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The Ohio State University, Ph.D., 1974
Agronomy

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SUBMERGENCE, DRAINAGE AND FREEZE-THAW EFFECTS
ON SOIL PHYSICAL AND CHEMICAL PROPERTIES

DISSERTATION

Presented in Partial Fulfillment of the Requirements for
the Degree Doctor of Philosophy in the Graduate
School of The Ohio State University

By

Sukhdev S. Hundal, B.Sc., M.Sc.

The Ohio State University
1974

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INTRODUCTION

Excessive soil moisture usually results in deterioration of soil structure. Most of the research reported on excessive moisture effects on soil properties is qualitative in nature, and a quantitative understanding is lacking. Although soil structure has recently been highly recognized in its relation to plant growth, its direct characterization is still very difficult. Interpretations of structural condition of the soil are made by evaluating certain, easily-measureable soil physical properties. Excess moisture usually leads to poor soil structure, resulting in higher moisture retention, higher bulk density, reduced soil aeration, low hydraulic conductivity and impeded drainage. Furthermore, excess moisture hinders land preparation, seeding and transplanting, fertilization, cultivation and harvesting operations. A major problem in wet soils is increased soil compaction due to equipment traffic.

Freezing and thawing of soil under excess moisture conditions that prevail during winter season are known to affect soil structure. However, conflicting reports are found in literature as to the beneficial and harmful effects of freeze-thawing on soil structure. There is a need to study the effect of different factors affecting soil structure under freeze-thaw conditions. Some of these factors that are considered prominent include the moisture content at the time
of freeze-thawing, initial size of soil aggregates, temperature of freezing and thawing, and the number of freeze-thaw cycles.

Besides changes in soil physical properties, excess moisture also alters soil chemical properties. The effect of flooding or waterlogged conditions on soil chemical properties have long attracted the attention of soil scientists and more recently the environmentalists. Submergence or water logging the soil creates conditions markedly different from those of a well drained soil and lead to changed soil physico-chemical properties. Drastic chemical changes are induced as the soil shifts from an oxidized to a reduced environment. The molecular oxygen gradually disappears, nitrates are lost through denitrification, ammonium nitrogen accumulates, redoxpotential decreases, electrical conductivity increases as usually does the pH of acid soils. There occurs an increase in solubility of iron, manganese, phosphate, and a number of other ions. Furthermore, the concentration of carbon dioxide (CO₂) and methane (CH₄) increases while sulfates are reduced to hydrogen sulfide (H₂S). These chemical changes are of significance in the mineral nutrition of growing plants and pollution of subsurface drainage waters. The solubility of iron, manganese and sulfur has recently attracted attention in subsurface drainage because of their contribution to the formation and accumulation of sludges in tile drains. These sludges result in clogged drain lines and restrict subsurface drainage.

Artificial drainage is necessary in soils with restricted internal drainage or high clay contents. Drainage reduces the frequency of excessive moisture and provides a more favourable plant-root environment. Despite the considerable economic investment in agricultural drainage,
there is surprisingly little quantitative data as to its effects on soil physical properties. The effects of different degrees of drainage, particularly the comparison of surface drainage with tile drainage, has never been evaluated by means of a well designed and controlled field experiment. Since drainage costs are usually high there is a need to evaluate different drainage systems with respect to their short term and long term effects on soil properties and crop yields.

The research work reported in this manuscript was conducted to study changes in soil physical and chemical properties under excessive soil moisture conditions. Freeze-thaw effects on soil structure were characterized for different moisture levels, aggregate sizes and freeze-thaw temperatures. Also, an evaluation of different field drainage systems was made in regard to their effects on soil physical properties.

These objectives were realized through a combination of laboratory and field studies. In the laboratory study, excess moisture conditions were provided by submergence of soil for prolonged periods. The principal structural indices studied were saturated hydraulic conductivity, moisture retention and pore size distribution. Similar determinations were used for evaluating soil structure before and after freeze-thawing. Soil chemical changes of pH, EC, ammonium, nitrates, iron, manganese, sulfate and anions were evaluated in the soil solution. In the field study, soil structure was characterized in an on-going drainage experiment with four different drainage systems installed in 1957 at North Central research station Castalia, Ohio.
This chapter reviews the literature on the effects of excessive moisture, drainage and freeze-thawing on soil physical properties and the soil chemical changes under submerged anaerobic conditions. Beyond a vaguely defined range of optimum soil moisture, crop production is hampered by excessive soil moisture. The practice of irrigation and drainage has been employed for a long time to keep the soil at its optimum moisture content. In spite of this, flooding of agricultural land occurs from time to time due to heavy rainfall, impervious subsoil and surface inflow into low lying areas. The presence of high water table is a further contributing factor to excessive moisture conditions.

The presence of excessive water reflects in changed soil and plant characteristics. This involves the complex interrelationships between the physical, chemical and biological properties of the soil that are interlinked with physiology of the plant. Much work has been done to study the direct effects of submergence on plant response. The latter is controlled by the duration of flooding, stage of plant growth, plant species and environmental factors. Excessive moisture is known to have some indirect effects. These include changes in soil structure and soil chemical environment that are mainly due to physical interaction of soil with water and absence of oxygen, respectively.
I Excess Moisture Effects On Soil Strength

Soil can deform by shear, by compression, or by a combination of the two. Shear deformation has been the process traditionally studied in soil mechanics because it has an overriding influence on the stability of earthen structures, such as slopes and foundations. Agricultural top soil is usually in a more loose and aerated state than the subsoil and hence is far more compressible. The shear and compressive strength of top soil is important in agriculture both in maintaining soil structure against compaction by farm machinery and in determining the draft requirements for tillage operations. Soil strength determines the mechanical impedance, which is a fundamental property governing plant root proliferation. Soil strength is characterized by its resistance to penetration and compressive strength measurements.

A. Resistance To Penetration

The resistance of a soil to the penetration of a probing instrument is an integrated index of soil compaction, moisture content, texture, structure and type of clay mineral. It is a determination that involves both soil consistency and soil structure (Baver et al, 1974). Fausey and Schwab (1969) reported that the resistance to penetration of undrained soil was much greater than tile drained soil.

B. Unconfined Compression Strength

The strength of a soil as measured in an unconfined
compression test is a manifestation of the energy required to separate the soil aggregates in the plane of shear or failure. The unconfined-compression test is a special case of the triaxial-compression test in that the lateral or confining pressure is zero. The unconfined-compression test is the simplest form of the unconsolidated-undrained shear test. It is the quickest and most common strength test for cohesive soil materials. The test is based on the assumption that there is no moisture loss during the test (Jumikis, 1962).

C. Shear Strength Of Soils

The shear strength of a soil is not a physical constant but rather varies with stress history, soil structure, degree of disturbance, water content and bulk density of the soil (Sallberg, 1965).

The shear strength of a soil is the maximum internal resistance of a soil to the movement of its particles; that is, resistance to slipping or sliding of soil over soil. Shear failure may occur in the form of fracture, in which the material disintegrates at a certain stress, or as yielding (plastic flow) along failure planes (Wu, 1966). General discussions of shear strength are presented in varying degrees of detail in several texts on soil mechanics (Terzaghi and Peck, 1967; Sowers and Sowers, 1971; Jumikis, 1962).

The shear strength of a soil is generally considered to be a function of cohesion between the soil particles and intergranular friction. This relationship is represented by Coulomb's law as follows:

\[ S = C + N \tan \phi \]

where \( S \) is the shear strength, \( C \) is the cohesion, \( N \) is the stress or
pressure normal to the shear plane, and $\phi$ is the angle of internal friction. The shear strength of a soil is basically made up of (1) the structural resistance to displacement of the soil because of the interlocking of the soil particles, (2) the frictional resistance to translocation between the individual soil particles at their contact points, and (3) cohesion (adhesion) between the surfaces of the soil particles.

Williams and Shaykewich (1970) reported that for a clayey soil, the shear strength increased rapidly with increasing matric suction. In a loamy soil it remained relatively constant over the range of $-0.59$ to $-15.1$ bars. The authors noted that $C$ and $\phi$ tended to vary with bulk density and degree of saturation. The influence of matric potential on germinating seeds and elongating roots was shown to be due to its contribution to mechanical strength of the soil system.

In shear tests on the A horizon of the Drummer soil series, Panwar and Siemens (1972) showed that shear strength increased as moisture content decreased and bulk density increased. They calculated the failure energy per unit soil volume from the unconfined compression tests. This was done by integrating the stress-strain curves to the point of maximum stress. The energy per unit volume was minimal at 16.5% moisture, and increased with increased moisture content to near the plastic limit, then decreased with added moisture. They also report other studies where the energy generally decreased throughout the increase in moisture content.

Tests by Farrell et al (1967) on a remolded loam soil under unconfined axial loading showed that an increase in soil water suction from 0.25 to 25 bars (corresponding moisture range being from
12 to 2 percent) produced a six fold increase in tensile strength of soil. In a study on rupture parameters (rupture stress, rupture strain, rupture modulus) of individual air-dry soil aggregates of size 2-8 mm from nine soils, Rogowski et al (1968) found that these parameters were significantly correlated with percent clay, bulk density, percent organic carbon and aggregate size distribution. A linear stress-strain relationship existed for the air-dry aggregates, thus suggesting the applicability of Hooke's law for brittle materials. In general, the rupture parameters were greater in fine textured than in coarse textured soils. Rupture stress values ranged from $0.5 \times 10^6$ dynes/cm$^2$ for sandy soils to $21 \times 10^6$ dynes/cm$^2$ for silty clays.

Results reported by Larson and Allmaras (1971) for surface horizons of three soil series show that cohesion (C) increased by a factor of 2, 2.5, and 4 for corresponding increases in bulk density from 1.5 to 1.7, 1.3 to 1.5, and 1.0 to 1.2 g/cc, respectively. At bulk density of 1.7 the angle of internal friction did not change at soil moisture suctions ranging from 0.3 bar to 0.7 bar while there was a slight increase for bulk density of 1.5 g/cc. Increasing bulk density in each soil was shown to increase the angle of internal friction in amounts ranging from 2 to 4 degrees (5 to 10%). Thus both water content and bulk density were shown to influence soil strength, but these variables apparently affected cohesion to a greater extent than internal friction.

Camp and Gill (1969) reported on the influence of drying on the soil strength parameters C and $\phi$ for three cohesive soils on samples prepared in the laboratory. Samples for any soil were molded
at the same moisture content and to the same bulk density and then were dried slowly to soil water contents between the 1/3-bar soil water suction level and air dryness. The parameters C and $\phi$ both increased with drying for the soils. The values of C ranged from 0 to 8 bars while those of $\phi$ were in the range of 0-60 degrees.

Using the penetrometer and modulus of rupture to measure soil strength, Gerard et al (1962) found that a slow rate of drying caused closer packing of soil particles and greater soil hardness on a fine sandy loam soil than did a fast rate of drying. In another study, Gerard et al (1966) reported that non-capillary porosity decreased and strength, as measured by modulus of rupture, increased with slow drying. The effect of slow drying of soil was considered equivalent to the dispersion of soil particles. Strength ($\gamma$) in m-bars decreased hyperbolically as the percent pore volume (x) drained at 60 cm suction increased as given by the following relation:

$$\gamma = 7499 \times x^{-1.721} \quad (R = -0.997).$$

Strength was also correlated with planes of weakness or large voids in the soils.

Dowdy and Larson (1970) measured the tensile strength and the axial tensile strain of Mg-montmorillonite using thin oriented clay samples. Over a relative water vapor pressure range ($P/P_o$) from 0.02 to 0.92, the tensile strength ranged from 210 Kg/cm$^2$ at $P/P_o = 0.02$ to 1.7 Kg/cm$^2$ for $P/P_o = 0.92$. The corresponding values for tensile axial strain were 173 and 65 $\mu$/cm, respectively. They stated that their experimental technique was sensitive enough to assess relative electrostatic and chemical interactions with a minimum interference from frictional force components in different clay systems.
Lotspeich (1964) tested the hypothesis of increasing coherence (strength) of soil with increase in the number of particle contacts. Using glass beads of different sizes and mixing them in different proportions with clay, he attempted to get cubic and tetrahedral packing. The tetrahedral packing involving beads of four different diameters gave the highest dry strength. Maximum strength and bulk density for any mixture was attained at a moisture content between 1 and 5 bar suction, suggesting that field soils may be compacted to a rather high degree within this range of moisture.

D. Implications For Crop Growth

Mechanical impedance may inhibit or even prohibit root and shoot growth. It is normally expressed in terms of density or strength. Recent investigations by Taylor et al (1966) and Barley et al (1965) have shown that soil strength rather than soil bulk density controls the penetration of plant roots into soil. The effects of mechanical impedance upon root penetration have been discussed in detail by Lutz (1952) and the response of plant roots to the physical effects of soil compaction and mechanical resistance have been reviewed by Rosenberg (1964) and Barley and Greacen (1967). Taylor and Ratliff (1969) have shown that increases in soil suction within the commonly accepted plant available range sometimes decreases root elongation rates of plants. However, part or all of that decrease may actually be caused by an increase in soil strength rather than by an effect of soil suction per se on root growth.

Critical values for soil strength have not been assigned
because strength is very much dependent on soil moisture suction. Soil strength should be measured at lower moisture contents where mechanical impedance may become an important factor in root penetration.

II Excess Moisture Effects On Other Soil Physical Properties

Most statements commonly made about the effects of excessive moisture and drainage on soil physical properties and ultimately on crop response are generalized, qualitative and lack factual evidence. This is mainly due to the complex nature of the problem and the difficulties in measuring and evaluating the various relationships. The direct characterization of soil structure is very difficult. Therefore certain easily measurable soil physical properties referred to as indices of soil structure are usually employed. The changes in these physical properties are ascribed to changes in soil structure. The most commonly used structural indices include:

- **Bulk density** - mass of soil solids per unit volume of soil.
- **Porosity** - the volume of void spaces in a unit volume of soil.
- **Moisture retention** - the volume of water per unit volume of soil.
- **Air filled porosity** - the air filled volume per unit volume of soil at any given suction.
- **Hydraulic conductivity** - coefficient of permeability, \( K \) in the Darcy's law.
- **Soil strength** - resistance to penetration or compression force.
- **Aggregate stability** - stability of aggregates against disruptive forces of water.
A. Soil Structure

Baver (1956) and Martin et al. (1955) pointed out that excessive soil moisture has a detrimental effect on all the factors involved in the formation and stabilization of soil aggregates. The two factors considered dominant in the structural degradation include hydration of the aggregates resulting in disruption through swelling and the explosive action of entrapped air. The other factors are a dispersion of the cementing materials and a reduction in cohesion with increasing moisture content. Kohnke (1968) reported that under water logged conditions that the organic cementing agents are decomposed and that no new ones can be formed. Pore spaces are clogged due to soil dispersion and the water and air regimes suffer even after the soil has dried.

Clay soils of low humus content exhibit structural changes including slaking, swelling and particle reorientation under the influence of wetting and drying cycles. Hillel (1966) reported that the major changes in soil structure resulting from the action of water usually occurred at the expense of larger pores, tending to reduce the mean pore size. In a study on evaluation of soil structure under water logged and non-waterlogged clay soil, Zaydelman (1963) reported that differences in total porosity and bulk density were smaller while appreciable differences existed in the maximum field moisture content. The permeability of non-waterlogged soil was 2.5 meters per day while for waterlogged soil the corresponding value was only 0.09 meters per day. Under conditions of prolonged submergence Chaudhary and Ghildyal (1969) found that initial large aggregates (2-5 mm) were broken down
to small aggregates in a puddled lateritic sandy clay loam soil used for growing of paddy rice.

To summarize, excessive moisture seems to be degradative to soil structure resulting in reduced aggregation, lower permeability, higher moisture retention, higher bulk density and lower volume of air filled pores.

B. Field Drainage Studies

It is well known that drainage of soils subject to waterlogging is necessary for successful crop growth. The statements usually made about the ameliorative effects of drainage on soil structure are qualitative, generalized and lack support of experimental evidence. Wesseling and VanVijk (1957) concluded from little available information that the improvements in soil structure from drainage are small. The removal of excess water by drainage results in a changed soil-water-air environment that governs the physical, chemical and biological properties of the soil. Hence the changes that occur under drainage reflect the combined effects of soil moisture regimes and plant residues.

In the Netherlands, an experiment was initiated on a heavy clay in 1942 to study the effect of water table depth on crop yields and soil structure. Hooghoudt (1952) reporting on this experiment indicated that the ground water levels were maintained at 40, 60, 90, 120 and 150 cm depths at all times. During the first five years no differences were noted in tillability and structure of the soil. After this time, however, the top soil became more compact and sticky for
the 40 cm water table depth and to a lesser extent on 60 cm water table depth. The other three water table depths did not show any of these effects. Six years later VanHoorn (1958) reporting on the same experiment stated that a distinct difference emerged between plots with the water table at 40 cm and the other plots having deeper water levels. The 0-20 cm surface layer on this plot was wetter and had a higher draft requirement in the spring, autumn and winter. Also there was a decrease in the percentage of large pores and the permeability to water.

Leyton and Yadav (1960) studied the effect of drainage on physical properties of an oxford clay in England. Three intensities of drainage were represented by 1) undrained (or control) – shallow drains designed only to prevent surface water logging, 2) drains, 60 cm deep, spaced 20 meters apart, and 3) drains, 60 cm deep, but spaced 10 meters apart. The area was planted to a variety of tree species. After five years of drainage the comparison of the physical properties of drained and undrained soils revealed a higher content of water stable aggregates, a higher proportion of larger pore spaces and a greater vertical and lateral hydraulic conductivity in the drained soil. The difference generally decreased with depth; at about 38 cm, there were only small differences. The authors could not provide quantitative effects of drainage because the soil in control and in drained treatments differed in texture.

Nesterova (1963) reported that subsurface drainage was most effective followed by surface drainage when compared to control or no drainage, in fast removal of excess water. The improvement in
Air-water relations due to drainage treatments decreased with depth.

The bulk density of plow layer decreased and total porosity increased as the degree of drainage increased. Both parameters showed a greater change between subsurface drainage and surface drainage than between surface drainage and control. Andriyauskayte (1961) and Milyauskas (1963) summarized drainage investigations in the Lithuanian SSR that had been in operation for periods as long as 60 years. Tile drained and undrained soils on similar neighboring fields and in the same crop rotation were studied simultaneously for 9 different locations. Compared to undrained soil the drained soils were characterized by decreased bulk density, increased porosity, better aeration and increased water permeability. The beneficial effect on soil physical properties decreased with distance from the drains. These studies were primarily qualitative in nature and no statistical analysis was given by the authors.

Lutz (1960) reported the results of a drainage experiment initiated in 1947 in North Carolina on a silt loam soil. The drainage systems consisted of open ditches 18 inches deep at 60, 90, and 120 feet spacings and tile drains at depths of 2, 3 and 4 feet with spacing between tile lines of 50, 75 and 100 feet at each depth. Lutz stated that tile drains increased the percentage of large and intermediate size pores in the soil (pores drained at 10 and 70 cm of water suction, respectively) during the first year and a half after their installation. The percentage of intermediate pores changed less than the percentage of large pores. The volume of large pores was practically doubled in the top soil while a five fold increase was shown in the subsoil (B-horizon). Changes in pore size distribution in such a short time
period are at variance with most data. Such a large magnitude of change may occur if these values were near zero. Lutz further stated that no appreciable changes in total porosity were found in either the top or the subsoil. The effect of different tile depths and spacings on bulk density and porosity after two years was not consistent. Lutz indicated, however, that greater changes occurred, particularly in the subsoil, when the drains were two rather than three or four feet deep. Among three spacings used, the 50 feet spacing had a greater effect on these physical parameters.

Fausey and Schwab (1969) and Fausey (1966) studied the influence of drainage systems involving no drainage, surface drainage alone, subsurface drainage alone and a combination of surface and subsurface drainage, on a lakebed silty clay for soil physical properties and characteristics of plant growth. After 8 years of drainage no significant differences were found in bulk density and in pore volumes drained at 0.01, 0.06 and 0.3 bar suction. However, significant differences were obtained for surface penetration force, field moisture content, soil temperature, root distribution and plant heights. Plot having subsurface or combined surface-subsurface drainage had lower field moisture contents, less resistance to surface penetration, taller plants and greater yields than plots with surface drainage alone. Subsurface drainage promoted a more favourable surface soil structure than did surface drainage or no drainage. On plots with no drainage, crop stand was sparse and crop growth essentially nil. There were long periods with ponded water and crusting, and adverse structure of the surface soil was evident.
C. Summary

The review of literature indicates that with improved drainage that bulk density decreases while drainable porosity increases, both changes being quite small. Also, there occurs an increase in permeability and aggregate stability while the resistance to penetration is decreased. These properties indicate changes in soil structure. The method of drainage influences the magnitude of these changes. Overall, drainage helps in soil structure improvement.

III Excess Moisture And Soil Chemical Properties

A. Characteristics Of Submerged Soils

Conditions existing in water logged soils are quite different from those of well drained soils. Generally in well drained soils a rather continuous supply of oxygen from the atmosphere is available to plant roots and micro-organisms. In poorly drained or water logged soils, diffusion of molecular oxygen into the profile is greatly impeded. Lemon and Kristensen (1960) found that diffusion of oxygen through water was 10,000 times slower than diffusion in gas-filled pores. A flooded soil, however, is not uniformly devoid of oxygen and the concentration of oxygen may be much higher in a surface layer of few mm thickness. This results in differentiation of a water logged soil into a surface oxidized layer and an underlying reduced layer as a result of a limited oxygen supply reaching the soil surface (Patrick and Mahapatra, 1968; Ponnampuruma, 1972). Takai et al (1956) found no oxygen in three soils 1 day after submergence. Turner and
Patrick (1968) could detect no oxygen in four soil suspensions within 36 hours of withdrawal of oxygen supply.

1. **Anaerobic Respiration**: — Flooding a soil cuts off the oxygen supply of the soil micro-organisms. The aerobic organisms use up the oxygen present in the soil and then become quiescent or die. The facultative anaerobes followed by obligate anaerobes, then take over the decomposition of soil organic matter. In the absence of molecular oxygen these organisms use NO$_3^-$, Mn$^{4+}$, Fe$^{3+}$, SO$_4^{2-}$, dissimilation products of organic matter, CO$_2$, N$_2$, and even H$^+$ ions as electron acceptors in their respiration. This process eventually reduces NO$_3^-$ to N$_2$, Mn$^{4+}$ to Mn$^{2+}$, Fe$^{3+}$ to Fe$^{2+}$, SO$_4^{2-}$ to H$_2$S, CO$_2$ to CH$_4$, N$_2$ to NH$_3$, and H$^+$ to H$_2$ (Ponnamperuma, 1972). The switch from aerobic to anaerobic respiration occurs at the very low oxygen concentration of $3 \times 10^{-6}$ M (Greenwood, 1961). During anaerobic respiration, organic matter is oxidized and soil components (Fe$^{3+}$, Mn$^{4+}$ etc.) are reduced.

2. **Sequential Reduction**: — The order of reduction of a submerged soil proceeds roughly in the sequence O$_2$, NO$_3^-$, Mn$^{4+}$, Fe$^{3+}$, SO$_4^{2-}$ (Ponnamperuma, 1955; Ponnamperuma and Castro, 1964; Turner and Patrick, 1968). Usually one component is not completely reduced before the next most easily reduced component begins to be reduced. Oxygen is the first soil component to be reduced, and it becomes undetectable within a day after submerging a soil as indicated earlier. The next oxidant to be attacked is NO$_3^-$, but NO$_3^-$ reduction begins only after the O$_2$ concentration has dropped to a very low value (Bremner and Shaw, 1958; Greenwood, 1962; Turner and Patrick, 1968). Similar to oxygen, the NO$_3^-$
retards the reduction of other redox components. NO$_3^-$ stabilizes the potential at 0.2 to 0.4 v, and prevents the release of Mn$^{2+}$, Fe$^{2+}$, s$^{2-}$, CH$_4$ and H$_2$ (Ponnamperuma, 1955; Ponnamperuma and Castro, 1964; Turner and Patrick, 1968).

MnO$_2$ follows nitrate in the reduction sequence. But its influence is weaker than that of NO$_3^-$ because it is insoluble in water and only a limited number of bacteria can utilize it as an electron acceptor in respiration. The next mineral system in thermodynamic sequence of reduction is the Fe(OH)$_3$ - Fe$^{2+}$ system but its influence on soil reduction is not as obvious as that of NO$_3^-$ or MnO$_2$. SO$_4^{2-}$ is reduced only under strictly anaerobic conditions associated with extremely low potentials (Ponnamperuma, 1972).

B. Electrochemical Changes

Submergence of a soil results in (1) a decrease in redox potential, (2) an increase in pH of acid soils and a decrease in pH of alkaline soils, (3) changes in specific conductance and ionic strength, (4) drastic shifts in mineral equilibrium, (5) cation and anion exchange reaction, and (6) sorption and desorption of ions.

1. Redox Potential ($E_h$): -- Redox potential of a soil is a measure of the tendency for reduction reactions to occur.

Oxidized state + n electrons $\rightarrow$ Reduced State. As the pH of a soil system is a measure of its proton supplying intensity, $E_h$ of a soil system is a measure of its electron accepting intensity. Oxidation - reduction is a chemical reaction in which electrons are
transferred from a donor to an acceptor. The electron donor loses electrons and increases its oxidation number (or is oxidized); the acceptor gains electrons and decreases its oxidation number or is reduced. The source of electrons for biological reduction is the organic matter. The state of reduction of a soil can be defined quantitatively by measures of intensity (redox potential) or capacity (total concentration of reduction products).

After an extreme interest in the $E_h$ of the soil in the 20's and 30's of this century, most agronomists have considered it to be of little value. In case of aerated soils it is known to be of little importance but there are indications of its possible use in characterizing anaerobic soils.

As there is a definite correlation between $E_h$ and water content of a soil, McKeague and Bently (1960) have suggested that field $E_h$ measurements might be useful in distinguishing soils of different drainage states. Meek et al (1968) from field observations indicated that measurements of $E_h$ can give an estimate of the dissolution of iron and manganese in the soil solution in the field and help locate areas of tile line problems. Parr (1969) suggested the controlled redox approach to prevent clogging of tile drains by sludges - through increasing internal drainage and aeration, addition of nitrate or synthetic compounds capable of acting as electron acceptors and applied in the soil or tile line.

Aerated soils have characteristic redox potentials in the range of +400 to +700 mv. From +110 to +400 mv, the soil is moderately reduced and redox potentials of -100 to -300 mv are
indicative of highly reduced conditions (Patrick and Mahapatra, 1968).

The approximate redox potentials at which oxidized form of several
inorganic compounds becomes unstable are, \(O_2 = +330\, \text{mv}\); \(\text{NO}_3^- = +220\, \text{mv}\);
\(\text{Mn}^{4+} = +200\, \text{mv}\); \(\text{Fe}^{3+} = +120\, \text{mv}\) and \(\text{SO}_4^{2-} = -150\, \text{mv}\) (Patrick, 1964;

2. pH: -- When an aerobic soil is submerged, its pH decreases
during the first few days (Motonura, 1962; Ponnampuruma, 1964) reaches
a minimum, and then increases asymptotically to a fairly stable value
of 6.5 - 7.5 a few weeks later. The decrease in pH shortly after
submergence is probably due to a) the accumulation of \(\text{CO}_2\) produced
by respiration of aerobic bacteria, because \(\text{CO}_2\) depresses the pH even
of acid soils (Nicol and Turner, 1957) and b) production of organic
acids (Motonura, 1962). The subsequent increase in pH of acid soils is
due to soil reduction (Ponnampuruma et al, 1966a). According to
Ponnampuruma (1972), since most soils contain more ferric oxide hydrates
than any other oxidant, the increase in pH of acid soils is largely due
to the reduction of iron.

\[
\text{Fe(OH)}_3 + 3 \text{H}^+ + e = \text{Fe}^{2+} + 3 \text{H}_2\text{O}
\]

The pH of the neutral and alkaline soils is regulated by the \(\text{CaCO}_3-\text{CO}_2-\text{H}_2\text{O}\) equilibrium. The pH and \(E_h\) values of submerged soils, whether acid
or alkaline are highly sensitive to loss of \(\text{CO}_2\), the fact which must be
borne in mind during the sampling of reduced soils and the extraction
and handling of their soil solutions. The pH value profoundly influences
hydroxide, carbonate, sulfide, phosphate, and silicate equilibria in
submerged soils which in turn regulates the concentration of
nutritionally significant ions like Al$^{3+}$, Fe$^{2+}$, H$_2$S, H$_2$CO$_3$ and undissociated organic acids.

3. **Electrical Conductance (EC):** -- The electrical conductance of the solutions of most soils not unduly high in NO$_3^-$ or SO$_4^{2-}$, increases after submergence, attains a maximum roughly coincident with peak reduction, and then declines to a fairly stable value, which varies with the soil. A number of workers have confirmed this, both in laboratory and field studies (Ponnampuruma et al., 1966; Biswas et al., 1972; Williams, 1972; Puttaswamygowda and Pratt, 1973). The increase in conductance during the first few weeks of flooding is due to the release of Fe$^{2+}$ and Mn$^{2+}$ from the insoluble ferric and manganic oxide hydrates, the accumulation of NH$_4^+$, HCO$_3^-$, and RCOr and (in calcareous soils) the dissolution of CaCO$_3$ by CO$_2$ and organic acids. An additional factor is the displacement of ions, especially cations, from soil colloids by reactions of the following type:

$$
\text{Ca}^{2+} \text{- colloid} + \text{Fe}^{2+} \rightleftharpoons \text{Fe}^{2+} \text{- colloid} + \text{Ca}^{2+}
$$

$$11 \text{Fe}_3\text{O}_4\cdot\text{nH}_2\text{O}
$$

The decline in EC after a peak value is due mainly to the precipitation of Fe$^{2+}$ as Fe$_3$O$_4\cdot$nH$_2$O and Mn$^{2+}$ as MnCO$_3$. In calcareous soils the decrease is the result of fall of partial pressure of CO$_2$ (P$_{CO_2}$) and the decomposition of organic acids. Among non-saline soils, the highest specific conductances are obtained in soils that have a low cation exchange capacity and are high in organic matter.
C. Chemical Changes

The subject of chemistry of submerged soils has been of prime interest in rice culture, Geochemistry, Limnology, and pollution, and has attracted the attention of a number of researchers all over the world. The chemical properties of a soil undergo a drastic transformation on submergence. The oxidized constituents, $\text{Fe}^{3+}$, $\text{Mn}^{4+}$, $\text{NO}_3^-$ and $\text{SO}_4^{2-}$ that characterize a well drained soil, virtually disappear and are replaced by their reduced counterparts, $\text{Fe}^{2+}$, $\text{Mn}^{2+}$, $\text{NH}_4^+$ and $\text{S}^{2-}$. The course of organic matter decomposition is diverted from $\text{CO}_2$ production to the formation of an array of unstable organic substances, followed by the evolution of $\text{CO}_2$ and $\text{CH}_4$.

1. Nitrogen

   a) Denitrification: -- Under submerged anaerobic conditions oxidized forms of nitrogen can be used by the microorganisms as electron acceptors and are reduced to $\text{N}_2$ or $\text{N}_2\text{O}$. Almost all the nitrate present in a soil disappears within a few days of submergence (Bremner and Shaw, 1958; Turner and Patrick, 1968). However, very little denitrification occurs until all the oxygen is depleted from the soil. The fluctuations in soil moisture content have a marked effect on the stability of nitrate because of the controlling effect of soil moisture on the supply of oxygen diffusing through the soil. Pilot and Patrick (1972) while studying the effect of soil moisture suction on nitrate reduction found that nitrate was stable above the suction of 20-40 cm of water for three soils varying in texture from loamy sand to silty clay loam. Nitrate can also be reduced in oxygen deficient
microzones, especially in the interior of soil aggregates, even though the surrounding soil is aerated (Greenland, 1962).

b) Accumulation Of Ammonia: -- The mineralization of organic nitrogen in submerged soils stops at the ammonia stage because of the lack of oxygen to carry the process via nitrite to nitrate. Thus ammonia accumulates in the soil solution. The soil solution may contain 2-100 ppm N as NH$_4^+$ depending on texture and organic matter content of the soil (IRRI, 1964). Ammonia is derived from anaerobic deamination of amino acids, degradation of purines and hydrolysis of urea. Very little of the nitrate is denitrified to ammonia. Moraghan (1961) reported this reaction to be of no significance during a study on waterlogged incubation of 8 Iowa soils. Broadbent and Reyes (1971) reported that inorganic nitrogen is released in greater quantities and faster in anaerobic soils than in aerobic soils because of lesser immobilization of nitrogen in anaerobic media. Aside from microbial production of ammonia it has been suggested (Bhattacharya, 1971), that expansion of clay crystal lattices in a flooded soil can result in release of exchangeable NH$_4^-$N from the fixed NH$_4^-$N fraction of the soil.

2. Manganese And Iron

a) Manganese: -- In flooded soils higher oxides of manganese (e.g. MnO$_2$, Mn$_2$O$_3$, Mn$_3$O$_4$) are reduced to Mn$^{2+}$ form. The reduction of Mn is both chemical and biological and precedes the reduction of iron. Manganese is present in anoxic soil solution as Mn$^{2+}$, MnHCO$_3^+$, and as organic complexes. The concentration of Mn in solution is governed by the organic matter, manganese content, soil reaction and
length of anaerobism. Alkaline soils and soils low in manganese rarely contain more than 10 ppm water soluble Mn\(^{2+}\) while acid soils high in manganese and organic matter may build up as high as 90 ppm within a week or two of submergence (Ponnamperuma, 1972). Phillips and Hossner (1972) reported Mn\(^{2+}\) concentrations in the soil solution to be in the range of 0.6 to 22.6 ppm for Texas soils. The accumulation of Mn\(^{2+}\) in soils is of practical importance due to its toxicity to plants. Mn toxicity was noticed when Mn\(^{2+}\) in soil solution exceeded 15-20 ppm (Harter, 1962).

b) Iron: — The most important chemical change that takes place when soil is submerged is the reduction of ferric iron and the accompanying increase in its solubility. Iron is the third (silica and aluminum being first and second) most abundant mineral element in the soil (Thompson, 1952). The reduction of iron is a consequence of the anaerobic metabolism of bacteria and appears to be chiefly a chemical reduction by bacterial metabolites (Bloomfield, 1951; Motomura, 1961), although direct reduction coupled with respiration may be involved (Kamura et al, 1963). According to Alexander (1965) no reduction occurred in soil sterilized prior to initiation of anaerobic conditions, whereas soil sterilized and then inoculated with bacteria did produce ferrous iron. The reoxidation of Fe\(^{2+}\) to Fe\(^{3+}\) has been reported as a result of biological oxidation (Alexander, 1965) and chemical reaction (Starkey and Halvorson, 1927; Harter and McLean, 1965). The bulk of the water-soluble iron in flooded soils is usually present as bicarbonate and salts of the lower fatty acids (Ponnamperuma, 1972) as well as complexes of organic matter (Olomu et al, 1973). The
concentration of water-soluble iron in submerged soil depends upon the iron content of soil, organic matter, soil reaction, and the period of submergence. In neutral and calcareous soils the Fe\(^{2+}\) concentration rarely exceeds 20 ppm, while in acid soils rich in organic matter and iron it may go up as high as 600 ppm (Ponnamperuma, 1972). Phillips and Hossner (1972) working with soils from 32 locations in Texas found that the water soluble iron ranged from 2.5 to 60.6 ppm in the soil solution. Iron concentrations <28 ppm have been reported to accelerate root growth in rice but concentrations >112 ppm were toxic (Takijima, 1965). Ford (1973) proposed that soils containing Fe\(^{2+}\) greater than 0.5 ppm are potentially susceptible to accumulation of sludges in drain lines.

The oxidation-reduction reactions of iron and manganese are of significance in the clogging of drain lines by sludges (Parr, 1969; Grass et al., 1973; Spencer et al., 1963; Ford and Beville, 1968; Meek et al., 1968). Under saturated conditions soluble forms of Fe\(^{2+}\) and Mn\(^{2+}\) can move from the surface soil down to the drain where they can be precipitated from solution within the drain or in the tile joints thereby reducing flow of water through the line or preventing entry of water into the tile itself. In severe cases, the effective life of drain lines may be reduced to only 5-10 years. Soils high in iron, sulfur, manganese and organic matter under excess moisture conditions provide a favorable medium for this type of drainage problem.

3. Sulfate

In a flooded soil the main changes are the reduction of \(\text{SO}_4^{2-}\)
to sulfide and the dissimilation of the amino acids cysteine, cystine, and methionine (derived from the hydrolysis of proteins) to \( \text{H}_2\text{S} \) (Ponnampерuma, 1972). Sulfate reduction occurs under highly reduced conditions with soil having redox potentials of about +100 to -150 mv (Connell and Patrick, 1968). The reduction of sulfate is brought about by a small group of obligate anaerobic bacteria of the genus *Desulfovibrio*, which use \( \text{SO}_4^{2-} \) as the terminal electron acceptor in respiration, and function best in the pH range of 5.5-9.0 (Starkey, 1966). They are capable of utilizing organic acids as electron donors in the reduction of sulfate:

\[
\begin{align*}
\text{H} & \\
2\text{CH}_3\text{C}-\text{COOH} + \text{SO}_4^{2-} & \rightarrow 2\text{CH}_3\text{COOH} + 2\text{CO}_2 + \text{H}_2\text{S} + 2\text{OH}^- \\
\text{Lactic Acid} & \quad \text{Acetic Acid}
\end{align*}
\]

The kinetics of water soluble sulfate (which is a measure of sulfate reduction) in anaerobic soils depends on soil properties (IRRI, 1965). In neutral and alkaline soils concentrations as high as 1500 ppm \( \text{SO}_4^{2-} \) may be reduced to zero within 6 weeks of submergence while the reduction proceeds slowly in submerged acid sulfate soils. Connell and Patrick (1969) reported that in a submerged soil well supplied with iron, \( \text{H}_2\text{S} \) formed by reduction of \( \text{SO}_4^{2-} \) is almost completely removed from solution as insoluble ferrous sulfide. Free \( \text{H}_2\text{S} \) with toxic levels is evolved only if the soil lacks active iron (Desai et al., 1957). Nitrate has been reported to inhibit \( \text{SO}_4^{2-} \) reduction (Vamos, 1958). No sulfide appeared until all of the nitrate had been reduced. Ford and Beville (1968) indicated that generation of \( \text{H}_2\text{S} \) under extremely reduced
condition was the principal cause for the disintegration of calcium silicate slag gravel filters around the tile lines.

4. Other Ions

Flooding a soil causes an increase in concentration of ions in the soil solution as indicated by increases in electrical conductance. In a reduced soil the major anions are \( \text{HCO}_3^- \), \( \text{Cl}^- \), and phosphates while the cations are chiefly \( \text{Ca}^{2+} \), \( \text{Mg}^{2+} \), \( \text{Na}^+ \), \( \text{K}^+ \), \( \text{NH}_4^+ \), \( \text{Fe}^{2+} \) and \( \text{Mn}^{2+} \). Out of these ions, \( \text{Ca}^{2+} \), \( \text{Mg}^{2+} \), \( \text{Na}^+ \), \( \text{K}^+ \), \( \text{Cl}^- \), are not involved in the reduction process, rather the increases in their concentrations is a secondary effect of submergence and reduction, chiefly solvent action of \( \text{CO}_2 \) and cation-anion exchange reactions.

D. Summary

Oxidizing conditions exist in well drained soils while absence of oxygen under submerged conditions leads to an anaerobic environment. The reducing conditions are stimulated and drastic chemical changes can be expected depending upon the length of submergence and soil properties. Under reducing conditions, solubilities of a number of mineral elements such as iron, manganese, phosphate and silica are increased. The pH of a submerged soil approaches neutrality, electrical conductance is increased, while redox potential is decreased. Nitrates are lost due to denitrification, ammonia accumulates due to lack of nitrification conditions, and a variety of toxic organic substances are generated. Sulfates are reduced to sulfide, and accumulation of carbon dioxide and methane gas occurs. The period of
intense reduction; production of ammonia; build up of high concentrations of CO$_2$; Fe$^{2+}$; Mn$^{2+}$ and organic reduction products is the first 2-6 weeks after submergence. The chemical changes under the submerged anaerobic soil environment are of significance to plant nutrition, ground water pollution, and impediment of subsurface drains.

**IV Freeze-Thaw Effects On Properties Of Wet Soils**

**A. Introduction**

In regions of humid and subhumid climate, land is often plowed in the autumn to utilize the action of frost for improving soil tilth. However, freezing and thawing may not always produce highly aggregated soils in the spring. Baver *et al* (1974) reported that the structure formed depends on the soil type and associated properties, the conditions of freezing and thawing and the water content at the time of freezing. Slater and Hopp (1949) challenged the concept of improving structure by alternate freezing and thawing. They found that repeated freezing and thawing decreased the water stability of aggregates especially at higher moisture contents. Although fall plowed clay soils became more friable in the spring as a result of frost action on dense clods, they postulated that the bonds within the aggregates were destroyed and there was little water stability remaining to maintain good soil tilth. Baver *et al* (1974) indicated that the aggregates formed by freezing and thawing are temporary in nature and not too stable unless sufficient organic matter is present to stabilize them.

A number of freeze-thaw cycles can occur in a soil
depending upon the thickness of the snow cover. Pelton et al (1968) reported that soils in Quebec, Canada, underwent as many as 20 freeze–thaw cycles per year in the surface 1 cm depth and the number decreased with depth.

Post and Dreibelbis (1942) working at Coshocton, Ohio, observed that the alternate freezing and thawing of soil usually started about the middle of November and continued to about the middle of March. Freezing to a depth of over 3 inches usually did not occur until January. Most of the deep freezing occurred during January and February. Dry soils thaw earlier and faster in spring but also freeze faster and deeper in winter, than wet soils.

B. Soil Structure

The effect of freeze–thawing on changes in structure of a soil depends upon the size of the aggregates, moisture content at freezing, freezing temperature, the number of freeze–thaw cycles and the conditions of drying of soil samples. Most of the studies on freeze–thawing have been conducted on disturbed soil samples for laboratory characterization of soil structure. Only a few field studies were noticed during literature survey of the subject.

1. Field Studies

Chepil (1954) reported that the percentage of aggregates <0.84 mm in diameter in the Kansas silt loam and clay soils studied, increased from fall to spring. Seasonal fluctuations in soil structure seldom exceeded 3 inches in depth and underwent little
changes from season to season.

A field study on changes in moisture and physical properties over-winter freezing in a loamy soil, was conducted by Krumbach and White (1964). The moisture content in the upper 15 inches usually exceeded the prefreeze field moisture content. Total pore space was always above and bulk density below the prefreeze values.

From USSR, Motuzov (1960) reported that freeze-thawing of a peat-gley soil decreased infiltration when the soil was at its maximum field moisture capacity; but at 60% of the maximum moisture capacity, freezing and thawing increased infiltration. A higher total porosity was reported in a sod-meadow soil after thawing of a frozen soil and it decreased subsequently. He concluded that the soils which are excessively wet at the time of freezing are more susceptible to erosion when the snow melts in spring than soils having an optimal moisture content at the time of freezing.

In another study from USSR, Gartsman and Moskaev (1971) reported that a heavy soil in Primore undergoes intensive surface moistening and deep seasonal freezing. With an increase in the intensity of moistening and freezing the bulk density decreases and porosity is increased. The variability of these properties of the soil were reported to be spacial and temporary in nature.

Leo (1963) conducted a laboratory and greenhouse study on 8 Canadian soils varying in texture from sandy to clayey. After freezing and thawing at saturation moisture, the total porosity of the soils decreased and their coefficient of permeability increased, while no significant differences were evident with respect to the capillary porosity and maximum water holding capacity. He ascribed
the increase in the coefficient of permeability of disturbed soil cores to the formation of continuous channels through rearrangement of pores during freezing and thawing. The influence of freeze-thawing was temporary and after growth of a crop of tomatoes or barley the differences were nullified. The author did not explain the reasons for these temporary changes in soil physical properties during plant growth. Compared to control, freeze-thawing resulted in poor growth and yield of tomato and barley. This was explained by the deterioration of soil structure during freezing and thawing.

2. Laboratory Studies

Soulides and Allison (1961) compared aggregation of two size fractions (1-2 mm and <2 mm) from a sandy loam, silt loam, and silty clay loam soil after 10 cycles of freeze-thawing. The soil was maintained at its moisture equivalent. Drying and freezing had an adverse effect on stability of soil aggregates of size 1-2 mm, but aggregation of composite soil <2 mm was enhanced perhaps due to decompositions of organic matter of this fraction.

Logsdail and Webber (1959) reported that the breakdown of soil structure with alternate freezing and thawing was more severe in an originally well aggregated soil and the effects were not significant for the poorly aggregated soil. Working with surface samples of Haldimand clay (<8.8 mm diam.) they observed that 0-3 cycles of freezing and thawing caused a significant breakdown of aggregates from the sod plots at all moisture levels employed (1.0, 0.33, 0.1, 0.01, 0.003 atm suctions) except the one with 1.0 atm suction.
Freezing and thawing decreased the erosive fraction (<1.0 mm diam.) of clay loam and fine sandy loam soils at higher moisture contents (Bisal and Nielsen, 1967). At low moisture levels the clay showed some breakdown from frost action but at high moisture levels there was as much evidence for a consolidating as for a disintegrating effect. The authors suggested that it was not a simple matter of freezing and thawing that causes a breakdown in clod structure over winter. There is a marked effect of moisture content at the time of freezing as well as the method of drying after freezing.

Sillanpaa (1961a) studied aggregate stability of a clay loam soil after 0-24 freeze-thaw cycles for different aggregate fractions incubated at saturation moisture content. The mean weight diameter of large aggregates (2-3 mm) decreased with an increasing number of freeze-thaw cycles rather rapidly during the first 10 cycles and more slowly afterwards; the effects on 0.25 - 0.83 mm size were insignificant while there occurred a continuous increase for aggregates of <0.25 mm up to 24 freeze-thaw cycles. At about the end of the experiment, however, all three aggregate fractions reached almost the same level of aggregation.

Willis (1955) has shown that alternate freezing and thawing of several soils (<8 mm) varying from silt loam to clay and maintained at saturation moisture content caused a decrease in the percentage of water stable aggregates. After 20 cycles of freezing and thawing, the greatest breakdown had occurred in the initial cycle and very little additional breakdown after the fifth cycle. Freeze-thawing resulted in a higher percentage of small sized (<0.25 mm) water
stable aggregate fraction compared to control.

In another study using four moisture levels (air dry, 15 bar, 1/3 bar, and maximum moisture retention) and two freezing temperatures (-3°C or -25°C), Sillanpaa (1961b) found that after five freeze-thaw cycles, the moisture contents near saturation significantly reduced the mean weight diameter (MWD) of the large (2-3 mm) aggregates but increased the MWD of aggregates <0.25 mm which were obtained by crushing the large size aggregates. In contrast, a significant decrease in MWD was found for original soil <0.25 mm at slow rate of freezing, which was assigned to their lower clay and organic matter content.

Dijk and Boekel (1965) working on a fresh peat soil found that freezing resulted in an increase in the average pore diameter. The moisture release at low suction (pF 0.4-2.0) increased while a decrease was noticed in the moisture range (pF 2.0-4.2). The main effect of freezing was reached at -5°C in 3-5 days and repeated freezing and thawing had little or no additional effect.

Benoit and Bornstein (1970) reported results of a freeze-thaw experiment on Cabot silt loam from Vermont. Three size fractions (0-2 mm; 2-4.8 mm; and 4.8-19.1 mm) two moisture levels (maximum water holding capacity and 0.5 bar) and two freezing temperatures (-18°C and -4°C) were compared before and after 15 freeze-thaw cycles for their effects on soil structure. Freeze-thawing increased the bulk density of soil cores with the amount of change increasing with aggregates size and with water content at time of freezing while freezing temperature did not have any effect. Water retention was increased to a great extent upon freeze-thawing. The higher the water content at freezing, the greater was the increase in water retaining ability for any
aggregate size and freezing temperature. However, the increases were small for 0-2 mm size fraction. Thus freezing and thawing at higher water content caused a breakdown of the soil aggregates and an increase in the volume of water the soil will hold. These effects increased with the increasing initial aggregate size. No proof of the statistical analysis on the data was evident from the results presented by the authors.

In a similar study as reported above, Benoit (1973) compared the hydraulic conductivity and water stability of aggregates using the aggregate size fractions (<0.8 mm; 0.8-1.2 mm; and 1.2-2.0 mm). In general, freeze-thawing at the maximum water content decreased hydraulic conductivity while it increased the conductivity of those cores frozen at the 0.5 bar moisture level. Water-stable aggregate breakdown was statistically greater at maximum water holding content. However, the water stable aggregates in the 0-0.8 mm size fraction increased by a factor of 1.26 from initial values after freezing and thawing at the 0.5 bar moisture level and -4°C freezing temperature.

Hinman and Bisal (1968) found that in a clay soil neither freezing and thawing nor method of drying had any appreciable effect on aggregation when the initial moisture content was at 15 atmospheres. At 0.1 atm, aggregates which were initially coarse (>4 mm) tended to breakdown slightly when exposed to alternate freezing and thawing followed by air drying at room temperature. The same treatment, however, favored aggregation of originally fine (<1.4 mm) soil. Compared to air drying, the freeze drying had more adverse effects on aggregation at all moisture levels.

Hinman and Bisal (1973) working with three Canadian soils
(loam, clay loam, and clay) concluded that compared to continuous freezing, alternate freezing and thawing for 25 cycles and subsequent drying increased the water percolation rate and water stable aggregation when the initial moisture content was at field capacity. At high moisture content (0.1 atm) freeze-thawing decreased the percolation rate while at very low moisture content (15 atm) no differences were apparent. The percolation rate of continuous frozen soil did not differ significantly from the unfrozen soil. Among the methods of drying it was seen that freeze-drying reduced the percolation rate significantly when compared to air drying, at all the three moisture levels.

Freezing and thawing influences the permeability of dispersed soils and may be utilized to good advantage as aids in restoring structure and permeability of alkaline soils (Gardner, 1945). In a laboratory study on Na- dispersed soil, additions of Ca\(^{2+}\) per se did not improve permeability but when accompanied by freeze-thawing, the permeability was restored due to channels made by net work of ice crystals.

To summarize the freeze-thaw effects on soil structure, it appears that the changes in soil structure are influenced by the moisture content during freeze-thawing, initial size of aggregates, the temperature of freezing and thawing and the number of freeze-thaw cycles. Freeze-thawing at moisture contents near saturation and for larger size aggregates, usually results in deterioration of soil structure. An improvement in soil structure may be noticed for finer soil fractions and at moisture contents nearing field capacity. No
consistent trend has been reported for the freezing temperatures and the number of freeze-thaw cycles.
MATERIALS AND METHODS

Effect of excessive moisture was studied on physical and chemical properties of the soil. The study was conducted in two parts namely, laboratory and field studies. In the first laboratory study, disturbed soil cores were used for different soil size fractions. The excess moisture conditions were obtained by submerging the soil for different lengths of time. Physical properties of submerged soil were compared with those of the non-submerged soil. In the second laboratory study on soil chemical properties, the soil solution was sampled from soil pots submerged up to a period of 60 days. The chemical composition of the soil solution was monitored at appropriate time intervals. A third laboratory study was conducted to determine the effects of freeze-thawing on soil physical properties under excessive moisture conditions. Soil physical properties before and after freeze-thaw treatments were determined on disturbed soil cores.

Field studies were undertaken to evaluate soil physical properties in a drainage experiment established in 1957 at North Central Research Station, Castalia, Ohio. Undisturbed soil cores were used to evaluate soil physical properties as affected by four drainage systems. These were: no drainage, surface drainage alone, tile drainage alone, and a combination of tile and surface drainage.
I  LABORATORY STUDIES

(1) Effect Of Submergence On Soil Physical Properties

(A) Soil

The soil used in laboratory experiments on physical and chemical studies was a Toledo silty clay loam. The physical analysis of the soil is given in Table 1 and the moisture retention characteristics are shown in Figure 1. A bulk quantity of the surface soil was obtained in spring 1972 from the tile drainage experimental field at North Central Research Station, Castalia, Ohio. Toledo is a very poorly drained soil that occurs in the lakebed areas of Northwestern Ohio. A more detailed description of this soil has been presented by Taylor et al (1961, 1970).

The soil was first air dried and then passed through 5 mm screen. Three soil size fractions were obtained by sieving the bulk sample. These were (1) soil <2 mm, (2) aggregates passing through 5 mm sieve but retained on a 2 mm sieve, and (3) soil <5 mm.

(B) Preparation Of Soil Cores

For reasons that will be given later on, each of the three soil size fractions were packed in a different manner.

(i) Soil <2 mm -- The soil was adjusted to a moisture content of 8% by weight and packed in 7.6 x 7.6 cm brass cylinders. Packing was done by initially placing two cylinders end to end and securing them with masking tape. With the cylinder in an upright position double layer of cheesecloth was placed at the lower end and
TABLE 1

PHYSICAL AND CHEMICAL CHARACTERISTICS OF THE TOLEDO SILTY CLAY LOAM SOIL USED IN LABORATORY STUDIES.

<table>
<thead>
<tr>
<th>Soil Size</th>
<th>Sand</th>
<th>Silt</th>
<th>Clay</th>
<th>Dp</th>
<th>O.C.</th>
<th>EC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%</td>
<td>%</td>
<td>%</td>
<td>g/cc</td>
<td>%</td>
<td>mmhos/cm</td>
</tr>
<tr>
<td>Soil &lt;2 mm</td>
<td>7.5</td>
<td>58.3</td>
<td>34.2</td>
<td>2.72</td>
<td>2.3</td>
<td>0.88</td>
</tr>
<tr>
<td>Aggregates 2-5 mm</td>
<td>6.9</td>
<td>53.0</td>
<td>40.1</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>pH</th>
<th>C.F.C.</th>
<th>Exchangeable cations, me/100g CaCO₃</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>me/100g</td>
<td>H⁺</td>
</tr>
<tr>
<td>Soil &lt;2 mm</td>
<td>7.5</td>
<td>25.1</td>
</tr>
</tbody>
</table>
Figure 1. Moisture Characteristic Curves of Toledo Silty Clay Loam.
held in place with rubber bands. A piece of sheet fiberglass was placed inside the cylinder and made contact with the cheesecloth. This was done to prevent loss of soil through the cheesecloth. A known amount of soil was used in order to obtain a bulk density of 1.20 g/cc. About one-third of the soil was poured into the cylinder and compacted using ten uniformly distributed strokes of a 5 lb 'Proctor' hammer. The upper surface of the compacted soil was loosened with a spatula and the previous step repeated another two times. When the bottom cylinder was full, the top cylinder was removed and the surface of the packed core was levelled off.

(ii) Aggregates 2-5 mm -- Packing of air dry aggregates with a compacting hammer was unacceptable because of physical deterioration of aggregates during compaction. A soil compacting apparatus described by Hassan (1970) was used for this purpose. Two cylinders held together by masking tape were secured on the apparatus. Enough soil was added to fill each pair of cylinders and the upper cylinder covered with a lid held in place by a spring attachment. The cylinders were raised and then dropped on a cushioned platform for 100 times through a distance of 1 inch. Four sets of soil cores could be packed at the same time. After compaction the top cylinder was removed and the soil in the bottom cylinder levelled off. The weights of the cylinders with and without the soil were known and hence bulk density of the packed soil could be calculated. The packing of the cores was fairly uniform with a bulk density of 0.94 ± 0.02 g/cc.

(iii) Soil <5 mm -- Cores of the soil <5 mm were not compacted
artificially. Instead, they were taken from pots which were previously used in the chemical study. The latter will be described in more detail in section (2). Prior to taking the cores, the soil in the pots was drained to near field capacity. Core samples were taken directly from the pots using cylinders 7.6 x 7.6 cm. The cylinder was forced into the soil and the soil core excavated. A piece of fiberglass and cheesecloth were put on one end of soil core to avoid any loss of soil in handling and during saturation.

C. Treatments

(i) With No Prior Wetting And Drying — The treatments consisted of submerging the soil under saturated conditions for different lengths of time, namely 15, 30, 45 and 60 days. Four soil cores were used under each period of submergence. In addition, four soil cores were maintained at approximately field capacity throughout the 60-day period and served as controls. In all, there were 20 soil cores for each soil size fraction. Initially the soil cores were placed in a pan and wetted by capillarity for 24 hours. The samples to be submerged were then flooded under 2 cm head of water. The unflooded cores were equilibrated to 1/3 atm pressure in a pressure plate apparatus. The latter were then removed from the pressure chamber, covered with polyethylene sheets to reduce evaporation, and placed in a constant temperature room (72°F), along with submerged cores, for the rest of the incubation period. The cores to be submerged for 60 days were initiated first, followed after 15 days by the 45-day flooded cores, etc. Hence, after 60 days, it was possible to run physical
analysis on all soil cores simultaneously for any one size fraction.

(ii) **After Two Wetting And Drying Cycles** -- In order to determine the effect of wetting and drying prior to submergence, twenty soil cores (soil <2 mm) were packed to a bulk density of 1.08 g/cc using the compaction machine. The soil was saturated by capillarity, and its hydraulic conductivity determined. The soil was then allowed to dry slowly in an oven for 3-4 days at 35°C. The soil cores were then resaturated and dried a second time, thus giving two wetting and drying cycles. Ten soil cores were then equilibrated at field capacity moisture content (0.3 atm moisture suction) while the other ten cores were kept submerged under 2 cm head of water. The incubation was continued for a period of one month after which soil physical properties were measured by the procedures outlined below.

D. **Procedures**

(1) **Hydraulic Conductivity** -- The unsaturated soil cores were wetted by capillarity for 24 hours. Water was then ponded about 1 cm above the soil surface for 4 hours. The cores were transferred to the hydraulic conductivity apparatus. This apparatus is designed to provide a constant (but adjustable) head of water using a Mariotte bottle arrangement. From measurements on volume of water flow per unit time, height of soil and the hydraulic head difference the saturated hydraulic conductivity was calculated by Darcy's equation:

\[ K = \frac{V}{AT} \frac{\Delta L}{\Delta \phi} \]
where:

\[ K = \text{saturated hydraulic conductivity, cm/hr.} \]
\[ v = \text{volume of flow, cm}^3. \]
\[ A = \text{cross sectional area of the soil core, cm}^2. \]
\[ T = \text{time, hrs.} \]
\[ \Delta L = \text{length of soil core, cm.} \]
\[ \Delta \phi = \text{hydraulic head difference, cm.} \]

(ii) **Moisture Retention And Pore Size Distribution** — Following hydraulic conductivity measurements, the saturated soil core was weighed and transferred to the tension table. The equilibrium weight of the soil core was taken at 20 cm and 60 cm suctions. Moisture retention at 0.3 and 1.0 atm was then determined using a porous plate extractor. The soil cores were removed from the extractor and weighed when the flow of water had ceased at the given pressure.

(iii) **Bulk Density And Porosity** — After equilibration of soil cores at 1.0 atm pressure, a bulk sample of soil was used to determine the moisture content by the thermogravimetric method at 105°C. From the known total weight of moist soil at 1.0 atm and the corresponding moisture percentage, the dry weight of the soil in the original core was computed and used to calculate the bulk density, \( D_b \). The mean particle density (\( D_p \)) of the soil was determined by the pycnometer method using water. The total porosity (\( E \)) was then obtained from the formula:

\[ E = (1 - \frac{D_p}{D_b}) \]
(iv) **Pore Volumes Drainable At Lower Suctions** -- The volume percent of pores drained at any suction was calculated as the difference between the total pore space and the volumetric moisture at the respective suction.

E. **Statistical Analysis**

The data were analysed using randomized block design with five treatments and four replications. Comparisons were made between the submerged and non-submerged treatments.

(2) **Effect Of Submergence On Soil Chemical Properties**

A. **Preparation Of Pots**

The Toledo soil was also used in soil chemical studies. A 3.5 kg sample of soil of size <5 mm and in the air dry state was packed in glazed pots of size 17 cm diam. x 17 cm high. A diagrammatic sketch of the pot as used in this study is shown in Figure 2. A layer of coarse sand about one inch thick was put at the bottom of the pot, and a perforated plastic tube covered with glass wool was placed in the sand layer to provide drainage. The soil solution sampling system consist of a porous ceramic filter, 5 cm long and 1.5 cm in diameter. The porous cup was centered in the pot at 10 cm depth from the soil surface. The ends of the porous cup as well as the drainage tube extended to the outside of the pot through polyethylene tubing connections. A common cork with a separate hole for each outlet was placed in the hole on the side of the pot at the bottom.
Figure 2. A Schematic Drawing of Submerged Soil Pot and Soil Solution Sampling Technique.
B. Treatments

The soil treatments consist of submergence periods of 0, 15, 30, 45 and 60 days. There were 4 pots for each period. The soil in the non-submergence pots was maintained at a moisture content of 33% on weight basis (approximately 60 cm of water suction) throughout the 60 day period. For the flooded treatments, about 1.7 liters of distilled water per pot were required to saturate and pond approximately 2 cm of water. These pots were then covered with an aluminum foil to minimize evaporation. Additional distilled water was added from time to time to maintain the original water level. The moisture level in non-submerged pots was maintained by first weighing the pots after each sampling and replacing any loss in weight with distilled water. The experiment was performed in a constant temperature room maintained at 72 ± 1°F.

C. Sampling Of Soil Solution

Sampling for soil solution was done at 0.5, 1, 3, 5, 8, 10, 15, 20, 24, 29, 34, 38, 43, 48, 52, 57, and 60 days after initiation of the flooding treatments. For flooded pots, the soil solution was obtained by gravity flow. Approximately 40 ml of solution was extracted in a 250 ml Erlenmeyer flask. Gravity sampling was not possible for unflooded pots and a suction of about 30 cm of Hg was employed to extract the soil solution. Prior to sampling, the flasks were flushed with nitrogen gas and kept air tight. About 5 to 10 minutes were required to collect approximately 40 cc of solution by gravity flow,
while 45 to 60 minutes were necessary for the unflooded pots. In some cases the solution extracted from a single pot in the unflooded treatment was not enough for analysis, and the extract from all four pots was composited for analysis. The chemical analysis was done immediately after collection of the soil solution. Care was taken to prevent oxidation of reduced soil solution from flooded pots by permitting minimum exchange of air while sampling. The analysis was done using demineralized double distilled water.

D. Chemical Analysis

(i) pH And Electrical Conductivity -- About 10-20 ml of the extract was taken to measure pH and EC. The pH of the solution was measured by using Beckman pH meter with a glass electrode and a calomel half-cell. Electrical conductivity was measured using a conductivity bridge. The cell constant of the conductivity cell was 1.06. The values of conductance were recorded as specific conductivity at 25°C.

(ii) NO$^-_3$ -- Nitrate was measured on the same extract by using an Orion specific NO$^-_3$- ion electrode, Model 92-07. The concentration of NO$^-_3$-N was obtained by comparing measured potential value for the sample with those of a standard 0.1 M NaNO$^-_3$ solution. The specific ion electrode is sensitive in the pH range of 2-12 and for NO$^-_3$ concentration of 0.01 to 6200 ppm.

(iii) NH$^+_4$ -- NH$^+_4$ was determined using the Nessler's method as described by Jackson (1965). To a 5 ml aliquot of the extract, was added 2 ml of 10% sodium tartrate solution and a little gum acacia
which serves as a protective colloid. Then 5 ml of Nessler's reagent was added and the volume made to 50 ml. The color was read after half an hour on a colorimeter using violet filter. A blank was also carried to make correction in the colorimetric readings. A 'Klett Summerson' type photoelectric colorimeter model 800-3 was used.

(iv) \( \text{Fe}^{2+} \) -- \( \text{Fe}^{2+} \) was determined by reading the pink color developed after the addition of dipyridyl (2, 2' bipyridine) according to the procedures used in standard methods for the examination of water and sewage (A.P.H.A., 1946). \( \text{Fe}^{2+} \) ion present does not give any color. The method is sensitive to 0.05 ppm of \( \text{Fe}^{2+} \) and the color is stable for six months. Five or 10 ml of the extract was used depending upon the concentration of \( \text{Fe}^{2+} \) in the solution. To an aliquot of extract, 4 ml of dipyridyl and 0.2 ml of 5N HCl were added and the volume made to 50 ml. The color was read using a green filter on a colorimeter.

(v) \( \text{Mn}^{2+} \) -- The periodate method (Jackson, 1965) was used to determine \( \text{Mn}^{2+} \). Five or 10 ml of the soil solution was taken and the organic matter destroyed by adding 5 ml of concentrated \( \text{HNO}_3 \) and 2 ml of 30% \( \text{H}_2\text{O}_2 \). The solution was evaporated to dryness and the residue was dissolved in 20 ml of distilled water plus 2 ml of \( \text{HNO}_3 \) and 5 ml of 85% \( \text{H}_3\text{PO}_4 \). About 0.3 grams of \( \text{KIO}_4 \) was then added, and the solution boiled gently for about 5 minutes. When the solution had cooled, its volume made to 50 ml and the color read on a colorimeter using a green filter.

(vi) \( \text{SO}_4^{2-} \) -- \( \text{SO}_4^{2-} \) in the extract was determined by the turbidimetric method of Chesnin and Yien (1950). To a 5 ml of the
extract was added 1.0 g of 30-60 mesh BaCl₂ crystals and the contents shaken for one minute. Then 2 ml of 0.25% gum acacia was added and the volume made to 25 ml. Turbidity readings were taken on a colorimeter using a blue filter within 5-30 minutes after precipitation had occurred.

(vii) CO₃⁻, HCO₃⁻, and Cl⁻ -- The analysis for CO₃⁻, HCO₃⁻, and Cl⁻ was performed by titration method using standard H₂SO₄ for CO₃⁻ and HCO₃⁻, and standard AgNO₃ for Cl⁻, according to USDA Agriculture Handbook No. 60 (1954).

3. Freeze-thawing Effects On Soil Physical Properties

In this study soil cores were prepared using different size aggregates. These soil cores were subjected to a number of freeze-thaw cycles under conditions of fast thawing or slow thawing. Comparison was made of the soil physical properties before and after freeze-thawing.

Phase I. Fast Freezing-fast Thawing

A. Soil And Size

Four different size fractions of the Toledo soil were obtained by sieving: Namely a) soil < 2 mm. b) soil < 0.42 mm, c) aggregates of 0.42 - 0.84 mm and d) aggregates 0.84 - 2.0 mm.

Each of the four size fractions was packed in brass cylinders 7.6 x 7.6 cm using the soil compaction apparatus as indicated earlier. A known amount of soil was used to give a predetermined bulk
density. The air-dry soil was packed in cylinders to a height of 6.6 cm and 1 cm space was left to accommodate any swelling during saturation. The bulk densities were: 1.20 g/cc for soil <2 mm and for soil <0.42 mm; 1.10 g/cc for aggregate sizes of 0.42-0.84 mm and 0.84-2.0 mm. The soil cores were first saturated and then dried at 35°C to provide firmness of the packed soil. Only one wetting-drying cycle was used.

B. Moisture Level

Three different pre-treatments with respect to moisture level were employed during freeze-thaw cycles:

a) soil cores submerged under water for one month prior to freeze-thawing and then freeze-thawed after allowing free drainage of saturated cores.

b) soil cores freeze-thawed after allowing free drainage of saturated cores but without prior submergence.

c) soil cores freeze-thawed at field capacity (1/3 atm moisture content).

For each soil size fraction, there were three moisture levels replicated four times.

C. Physical Properties Of Soil Cores Before Freeze-thawing

The initial physical properties of soil cores were measured prior to freeze-thawing. The soil cores of treatments 'b' and 'c' were saturated for 24 hours. Those of treatment 'a' were
previously saturated, having been submerged for one month. The following physical properties were evaluated using the procedures outlined earlier:

a) saturated hydraulic conductivity.

b) moisture retention and pore-size distribution at 20 cm, 60 cm and 1/3 atm suction.

c) bulk density and porosity.

D. Freeze-thawing Treatments

The soil cores after equilibration at 1/3 atm suction (obtained during determination of initial physical properties) were resaturated and equilibrated at the respective moisture contents as mentioned earlier. Eight freeze-thaw cycles were conducted. Freezing was done at 0°C for one day by placing samples in a freezer. The soil samples were placed in a cardboard container and were insulated at the bottom side only. Freezing occurred from the top and sides. A few trial cores were frozen after insulating them from the bottom and sides to observe any visual differences in swelling or freezing compared to those that were insulated from the bottom only. No differences were apparent and hence all the samples were frozen without insulation from the sides. Thawing of frozen samples was allowed by taking the cores out of the freezing chamber and keeping at room temperature (72°C) for one day. A thin plastic cover was used over the top of soil cores to reduce evaporation.
E. Physical Properties of Soil Cores After Freeze-Thawing

After the 8th cycle of freeze-thawing the soil cores were wetted by capillarity and determinations made of hydraulic conductivity, bulk density, porosity, and moisture retention and pore size distribution at 20 cm, 60 cm, 1/3 atm, and 1.0 atm suction.

F. Statistical Analysis

The data on freeze-thawing experiment was treated in a double split plot arrangement with soil size as the main treatment, moisture level as the sub-treatments and time (before and after freeze-thawing) as the sub-sub treatment level.

Phase II. Fast Freezing-slow Thawing

The freeze-thawing procedure used in phase I was selected to corroborate the procedures reported in the literature. Most investigators (Sillanpaa, 1961b; Benoit and Bornstein, 1970 and 1973) have studied the effect of slow or fast freezing but thawing has usually been done at ambient room temperatures. This procedure does not seem to represent field conditions (Wilding*, 1974) where the thawing is usually slow, extends over longer periods, and is probably accompanied by moisture sublimation. In order to simulate slow thawing after freezing, phase II of the freeze thaw experiment was conducted.

*Personal Communication
A. Preparation of Soil Cores

Soil cores were packed as in phase I but only three soil size fractions: Soil <2 mm; aggregates 0.42-0.84 mm and 0.84-2.0 mm were used. Only one moisture level was employed, i.e. maximum moisture retention after free drainage. There were three replications. The soil cores received one wetting and drying cycle as under phase I. The same initial soil physical properties were determined as under phase I.

B. Freeze-thawing Treatments

The soil was frozen and thawed five times. The freezing was done as before at 0°F but thawing was allowed to proceed slowly by keeping the soil at 40°F in a cold room. The soil was kept uncovered during freeze-thawing to allow evaporation from the surface. Freezing was done overnight while thawing was completed in 3-4 days. Before starting the next freeze-thaw cycle the moisture level in the cores was adjusted to original moisture content and allowed to equilibrate overnight.

C. Physical Properties After Freeze-thawing

After the fifth freeze-thaw cycle, the soil cores were wet by capillarity and determinations made for hydraulic conductivity, bulk density, porosity, and moisture retention and pore size distribution at 20 cm, 60 cm, 1/3 atm and 1 atm suctions.

D. Statistical Analysis

The statistical analysis was made using split-plot
design. The soil size was taken as main treatment while the time (before and after freeze-thawing) was treated as sub-treatment.

II  FIELD STUDIES

Drainage System Effects On Soil Physical Properties

A. Description And History Of The Drainage Experiment

The drainage experiment was established in 1957 in the lakebed area at North Central Research Station, Castalia, Ohio. Sixteen plots were laid out to provide four treatments in four replications, utilizing a randomized block design. Each plot (120 ft x 200 ft) was surrounded with a dike six inches high to eliminate water interchange between plots. The treatments consist of (1) no artificial drainage, (2) surface drainage only, (3) tile drainage only, and (4) both tile and surface drainage. The non-drained and tile drained plots are level. Surface drainage is provided by 0.2% surface slope across the narrow dimension to a surface channel. The subsurface drains are concrete tiles of four inch diameter, 3 feet deep, and 40 feet spacing between drain lines. "No drainage" plots are wet and inundated for prolonged periods, causing delays in tillage and planting. During November 1969, shallow drains were installed in the previously non-drained plots. The drains are 1.5 inch diameter, corrugated plastic tubing placed 1.5 feet deep and 20 feet apart. The physical layout of the experiment is shown in Figure 3.

The soil in the experimental area is primarily Toledo silty clay, a fine textured humic gley, with some Fulton silty clay, an
Figure 3. Physical Layout of the Drainage Experiment at North Central Branch, OARDC, Castalia, Ohio. (Adopted from Schwab et al, 1963).
imperfectly drained grey-brown podzol. The soil is a typical of much of the poorly drained areas of Northwestern Ohio and adjoining areas of Indiana and Michigan. Some physical characteristics of the soil from the experimental field are shown in Table 2. A more complete description of experimental field soil is given by Schwab et al (1963).

The experimental area had been under an alfalfa sod meadow for several years prior to the installation of the experiment. Since the initiation of the experiment, the field has been planted to hay or grain crops, principally the latter. The field was planted to alfalfa in 1957-58; to Kentucky 31 Fescue in 1959-61; to corn in 1962-64; to soybeans in 1965; to oats in 1966; to corn in 1967-71; to oats in 1972 and alfalfa in 1973-74.

The objectives of the drainage experiment are:

1. To determine the relative effect of no drainage, surface drainage alone, tile drainage alone, and a combination of both surface and tile drainage on crop response, soil moisture conditions, and soil physical characteristics;
2. To determine the tile outflow, surface runoff, and soil and plant nutrient loss data for improving design standards of drainage systems;
3. To determine the effect of time on backfill consolidation over tile; and
4. To determine the effect of soil moisture level on the physiology of plants under field conditions. For the study reported here, only the first objective was considered, namely, to typify soil physical characteristics under different drainage systems.
TABLE 2

SOME PHYSICAL CHARACTERISTICS OF THE SOIL FROM THE DRAINAGE EXPERIMENT LOCATED AT NORTH CENTRAL RESEARCH STATION, CASTALIA, OHIO.

<table>
<thead>
<tr>
<th>Soil Property</th>
<th>Depth (cm)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>5-15</td>
<td>15-25</td>
<td></td>
</tr>
<tr>
<td>Mechanical Analysis:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clay ---- %</td>
<td>47.2</td>
<td>52.3</td>
<td></td>
</tr>
<tr>
<td>Silt ---- %</td>
<td>49.3</td>
<td>41.1</td>
<td></td>
</tr>
<tr>
<td>Sand ---- %</td>
<td>3.5</td>
<td>6.6</td>
<td></td>
</tr>
<tr>
<td>Plasticity Constants:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plastic Limit --- %</td>
<td>32</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>Liquid Limit --- %</td>
<td>52</td>
<td>53</td>
<td></td>
</tr>
<tr>
<td>Plastic Index --- %</td>
<td>20</td>
<td>20</td>
<td></td>
</tr>
<tr>
<td>Miscellaneous:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Particle Density -- g/cc</td>
<td>2.70</td>
<td>2.70</td>
<td></td>
</tr>
<tr>
<td>Organic Carbon --- %</td>
<td>2.44</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>EC_e --- mmhos/cm</td>
<td>1.04</td>
<td>--</td>
<td></td>
</tr>
</tbody>
</table>
Pertinent to the other objectives the results on (1) hydrologic characteristics under grass cover have been reported by Schwab and Thiel (1963) and Schwab et al (1963); (2) water table levels, tile flow and surface runoff by Schwab and Fouss (1967) and Hoffman and Schwab (1964); soil moisture status, tilth and plant root distribution by Fausey and Schwab (1969); and crop response by Schwab et al (1966).

B. Cultural And Management Conditions During 1973 and 1974

Since the cultural and management conditions just prior to sampling and field measurements might influence the results, they are described here in a chronological order. Prior to 1973 the field had been grain-cropped to corn for five consecutive years from 1967-1971. A tillage variable was studied through these years. Replications I and II of the experiment were under conventional tillage while no-tillage was practiced in replications III and IV. Conventional tillage consisted of plowing during the previous fall or before March of the crop year. In "no tillage", weeds were controlled by herbicides. The field was planted in oats in 1972 with conventional tillage on all replications. Sampling of soil cores was done during the first week of May 1973 before seeding of alfalfa.

Alfalfa was seeded on May 7, 1973, but heavy rain followed planting and resulted in poor germination. The field was tilled on Aug. 8, 1973 with a field cultivator and alfalfa was reseeded on Aug. 17, 1973. Soil core samples were taken the second time in April 1974.
C. Procedures

(1) Soil Physical Properties: May 1973

Two soil cores 7.6 x 7.6 cm were taken from the surface 5-15 cm of each plot. The cores were trimmed to the length of the brass cylinders, and a piece of filter paper and cheesecloth was put at the bottom of the core to prevent loss of the soil. The cores were saturated under vacuum. The following physical properties were determined using the same procedures as outlined earlier in section I of this chapter: saturated hydraulic conductivity, moisture retention at 60 cm, 0.3 atm and 1.0 atm suction, bulk density, pore size distribution, and unconfined compressive strength.

(2) Soil Physical Properties: April 1974

Sampling was done after snow melt and thawing and before the soil could dry and develop cracks. Soil core samples were taken on April 13 from replicates 1 and 2 and on April 16 from replicates 3 and 4. The soil was saturated without using a vacuum and the same set of physical properties was evaluated as in 1973.

(3) Resistance To Surface Penetration

On April 20, 1974, ten measurements per plot were made of the force required to penetrate the soil crust surface to a depth of 1 cm with a blunt end foot of diameter 1.65 cm. These measurements were made with a 'Proctor' type penetrometer obtained from 'Humboldt Mfg. Co. Chicago.' Samples of crust for soil moisture determination
were also collected adjacent to where penetration measurements were made.

(4) Crust Density

Representative samples of crust from each drainage treatment were collected, oven dried, and used for determining dry bulk density of the crust units after oven drying. The volume of a crust unit was obtained by coating it with Saran resin and recording the volume by displacement under water.

(5) Unconfined Compressive Strength

**Instrumentation:** -- An Instron Universal Testing Instrument (Figure 4) was used for unconfined compression strength measurements. The electronic load detecting system is comprised of sensitive bonded-wire strain gage transducers having an accuracy of ± 0.5% of indicated load. The applied load on the cell causes a proportional change in the resistance of the strain gages. Constant rates of strain (± 0.1%) are controlled by a low-torque synchronous motor driving through a unique gear box that provides a considerable flexibility of control over the rate of strain to be used. The experimental load-deformation plot is recorded by an x-y recorder with an accuracy of ± 0.25% of scale used. The recorder operates as an automatic null-balancing potentiometer. The chart of the recorder can be driven synchronously at a wide variety of speeds. The area under the experimental load-deformation curve can be recorded using the Instron integrator with an accuracy of ± 1%. The integrator is an electro-mechanical device and the output is
Figure 4. A photograph of Instron Universal Testing Instrument used in unconfined compression strength measurements. Sample compression chamber is on extreme right; chart recorder is in the center and on extreme left is the Integrator.
[Courtesy of Agric. Eng. Dept., The Ohio State University].
recorded as number of counts employing a mechanical revolution counter.

From integrator readings the area and energy are calculated as follows:

(1) Area, \[ A = \frac{X}{5000} \times W \times C \]

where
- \( A \) = Area in \( \text{cm}^2 \).
- \( X \) = Integrator reading.
- \( W \) = Full scale width of the chart in cm.
- \( C \) = Chart speed in cm/min.

(2) Energy, \[ E = \frac{X}{5000} \times L \times S \]

where
- \( E \) = Energy in \( \text{cm-gm} \).
- \( L \) = Full scale load in gm.
- \( S \) = Rate of sample compression in cm/min.
- \( X \) = Integrator reading.

Testing: -- For both 1973 and 1974, the soil cores equilibrated at 1 atm pressure were used in an unconfined compression test. A subsample 5.3 cm long and 2.67 cm in diameter was taken from large (7.6 cm x 7.6 cm) core using a cylindrical core sampler and the screw jack type apparatus shown in Figure 5. The sample was trimmed to exact dimensions using a Vernier caliper and a sharp blade. The ends were cut smooth and flat, and the weight of the sample was recorded. Care was taken to avoid any loss of moisture during preparation of the samples. The cores were kept covered and transferred to the compression chamber of Instron within 2-5 minutes of exposure. Still a
Figure 5. A photograph showing the cylindrical core sampler and the screw-jack apparatus used in taking subsamples (2.67 cm diam. x 5.3 cm height) from large (7.6 x 7.6 cm) soil cores.
small amount of moisture loss was observed (Appendix Table 1). The instrument was calibrated before conducting the test. The sample was placed upright in compression chamber. The chart speed was adjusted to 5 cm/min and the appropriate load range of 0-10 or 0-20 or 0-50 Kg was selected. A constant strain rate of 2% of the sample length per minute was used. The test was discontinued after peak compression strength had been reached or the sample had undergone 20% deformation. The maximum compressive strength at rupture was taken as the unconfined compressive strength. A representative type of failure plane developed during rupture is shown in Figure 6. The stress per unit at any stage was obtained by dividing the load at that point by the corrected area given by:

\[ A_{corr} = \frac{A_o}{(1-E)} \]

where \[ E = \frac{\Delta H}{H_o} \]

\( \Delta H \) = Deformation in height of sample during compression.

\( H_o \) = Original height of sample.

\( A_o \) = Original area of cross section.

For the purpose of calculating the stress, it is assumed that the sample remained a cylinder of constant volume. After the compression test the sample was oven dried at 105°C and the moisture content and bulk density of the sample were calculated.

D. Field Observations

Observations on soil tilth under different drainage
A = Undrained
B = Surface drained
C = Tile drained only
D = Tile plus surface drained

Figure 6. A photograph showing representative failure planes at rupture in soil samples during unconfined compression strength measurements.
treatments were taken during preparation of the field for seeding alfalfa in May 1973. Also, as the soil dried during the spring the crust size distribution and severity of crusting was observed as well as surface ponding of water on undrained plots after a rain.

E. Statistical Analysis

The statistical analysis was done utilizing randomized block design with subsamples. Use was made of the 'statistical analysis system' available on file at the computer center of the Ohio State University.
RESULTS AND DISCUSSION

I LABORATORY STUDIES

1. Soil Physical Properties Under Submerged Conditions

A. Without Wetting And Drying Treatment

The data on soil bulk density, total porosity and air-filled porosity for soil <2 mm, 2-5 mm and <5 mm are given in Tables 3, 4 and 5, respectively. Compared to the non-submerged soil (control) bulk density increased and total porosity decreased a small amount with submergence for all the three soil-size fractions. Compared to non-submerged soil the maximum increase in bulk density of submerged soil was 0.03 g/cc for soil <2 mm, 0.06 g/cc for 2-5 mm aggregates and 0.06 g/cc for soil <5 mm. The period of submergence did not produce significant differences. The magnitude of both bulk density and total porosity differed for the three soil size fractions. Apparently, these differences were a reflection of initial density of packing. The initial density of soil <2 mm was 1.20 g/cc while the corresponding value for 2-5 mm aggregates was 0.94 g/cc. For soil <5 mm core samples were taken from pots previously submerged in the chemical study. The soil in the pots was originally packed to a density of approximately 1.2 g/cc. Compared to initial densities,
TABLE 3

INFLUENCE OF CONTINUOUS SUBMERGENCE OR INCUBATION AT FIELD CAPACITY MOISTURE CONTENT ON TOTAL POROSITY, BULK DENSITY AND AIR FILLED POROSITY OF TOLEDO SILTY CLAY LOAM FOR <2 MM SOIL SIZE FRACTION.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Bulk Density g/cc</th>
<th>Air Filled Porosity at Indicated Suction</th>
<th>Total Porosity %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.06 atm</td>
<td>0.33 atm</td>
</tr>
<tr>
<td>Field Capacity</td>
<td>1.27</td>
<td>14.1</td>
<td>20.6</td>
</tr>
<tr>
<td>Submerged 15 Days</td>
<td>1.28</td>
<td>7.9</td>
<td>14.7</td>
</tr>
<tr>
<td>&quot; 30 &quot;</td>
<td>1.28</td>
<td>7.9</td>
<td>13.8</td>
</tr>
<tr>
<td>&quot; 45 &quot;</td>
<td>1.29</td>
<td>8.4</td>
<td>13.3</td>
</tr>
<tr>
<td>&quot; 60 &quot;</td>
<td>1.30</td>
<td>8.1</td>
<td>13.8</td>
</tr>
<tr>
<td>LSD (.01)</td>
<td>0.02</td>
<td>2.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>
### Table 4

Influence of Continuous Submergence or Incubation at Field Capacity Moisture Content on Total Porosity, Bulk Density, and Air Filled Porosity of Toledo Silty Clay Loam for 2-5 mm Soil Size Fractions.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Bulk Density</th>
<th>Air Filled Porosity</th>
<th>Total Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/cc</td>
<td>0.02 atm</td>
<td>0.06 atm</td>
</tr>
<tr>
<td>Field Capacity</td>
<td>0.95</td>
<td>30.1</td>
<td>33.7</td>
</tr>
<tr>
<td>Submerged 15 Days</td>
<td>1.01</td>
<td>24.9</td>
<td>29.0</td>
</tr>
<tr>
<td>&quot; 30 &quot;</td>
<td>1.01</td>
<td>22.8</td>
<td>27.3</td>
</tr>
<tr>
<td>&quot; 45 &quot;</td>
<td>1.00</td>
<td>21.6</td>
<td>26.4</td>
</tr>
<tr>
<td>&quot; 60 &quot;</td>
<td>1.00</td>
<td>21.5</td>
<td>26.7</td>
</tr>
<tr>
<td>LSD (.01)</td>
<td>0.02</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>
### TABLE 5

INFLUENCE OF CONTINUOUS SUBMERGENCE OR INCUBATION AT FIELD CAPACITY MOISTURE CONTENT ON TOTAL POROSITY, BULK DENSITY AND AIR FILLED POROSITY OF TOLEDO SILTY CLAY LOAM FOR <5 MM SOIL SIZE FRACTION.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Bulk Density</th>
<th>Air Filled Porosity At Indicated Suction</th>
<th>Total Porosity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>g/cc</td>
<td>0.02 atm 0.06 atm 0.33 atm 1.0 atm</td>
<td></td>
</tr>
<tr>
<td>Field Capacity</td>
<td>1.29</td>
<td>14.1 15.7 17.1 18.8</td>
<td>52.8</td>
</tr>
<tr>
<td>Submerged 15 Days</td>
<td>1.36</td>
<td>2.8 6.2 11.8 14.7</td>
<td>50.0</td>
</tr>
<tr>
<td>&quot; 30 &quot;</td>
<td>1.33</td>
<td>4.6 8.5 14.5 17.0</td>
<td>51.0</td>
</tr>
<tr>
<td>&quot; 45 &quot;</td>
<td>1.34</td>
<td>3.6 8.8 15.6 18.3</td>
<td>50.5</td>
</tr>
<tr>
<td>&quot; 60 &quot;</td>
<td>1.35</td>
<td>2.3 6.4 11.9 15.9</td>
<td>50.2</td>
</tr>
<tr>
<td>LSD (.01)</td>
<td>0.04</td>
<td>4.2 4.5 4.2 4.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>
the final bulk density values were higher in all cases. Since each of
the three soil-size fractions were compacted to different initial
bulk densities, comparisons should be made for submerged and control
treatments within a particular soil-size fraction. Comparison over
three soil-size fractions is not intended because of the varying packing
density and proportion of different size aggregates present in each
soil-size catagory.

The air-filled porosity indicates the volume of pores drained
at various suctions (Table 3, 4, and 5). Air-filled porosity of
submerged soil was significantly lower than that of the control. Again
the length of submergence had little effect. The means of all four
submergence periods are compared with those of the control in Figure 7.
The major reduction in air-filled porosity due to submergence occurred
at relatively lower suctions of 0.02 and 0.06 atmospheres.

The effect of submergence on moisture retention is shown
in Figure 8, 9, and 10 for soil <2 mm, 2-5 mm aggregates and soil <5 mm,
respectively. Compared to the control, submerged soil resulted in
increased moisture retention for the suction range of 0-1.0
atmospheres. The increase was more pronounced at suctions of 0.02 and
0.06 atmospheres.

From the results it is clear that differences between
submerged and the control treatments for total porosity were not great,
and the major effect was on the size-distribution of pores. The
changes in soil structure are best characterized at lower suctions.
The pores that can be drained at a suction of <0.06 atmospheres may be
considered 'large pores' while the 'intermediate size pores' may be
Figure 7. Effect of Submergence on Air-filled Porosity at 0.02, 0.06, 0.33 and 1.0 atm. Suction for Three Soil Size Fractions.
Figure 8. Effect of Submergence or Incubation at Field Capacity, on Moisture Retention of Soil (Size ≤2 mm). [Each Value is an Average of Four Soil Cores. The Suctions are Indicated in Atmospheres].
Figure 9. Effect of Submergence or Incubation at Field Capacity on Moisture Retention of Soil (Size 2-5 mm) [Each Value is an Average of Four Soil Cores. The Suctions are Indicated in Atmospheres].
Figure 10. Effect of Submergence or Incubation at Field Capacity, on Moisture Retention of Soil (Size < 5 mm) [Each Value is an Average of Four Soil Cores. The Suctions are Indicated in Atmospheres].
those that are drained at suction of 0.06-1.0 atmospheres. In so far as plant growth is concerned, pore-size distribution is one of the most pertinent aspects of soil structure. It affects water infiltration into soil, water availability to plants, root development, soil water storage capacity and, most important, the aeration status of poorly drained soil. Air-filled porosity of 10-15 percent is generally required for satisfactory plant growth (Baver and Farnsworth, 1940; Vomocil and Flocker, 1961). For the soil <2 mm and <5 mm used in the present study the volume of air-filled pores remained less than 10 percent at suctions <0.06 atmospheres.

The data on hydraulic conductivity of submerged and the control treatments for soil <2 mm and 2-5 mm aggregates, are shown in Figure 11. Soil <5 mm was not evaluated for hydraulic conductivity. Compared to initial values, the final hydraulic conductivity of submerged soil decreased and that of non-submerged soil was increased. Submerged soil had significantly lower hydraulic conductivity than the control. Submergence for 15 days resulted in a sharp decrease in hydraulic conductivity. For the soil <2 mm diameter, the hydraulic conductivity of the non-submerged soil was twelve-fold greater than for the submerged treatments, while for 2-5 mm aggregates a 2-3 fold increase was obtained. Practically no water flowed through soil cores of <2 mm size fraction that were submerged for 15-60 days. For 2-5 mm aggregates, the hydraulic conductivity decreased more slowly during submergence. It can be seen from Figures 8, 9 and 11 that the percentage of large-sized pores is directly related to soil hydraulic conductivity. Mason et al (1957) using 10,000 individual core samples
Figure 11. Saturated Hydraulic Conductivity of Two Soil Size Fractions After Submergence or Incubation at Field Capacity (Each Treatment Represents an Average of Four Replications).
from 900 sites and from seven states concluded that hydraulic conductivity was better related to percentage large-pores (pores drained at suction <0.06 atmospheres) and only poorly related to bulk density. Submergence beyond 15 days had little additional effect on deterioration of soil structure indicating that the deterioration of soil structure occurs within the first two weeks.

B. Effect Of Previous Wetting And Drying

Soil <2 mm diameter was used in this study. Two wetting and drying treatments were given to soil cores before they were submerged under water or incubated at 0.3 atmospheres of suction (control) for a period of 30 days. There were 10 replications of each treatment.

The data on bulk density, total porosity are shown in Table 6. The final bulk densities were higher and the total porosities lower than the initial values. A difference of only 0.03 g/cc was found in the final bulk densities of submerged and non-submerged soil. Though this difference was statistically significant, it is too small to have any practical significance.

Soil moisture retention in the suction range of 0-0.33 atmospheres is shown in Figure 12. A significantly larger amount of moisture was retained by the submerged soil for the suction range of 0-0.06 atmospheres. The data for air-filled porosity are shown in Figure 13. Compared to non-submerged soil the submerged soil had significantly lower volume of air-filled pores at lower suctions of 0.02-0.06 atmospheres.
### TABLE 6

CHANGES IN BULK DENSITY AND TOTAL POROSITY OF SOIL <2 MM, KEPT SUBMERGED OR AT FIELD CAPACITY FOR ONE MONTH.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Bulk Density (g/cm³)</th>
<th>Total Porosity (Percent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial</td>
<td>Final</td>
</tr>
<tr>
<td>1. Soil Submerged</td>
<td>1.08</td>
<td>1.13</td>
</tr>
<tr>
<td>for one month</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2. Soil at Field Capacity</td>
<td>1.08</td>
<td>1.16</td>
</tr>
<tr>
<td>LSD (.05)</td>
<td>0.01</td>
<td>0.02</td>
</tr>
</tbody>
</table>

a= Initial values were obtained before giving two wetting and drying cycles and subsequent submergence.
b= Values after two wetting-drying cycles and followed by submergence or incubation at 1/3 atm suction.
Figure 12. Effect of Submergence for One Month or Incubation at Field Capacity on Moisture Retention of Soil (Size < 2 mm). The Suctions are Indicated in Atmospheres. The Soil was Subjected to Two Wetting and Drying Cycles before Initiating Treatments. Each Value is an Average of 10 Replications.
Figure 13. Air-Filled Porosity at Various Suctions for Soil <2 mm Subjected to Submergence or Field Capacity Incubation for One Month. [Soil was Subjected to Two Wetting-Drying Cycles Before Applying Treatments. Each Value is an Average of Ten Replications].
The hydraulic conductivity of soil before and after submergence is shown in Figure 14. Compared to initial values, the final hydraulic conductivity decreased slightly after submergence while a significant increase was found for the control. The initial hydraulic conductivity for the two treatments was essentially the same but the final hydraulic conductivity of soil incubated at field capacity (control) was more than twice that of submerged soil. It may be recalled that the same trend in hydraulic conductivity of soil <2 mm was seen when no wetting-drying cycles were given (see Figure 11). However, the magnitude of hydraulic conductivities are quite different. These differences were probably due to method of packing used in preparing soil cores. When no wetting-drying was done, soil was packed in moist condition using a 'Proctor' hammer. This procedure probably resulted in some breakdown of soil aggregates thus giving very low hydraulic conductivity. In second case where wetting-drying was employed, air-dry soil was used in packing. The packing was done using the compaction apparatus of Hassan (1970) which reduced the breakdown of soil aggregates, thus giving higher hydraulic conductivity. The data on moisture retention and air-filled pores at lower suctions for the two cases substantiates the above hypothesis of aggregate breakdown during packing.

Wetting and drying treatments probably resulted in some rearrangement of pores and stability of soil aggregates. These changes seem to be more favourable to non-submerged soil than the submerged soil as was indicated by the data on pore-size distribution (Figure 13) and hydraulic conductivity (Figure 14).
Figure 14. Effect of Submergence on Hydraulic Conductivity of Soil. [Initial and Final Values Indicate Hydraulic Conductivity Before and After Applying Treatments, Respectively. Each Value is an Average of Ten Replications].
2. Effect Of Submergence On Soil Chemical Properties

This study pertains to the changes in chemical composition of soil solution drawn periodically from submerged and non-submerged soil pots during a 60 day period. Soil solution was drawn out by gravity from the submerged pots using porous ceramic cups. Suction was used to withdraw soil solution from non-submerged pots. The chemical analyses made were: pH, electrical conductivity (EC), $\text{NO}_3^-$, $\text{NH}_4^+$, $\text{Fe}^{2+}$, $\text{Mn}^{2+}$, $\text{SO}_4^{2-}$, $\text{HCO}_3^-$, $\text{CO}_3^{2-}$, and $\text{Cl}^-$. It was not intended to analyze the soil solution for all possible anion and cation species. Instead the analysis was restricted to the ions that are most affected under submerged soil conditions. The data on submerged treatments represent an average of approximately 8 replications. Due to limitations of sampling by suction the data for non-submerged soil are only for 1-2 replications.

pH: — Data showing the pH of submerged and non-submerged soil for an incubation period of 60 days is presented in Figure 15 and Appendix Tables 2-3. The pH of submerged soil decreased only 0.3 unit for the first 15 days of submergence and then remained fairly constant at pH 7.8 for the remaining incubation period. A decrease in pH of neutral and alkaline soils usually occurs during initial period of submergence and similar observations have been reported by Ponnamperuma (1965), Biswas et al (1972) and Olomu et al (1973). The decrease in pH is mainly due to the evolution of $\text{CO}_2$ and organic acids during the anaerobic decomposition of organic matter. The change in pH is influenced by the buffer capacity of the soil and a soil with high CEC does not exhibit large changes in pH (Olomu et al, 1973). The solution
Figure 15. Changes in pH of Soil Solution Extracted from Submerged and Non-submerged Toledo Silty Clay Loam.
pH of non-submerged soil was 0.2 units higher than the submerged soil throughout the incubation period and remained fairly stable at pH of about 8.1. Changes in pH of either submerged or non-submerged soil were too small to have any practical significance on the concentration of other ions like Fe$^{2+}$, S$^{2-}$, HCO$_3^-$ etc.

**EC:** Electrical conductivity of soil solution from submerged and non-submerged soil is shown in Figure 16 and Appendix Tables 2-3.

In general, the EC of both submerged and non-submerged soil increased with time. For the submerged soil there was a drop in EC from 1.4 to about 1.0 mmhos/cm during the first day of submergence after which it increased consistently and reached a maximum of 2.27 mmhos/cm on 24th day of submergence. Thereafter a slight tendency to decrease was evident until the end of 60 day submergence period. The initial decrease in EC of submerged soil was probably due to reduction of NO$_3^-$ and SO$_4^{2-}$. As will be shown later (Figure 17), NO$_3^-$ virtually disappeared within the first day of submergence. Furthermore, it is possible that initially a dilution effect occurred which decreased EC. The increase in conductance of submerged soil is due to the release of soluble ions like Fe$^{2+}$ and Mn$^{2+}$, and accumulation of NH$_4^+$, HCO$_3^-$, Cl$^-$, and ROO$. Table 7 gives the correlation coefficients and linear regression equations of different ion species as they influenced the EC of soil solution. A significant positive correlation existed between EC and the concentrations of Fe$^{2+}$, Mn$^{2+}$, NH$_4^+$, HCO$_3^-$ and Cl$^-$. A small decline in EC of submerged soil after a peak value was probably due to a combination of factors like precipitation of Fe$^{2+}$ as Fe$_3$O$_4$, nH$_2$O and Mn$^{2+}$ as MnCO$_3$, a decline in the concentration of CO$_2$ and the
Figure 16. Changes in Electrical Conductivity of Soil Solution Extracted from Submerged and Non-submerged Toledo Silty Clay Loam.
TABLE 7

SIMPLE CORRELATION AND LINEAR REGRESSION EQUATIONS FOR EC AND CONCENTRATION OF VARIOUS ION SPECIES IN SOIL SOLUTION OBTAINED FROM SUBMERGED AND NON-SUBMERGED SOIL.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Independent Variable</th>
<th>Correlation Coefficient $r$</th>
<th>Regression Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Submerged Soil**

<table>
<thead>
<tr>
<th>EC, mmhos/cm</th>
<th>Fe$^{2+}$, ppm</th>
<th>+0.63*</th>
<th>$Y = 1.691 + 0.086X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>Mn$^{2+}$, ppm</td>
<td>+0.78**</td>
<td>$Y = 1.376 + 0.134X$</td>
</tr>
<tr>
<td>EC</td>
<td>NH$_4^+$, ppm</td>
<td>+0.85**</td>
<td>$Y = 0.671 + 0.080X$</td>
</tr>
<tr>
<td>EC</td>
<td>HCO$_3^-$, me/l</td>
<td>+0.96**</td>
<td>$Y = 0.438 + 0.082X$</td>
</tr>
<tr>
<td>EC</td>
<td>Cl$^-$, me/l</td>
<td>+0.79**</td>
<td>$Y = 0.270 + 0.241X$</td>
</tr>
<tr>
<td>EC</td>
<td>SO$_4^{2-}$, ppm</td>
<td>-0.77**</td>
<td>$Y = 2.298 - 0.007X$</td>
</tr>
</tbody>
</table>

**Non-Submerged Soil**

<table>
<thead>
<tr>
<th>EC, mmhos/cm</th>
<th>NO$_3^-$, me/l</th>
<th>+0.83**</th>
<th>$Y = 1.646 + 0.164X$</th>
</tr>
</thead>
<tbody>
<tr>
<td>EC</td>
<td>HCO$_3^-$, me/l</td>
<td>+0.60*</td>
<td>$Y = 1.155 + 0.160X$</td>
</tr>
<tr>
<td>EC</td>
<td>Cl$^-$, me/l</td>
<td>-0.36</td>
<td>$Y = 2.467 - 0.075X$</td>
</tr>
<tr>
<td>EC</td>
<td>SO$_4^{2-}$, me/l</td>
<td>+0.16</td>
<td>$Y = 1.890 + 0.116X$</td>
</tr>
</tbody>
</table>

* Significant at .05 level.
** Significant at .01 level.
decomposition of organic acids as has been reported by Ponnamperuma (1972). The EC of non-submerged soil also increased from an initial value of 1.7 to a maximum value of 2.3 mmhos/cm on 20th day of incubation and then remained fairly constant for the rest of the period. Electrical conductivity of non-submerged soil was directly correlated with the concentrations of nitrates \( (r = +0.83) \) and bicarbonates \( (r = +0.60) \) in the soil solution. The soil was fairly moist in this treatment and this probably was a factor in release of soluble ions. At any given time, the EC of non-submerged soil was slightly higher than the corresponding EC of submerged soil. This might be due to some differences in the composition of soil solution extracted by gravity and by suction. Sampling of soil solution by gravity probably extracted more soil solution from soil macropores - the so called 'outer solution'. On the other hand sampling by suction from the non-submerged soil might have extracted a higher proportion of soil solution from soil micropores thus getting lesser contribution from the so called 'outer solution' and greater contribution from the so called 'inner solution' of the diffuse double layer of soil colloids.

\[ \text{NO}_3^- - \text{N}: \quad \text{Figure 17 shows the concentration of NO}_3^- -\text{N under submerged and non-submerged conditions. Under submerged conditions NO}_3^- \text{ was probably denitrified rapidly and disappeared completely in about 1-3 days. The original NO}_3^- \text{ concentration was about 70 ppm NO}_3^- -\text{N which declined to about 32 ppm after 12 hours, 16 ppm after 18 hours and only 2 ppm after 24 hours of submergence. It has been reported by Turner and Patrick (1968) and Ponnamperuma (1964) that very little denitrification occurs until all the oxygen is depleted from the soil.} \]
Figure 17. Changes in NO$_3$-N of Soil Solution Extracted from Submerged and Non-submerged Toledo Silty Clay Loam.
Almost all the nitrate present in a soil disappeared within a few days of submergence (Bremner and Shaw, 1958). This indicates that in the present study soil oxygen was lost within a few hours of submergence and lead to anaerobic conditions. In the absence of oxygen, microorganisms can use NO$_3^-$ as an electron acceptor in the respiration process and the NO$_3^-$ is reduced to N$_2$ or N$_2$O. The NO$_3^-$ content of non-submerged soil remained stable and increased with time of incubation. This indicates that the soil had a reserved supply of mineralizable nitrogen. The presence of moisture near the field capacity range and optimum temperature during incubation provided a favourable environment for the nitrifying microorganisms. The nitrate content increased from about 70 ppm to 280 ppm NO$_3^-$N, an increase of four fold. Pilot and Patrick (1972) reported that nitrate was stable above a moisture suction of 30-40 cm of water for a Mhoon Silty Clay Loam. The moisture suction in the present study was higher (60 cm water suction) than that reported by the above workers. Hence oxidizing conditions were most likely present throughout the incubation period, thus favouring nitrification.

NH$_4^+$-N: -- The data on NH$_4^+$ is presented in Figure 18 and also in Appendix Tables 2-3. An increase in the accumulation of NH$_4^+$ was found for the first 3-4 weeks of submergence after which only a slight increase was obtained. The concentration of NH$_4^+$-N increased from 8 ppm at the start to 19 ppm at the end of 60-day submergence period. In an unfertilized soil the only significant source of ammonium ion is the bacterial decomposition of organic matter. The accumulation of ammonium under submerged conditions serves as an index of anaerobic conditions, since under aerobic (non-submerged) conditions,
Figure 18. Changes in NH$_4^+$-N of Soil Solution Extracted from Submerged and Non-submerged Toledo Silty Clay Loam.
nitrification would remove the ammonium ion as fast as it is formed. Thus the data of Figure 18, indicate that the ammonium production during submergence can be divided into three segments in accordance with the type of microbial activity apparently involved. 1) The first through 8th day: An initiation of ammonium production where the microorganisms responsible for NH$_3$ production have not yet flourished. It is also possible that initial flush of microbial growth may have resulted in an incorporation of some NH$_4^+$-N into proteinaceous material, thus accounting for slow release of ammonium to the soil solution. 2) Eighth to 29th day: Anaerobic conditions existed resulting in rapid rate of ammonia production. 3) Twenty-nineth day to end of submergence: original flush of microbial activity slowed down. Some immobilization of nitrogen might have occurred under reduced conditions. Similar response of ammonium under saturated conditions have been reported by Harter and McLean (1965) and Biswas et al (1972). They reported a peak concentration of ammonium after about 30 days of submergence. Ammonium concentration in the soil solution of non-submerged pots was erratic in the sense that no ammonium were detected at some sampling dates while an ammonium concentration of 4-5 ppm was observed at others. This happened probably when fresh water was added to make up the evaporation and soil solution sampling losses. Temporary anaerobic conditions might have resulted in accumulation of ammonia in the non-submerged pots. When moisture equilibrium in soil was established, ammonium being converted to nitrates by nitrification as fast as it was produced.
\( \text{Fe}^{2+} \) and \( \text{Mn}^{2+} \) -- The concentration of reduced forms of iron (\( \text{Fe}^{2+} \)) and manganese (\( \text{Mn}^{2+} \)) under submergence conditions is presented in Figure 19 and Appendix Tables 2-3. No \( \text{Fe}^{2+} \) or \( \text{Mn}^{2+} \) was detected in the soil solution of non-submerged treatment. For the submerged treatment \( \text{Mn}^{2+} \) appeared earlier than \( \text{Fe}^{2+} \) in the soil solution. Manganese (\( \text{Mn}^{2+} \)) and iron (\( \text{Fe}^{2+} \)) were first detected in the soil solution after 3 and 5 days of submergence, respectively. Similar observations were reported by a number of workers (Ponnamperuma and Castro, 1964; Turner and Patrick, 1968; Hossner and Phillips, 1972). Manganese is reduced at a higher reduction potential than iron and the reduction of both iron and manganese follows the reduction of \( \text{NO}_3^- \). As long as \( \text{NO}_3^- \) is present, it inhibits the reduction of iron and manganese. The fact that this happened, is shown by the appearance of \( \text{Mn}^{2+} \) after 3 days of submergence when \( \text{NO}_3^- \) had virtually disappeared from the soil solution (see Figure 17 for \( \text{NO}_3^- \) under submerged conditions). The concentration of \( \text{Mn}^{2+} \) was little higher than \( \text{Fe}^{2+} \) and the concentration of both ions increased up to the 52nd day of submergence after which a decline was noted. Reduction of iron and of manganese paralleled one another (Figure 19), and their concentrations in solution were significantly correlated (\( r = +0.88 \)) as shown in Table 8. The reduced forms of iron and manganese were also correlated with bicarbonates in the soil solution (Table 8) suggesting that the soluble forms of iron and manganese existed in the form of bicarbonates. Ponnamperuma (1972) indicated that the bulk of water-soluble iron and manganese in flooded soils is usually present as bicarbonates, salts of lower fatty acids and complexes of organic matter. The maximum concentration of \( \text{Fe}^{2+} \) was 5.9 ppm and that of \( \text{Mn}^{2+} \), 7 ppm. These concentrations are low and
Figure 19. Changes in Fe$^{2+}$ and Mn$^{2+}$ of Soil Solution Extracted from Submerged Toledo Silty Clay Loam.
**TABLE 8**

SIMPLE CORRELATION AND LINEAR REGRESSION EQUATIONS FOR BICARBONATES, IRON, MANGANESE AND SULFATES IN SOIL SOLUTION OF SUBMERGED SOIL.

<table>
<thead>
<tr>
<th>Dependent Variable</th>
<th>Independent Variable</th>
<th>Correlation Coefficient</th>
<th>Regression Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\text{Fe}^{2+}$, ppm</td>
<td>$\text{HCO}_3^-$, me/l</td>
<td>$+0.76^{**}$</td>
<td>$Y = -5.771 + 0.480X$</td>
</tr>
<tr>
<td>$\text{Mn}^{2+}$</td>
<td>$\text{HCO}_3^-$</td>
<td>$+0.80^{**}$</td>
<td>$Y = -3.088 + 0.394X$</td>
</tr>
<tr>
<td>$\text{Mn}^{2+}$</td>
<td>$\text{Fe}^{2+}$</td>
<td>$+0.88^{**}$</td>
<td>$Y = 1.478 + 0.844X$</td>
</tr>
<tr>
<td>$\text{Fe}^{2+}$</td>
<td>$\text{SO}_4^{2-}$</td>
<td>$-0.96^{**}$</td>
<td>$Y = 5.939 - 2.533X$</td>
</tr>
</tbody>
</table>

**Significant at .01 level.**
would not be toxic to plant roots. Toxic effects of $\text{Fe}^{2+}$ usually occur at concentrations greater than 112 ppm (Takijima, 1965) and for $\text{Mn}^{2+}$ above 15-20 ppm (Harter, 1962). However, it seems that the concentrations of $\text{Fe}^{2+}$ and $\text{Mn}^{2+}$ was in the range which can contribute to the formation of sludges in subsurface drains. Ford (1973) pointed out that soil solution $\text{Fe}^{2+}$ content greater than 0.5 ppm is a favourable factor for accumulation of sludges in drain lines.

**Sulfate:** Figure 20 shows the concentration of $\text{SO}_4^{2-}$ under submerged and non-submerged soil conditions. In the submerged soil sulfate concentration decreased with time and $\text{SO}_4^{2-}$ was negligible at the end of the incubation period. Practically no reduction of $\text{SO}_4^{2-}$ occurred during the first 3-5 days of submergence after which a fast increase in reduction rate was evident. The presence of nitrate inhibits $\text{SO}_4^{2-}$ reduction (Connell and Patrick, 1969) and no sulfide appears until all nitrate has been reduced. Sulfate is reduced to sulfide under anaerobic conditions by a group of obligate anaerobic bacteria of genus *Desulfovibrio*. These microorganisms use $\text{SO}_4^{2-}$ as the terminal electron acceptor in respiration while organic acids serve as electron donors. The odor of $\text{H}_2\text{S}$ was absent during the incubation period probably because of the reaction of ferrous iron and sulfide to form insoluble FeS. A significant negative correlation ($r = -0.96$) was obtained between $\text{Fe}^{2+}$ and $\text{SO}_4^{2-}$ concentrations in the soil solution as shown in Table 8. Connell and Patrick (1969) and Desai et al (1957) have shown that $\text{H}_2\text{S}$ formed by the reduction of $\text{SO}_4^{2-}$ is almost completely removed from solution as ferrous sulfide. The sulfate content of non-submerged soil varied in an erratic pattern around a mean value of about 90 ppm $\text{SO}_4^{2-}$. 
Figure 20. Changes in \( \text{SO}_4^{2-} \) of Soil Solution Extracted from Submerged and Non-submerged Toledo Silty Clay Loam.
No consistent trend was apparent with time of incubation. The erratic variations could have been the result of alternative reduction-oxidation conditions as was seen for the ammonium content of this non-submerged treatment.

\[ \text{CO}_3^{2-}, \text{HCO}_3^-, \text{and } \text{Cl}^- \] Carbonates were usually absent and were not detected under either of the submerged or non-submerged treatments. The changes in concentration of \( \text{HCO}_3^- \) and \( \text{Cl}^- \) under the two treatments are shown in Figures 21 and 22 and also in Appendix Tables 2-3. The \( \text{HCO}_3^- \) and \( \text{Cl}^- \) in submerged soil generally increased with time for the first three weeks and then remained fairly constant afterwards. The concentrations of \( \text{HCO}_3^- \) and \( \text{Cl}^- \) were significantly correlated with the electrical conductivity as shown already in Table 7. Similar results were reported by Biswas et al. (1972) and Ponnamperuma (1966). The increase in concentration of anions is attributed to effects of submergence and reduction, chiefly solvent action of \( \text{CO}_2 \) and cation-anion exchange reactions. The \( \text{HCO}_3^- \) and \( \text{Cl}^- \) content of non-submerged soil was also related to EC and the values were usually lower than the corresponding values obtained under the submerged treatment.

III FREEZE-THAW EFFECTS ON SOIL PHYSICAL PROPERTIES

Phase I Fast Freezing - Fast Thawing

In this study treatments consist of 4 soil aggregate sizes and 3 moisture levels. Freezing was done at \( 0^\circ\text{F} \) and thawing at room temperature (72\(^\circ\text{F}\)) for 8 freeze-thaw cycles. The effects of repeated freezing and thawing on the soil's structural stability, water
Figure 21. Changes in $\text{HCO}_3^-$ of Soil Solution Extracted from Submerged and Non-submerged Toledo Silty Clay Loam.
Figure 22. Changes in Cl\(^-\) of Soil Solution Extracted from Submerged and Non-submerged Toledo Silty Clay Loam.
conducting capabilities and pore size distribution are presented in Tables 9 and 10. Table 9 show the initial soil physical properties, namely: volume of pores drained, bulk density, total porosity, moisture retention and hydraulic conductivity. The bulk density of the samples indicates good uniformity of packing of soil cores used for different moisture level treatments. The packing was also uniform between two soil size groups (0.0-2.0 and 0.0-0.42 mm) and two aggregate size groups of 0.42-0.84 mm and 0.84-2.0 mm. The data on moisture retention and drainable pore volumes (Table 9) indicates that the moisture retention decreases with increasing aggregate size while the drainable pore volume is increased. Similar observations have been reported by Trzecki (1973) and Benoit (1973). The moisture retention at 0.33 atm suction for the two larger aggregate size fractions is the same but is lower than that of the smaller size fractions of soil 0-2.0 mm and 0-0.42 mm.

The data on moisture retention and drainable pore volumes under the three moisture level treatments indicates uniformity between $M_2$ and $M_3$ samples. The moisture retention of $M_1$ samples was much higher and drainable pore volume was lower than the $M_2$ and $M_3$ samples. This is explained by the fact that $M_1$ samples were subjected to one month's submergence under water before initial physical properties were determined. Submergence increased moisture retention and decreased drainable pore volumes as has already been reported in section I of this chapter.

The hydraulic conductivity of samples under different soil sizes increased with increase in aggregate size and is directly related to the volume of pores drained at lower suctions. No differences in
TABLE 9

INITIAL SOIL PHYSICAL PROPERTIES OF SOIL CORES USED IN FREEZE-THAW STUDY.

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Bulk Density g/cc</th>
<th>Total Porosity %</th>
<th>Percent Air Filled Porosity at Indicated Suction</th>
<th>Moisture Retention (% By Volume) at Indicated Suction</th>
<th>Hydraulic Conductivity cm/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02 atm 0.06 atm 0.33 atm</td>
<td>0.02 atm 0.06 atm 0.33 atm</td>
<td></td>
</tr>
<tr>
<td>Aggregate Size (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.0 -0.42</td>
<td>1.17</td>
<td>56.9</td>
<td>6.2   8.1   16.1</td>
<td>51.1  48.9  40.7</td>
<td>0.05</td>
</tr>
<tr>
<td>0.0 -2.00</td>
<td>1.16</td>
<td>57.3</td>
<td>9.6   14.8  25.7</td>
<td>47.7  42.5  31.6</td>
<td>3.40</td>
</tr>
<tr>
<td>0.42-0.86</td>
<td>1.07</td>
<td>60.8</td>
<td>17.3  23.4  30.8</td>
<td>43.5  37.4  30.0</td>
<td>2.46</td>
</tr>
<tr>
<td>0.84-2.00</td>
<td>1.07</td>
<td>60.8</td>
<td>20.4  24.0  30.6</td>
<td>40.4  36.8  30.2</td>
<td>10.72</td>
</tr>
<tr>
<td>LSD (.01)</td>
<td>.01</td>
<td>0.1</td>
<td>0.6   0.4   0.9</td>
<td>0.6   0.4   0.9</td>
<td>3.70</td>
</tr>
<tr>
<td>Moisture Level</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Submergence for one month followed by maximum moisture retention after free drainage ($M_1$)</td>
<td>1.11</td>
<td>59.0</td>
<td>9.9  13.5  24.7</td>
<td>49.4  45.5  34.4</td>
<td>3.48</td>
</tr>
<tr>
<td>Maximum moisture retention after free drainage ($M_2$)</td>
<td>1.12</td>
<td>58.9</td>
<td>15.2 19.4  27.3</td>
<td>43.8  39.5  31.7</td>
<td>2.93</td>
</tr>
<tr>
<td>Treatment</td>
<td>Bulk Density (g/cc)</td>
<td>Total Porosity (%)</td>
<td>Percent Air Filled Porosity at Indicated Suction</td>
<td>Moisture Retention (% by Volume) at Indicated Suction</td>
<td>Hydraulic Conductivity (cm/hr)</td>
</tr>
<tr>
<td>-------------------------------</td>
<td>---------------------</td>
<td>--------------------</td>
<td>-----------------------------------------------</td>
<td>-------------------------------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02 atm</td>
<td>0.06 atm</td>
<td>0.33 atm</td>
</tr>
<tr>
<td>1/3 atm suction (M&lt;sub&gt;3&lt;/sub&gt;)</td>
<td>1.12</td>
<td>58.9</td>
<td>15.1</td>
<td>19.7</td>
<td>25.5</td>
</tr>
<tr>
<td>LSD (.01)</td>
<td>.01</td>
<td>0.1</td>
<td>0.5</td>
<td>0.4</td>
<td>0.6</td>
</tr>
<tr>
<td>Grand Mean &lt;sup&gt;c&lt;/sup&gt;</td>
<td></td>
<td></td>
<td>1.12</td>
<td>59.0</td>
<td>13.4</td>
</tr>
</tbody>
</table>

<sup>a</sup>, <sup>b</sup> and <sup>c</sup> correspond to 12, 16 and 48 replications, respectively.
hydraulic conductivity were seen among soil 0-2.0 mm and the aggregates of size 0.42-0.84 mm. However, they were seen to possess significantly different pore volumes. This might be due to differences in pore geometry of the two soil sizes. Hydraulic conductivity is a function of the total pore volume as well as geometry and continuity of the pores (Klute, 1965; Benoit, 1973). The data listed under grand mean (Table 9) indicates the mean initial values of soil physical properties after summation over all treatments of aggregate sizes and moisture levels.

The data of Table 10 show the relative change in soil physical properties for various treatments after having been exposed to 8 freeze-thaw cycles. The change is expressed as the ratio of the final to the initial values. The use of ratios tends to reduce the effect of initial differences in the measured properties. The greater the number listed in the table the greater was the increase and vice-versa. A summary of the statistical analysis is given in Appendix Table 4.

**Effect Of Aggregate Size**

The data on aggregate size (Table 10) show that freezing and thawing of soil decreased moisture retention and increased the volume of pores drained in the suction range of 0.02-0.33 atm used in the study. Also, an increase in hydraulic conductivity occurred while there were slight differences in bulk density and total porosity. This pattern was apparent for all the four aggregate size fractions. The smaller the size fraction used, the greater was the change in soil structure. The increase in hydraulic conductivity is accompanied by an increase in the volume of pores drained at lower suctions. There was
TABLE 10

EFFECT OF AGGREGATE SIZE AND INCUBATION MOISTURE LEVEL ON RELATIVE CHANGE IN SOIL PHYSICAL PROPERTIES AFTER FREEZING SOIL CORES AT 0°F AND THAWING AT ROOM TEMPERATURE USING 8 FREEZE-THAW CYCLES (RATIO OF FINAL TO INITIAL VALUES).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Bulk Density</th>
<th>Total Porosity</th>
<th>Volume Of Pores Drained At Indicated Suction</th>
<th>Moisture Retention At Indicated Suction</th>
<th>Hydraulic Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02 atm</td>
<td>0.06 atm</td>
<td>0.33 atm</td>
</tr>
<tr>
<td>Aggregate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sizea (mm)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.00-0.42</td>
<td>0.99</td>
<td>1.01</td>
<td>1.61</td>
<td>1.56</td>
<td>1.14</td>
</tr>
<tr>
<td>0.00-2.00</td>
<td>0.99</td>
<td>1.01</td>
<td>1.47</td>
<td>1.43</td>
<td>1.03</td>
</tr>
<tr>
<td>0.42-0.84</td>
<td>0.99</td>
<td>1.01</td>
<td>1.20</td>
<td>1.19</td>
<td>1.05</td>
</tr>
<tr>
<td>0.84-2.00</td>
<td>0.99</td>
<td>1.01</td>
<td>1.23</td>
<td>1.22</td>
<td>1.08</td>
</tr>
<tr>
<td>Moisture Levelb</td>
<td>Submergence for one month followed by maximum moisture retention after free drainage (M₁)</td>
<td>0.99</td>
<td>1.01</td>
<td>1.72</td>
<td>1.72</td>
</tr>
<tr>
<td></td>
<td>Maximum moisture retention after free drainage (M₂)</td>
<td>0.99</td>
<td>1.01</td>
<td>1.19</td>
<td>1.14</td>
</tr>
<tr>
<td>Treatment</td>
<td>Bulk Density</td>
<td>Total Porosity</td>
<td>Volume Of Pores Drained At Indicated Suction</td>
<td>Moisture Retention At Indicated Suction</td>
<td>Hydraulic Conductivity</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------</td>
<td>----------------</td>
<td>---------------------------------------------</td>
<td>----------------------------------------</td>
<td>------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02 atm</td>
<td>0.06 atm</td>
<td>0.33 atm</td>
</tr>
<tr>
<td>1/3 atm suction (M₃)</td>
<td>0.99</td>
<td>1.01</td>
<td>1.16</td>
<td>1.16</td>
<td>1.08</td>
</tr>
<tr>
<td>Grand Mean after freeze-thaw</td>
<td>0.99</td>
<td>1.01</td>
<td>1.32</td>
<td>1.30</td>
<td>1.08</td>
</tr>
</tbody>
</table>

a, b and c correspond to 12, 16 and 48 replications, respectively.
a 45 fold increase in the hydraulic conductivity of soil <0.42 mm diameter. A part of this increase is apparently due to an increase in the volume of large pores (pores drained at suction <0.06 atm). In addition, soil in these cores developed surface cracks during freeze-thaw cycles which might have inflated the hydraulic conductivity of this soil.

**Effect Of Moisture Level**

The data on effect of incubation moisture level (Table 10) indicate that generally freeze-thawing decreased moisture retention and increased hydraulic conductivity as well as the volume of pores drained at lower suction. The greatest changes occurred for the $M_1$ treatment which had relatively poor structure prior to freeze-thawing. The extent of change among $M_2$ and $M_3$ treatments appears to be more or less the same.

The data listed under grand mean (Table 10) is a cumulative mean of all soil size and moisture level treatments. The results indicate that there was an increase in volume of pores drained and a decrease in soil moisture retention after freeze-thawing. The greatest changes were found at lower suction of 0.02 and 0.06 atmospheres. Minor changes were seen in bulk density and the total pore space. The result of the soil physical changes that occurred should be an increase in the soil's hydraulic conductivity. That increase did occur is shown by the data of Table 10. Similar increase in permeability of different soils after freeze-thawing were reported by Leo (1963).
Hinman and Bisal (1973) also reported an increase in permeability of soil <4 mm that was freeze-thawed at field capacity (0.33 atm suction) but the effect was reversed at higher moisture content of 0.1 atm suction. Benoit (1973) found a higher permeability after freeze-thawing at 0.05 atm suction for soil 0.8-2.0 mm. The changes in permeability of the soil after freeze-thawing have been ascribed to the rearrangement of pores during the process of freezing and thawing (Leo, 1963) and due to an increase in water stable aggregation (Hinman and Bisal, 1973). Water stable aggregation is probably the result of local ice expansion pressures and dehydration which are both positive forces in building stable aggregates. The mechanism that causes a soil particle orientation under certain freeze-thaw conditions is not clear and needs investigation (Benoit, 1973).

Phase II. Fast Freezing - Slow Thawing

In this study treatments consisted of three soil aggregate sizes that were used at only one moisture level. Five freeze-thaw cycles were conducted. Freezing was done at 0°F and thawing was done at 40°F. The effects of repeated freezing and thawing on bulk density, total porosity, hydraulic conductivity, air filled porosity and soil moisture retention are shown in Tables 11 and 12.

The data of Table 11 show the initial soil physical properties of prepared soil cores. Compared to aggregate size fractions of 0.42-0.84 mm or 0.84-2.0 mm the composite soil of size <2 mm diameter had significantly higher packing bulk density, lower total porosity, lower volume of drainable pores and higher moisture retention at suctions of
TABLE 11

INITIAL BULK DENSITY, TOTAL AND AIR FILLED POROSITY, MOISTURE RETENTION AND HYDRAULIC CONDUCTIVITY OF PREPARED SOIL CORES (FREEZING AT 0°F AND THAWING AT 40°F). EACH VALUE IS A MEAN OF 3 REPLICATIONS.

<table>
<thead>
<tr>
<th>Aggregate Size (mm)</th>
<th>Bulk Density g/cc</th>
<th>Total Porosity %</th>
<th>Percent Air Filled Porosity At Indicated Suction</th>
<th>Moisture Retention (% By Volume) At Indicated Suction</th>
<th>Hydraulic Conductivity cm/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02 atm</td>
<td>0.66 atm</td>
<td>0.33 atm</td>
</tr>
<tr>
<td>0.00-2.00</td>
<td>1.11</td>
<td>59.3</td>
<td>12.3</td>
<td>20.7</td>
<td>26.7</td>
</tr>
<tr>
<td>0.42-0.84</td>
<td>1.01</td>
<td>62.9</td>
<td>19.2</td>
<td>27.3</td>
<td>32.1</td>
</tr>
<tr>
<td>0.84-2.0</td>
<td>1.00</td>
<td>63.3</td>
<td>24.1</td>
<td>29.5</td>
<td>33.3</td>
</tr>
<tr>
<td>LSD (.05)</td>
<td>.02</td>
<td>0.8</td>
<td>1.2</td>
<td>2.5</td>
<td>2.0</td>
</tr>
<tr>
<td>LSD (.01)</td>
<td>.04</td>
<td>1.4</td>
<td>2.1</td>
<td>4.1</td>
<td>3.3</td>
</tr>
</tbody>
</table>
0.02-0.33 atm. The hydraulic conductivity of larger size fraction (0.84-2.0 mm) was significantly greater than either of the 0-2.0 or 0.42-0.84 size fractions. This is probably due to a higher proportion of large sized pores (pores drained at suction <0.06 atm) in the 0.84-2.0 mm size fraction.

The two aggregate size fractions (0.42-0.84 mm and 0.84-2.0 mm) had similar packing and had approximately same bulk density, total porosity, volume of pores drained and moisture retention at suction of 0.06-0.33 atm. The only significant difference was found in the volume of pores drained and moisture retention at 0.02 atm suction and the hydraulic conductivity. Apparently, the 0.84-2.00 mm size fraction had higher proportion of large pores compared to those in the 0.42-0.84 mm size fraction.

After freeze-thawing, the relative changes in bulk density, total porosity, air filled porosity, moisture retention and the hydraulic conductivity of soil are shown in Table 12. The data indicate that freeze-thawing increased bulk density and decreased: total porosity, hydraulic conductivity and the volume of pores drained at suction of 0.02-0.33 atm in all soil size fractions. Also, the soil moisture retention increased after freeze-thawing. The larger the soil size fraction used, the greater was the change in soil structure. A summary of the statistical analysis is given in Appendix Table 5.

The deteriorative effects on soil structure after freeze-thawing at higher moisture contents have also been reported by a number of workers (Benoit, 1970 and 1973; Hinman and Bisal, 1973; Sillanpaa, 1961; Logsdail and Webber, 1959). These workers found that higher the
## TABLE 12

Relative change in bulk density, total and air filled porosity, moisture retention and hydraulic conductivity, on freezing at 0°F and thawing at 40°F after five freeze-thaw cycles (ratio of final to initial values).

<table>
<thead>
<tr>
<th>Aggregate Size (mm)</th>
<th>Bulk Density</th>
<th>Total Porosity</th>
<th>Air Filled Porosity At Indicated Suction</th>
<th>Moisture Retention At Indicated Suction</th>
<th>Hydraulic Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02 atm</td>
<td>0.66 atm</td>
<td>0.33 atm</td>
</tr>
<tr>
<td>0.00-2.00</td>
<td>1.02</td>
<td>0.98</td>
<td>0.94</td>
<td>0.81</td>
<td>0.94</td>
</tr>
<tr>
<td>0.42-0.84</td>
<td>1.05</td>
<td>0.97</td>
<td>0.73</td>
<td>0.72</td>
<td>0.90</td>
</tr>
<tr>
<td>0.84-2.00</td>
<td>1.08</td>
<td>0.95</td>
<td>0.69</td>
<td>0.75</td>
<td>0.85</td>
</tr>
</tbody>
</table>
aggregate size; higher the moisture content and faster the freezing, the more is the possibility of degradation of aggregation and soil structure after freeze-thawing. The effect of thawing temperature has not been studied extensively. In all freeze-thaw studies thawing has usually been reported at room temperatures which indicates fast thawing. Freeze-drying has been reported to be more harmful than air drying (Hinman and Bisal, 1968) but it does not represent thawing conditions in the field. In the field soil, the processes of thawing and evaporation proceed simultaneously. On the other hand, during freeze-drying moisture is lost by sublimation without actually thawing the soil.

**Fast Vs. Slow Thawing**

In order to compare the fast and slow thawing condition, data on three soil sizes and one moisture level (equivalent to those used in Phase II) was extracted from study reported in phase I and is shown in Tables 13 and 14. The phase I and II of freeze-thaw study was conducted at two different times and the initial physical properties are in variance due to differences in packing density of soil cores. Hence, the effects of freeze-thawing in each study should be evaluated taking into consideration its initial physical properties. Comparisons of freeze-thaw response should be evaluated on a relative basis between phase I and phase II. The data on soil moisture retention, air filled pore volumes and hydraulic conductivity of different size fractions under fast and slow thawing conditions is shown in Figures 23, 24 and 25 respectively. An opposite response in soil physical changes was found under fast and slow thawing conditions. The fast thawing of phase
TABLE 13

INITIAL HYDRAULIC CONDUCTIVITY, BULK DENSITY, TOTAL AND AIR FILLED POROSITY OF PREPARED SOIL CORES. (FREEZING AT 0°F, THAWING AT ROOM TEMPERATURE). EACH VALUE IS A MEAN OF FOUR REPLICATIONS.

<table>
<thead>
<tr>
<th>Aggregate Size (cm)</th>
<th>Bulk Density g/cc</th>
<th>Total Porosity %</th>
<th>Percent Air Filled Porosity At Indicated Suction</th>
<th>Moisture Retention (% by Volume) At Indicated Suction</th>
<th>Hydraulic Conductivity cm/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00-2.00</td>
<td>1.16</td>
<td>57.3</td>
<td>11.4 16.1 26.9</td>
<td>45.9 41.2 30.4</td>
<td>3.68</td>
</tr>
<tr>
<td>0.42-0.84</td>
<td>1.07</td>
<td>60.8</td>
<td>18.6 25.3 31.2</td>
<td>42.2 35.5 29.6</td>
<td>3.37</td>
</tr>
<tr>
<td>0.84-2.00</td>
<td>1.07</td>
<td>60.8</td>
<td>21.4 25.7 31.2</td>
<td>39.4 35.1 29.5</td>
<td>4.64</td>
</tr>
</tbody>
</table>
TABLE 14

RELATIVE CHANGE IN HYDRAULIC CONDUCTIVITY, BULK DENSITY, TOTAL AND AIR FILLED POROSITY ON FREEZING AT 0°F AND THAWING AT ROOM TEMPERATURE AFTER 8 FREEZE–THAW CYCLES (RATIO OF FINAL TO INITIAL VALUES).

<table>
<thead>
<tr>
<th>Aggregate Size (mm)</th>
<th>Bulk Density</th>
<th>Total Porosity</th>
<th>Air Filled Porosity at Indicated Suction</th>
<th>Moisture Retention at Indicated Suction</th>
<th>Hydraulic Conductivity</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.02 atm 0.06 atm 0.33 atm</td>
<td>0.02 atm 0.06 atm 0.33 atm</td>
<td></td>
</tr>
<tr>
<td>0.00–2.00</td>
<td>.99</td>
<td>1.01</td>
<td>1.43 1.28 0.96</td>
<td>0.91 0.90 1.05</td>
<td>2.21</td>
</tr>
<tr>
<td>0.42–0.84</td>
<td>.99</td>
<td>1.01</td>
<td>1.16 1.05 1.02</td>
<td>0.94 0.97 0.99</td>
<td>1.49</td>
</tr>
<tr>
<td>0.84–2.00</td>
<td>.99</td>
<td>1.01</td>
<td>1.14 1.09 1.08</td>
<td>0.93 0.95 0.94</td>
<td>1.30</td>
</tr>
</tbody>
</table>
Figure 23. Relative Increase or Decrease in Moisture Retention at Different Suctions, after Fast and Slow Thawing of Soil for Three Soil-Size Fractions. [Based on Initial Values the Positive and Negative Values Indicate an Increase and Decrease, Respectively, in Moisture Retention after giving Thawing Treatments].
Figure 24. Relative Increase or Decrease in Air-Filled Porosity at Different Suctions, after Fast and Slow Thawing of Soil for Three Soil Size Fractions. [Based on Initial Values the Positive and Negative Values Indicate an Increase and Decrease, Respectively, in Air-Filled Porosity after giving Thawing Treatments].
Figure 25. Changes in Hydraulic Conductivity of Three Soil-Size Fractions Under Fast and Slow Thawing Temperatures.
I favoured soil structure while slow thawing of phase II resulted in deterioration of soil structure. Improvement in soil structure was greater for the smaller soil size fractions while destruction of soil structure is greater for the larger aggregate size fraction. This indicates that thawing temperature affects the soil structure during freeze-thawing. The visual observations were taken for the soil surface during fast and slow thawing. The surface of the soil cores had a porous sponge like appearance under fast thawing conditions and probably developed continuous channels within the soil. On the other hand the surface of the soil used in slow thawing looked dispersed and showed a more compact and fine appearance indicating destruction of soil structure.

II  FIELD STUDIES

Effect Of Drainage Systems On Soil Physical Properties

This section deals with the results on soil physical changes brought about by different drainage systems sixteen years after installation. The drainage experiment is located at North Central Research Station, Castalia, Ohio. Four drainage treatments are represented by no drainage (undrained), surface-drainage alone, tile-drained alone, and a combination of tile and surface-drainage. Starting from the installation of the experiment in 1957, the undrained plots were devoid of any artificial drainage and have been excessively wet. Planting have been delayed and plant growth has been poor. In 1969 shallow plastic drains were installed in these plots to improve the
drainage. In this study these plots will be referred to as 'undrained'. The results that follow are based on field sampling and laboratory characterization of undisturbed soil cores taken during 1973 and 1974.

1. Crust Density And Resistance To Surface Penetration

The data on dry bulk density of soil crust are shown below:

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Density (g/cc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Undrained</td>
<td>1.55</td>
</tr>
<tr>
<td>Surface-drained only</td>
<td>1.49</td>
</tr>
<tr>
<td>Tile-drained only</td>
<td>1.48</td>
</tr>
<tr>
<td>Tile plus surface-drained</td>
<td>1.46</td>
</tr>
<tr>
<td>LSD (0.05)</td>
<td>0.05</td>
</tr>
<tr>
<td>Coefficient of variation</td>
<td>1.92%</td>
</tr>
</tbody>
</table>

The crust density of undrained plots was significantly greater than that of any other treatment. Also, the individual crust units in the undrained plots were much thicker, larger in cross-sectional area, and resulted in wider crack spacing. A representative crusting pattern under different drainage treatments is shown in Figure 26.

The data on resistance to surface penetration for the four drainage treatments are presented in Figure 27. Each value represents a mean of 40 measurements. Since penetration resistance is strongly dependent on soil moisture, field moisture contents were obtained and are also shown in Figure 27. A penetration pressure of 14.5, 12.8, 7.8 and 6.3 Kg/cm² was recorded for the undrained,
Figure 27. Pressure Required to Penetrate Soil Surface Through a Depth of 1 cm at Field Moisture Content Under Different Drainage Systems. [A Proctor Type Blunt End Penetrometer With a Foot Size of 1.65 cm Diameter Was Used. Each Treatment Represents an Average of 40 Penetration Measurements]. The Measurements Were Taken on April 20, 1974 When the Soil Surface Was Air Dry. A Rainfall of 0.25 Inches Had Occurred During the Week of April 6-12, 1974. The Field Had Been Cultivated in Summer, 1973 and Alfalfa Was Seeded.
surface-drained, tile-drained and tile plus surface-drained treatments, respectively. A statistical analysis of these data showed that the undrained and the surface-drained treatments offered significantly greater resistance than the two subsurface-drained treatments. No significant differences were obtained between undrained and surface-drained or between tile-drained and tile plus surface-drained treatments.

The resistance to penetration is known to markedly increase with decreasing moisture content. An interesting point is that the undrained treatment required the greatest force for surface penetration even though it resulted in the highest moisture content. If the moisture content in the undrained treatment had been as low as in the subsurface-drained treatments, its resistance to penetration would have been much greater. A similar line of reasoning applies to the surface-drained treatment. There were no differences in moisture content between the two tile-drained treatments.

Soil-crust formation and soil strength are important indices of soil structure. Penetrometer measurements have been used to correlate soil strength and plant root growth (Taylor, 1971). The formation of crust affects crop growth directly and indirectly. The direct effects are mechanical obstruction to the emergence of germinating seedlings and damage to their roots by bending and twisting during the crack formation in the drying crust. The indirect effects include the decrease in water-intake rates, increase in runoff and erosion, a reduction of air capacity and the impediment of internal aeration.
The data of Figure 27 indicate the superiority of tile + surface-drained treatment with respect to surface soil structure. Improved soil structure is indicated by lower crust density, reduced penetration resistance and smaller crust units. Based on these criteria the structural condition of undrained and surface drained treatment seems to be poor. Several factors contribute to the development of this condition. The soil under these treatments remains wetter during winter and spring due to absence of subsurface drainage. Freezing and thawing under excess moisture conditions may contribute to the destruction of soil structure. The aggregated structure is more or less destroyed through particle rearrangement during natural wetting and drying cycles by the processes of slaking and dispersion. Hillel (1960) found that crusting was a function of wetting duration. Modulus of rupture increased with length of wetting time. Also, the crust strength increased with slow rate of drying. In the present study, the structure was much worse on the undrained treatment, followed by the surface-drained treatment. Fausey (1966) studied the field moisture contents under different drainage treatments from this same experiment. He reported significantly higher moisture contents in the undrained plots, followed by the surface-drained plots. The lowest moisture contents were obtained in the tile + surface-drained treatment.

2. Unconfined Compressive Strength

a) Surface Soil (5-15 cm depth)

The maximum strength at rupture in the unconfined compression test was recorded on samples after equilibrating to a
uniform moisture content at 1.0 atmosphere suction. Measurements of unconfined compressive strength were taken twice, once in May 1973 and again in April 1974. The unconfined compressive strength of soil under different drainage treatments is shown in Figure 28.

The data of May, 1973 showed significant differences in unconfined compressive strength among all four drainage treatments. The undrained treatment registered the highest compressive strength of 3.69 Kg/cm². It is two times as great as the lowest compressive strength recorded for the combination of tile and surface-drained treatment. The order of compressive strength was: undrained > surface-drained > tile drained > tile + surface drained.

The same trend is also apparent from the data of April, 1974; however the differences are smaller. The compressive strength of undrained treatment was 1.5 times as great as that for combined tile and surface-drained. The compressive strength of tile-drained (alone) treatment was also significantly lower than the undrained treatment. No major differences were seen between the undrained and the surface-drained (alone) treatments. The surface-drained (alone) treatment had significantly greater compressive strength when compared to combined tile + surface-drained, but when compared to tile-drainage alone, the differences are not statistically significant.

The 1974 values of unconfined compression strength were generally lower than those recorded in 1973. The decrease was more pronounced for the undrained and surface-drained treatments that had relatively poor soil structure and had higher bulk density during 1973. In 1973 the bulk density of soil used in the unconfined compression
Figure 28. Maximum Unconfined Compressive Strength of Surface (5-15 cm) Soil Under Different Drainage Systems During 1973 and 1974.
test was 1.53 and 1.48 g/cc for the undrained and surface-drained treatments, respectively. The corresponding bulk densities in 1974 were low and were 1.46 and 1.45 g/cc. No apparent differences in bulk density of sub surface-drained treatments were found for the data of two years. The decrease in unconfined compression strength was probably the result of soil loosening by disk ing operation conducted in May 1973 for seeding of alfalfa. The sampling for 1973 was completed before the disk ing operation.

b) Subsurface Soil (15-25 cm depth)

Figure 29 shows the unconfined compressive strength of soil just below the plow-layer at 15-25 cm depth. Significant differences are seen among the drainage treatments, with undrained treatment showing the highest compressive strength of 3.1 Kg/cm². Compared to the undrained treatment, the tile-drained or combination of tile and surface-drained treatment resulted in a significantly lower compressive strength. Surface-drainage alone did not give significantly different results from those of the undrained treatment or those of tile-drainage alone but they were significantly greater than those from the combined tile + surface-drainage treatment. No statistically significant differences in results were seen among the two subsurface drainage treatments.

The unconfined compression strength of subsoil was greater than that of the surface soil as indicated by the data of 1974 (Figures 28 and 29). In 1973, the sampling was done only for the surface soil. The higher soil strength of subsoil is a result of a
Figure 29. Maximum Unconfined Compressive Strength of Subsurface (15-25 cms) Soil Under Different Drainage Systems During April 1974.
combination of factors like higher bulk density, poor soil structure, higher clay content and prolonged wet periods throughout the year.

3. **Total Rupture Energy**

Total energy for each sample was obtained by integrating the area under the load-deformation curves. Total energy represents the integrated energy used in compression of the sample from the start of compression to the rupture point. The data in Figure 30 show the total energy used for surface and subsurface soil under the different drainage systems. Each value represents an average of eight replications for surface soil and six replications for subsoil.

a) **Surface Soil (5-15 cm depth)**

The results of the surface soil indicate that both undrained and surface-drained treatments required greater than 41 percent more total rupture energy than the other two subsurface-drained treatments. Tile-drained treatment used 32 percent more energy as compared to tile + surface-drained treatment. The data on total rupture energy for the various drainage treatments follow the same general pattern as seen earlier for the maximum strength at rupture.

b) **Subsurface Soil (15-25 cm depth)**

The same general trend as seen for the surface soil is also apparent for the subsurface soil. Both undrained and surface-drained (alone) treatments required greater than 48 percent more energy than the other two treatments. Tile-drained treatment used 24 percent
Figure 30. Total Energy Used Until Rupture Point During Unconfined Compression of Samples from Surface (5-15 cm) and Subsurface (15-25 cm) Soil Under Different Drainage Treatments in April 1974.
more energy than the combination of tile and surface-drained treatment. The data of total energy follows the same pattern as seen for the unconfined compression strength.

The energy used in subsurface soil was greater than the surface soil for all the four drainage systems. However, the differences are more marked for the undrained and surface-drained treatments. Compared to surface soil the subsurface soil had higher bulk density and higher total strain, both factors responsible for increasing the integrated stress during the rupture of the soil sample. The mean total strain for all the four drainage treatments was 10.5% and 11.3% for the surface and subsurface soil, respectively.

4. Stress Strain Relations

Unconfined compressive strength is plotted against normalized strain in Figure 31 for surface soil samples. Figure 32 shows the normalized stress vs. normalized strain curves.

The maximum stress and strain at rupture point have been used as the normalizers for this data. For this purpose, the total stress and strain up to rupture point was divided into ten equal intervals. The normalized values of stress or strain along the axis were obtained by dividing the non-normalized stress or strain at each 1/10 interval by the maximum value of that parameter. The mean strain at rupture for the four drainage treatments was: undrained-11.8%, surface-drained-11.4%, tile-drained-10.2% and tile plus surface-drained-8.9%.

Maximum strain for samples under any one treatment was also quite variable. Plotting mean stress against normalized values
Figure 31. Stress-Strain Relations for Different Drainage Treatments at 5-15 cm Depth for April-1974 Sampling Date.
Figure 32. Normalized Stress vs. Normalized Strain for Soil Under Different Drainage Treatments at 5-15 cm Depth for April-1974 Sampling Date.
of strain at fixed intervals provided an averaging effect and resulted in a representative and smooth stress-strain curve. Figure 31 show that undrained treatment always had a higher compressive stress followed by surface-drained, tile-drained, and tile + surface-drained treatments in the decreasing order. Figure 32 indicates that normalized stress vs. normalized strain curves for the soil from all drainage treatments have the same general shape and pattern. This indicates that the soil sampled from different drainage treatments had identical stress-strain behaviour.

The stress-strain data for subsoil is plotted in Figures 33 and 34. The mean values of strain for the drainage treatments were: undrained-12.9%, surface-drained-10.4%, tile-drained-11.7% and tile + surface-drained-10.2%. Figures 33 and 34 indicate that the subsurface soil followed the same pattern as for the surface soil with respect to their stress-strain relations.

The consistently higher values of unconfined compression strength and integrated energy used in rupture of surface and sub-surface samples for the undrained and surface drained-treatments reflect in a greater draft requirement to cultivate these plots compared to the subsurface-drained plots. The farm manager* at the drainage site reported that during plowing operations greater tractor power was required for plowing of undrained and surface-drained plots than for subsurface-drained plots. There appears to be no data in the literature on draft requirement of differentially drained soil. VanHoorn (1958) observed that soil having a constant water table depth at 40 cm remained excessively wet in the surface 20 cm and was compact, sticky, and had a

*Personal Communication with Charles C. Willer.
Figure 33. Stress-Strain Relations for Different Drainage Treatments at 15-25 cm Depth for April-1974 Sampling Date.
Figure 34. Normalized Stress vs. Normalized Strain for Soil Under Different Drainage Treatments at 15-25 cm Depth for April-1974 Sampling Date.
higher draft requirement. This was not found when water table was maintained at depths of more than 40 cm. Low and Piper (1973) reported that reduction in drawbar pull was related to increased pore space, decreased density of soil clods, and stability of aggregates. Like permeability, strength is highly correlated with planes of weakness or large voids in the soil (Gerard et al, 1966). The latter reported a decrease in soil strength with a corresponding increase in the volume of pores drained at 0.06 atmospheres of suction.

Other effects of higher soil strength would be reflected in restricted root growth. In this study root distribution was not studied in the field. However, in an earlier study on this experiment, Fausey (1966) reported that more shallow soybean root systems were found in the undrained than in the other three drainage treatments. The root length of surface-drained plots was also more shallow than the two subsurface-drained treatments.

5. Other Physical Properties

a) Hydraulic Conductivity

The hydraulic conductivity was measured on undisturbed soil cores sampled during May 1973 and are shown in Figure 35. Sampling was done only for the surface 5-15 cm depth, and each value is a mean of eight replications. Before making the measurements the soil cores were wet under vacuum. Appreciable swelling of soil occurred within the brass cylinders, apparently due to entrapped air. The soil protruding from the top of the container was cut and removed. This operation may have resulted in some puddling at the surface. Since
Figure 35. Saturated Hydraulic Conductivity of Surface (5-15 cm) Soil Under Different Drainage Systems. May-1973
hydraulic conductivity values may have been altered, differences among treatments should be treated on a relative basis. The hydraulic conductivity of the cores from the tile + surface-drained treatment was highest (0.4 cm/hr) and was significantly greater than that of those from any of the other three treatments. The tile-drained treatment reflected a higher conductivity than surface-drained or undrained treatments but the differences are not statistically significant. The hydraulic conductivity of surface-drained and undrained treatments gave results which were practically the same, the former showing 0.07 cm/hr and the latter 0.02 cm/hr. The variability of the measurements was quite high as can be expected for this kind of determination. A coefficient of variation of 95% was observed.

Figure 36 contains the hydraulic conductivity data of top soil (5-15 cm depth) and subsoil (15-25 cm depth) determined during April 1974. The same trend was observed as in the previous year. For the surface soil, tile-drained treatments gave significantly higher conductivities than the other two treatments. The subsoil conducted water at a much slower rate than the top soil, being approximately one third that of the top soil. For the subsoil the data show essentially the same trend as for the top soil. It is generally agreed that hydraulic conductivity is a valuable soil property for predicting the efficiency of drainage systems. Since hydraulic conductivity is a function of soil porosity and the size distribution of the pores, the conductivity data generally reflect soil aggregate stability and pore space relations.

The data of Figures 35 and 36 lead one to the conclusion that the combined surface and tile-drainage is the most favorable to
Figure 36. Saturated Hydraulic Conductivity of Surface (5-15 cm) and Subsurface (15-25 cm) Soil Under Different Drainage Systems. April 1974.
soil structure and in order followed by tile-drainage (alone). The surface-drained and undrained treatments have poor soil structure. Field observations show that water ponds for long periods of time on the undrained plot after heavy rains. Figure 37 shows a photography of all the four drainage treatment plots from replication I, taken on April 13, 1974. A rainfall amounting to 0.23 inches and 0.03 inches had occurred on April 7 and April 12, respectively. Ponded water was still present in the undrained plot but not in the others.

b) Drainable Porosity And Pore-size Distribution

The percentage volume of air-filled pores in the top soil at suction of 0.02-1.0 atm is shown in Figure 38. These data showed the same trend among drainage treatments as the hydraulic conductivity findings. The undrained treatment had significantly lower values of air-filled porosity at all suction than the two subsurface-drained treatments.

Figure 39 shows corresponding data for the subsoil. These data show the same general pattern as in the top soil. However, only the undrained treatment showed significantly lower values. The data of both surface and subsurface soil indicate that the increase in drainable porosity at suction of 0-1.0 atmospheres was due to increase in the proportion of both large and medium-sized pores. The pores drained at suction less than 0.06 atmospheres are generally considered as large pores. The medium-sized pores are drained at suction in the range of 0.06-0.33 atmospheres. Generally, the higher the percentage of
Figure 37. A view of surface ponding of water after a heavy rain for different drainage systems.
Figure 38. Drainable Pore Space at Various Suctions in Toledo Silty Clay Under Different Drainage Systems [5-15 cm Depth].
Figure 39. Drainable Pore Space at Various Suctions in Toledo Silty Clay Under Different Drainage Systems [15-25 cm depth].
large pores in a soil, the greater is its hydraulic conductivity. This relationship appears to be true for these data as seen in Figures 35 and 36 on hydraulic conductivity. The volume of air-filled pores in the surface soil was generally low at suction of 20 and 60 cm of water for all drainage systems. The values under undrained and surface-drained treatments are quite low and may adversely affect oxygen diffusion to growing roots. The air-filled pores of subsoil (15-25 cm depth) are still lower than in the surface soil, and one might predict that such low values would adversely affect plant growth during periods of wetness when roots were growing in this layer.

c) Bulk Density, Total Porosity And Moisture Retention

The data on bulk density and total porosity for the top 5-15 cm depth and subsoil 15-25 cm depth are given in Table 15. Significant differences in bulk density and total porosity were obtained only for the top soil, and the magnitude of these differences is not appreciable. The moisture retention in the top soil and subsoil at suctions of 0-1.0 atmospheres is also given in Table 15. No appreciable differences were apparent among different drainage treatments at these suctions.

d) Soil Tilth

Figure 40 shows the distribution of aggregate size following seed-bed preparation. The picture was taken while the field was being prepared for seeding alfalfa in May 1973. Larger and more dense aggregates were observed in the undrained plots than in the two
TABLE 15

EFFECT OF DRAINAGE SYSTEMS ON BULK DENSITY, TOTAL POROSITY AND MOISTURE RETENTION IN THE SURFACE AND SUBSURFACE OF TOLEDIO SILTY CLAY.

<table>
<thead>
<tr>
<th>Drainage Treatment</th>
<th>Undrained</th>
<th>Surface Drained</th>
<th>Tile Drained</th>
<th>Tile + Surface Drained</th>
<th>LSD (.05)</th>
<th>LSD (.01)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Only</td>
<td>Only</td>
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<tr>
<td>5-15 Cm Depth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Density - g/cm³</td>
<td>1.29</td>
<td>1.26</td>
<td>1.25</td>
<td>1.22</td>
<td>0.04</td>
<td>0.06</td>
</tr>
<tr>
<td>Total Porosity - %</td>
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<td>53.4</td>
<td>53.5</td>
<td>54.6</td>
<td>1.6</td>
<td>2.3</td>
</tr>
<tr>
<td>Moisture Retention-Percent By Volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 cm of water suction</td>
<td>51.6</td>
<td>52.6</td>
<td>53.3</td>
<td>53.6</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>20 &quot; &quot; &quot; &quot;</td>
<td>48.6</td>
<td>48.2</td>
<td>47.0</td>
<td>46.6</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>60 &quot; &quot; &quot; &quot;</td>
<td>47.6</td>
<td>46.8</td>
<td>45.7</td>
<td>45.1</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>0.33 atm suction</td>
<td>43.5</td>
<td>42.3</td>
<td>41.1</td>
<td>40.4</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>1.0 &quot; &quot; &quot;</td>
<td>39.4</td>
<td>38.4</td>
<td>37.6</td>
<td>36.8</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>15-25 Cm Depth</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Density - g/cm³</td>
<td>1.34</td>
<td>1.33</td>
<td>1.34</td>
<td>1.32</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Total Porosity - %</td>
<td>50.2</td>
<td>50.6</td>
<td>50.3</td>
<td>51.0</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>Moisture Retention-Percent By Volume</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0 cm of water suction</td>
<td>49.2</td>
<td>50.8</td>
<td>50.8</td>
<td>51.4</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>20 &quot; &quot; &quot; &quot;</td>
<td>47.4</td>
<td>47.8</td>
<td>47.7</td>
<td>48.0</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>60 &quot; &quot; &quot; &quot;</td>
<td>46.1</td>
<td>46.6</td>
<td>46.4</td>
<td>46.7</td>
<td>NS</td>
<td></td>
</tr>
<tr>
<td>0.33 atm suction</td>
<td>42.8</td>
<td>42.9</td>
<td>42.7</td>
<td>43.0</td>
<td>NS</td>
<td>1.48</td>
</tr>
<tr>
<td>1.0 &quot; &quot; &quot;</td>
<td>39.3</td>
<td>39.1</td>
<td>39.1</td>
<td>39.1</td>
<td>NS</td>
<td></td>
</tr>
</tbody>
</table>
Figure 40. Soil tilth following seedbed preparation for alfalfa in May 1973. (Each print covers 75 x 75 cm area).

A = Undrained  
B = Surface drained  
C = Tile drained  
D = Tile + surface drained
subsurface-drained treatments. The surface-drained plots resulted in intermediate size aggregates. The poor soil tilth and severe crusting as was seen in Figure 26 for the undrained and surface-drained treatments indicates that adverse structure was much in evidence. The subsurface-drained treatments provided comparatively better soil structure.
SUMMARY

In a laboratory study, soil physical properties of a Toledo silty clay loam were evaluated under submerged and non-submerged conditions. Using different soil aggregate sizes (<2 mm; <5 mm; 2-5 mm diam.), it was found that submergence had a deteriorative effect on soil structure. It increased moisture retention and decreased the volume of pores drained at suction of 0.02-0.33 atmospheres.

It decreased the hydraulic conductivity but brought about no differences in bulk density and total pore space. The results were the same for soil with or without previous wetting and drying cycles and for different aggregate sizes. The major changes that occur from submergence under water seem to be in the rearrangement of pores. Excessive water probably results in destruction of aggregates thus reducing the proportion of larger pore spaces.

In a second laboratory study, changes in chemical composition of the soil solution from submerged and non-submerged soil were monitored for a period of 60 days. Under submerged conditions, pH remained relatively constant; electrical conductivity increased; nitrates disappeared within a day; ammonium concentration increased; reduced forms of iron (Fe^{2+}) and manganese (Mn^{2+}) increased; sulfates decreased while concentration of anions (HCO_3^-, Cl^-) increased. These results are probably due to reducing conditions and increased solubility of certain
ions. The non-submerged soil was kept moist (0.06 atm suction), and this apparently favored oxidizing conditions and increased nitrification. The moist conditions also increased solubility of ions and consequently increased the electrical conductance. Reduced forms of iron and manganese were absent while negligible changes were found in pH and in NH$_4^+$ and SO$_4^{2-}$ concentrations. Submergence did not increase EC or the concentrations of Fe$^{2+}$ and Mn$^{2+}$ to the extent that they would be toxic to plant growth.

In a third laboratory study, disturbed soil cores of different aggregate sizes (<2 mm; <0.42 mm; 0.42-0.84 mm; 0.84-2.0 mm diam.) and at high moisture contents were used to study changes in soil structure after freeze-thaw treatments. In one case, soil cores were frozen at 0°F and fast thawed at room temperature (72°F). In another case, soil cores were frozen at 0°F but thawed slowly at 40°F. Compared to initial soil condition, fast thawing favored soil structure by decreasing moisture retention at small suction, increasing hydraulic conductivity and increasing the volume of pores drained between 0.02 and 0.33 atm suctions. On the other hand, slow thawing resulted in destruction of soil structure. The destruction of soil structure was more pronounced for the larger size aggregates, while the favourable effects were more pronounced for the smaller soil size fractions.

A field study was conducted to evaluate the effect of no drainage surface-drainage alone, tile-drainage alone and a combination of surface-+ tile-drainage systems on physical properties of the same soil used in the laboratory studies. The drainage experiment was initiated sixteen years previously. During this period excess moisture conditions
were created each season by artificial irrigation applied in excess of plant requirements. Field observations and laboratory evaluations based on undisturbed field soil cores showed that soil structure under undrained and surface-drained treatments was less favourable when compared to either of the subsurface-drained treatments. The absence of subsurface drainage is characterized by severe surface crusting, higher crust density, and greater crust penetration resistance; higher soil strength; lower hydraulic conductivity and lower percentages of air-filled pores at small suctions. The combination of tile and surface-drainage was found to have the most favourable soil structure and was followed by tile-drainage (alone).
TABLE 1

COMPARISON OF BULK DENSITY AND MOISTURE CONTENTS AT 1.0 ATM. SUCTION BETWEEN BULK SAMPLES (7.6 x 7.6 CM) AND SUBSAMPLES (2.67 x 5.3 CM) USED IN UNCONFINED COMPRESSION TESTS.

<table>
<thead>
<tr>
<th>Drainage Treatment</th>
<th>Undrained</th>
<th>Surface Drained</th>
<th>Tile Drained</th>
<th>Tile and Surface Drained</th>
<th>LSD (0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>5-15 cm Depth</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Density-g/cm³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Sample</td>
<td>1.29</td>
<td>1.26</td>
<td>1.25</td>
<td>1.22</td>
<td>.04</td>
</tr>
<tr>
<td>Subsample</td>
<td>1.46</td>
<td>1.45</td>
<td>1.44</td>
<td>1.44</td>
<td>NS</td>
</tr>
<tr>
<td>1 atm. Moisture-% By Weight</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Sample</td>
<td>30.4</td>
<td>30.6</td>
<td>29.9</td>
<td>30.1</td>
<td>NS</td>
</tr>
<tr>
<td>Subsample</td>
<td>29.6</td>
<td>28.8</td>
<td>29.0</td>
<td>28.9</td>
<td>NS</td>
</tr>
<tr>
<td><strong>15-25 cm Depth</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Density-g/cm³</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bulk Sample</td>
<td>1.36</td>
<td>1.33</td>
<td>1.36</td>
<td>1.32</td>
<td>NS</td>
</tr>
<tr>
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<td>1.49</td>
<td>1.47</td>
<td>1.48</td>
<td>1.46</td>
<td>NS</td>
</tr>
<tr>
<td>1 atm. Moisture-% By Weight</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Bulk Sample</td>
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<td>29.6</td>
<td>29.2</td>
<td>29.6</td>
<td>NS</td>
</tr>
<tr>
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<td>29.0</td>
<td>NS</td>
</tr>
<tr>
<td>Submergence (Days)</td>
<td>pH</td>
<td>EC mmhos/cm</td>
<td>Fe^2+ ppm</td>
<td>Mn^2+ ppm</td>
<td>NH_4^+ ppm</td>
</tr>
<tr>
<td>-------------------</td>
<td>------</td>
<td>-------------</td>
<td>-----------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>0.5</td>
<td>8.12</td>
<td>1.42</td>
<td>A*</td>
<td>A</td>
<td>7.8</td>
</tr>
<tr>
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<td>0.97</td>
<td>A</td>
<td>A</td>
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<tr>
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<td>1.65</td>
<td>0.49</td>
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<td>1.21</td>
<td>3.63</td>
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<td>2.12</td>
<td>3.13</td>
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<td>2.53</td>
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<td>3.83</td>
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<td>3.68</td>
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<td>4.09</td>
<td>5.91</td>
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<td>1.86</td>
<td>5.05</td>
<td>3.60</td>
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</table>

*Absent
TABLE 3
CHEMICAL ANALYSIS OF SOIL SOLUTION OBTAINED FROM NON-SUBMERGED SOIL INCUBATED AT A SUCTION OF APPROXIMATELY 60 CM OF WATER UP TO 60 DAYS.

<table>
<thead>
<tr>
<th>Incubation Days</th>
<th>pH</th>
<th>EC mmhos/cm</th>
<th>NO$_3^-$ ppm</th>
<th>NH$_4^+$ ppm</th>
<th>SO$_4^{2-}$ ppm</th>
<th>HCO$_3^-$ me/l</th>
<th>Cl$^-$ me/l</th>
<th>CO$_3^{2-}$ me/l</th>
<th>Fe$^{2+}$ Mn$^{2+}$</th>
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</thead>
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<td>7.80</td>
<td>1.70</td>
<td>72</td>
<td>--</td>
<td>77</td>
<td>5.0</td>
<td>2.8</td>
<td>2.0 Absent</td>
<td>&quot;</td>
</tr>
<tr>
<td>3</td>
<td>8.17</td>
<td>1.55</td>
<td>90</td>
<td>4.1</td>
<td>81</td>
<td>5.5</td>
<td>5.6</td>
<td>--</td>
<td>&quot;</td>
</tr>
<tr>
<td>5</td>
<td>8.04</td>
<td>1.82</td>
<td>100</td>
<td>--</td>
<td>95</td>
<td>9.5</td>
<td>--</td>
<td>--</td>
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**TABLE 4**

**ANALYSIS OF VARIANCE TABLE ON FREEZE-THAW EXPERIMENT-PHASE I**

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Volume Of Pores Drained</th>
<th>Moisture Retention By Volume</th>
<th>Bulk Density</th>
<th>Total Porosity</th>
<th>Hydraulic Conductivity</th>
</tr>
</thead>
<tbody>
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<td></td>
<td>At Suction Of</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>.02 atm .06 atm 0.33 atm</td>
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</tr>
<tr>
<td>Aggregate Size (S)</td>
<td>3</td>
<td>2616** 8396** 1208**</td>
<td>1176** 4297** 642**</td>
<td>8206**</td>
<td>7826**</td>
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<tr>
<td>Moisture Level (M)</td>
<td>2</td>
<td>178** 207** 21.5**</td>
<td>198** 220** 28.5**</td>
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<td>1295** 2328** 88.1**</td>
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<td>1.5</td>
<td>5.0**</td>
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<tr>
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<td>9.4** 21.5** 6.5**</td>
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<td>4.5*</td>
<td>3.2*</td>
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<td>54.4** 35.2** 2.1**</td>
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<td>0.7</td>
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</table>

*F-ratio significant at 5% level of probability.

**F-ratio significant at 1% level of probability.
TABLE 5

ANALYSIS OF VARIANCE TABLE ON FREEZE-THAW EXPERIMENT-PHASE II

<table>
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<tr>
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<th>Volume Of Pores Drained At Suction Of</th>
<th>Moisture Retention By Volume</th>
<th>Bulk Density</th>
<th>Total Porosity</th>
<th>Hydraulic Conductivity</th>
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</thead>
<tbody>
<tr>
<td></td>
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<td>.02 atm .06 atm 0.33 atm</td>
<td>.02 atm .06 atm 0.33 atm</td>
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<tr>
<td>Aggregate Size (S)</td>
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<td>180** 33** 29**</td>
<td>237** 21** 8.3*</td>
<td>68**</td>
<td>69**</td>
<td>5.3</td>
</tr>
<tr>
<td>Time Level (T)</td>
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<td>407**</td>
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<tr>
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<td>22** 23** 18.7**</td>
<td>30**</td>
<td>30**</td>
<td>11.9**</td>
</tr>
</tbody>
</table>

*F-ratio significant at 5% level of probability.
**F-ratio significant at 1% level of probability.
BIBLIOGRAPHY


