. APPENDIX C

Table 11 The relationship between the volumetric percent moisture retained, aggregate size, bulk density and soil moisture tension

Soil moisture tension in bars	Volumetric percent moisture[a] Aggregate size 0.5 mm.	 1.0 mm.	 3.0 mm.
	Bulk density 0.95 g. per cc.		
0.10	24.6	25.8	29.5
0.20	21.9	23.1	26.0
0.33	19.5	21.5	24.2
0.50	17.6	19.9	22.5
1.0	16.0	17.8	19.9
3.0	12.8	14.5	16.6
5.0	11.9	13.3	14.8
15.0	11.6	11.4	11.9
	Bulk density 1.15 g. per cc.		
0.10	32.0	32.7	35.7
0.20	28.6	29.4	32.0
0.33	25.5	27.2	29.9
0.50	23.6	25.2	28.2
1.0	20.7	22.5	25.1
3.0	16.7	19.0	20.7
5.0	15.5	17.5	18.8
15.0	14.5	14.3	14.6
	Bulk density 1.36 g. per cc.		
0.10	39.5	39.5	43.4
0.20	34.4	35.7	38.8
0.33	30.6	32.8	36.1
0.50	28.3	30.6	34.1
1.0	25.2	27.4	30.0
3.0	21.0	23.2	25.0
5.0	19.3	21.3	22.9
15.0	17.7	17.3	17.4

[a] Each value in the table is an average of three determinations.

Table 12. Analysis of variance of the volumetric percent moisture retained by three aggregate sizes at three levels of packing, at each of the soil moisture tension levels (from the data presented in Table 11)

Soil moisture tension in bars	Source of variation	d.f.	M.S.S.	Calculated F
0.10	Agg. size	2	42.4	6422.9*
	bulk density	2	460.0	69699.9*
	Agg. x b.d.	4	0.4	53.3*
	error	18	.006	
0.20	Agg. size	2	37.5	1676.3*
	bulk density	2	359.9	16065.3*
	Agg. x b.d.	4	0.1	6.7*
	error	18	0.02	
0.33	Agg. size	2	53.7	1256.4*
	bulk density	2	292.7	6840.4*
	Agg. x b.d.	4	0.2	5.0*
	error	18	0.04	
0.50	Agg. size	2	59.6	1628.5*
	bulk density	2	274.1	7489.3*
	Agg. x b.d.	4	0.4	10.0*
	error	18	0.04	
1.0	Agg. size	2	42.5	1922.1*
	bulk density	2	208.8	9449.4*
	Agg. x b.d.	4	0.2	9.3*
	error	18	0.02	
3.0	Agg. size	2	34.8	3354.0*
	bulk density	2	158.1	15205.4*
	Agg. x b.d.	4	0.1	8.7*
	error	18	0.01	
5.0	Agg. size	2	24.1	3436.9*
	bulk density	2	137.6	19650.5*
	Agg. x b.d.	4	0.1	15.8*
	error	18	0.007	
15.0	Agg. size	2	0.2	42.5*
	bulk density	2	76.5	15292.8*
	Agg. x b.d.	4	.08	16.6*
	error	18	.005	

*Significant at 1 percent level, Tabular $F_{2.18}(.01)$ = 6.0, Tabular $F_{4.18}(.01)$ = 4.6.

Table 13. Comparison of mean values of volumetric percent moisture retained by three aggregate sizes, at three levels of packing at each of the soil moisture tension levels (from the data presented in Table 11)

Tension in bars	Volumetric percent moisture[a] 3.0 mm.	1.0 mm.	0.5 mm.	D
0.10	36.1	32.7	32.0	0.2
0.20	32.2	29.4	28.3	0.3
0.33	30.1	27.1	25.2	0.4
0.50	28.3	25.2	23.2	0.4
1.0	25.0	22.6	20.6	0.3
3.0	20.8	18.9	16.8	0.2
5.0	18.8	17.3	15.6	0.1
15.0	14.6	14.4	14.6	0.05
		Bulk density		
	1.36	1.15	0.95	D
0.10	40.8	33.4	26.5	0.2
0.20	36.3	30.0	23.6	0.3
0.33	33.1	27.5	21.8	0.4
0.50	31.0	25.6	20.0	0.4
1.0	27.5	22.8	17.9	0.3
3.0	23.0	18.8	14.7	0.2
5.0	21.2	17.3	13.3	0.1
15.0	17.5	14.5	11.6	0.05

[a] D is the significant difference at 5 percent level.

XI. APPENDIX D

Table 14. Percent destruction caused to the aggregates of 0.5, 1.0 and 3.0 mm. diameter sizes, due to packing at three levels of bulk densities and due to wetting[a]

Agg. size in mm.	Bulk density in g. per cc.	% destruction caused to aggregates					
		Dry sieving of packed aggregates before wetting		Dry sieving of packed aggregates after wetting under atmospheric pressure and air drying		Dry sieving of packed aggregates after wetting under partial vacuum and air drying	
		un-treated	Krilium treated	un-treated	Krilium treated	un-treated	Krilium treated
> 0.5 < 1.0	0.95	1.8	1.7	1.9	1.9	1.5	0.9
	1.15	23.3	22.7	22.3	15.1	18.6	12.7
	1.36	45.8	47.4	43.7	35.5	39.9	33.7
> 1.0 < 2.0	0.95	2.5	2.0	2.3	1.1	2.1	0.3
	1.15	27.3	19.9	25.0	21.2	22.3	18.4
	1.36	58.2	60.4	51.4	44.9	46.2	42.0
> 3.0 < 5.0	0.95	2.4	2.4	1.9	1.0	1.4	0.6
	1.15	13.4	11.6	12.2	9.1	11.1	6.5
	1.36	60.3	59.5	58.9	45.8	56.8	44.3

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[a] Each value in the table is an average of two determinations.

XII. APPENDIX E

Table 15. Percent of total pores of various diameters filled with water at tensions between 0.10 and 15 bars at three levels of packing of three aggregate sizes

% of total pores filled with water				
Agg. size in mm. 0.5	1.0	3.0	Tension in bars	Pore size diameter μ
Bulk density = 0.95 g. per cc., total porosity = 65%				
37.8	39.7	45.2	0.10	30
33.7	35.7	40.0	0.20	15
30.0	33.0	37.2	0.33	10
27.0	30.6	34.6	0.50	6
24.6	27.3	30.6	1.0	3
19.6	22.2	25.5	3.0	1
18.3	20.4	22.7	5.0	0.6
17.8	17.5	18.3	15.0	0.2
Bulk density = 1.15 g. per cc., total porosity = 58%				
55.1	56.3	61.5	0.10	30
49.2	50.7	55.1	0.20	15
43.9	46.9	51.5	0.33	10
40.7	43.4	48.6	0.50	6
35.7	38.8	43.2	1.0	3
28.7	32.7	35.7	3.0	1
26.8	30.1	32.5	5.0	0.6
25.0	24.7	25.1	15.0	0.2
Bulk density = 1.36 g. per cc., total porosity = 49%				
80.6	80.6	88.5	0.10	30
70.2	72.8	79.1	0.20	15
62.4	66.9	73.6	0.33	10
57.7	62.4	69.6	0.50	6
51.4	55.9	61.2	1.0	3
42.9	47.3	51.0	3.0	1
39.4	43.4	46.7	5.0	0.6
36.1	35.3	35.5	15.0	0.2