THE EFFECT OF MOLDING WATER CONTENT ON THE HYDRAULIC EROSION POTENTIAL OF COHESIVE SOILS

by

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

INTRODUCTION

Soil erosion is not a new problem. Denudation resulting from severe erosion has long been recognized as a major contributor to stream pollution, reduction of reservoir capacity, excessive sediment deposits in lowlands, rivers and harbors, in addition to scarring the natural beauty of the landscape. In recent years, increasing emphasis has been placed on the study of the erosional characteristics of cohesive soils. The properties of a cohesive soil which govern its resistance to water erosion are numerous and difficult to identify. A soils physical, chemical and mineralogical properties combine to control its hydraulic erosional resistance.

The most common method presently used to minimize erosion in the design of unlined canals and ditches is to define a maximum permissible flow velocity within the structure. The criteria for determining the maximum flow velocity is usually the texture or the range of permissible particle sizes used in the lining. The disadvantage of using this form of design is that it does not adequately take into consideration many of the properties of a soil which control its erodibility. Research and field studies have shown that soils having similar texture and grain-size distributions can display entirely different erosional characteristics.

Compaction and the formation of a vegetative cover are the means widely used on construction sites to protect unlined embankments and slopes from erosion. It is known that an increase in compactive effort applied to a slope will decrease initial erosion. However, an increase in the compactive effort causes an increase in soil density which often times results in a retardation or a prohibition of seed germination. Since the development of a good vegetative cover is the most cost-effective means of long-term erosional control on slopes, rapid and complete seed germination is critical. Therefore, often times the compaction effort is decreased to allow for rapid germination with the results often being that severe erosion occurs under the cover before germination can take place causing both the seeds and topsoil to be lost.

Numerous attempts have been made to correlate the potential erodibility of a cohesive soil and its physical characteristics which can be easily determined in the laboratory, such as grain size, percentage of clay-size particles, plastic index, and density. From an engineering standpoint such a correlation is desirable because of the simplicity of the testing procedures, personnel and equipment required. At the present time there is a lack of sufficient data to develop a comprehensive model based on the parameters determined from these relatively simple forms of testing. However, there have been some studies conducted which indicated that such an interdependency may exist.

Objective

The primary objective of this study was to evaluate the effect of initial molding water content on the erosional resistance of cohesive soils using a constant compactive effort. It is well known that a change in the initial molding water content of a cohesive soil, subjected to the same compactive effort, has a considerable effect on the resulting structure of the soil. It is believed by this researcher that changes in the initial molding water content of a cohesive soil which causes a change to occur in the compacted structure should cause a corresponding change in shear resistance to occur. This change in structure and shear resistance should produce a change in the erosional resistance of the soil. It is intended that the results of this investigation will lead to a better understanding of the interdependency between soil structure and the potential hydraulic erosion of cohesive soils.

Scope and Method of Study

The scope and method of approach used in this study consisted of five parts; problem identification, review of pertinent literature, testing, data analysis and conclusions. The problem of surface erosion was chosen because of the critical problems currently experienced by construction industry on newly placed fills. A review and critique of pertinent literature was conducted. Although a large amount of literature was reviewed for this study only those directly applicable to this research have been included.

The testing phase consisted of identifying the appropriate soils, conducting identification tests and determining their erosive characteristics as a function of the initial molding water content. Three different naturally occurring cohesive soils were used in this study. The engineering properties of the samples were determined using current ASTM procedures. The physical identification tests performed included Atterberg limits, grain size analysis, specific gravity, pH-value and Standard Proctor Compaction. Harvard Miniature Compaction tests were used to control the density and water content prior to testing. The effect of initial molding water content on the erosion potential of the soils was evaluated using test procedures and equipment similar to that used in the Physical Erosion Test (27).

Correlations between the erosional resistance and the initial molding water content were made based upon the testing results of this study and those of previous studies. The correlations made in this study are presented graphically. The development of several conclusions and recommendations for future research based upon this and previous research completes this study.

CHAPTER II

REVIEW OF PERTINENT LITERATURE

Introduction

Since the 19th century, engineers have been concerned with the problem of hydraulic erosion of soil. During that time, most investigations were directed toward gaining an empirical approach to the design of stable channels which consisted of the establishment of certain critical flow parameters for various channel geometries and soil types. Data to establish these parameters have been gathered from canals which were subjected to various degrees of scouring and deposition. This information has been presented either in tabular form, giving ranges of critical velocities or shear stresses corresponding to stable channel configuration, or by empirical equations derived from these parameters. For example, a special committee on Irrigation Hydraulics of the ASCE (14) presented estimates of experienced irrigation engineers for critical design velocities ranging from 1.5 fps (0.46 m/s) to 3 fps (0.91 m/s) for fine sandy loam and from 2.5 fps (0.76 m/s) to 5 fps (1.52 m/s) for stiff clays. Similar values were presented later on by the ASCE Irrigation Hydraulics Committee (14) on the basis of all available field data for canals with clear water, and water carrying cohesive and non-cohesive silts. The soil properties were described by particle size classification.

In reviewing a very large number of publications, it became evident from the earlier investigations that the soil properties which control erosion are far too complicated to be described by mere classification or soil density. Flow parameters, in addition to the gross average velocity or gross boundary shear, may also be important. Recent investigations have been directed toward gaining a better understanding of the interaction between the fine particles and the moving fluid and toward the discovery of flow variables and soil properties which control erosion.

Understanding the hydraulic erosional process is the first step in being able to predict the erosional behaviors of cohesive soils. In this study, the erosional problems have been limited to those caused by the overland flow of water, known as hydraulic surface erosion. Generally, this phenomenon occurs when the flow-induced shearing stresses on a soil surface reach values great enough to cause the removal of particles from that surface. (In the case of cohesive soils the particles adhere to each other, thus requiring the application of a force to effect their separation.)

New Construction Sites

Soil erosion is occurring at accelerated rates in many places where man has disturbed or modified the surface of the ground, such as unprotected road cuts, drainage ditches, embankments, and other surfaces from which vegetation has been removed. On highway cuts, annual losses up to several hundred cubic yards per exposed acre (3-4 x 10^{-2} m^3/m^2) have been measured (9). Briggs (6) stated that on the average every 4 miles (6437 m) of roadside has been found to need some kind of erosion control.

The seriousness of the erosion problem around construction sites has been shown by enactment of various forms of legislation, at both the state and federal level, to control water pollution resulting from construction activities. To reduce the pollution resulting from the sedimentation produced by construction activities, many guidelines and regulations have been set down. The control of sediments released during construction is viewed by many regulatory agencies as a part of broader land use and watershed management programs. For this reason, surface erosion is now considered to be one of the major problems faced by the construction industry requiring both immediate and long-term solutions.

Parametric Studies

Many physical, chemical, and minerological properties combine to give a soil its erosional resistance characteristics. Generally, the resistance of cohesive soils to erosion is attributed to both the interparticle forces and the electrochemical forces between the clay particles. The magnitude and rate of hydraulic erosion is a function of the applied tractive stresses, water temperature, soil density, water content, clay type, percentage of clay fraction, cation concentration, and compactive energy. Numerous researchers (3,13,28,33) have investigated the effect of some of these flow variables and soil parameters on erosion which have occurred under laboratory and field conditions. Only those studies which directly relate to this research study will be presented.

Temperature

In 1973 a series of erosion tests were conducted by Christensen and Das (8) on kaolinite and grundite soil samples using flowing water at various temperatures as the eroding fluid. During the tests the other parameters such as the molding moisture content, hydraulic tractive stress and test duration were held constant. A definite relationship was found to exist between the rate of erosion and absolute temperature of the fluid. These researchers concluded that there was a significant increase in the rate of erosion as the temperature of the eroding water increased. The erosional response to changes in temperature appeared to be typical of a thermally activated process.

Density

In 1965, Grissinger (16) evaluated the relative erodibility of compacted clays subjected to a fluid flow normal to the orientation of the particle packing. From his test results, he inferred that the relative erodibility of a clay soil decreased only slightly with an increase in soil density. Based upon Grissinger's test results and conclusions, Partheniades and Paaswell (26) stated that "the resistance to erosion increases slightly with increasing bulk density of the soil, although the results were not conclusive. While bulk density refers to the average density of the entire sample it is likely that surface densities due to compaction techniques, and expansions under flow conditions, would not show the same marked degree of variance from sample to sample. Hence, bulk density is not as good an index as would be moisture content or void ratio in the erodible zone, for samples not fully saturated prior to testing."

In 1969, a laboratory investigation was conducted by Foster and Martin (15) to qualitatively evaluate the effect of slope and unit weight on the erosional characteristics of prepared cohesive soils. The desired unit weights were obtained by compressing a known weight of soil into a specially designed mold of known volume. It was concluded that there was a unique unit weight from which the maximum amount of erosion would occur for a given slope. Since the test specimens were statically compacted and no explanation was offered for determining the unique unit weight, direct correlation with the more conventional Standard Proctor Density is not possible. In addition, it was unknown whether the compaction water content (21%) was dry or wet of optimum.

To study the effect of compaction on the critical tractive forces in cohesive soils, Laflen and Beasley (19) performed laboratory tests on five Missouri soils in a hydraulic flume. They concluded that the degree to which a soil is compacted affects its erodibility, but a definite correlation was not presented. A number of flume tests also have been performed to determine the relationship between critical tractive forces and various soil properties. Among the most notable were those by Lyle and Smerdon (22). In the Lyle and Smerdon studies, data from hydraulic and physical tests on soils were analyzed statistically to determine the correlation between critical tractive force and pertinent soil properties. From the analysis of the data it was found that the erosion resistance of a soil increases as direct linear function with compaction.

Water Content

In 1964, Enger (11) reported on studies made in a boundary shear flume. In these studies, samples of cohesive sediments were tested by gradually increasing the boundary shear stress acting on a sample until the shear became critical and the sample began to erode. For the soils tested, the boundary shear stress required to produce erosion was found to be a function of the moisture content at which the soil was compacted.

The water content of the sample after compaction, prior to testing, was shown to have a significant effect on erosion rates by Grissinger (16). He studied the effect of bulk density, clay type and particle orientation on erosion for constant flow conditions. In order to determine the influence of molding water content on soil particle orientation after compaction the orientation of clay minerals was also measured using an x-ray diffraction procedure. Results from the tests showed that the orientation of clay particles had a pronounced effect on erodibility. It was concluded that erosion rates should decrease with an increasing degree of particle orientation. Kandiah and Arulanandam (18) examined the effect of initial water content on the tractive stress required to initiate erosion by conducting tests on saturated and non-saturated soils in a rotating cylinder and circulating flume. It was concluded that the critical shear stress in saturated samples, which were uncompacted, was independent of the water content, whereas in compacted soils the critical shear stress was highly dependent on the water content.

Christensen and Das (8) developed a special testing apparatus and procedure to evaluate the effect of water content on erosion. The technique consisted of lining a brass tube with a cohesive soil by an intrusion process. From the test results, the authors concluded that a significant decrease in erosion should have occurred with an increase in water content. It was also concluded based on visual observation that surface roughness is more critical than density in reducing erosion.

The engineering properties of cohesive soils are significantly affected by the compacting water content. According to Lambe (21), the structure that the soil possesses after compaction depends on the water content used during compaction. As the water content at the time of compaction increases, the resulting soil structure becomes more oriented. Generally, a flocculated soil structure is associated with low water content and a dispersed soil structure is associated with compaction at higher water contents. Based upon Hogentogler's viscous water theory (17), if in the compaction test, the water content is quite low relative to the optimum water content, the only moisture in the soil is a thin layer of absorbed (adhesive) viscous water. This viscousity will endow the soil with a higher shear strength. As the water content in the compaction test is increased, a point is reached where additional increase in water surrounding the particles reduces the shear strength and increases the compacted density resulting in a more dispersed structure. This "lubrication effect" increases up to a water content which has been termed the "optimum water content."

Lambe (21) states that the term "lubrication" actually describes the increased interparticle repulsion which permits the soil particles to slide past each other into a more oriented bed. Once the water content is greater than the "optimum water content", Lambe deduces that a more orderly parallel (dispersed) arrangement of soil particles will appear. Schroeder (29) presents the results of studies which were conducted on compacted soils at the microlevel. These studies show that soils compacted on the dry side of optimum water content have a flocculent arrangement of soil particles, while soils compacted on the wet side of optimum using the same compactive effort result in a dispersed soil structure.

Based upon the literature review previously presented there is strong evidence which suggests that the physical structure of the cohesive material plays a major role in its resistance to erosion, and these structural characteristics are determined by the initial mode of compaction or deposition. Soils that were deposited and then compacted in place, or natural deposits that were artificially compacted, have structure characteristics significantly different from soils that are naturally deposited and untouched. Interparticles orientation varies from highly random (flocculated) to highly oriented with parallelism (dispersed) with a parallel orientation to the bed surface. When a deposit of dispersed soil is being formed by compaction, sufficient moisture must be present to allow the particles to slide past one another to parallel positions giving a very efficient packing orientation. When insufficient moisture and compactive effort are not present the particles stick to one another resulting in the formation of a flocculated structure. Mechanical manipulation without the addition of water is much less effective means of controlling the orientation of soil particles.

In 1970, Barden and Sides (4) made a series of tests using a modified triaxial and Rowe consolidation cells to investigate the mechanical properties of compacted Waste Water Clay as a function of the water content used during compaction. It was found that the soil structure is markedly affected by the compacting water content. They summarized their results by stating that optimum compaction provides a distinct division in the engineering behavior of compacted clay soils as it marks a significant change in both soil and the conditions of the pore fluid.

Effect of Saturation on Shear Strength

The shear strength of a compacted cohesive soil is primarily affected by: water content, gradation, density, structure, thixotropy and effective stress. It is known that for a given remolded cohesive soil, a change in dry density produces a corresponding change in shear strength. Lambe (21) concluded that for a given compactive effort, the shear strength of a cohesive soil increases with an increase in molding water content, dry of the optimum water content. However, when a soil is compacted wet of optimum, the shear strength decreases with increasing water content. Therefore, the shear strength of a cohesive soil compacted on the dry side of optimum is greater than the same soil compacted to the same dry density on the wet side of optimum. Under saturated conditions at very low confining pressures the relationships between shear strength, molding water content and density may be different from those previously described. Several researchers (7,20,30) have pointed out that soils compacted at water contents below optimum will swell more than the same soils compacted at water contents above optimum and then saturated at low confining pressures. It is believed by these researchers that the flocculate structure resulting from dry side compaction will cause greater swell upon saturation at low confining pressures which will result in a reduced dry density and corresponding shear strength than the same soil compacted to the same dry density on the wet-side of optimum. This belief is supported by Turbull and Foster (34), who conducted studies in which they used the CBR Test to measure the soil strength under saturated conditions at very low confining pressures. The results of their studies indicate that the shear strength of soils compacted dry of optimum is less than that compacted wet of optimum for the same initial dry density at low confining pressures.

<u>Hydraulic Tractive Stresses</u>

The form of soil erosion considered in this study is that of a surface rather than a deep-seat phenomenon. For this reason, at any given instant in time, if there are no external forces acting on the surface of the clay soil, the soil particle is in a state of equilibrium for a given environmental condition. Imposing an externally applied boundary shear stress, some deformation of the soil structure would occur, assuming that the clay particle is rigid. This boundary shear stress, termed hydraulic tractive stress expressed by Equation 1, is a function of the flow velocity,

$$\tau_{TS} = \frac{1}{8g} \gamma_f \, fV^2 \qquad (1)$$

where:

τ_{TS} = hydraulic tractive stress

f = frictional factor

γ_f = unit weight of fluid

V = average flow velocity

g = gravitational acceleration

surface roughness and fluid density. For one-dimensional laminar flow in a pipe, the friction factor can be expressed by Equation 2.

$$f = \frac{64}{Re} \qquad (2)$$

where:

f = frictional factor

Re = Reynold's number

If the tractive stresses are small, movement of the particles will cause a readjustment within the internal force system, and a new position of equilibrium will exist. However, if the tractive stress is large, excessive deformation may occur at the particle interface which would result in the soil particle being entrained in the flowing fluid and initiation of erosion. The threshold stress necessary to cause dislodgement of the soil particles is expressed as the critical hydraulic tractive stress. For a given soil, surface roughness and fluid, once the critical hydraulic tractive stress has been exceeded, increasing the flow velocity causes a corresponding increase in the amount of erosion.

CHAPTER III

RESEARCH MATERIALS, EQUIPMENT AND PROCEDURES

Materials

Three naturally occurring Kansas soils were chosen for testing in this study. The first sample chosen was a Sogn Silty Clay. This soil was obtained from an embankment on the south side of U. S. Highway 18, about one thousand feet west of its intersection with Seth Child's Road in Manhattan, Kansas. The soil, a gray residual calcareous soil was weathered from shale and limestone (31). Sogn Silty Clay was chosen for two reasons. The first reason is that this soil is common to many portions of Kansas which are underlain at relatively shallow depths with limestone. The second reason and the one basic to this study is that once the natural vegetation has been removed, the soil is easily eroded by water.

The second soil chosen for this research was a clayey silt which was obtained from a compacted embankment on the north side of U. S. Highway 24, approximately one-half mile east of the intersection with U. S. Highway 99 in Wamego, Kansas. The soil, primarily a reddish-brown loessial silt, is common to many areas of Kansas. Although this material is stable when covered by vegetation it erodes easily if the vegetation is removed.

The third sample chosen was a Wymore Silty Clay which was obtained from an excavation on the north side of St. Mary's Hospital in Manhattan, Kansas. This material was excavated for new construction at the hospital. The soil is dark grayish-brown in color and derived from weathered shales.

Wymore Clays are common to many parts of Kansas and are subject to severe erosion if vegetative covering is removed.

Equipment

The test equipment utilized for this investigation was similar to that used by Petry and Haliburton (27). It was called Permeability-Physical Erosion Testing Apparatus which was designed and set up by Arnold (2). A brief description of the main components of the erosion testing apparatus are included in the following discussion.

Water-Flow System

The water flow system is the primary component of the apparatus. It is composed of a primary and secondary storage tank, piping and a channel splitting system. The flow system provides for a constant uniform supply of water to the test cells. A conceptual drawing of the flow system is shown in Figure 1.

As can be seen in this figure, a central pressurized tank provides the water supply for the entire system. The tank, which has a capacity of 25 gallons ($9.5 \times 10^{-2} m^3$), is sufficient to provide the quantity of water necessary to conduct two complete sets of erosion tests.

The water is routed from the central holding tank to a secondary holding tank. This tank, constructed from a one liter lucite cylinder, reduces the possibility of any fluctuation in the supply of water to the test cells. The use of this secondary holding tank also allows smaller supply piping to be used than would be required without it.

From the secondary holding tank the water is routed to a channel splitter. As can be seen in Figure 1, the splitter divides the primary

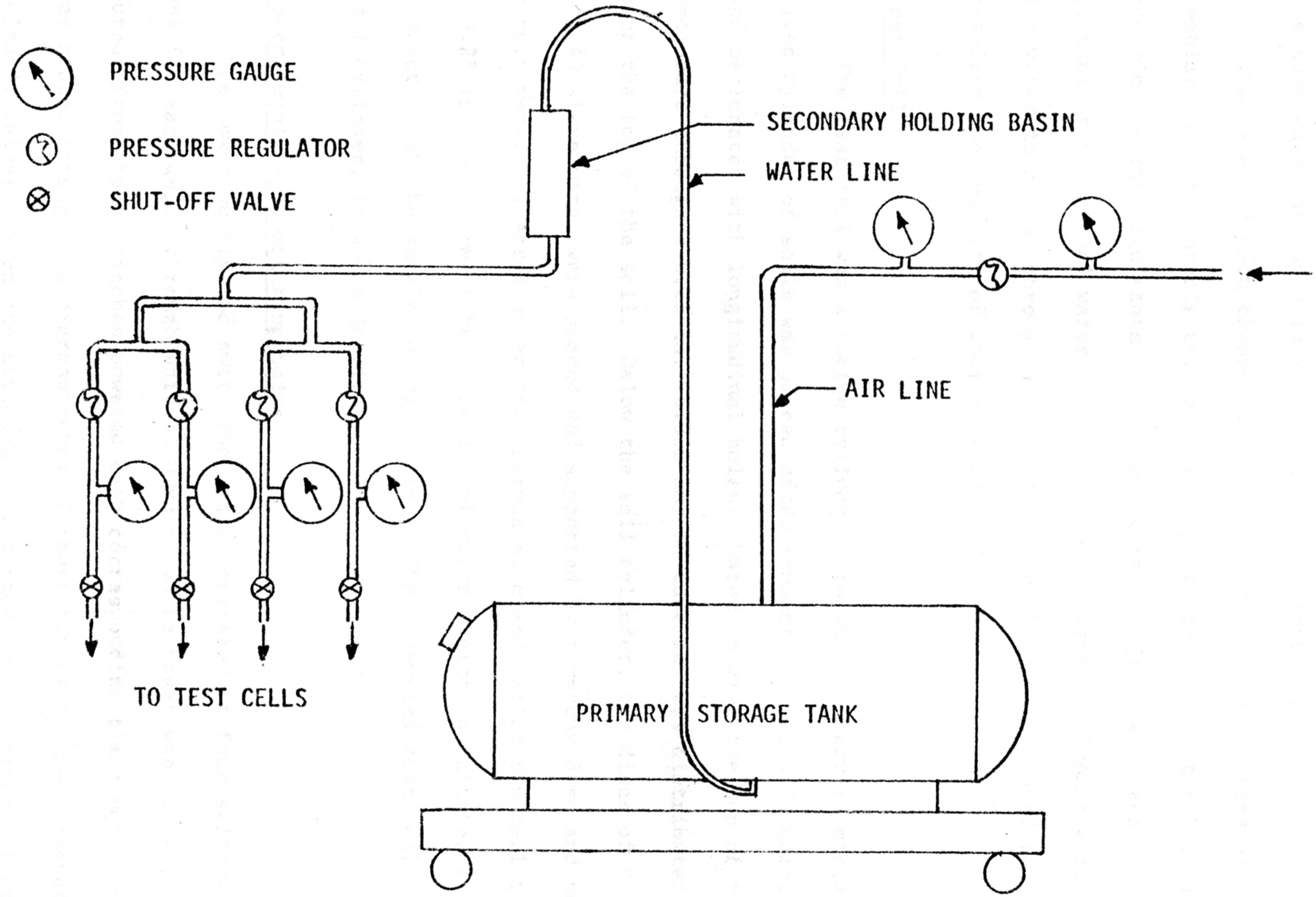

Figure 1. Schematic of the Water Flow System for the Testing Apparatus

supply line into four separate lines which lead to the test cells. The channel splitter was designed in a parallel configuration to provide the same water pressure to each of the four channels.

The water in each channel is then directed through a separate regulator which controls the pressure applied to each test cell. In addition to the regulators, separate pressure gauges have been included to monitor the actual water pressure in each channel. From the regulator the water is routed through a shut-off valve which can be used to regulate the quantity of flow to each cell.

Test Cell

The test cell was a lucite cylinder into which a Harvard miniature-sized cylinder of soils was placed after compaction, slightly compressed and perforated with longitudinal holes. Water entered the top of this enclosure through a 0.25 in. (6.350 mm) OD tube and was distributed over the top of the soil. Below the soil cylinder, two discs of USBS No. 40 sieve wire, were placed and supported by a porous disc and support ring. Water collected under this porous disc and exited the cell through a 0.25 in. (6.350 mm) tube. The use of clear lucite facilitated visual inspection of the sample during testing. The assembled test cell, with soil cylinder, is shown in Figure 2.

Power Supply and Switching Units

The power supply and switching units consisted of four switches, one for each cell, through which 110 volt, 60 Hz power was routed. The output from these switches powered each corresponding timer motor and was routed through the microswitches of these timers to their respective solenoid valves. When the switches were turned on, the timers of each

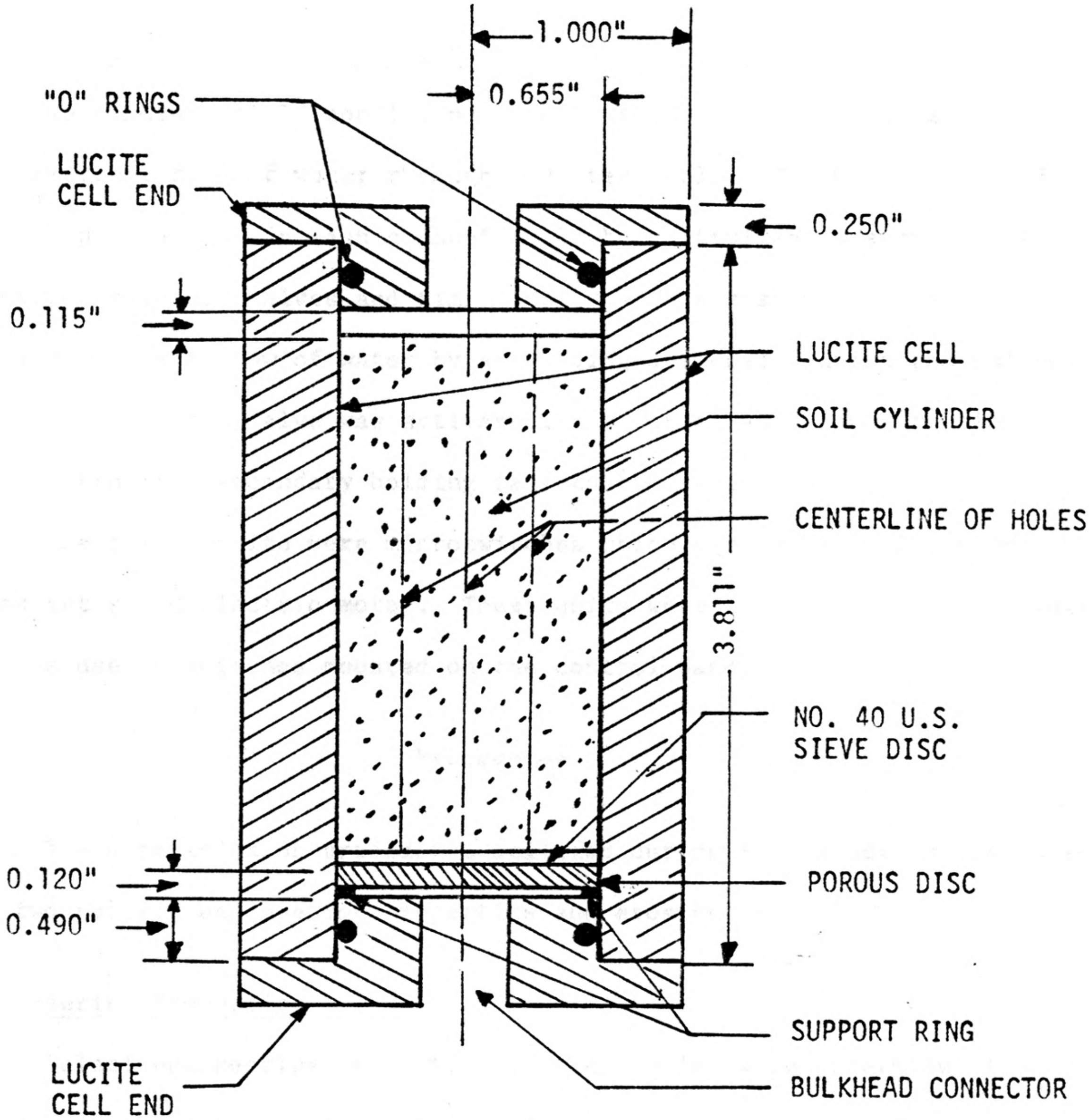

Figure 2. Assembled Test Cell with Soil Cylinder (1 in. = 25.4 mm)

cell were energized and power was available to operate the respective solenoid valves as each microswitch was closed.

Timing Units and Solenoid Valves

To simulate field conditions, the testing apparatus utilized an intermittent flow of water through each test cell. To incorporate this function, the flow in each channel could be controlled by a system of electric solenoid valves and timing units. This system provided for an intermittent flow of water by activating and deactivating the solenoid valves. When the valve was activated, the water was allowed to flow freely from the secondary holding tank to the test cells.

The timing units were microswitches which used a 110 volt, 6 rpm constant speed electric motor. These units were activated and deactivated by the use of switches mounted on the control panel.

Procedures

The discussion of procedures utilized during this study is presented in two parts: engineering properties and erosion test.

Engineering Properties

Select engineering properties of the samples were determined to provide background and identification data for their use in this study. The engineering properties tests performed included Atterberg limits, grain size analysis, specific gravity, pH value, Standard Proctor and Harvard miniature compactions. All samples were oven dried and ground to pass the No. 40 sieve prior to the testing to ensure homogeneity during testing.

Liquid and plastic limits were determined using ASTM D423-66 and D425-59 recommended procedures (1). Grain size analysis was accomplished by using the ASTM D421-58 and the Hydrometer method (1). The specific gravity of the solids was determined using the ASTM D854-58 recommended procedure (1). The pH-value for each sample was provided by the Sanitary Engineering Laboratory which is within the Department of Civil Engineering at Kansas State University. A summary of these properties is presented in Tables 1 and 2.

Erosion Test

In this study, the erosion test was conducted on two types of samples; wet and air-dry. All samples tested for erosion potential were compacted utilizing the Harvard miniature compaction technique (35). The soil chosen for this laboratory simulation was a Harvard miniature-sized cylinder (Diameter = 1.313 in. (33.350 mm), Height = 2.816 in. (71.526 mm) compacted to specifications normally for field density control by geotechnical engineers. Since it was believed that with proper control of both density and compaction water these cylinders of soil would represent the physical soil in the field, the samples were compacted to a density equivalent to the maximum standard proctor density, as specified by the American Society for Testing Materials (ASTM D698-78).

After compaction, the Harvard miniature mold was placed in an extrusion press, top down. The sample extraction spacer was placed between the mold and extrusion rod. The extraction spacer was forced into the mold until the top stop block was reached. The extruded length of the sample, 0.406 in. (10.312 mm) long, was cut off. Two brass compression-spacing blocks were used to simultaneously vertically space and slightly

TABLE 1

GRAIN SIZE ANALYSIS

Sample	Percent Finer (U. S. Sieve No. or Equivalent Stokes Diameter)								
	#20	#40	#60	#100	#200	.05 mm	.02 mm	.005 mm	.002 mm
Sogn Clay	100	99.6	98.5	97.1	95.3	94.0	88.0	64.0	38.0
Wamego Clayey Silt	100	99.9	97.6	93.6	76.5	75.0	42.5	24.0	17.0
Wymore Clay	100	99.9	99.8	99.6	95.1	89.0	72.0	44.0	32.5

TABLE 2

ENGINEERING PROPERTIES

Sample	Specific Gravity	Liquid Limit %	Plastic Limit %	pH Value	Standard Proctor γd (max.) pcf	Harvard Miniature γd (max.) pcf	Optimum Water Content %
Sogn Clay	2.72	34.6	13.4	7.0	107.0	102.5	18
Wamego Clayey Silt	2.68	30.6	20.2	7.1	114.0	109.0	17
Wymore Clay	2.72	46.8	26.7	6.7	91.5	90.0	23

compress the compacted soil cylinders. The slight compression was necessary to insure a space of 0.125 in. (3.175 mm) at each end of the completed cell and press the soil against the cell wall, to avoid water flow around the sample perimeter.

Location and Drilling of Holes

Holes for water flow were placed 120° apart, located at one-half the radius of the sample cross-section. Their location was marked on the top of each compressed soil cylinder using the marking device. Holes 0.125 in. (3.175 mm) in diameter were drilled through each soil cylinder using a drill press and specially purchased **drill bits.** A commercial variable speed table model drill press was utilized. The table of the drill press was modified by adding a cell securing jig, which prevented lateral movement of the soil cylinder and cell during the drilling process.

The erosion potential of a soil was determined by subjecting a sample to an intermittent flow of water. In order to eliminate influences on test results by the chemical properties of compaction water, demineralized distilled water was used. For practical considerations, field conditions were simulated by drilling three equi-distant longitudinal holes in the sample prior to the start of the test. By the use of pressure regulators and gauges, the system can be adjusted and maintained at the desired pressure head of 15 psi. (1.0×10^5 Pa). To exaggerate the erosive effect, the intermittent flow of water was continued a period of four hours after which the sample remaining in the test cell was removed and placed in a drying oven. The erosional loss was determined by using Equation 3:

$$\text{Erosional Loss (\%)} = \left(1 - \frac{\text{Final Dry Weight of Soil}}{\text{Initial Dry Weight of Soil}}\right) \times 100\% \quad \text{-- (3)}$$

During this investigation, the physical erosion test (including wet and air-dry samples) was conducted on three different soil samples. The samples were composed predominately of silt sized particles with varying percentages of clay. The procedures used in this research study for testing the erodibility of a soil are outlined in detail in Appendix A.

CHAPTER IV

RESULTS AND DISCUSSION

This Chapter discusses the methods employed in the correlation of the data obtained from the engineering and soil hydraulic erosion tests, relationships between erosional loss and molding water content, correlation and evaluation of data collected in this investigation with data from previous research endeavors.

Engineering Properties

A general summary of the engineering properties determined for the samples are contained in Chapter III. The following presentation was useful for analysis of sample characteristics.

During initial preparation each sample was oven-dried, ground and sieved through a U. S. No. 40 sieve. In all cases the sample almost entirely passed through this sieve. The results of the grain size analysis are shown in Table 1. The samples were fairly well-graded and similar in composition. The grain size distribution curve indicated that the Sogn Clay contained approximately 4% sand, 61% silt, and 35% clay. For the Wymore Clay the distribution was similar with 6% sand, 60% silt, and 34% clay. The grain size analysis for the Wamego Clayey Silt indicated that the sample contained 19% sand, 64% silt, and 17% clay.

Among the most accepted indicators of the physical behavior of soils are the Atterberg limits. Those determined for this research study included the liquid limit and plastic limit. These values in addition to specific gravity of solids and pH value are shown in Table 2.

All the samples tested had properties representative of a clay soil with low plasticity. The low plasticity like behavior of the sample was believed to be caused by the relatively large fraction (over 60%) of fine silt between 0.005 mm and 0.002 mm sizes.

The remaining engineering property determined was the Standard Proctor compaction relationship. The information gained from the compaction tests conducted for this research was the maximum dry densities and the corresponding optimum moisture contents. The reason for determining the maximum Proctor densities and corresponding water contents was twofold: 1) samples tested at these densities permitted correlation of this research data with that of field construction, and 2) these known densities and water contents made possible quality control of the samples being tested. The maximum dry densities and associated water content are shown in Table 2. The compaction curves for the samples are shown in Appendix B.

Test Results

The soil samples (including wet and dry specimen) were prepared at a given moisture content, density and tested in a saturated condition to determine the effect of molding water content on the hydraulic erosion potential. During testing, some data was in error because of equipment failure, therefore, not all the data is shown. It was believed at the start of this research study that the amount of erosional loss of a soil would decrease with increasing compaction water content.

Wet Samples

The relationship between erosional loss and compaction molding water content is shown in Figures 3, 4 and 5 for the samples tested. It can be seen from these figures that there appears to exist a relationship between the molding water content and erosional loss expressed as a percentage. Although this relationship is not linear, there is a sharp decrease in erosion with an increase in molding water content near the optimum water content. As can be seen from these figures the soil compacted at optimum water content or wet of optimum had a significantly lower erosion potential than those soils compacted dry of the optimum water content.

Air-Dried Samples

The air-dried samples were compacted at a given water content and then air-dried for more than twenty-four hours. It was believed that the dehydration by air-drying would not significantly change the soil structure (17). Since there should be no significant structural change, there should be no significant change in the erosional potential as compared to a sample tested prior to dehydration. For this reason, only several air-dried samples were tested to verify that the amount of erosional loss is dependent upon the initial compacting water content and independent of any change in water content after compaction prior to testing.

The test results for air-dried samples are shown in Figures 6, 7 and 8. The results obtained from erosion testing of air-dried samples illustrated a substantial decrease in the percent erosion with increase in the compaction water content until optimum water content. The

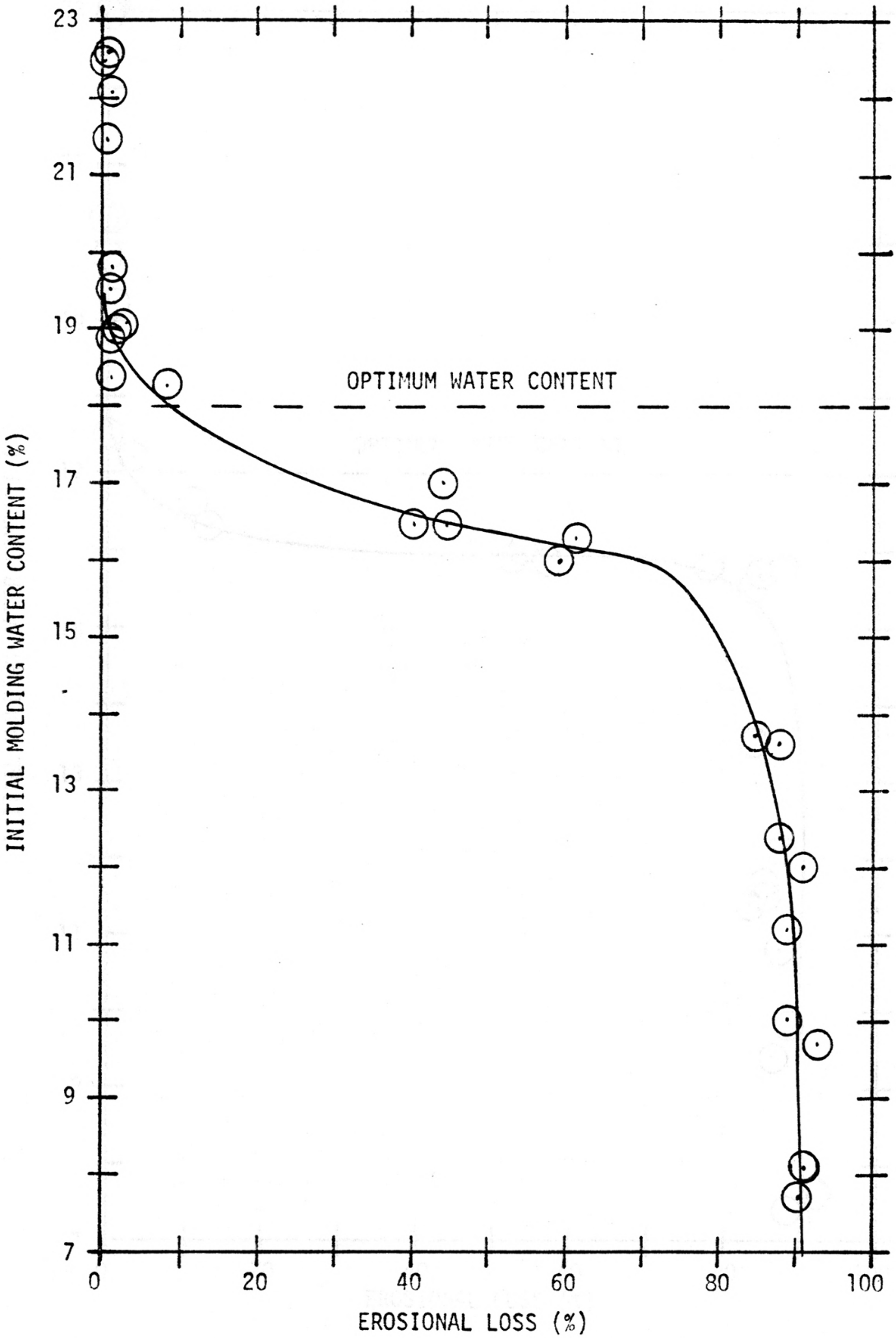

Figure 3. The Relationship Between Initial Molding Water Content and Erosional Loss for Sogn Clay (Wet)

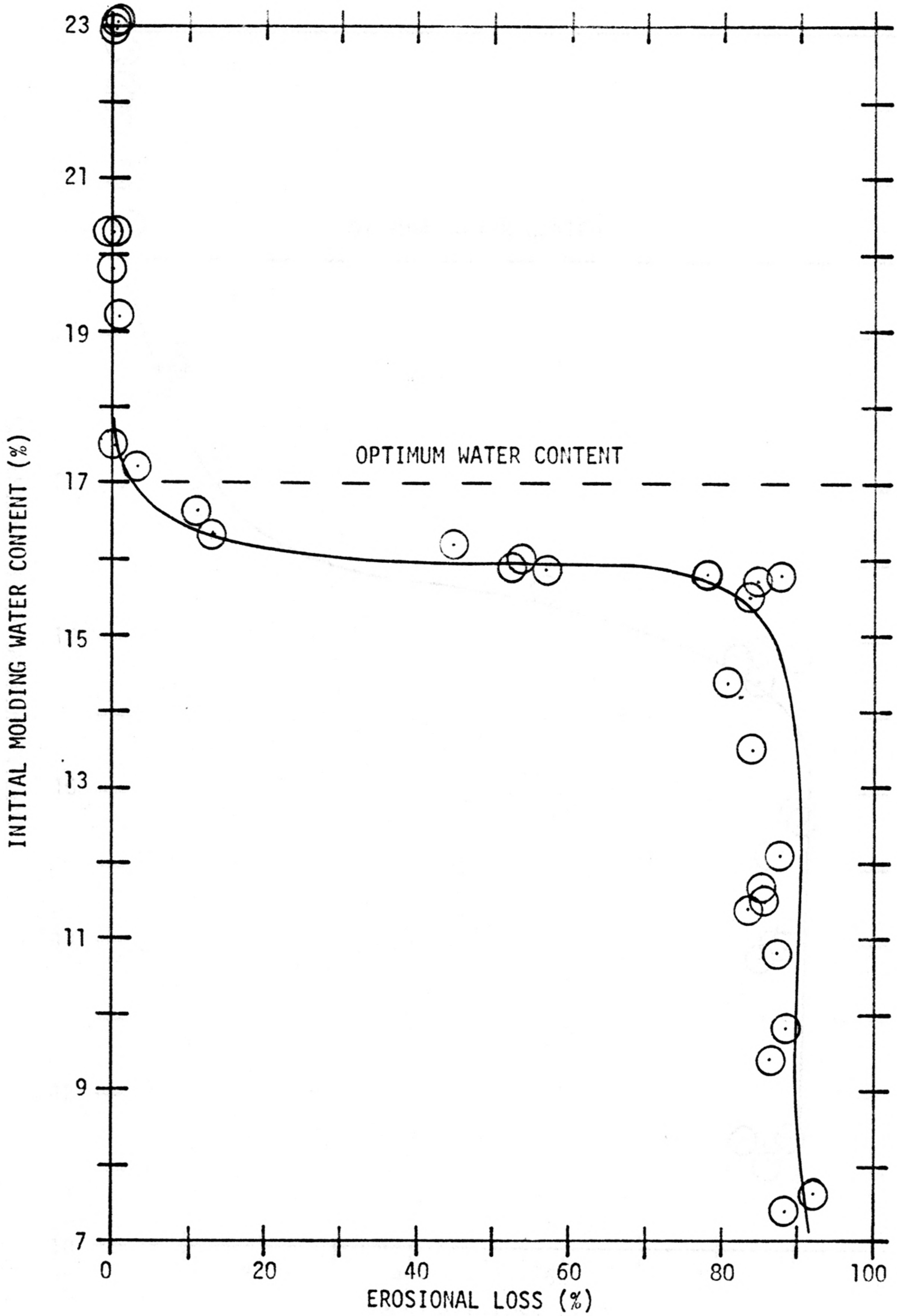

Figure 4. The Relationship Between Initial Molding Water Content and Erosional Loss for Wamego Clayey Silt (Wet)

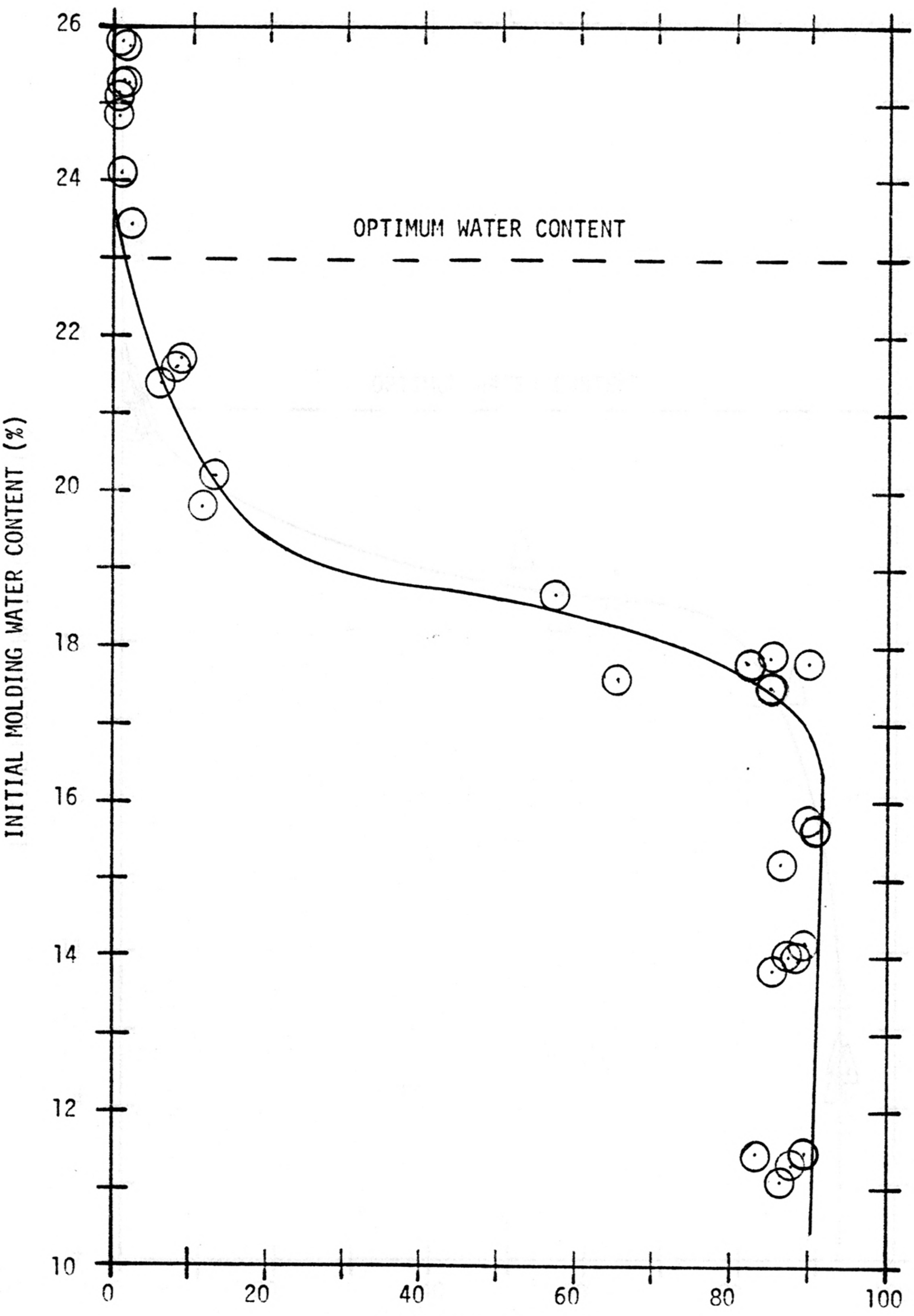

Figure 5. The Relationship Between Initial Molding Water Content and Erosional Loss for Wymore Clay (Wet)

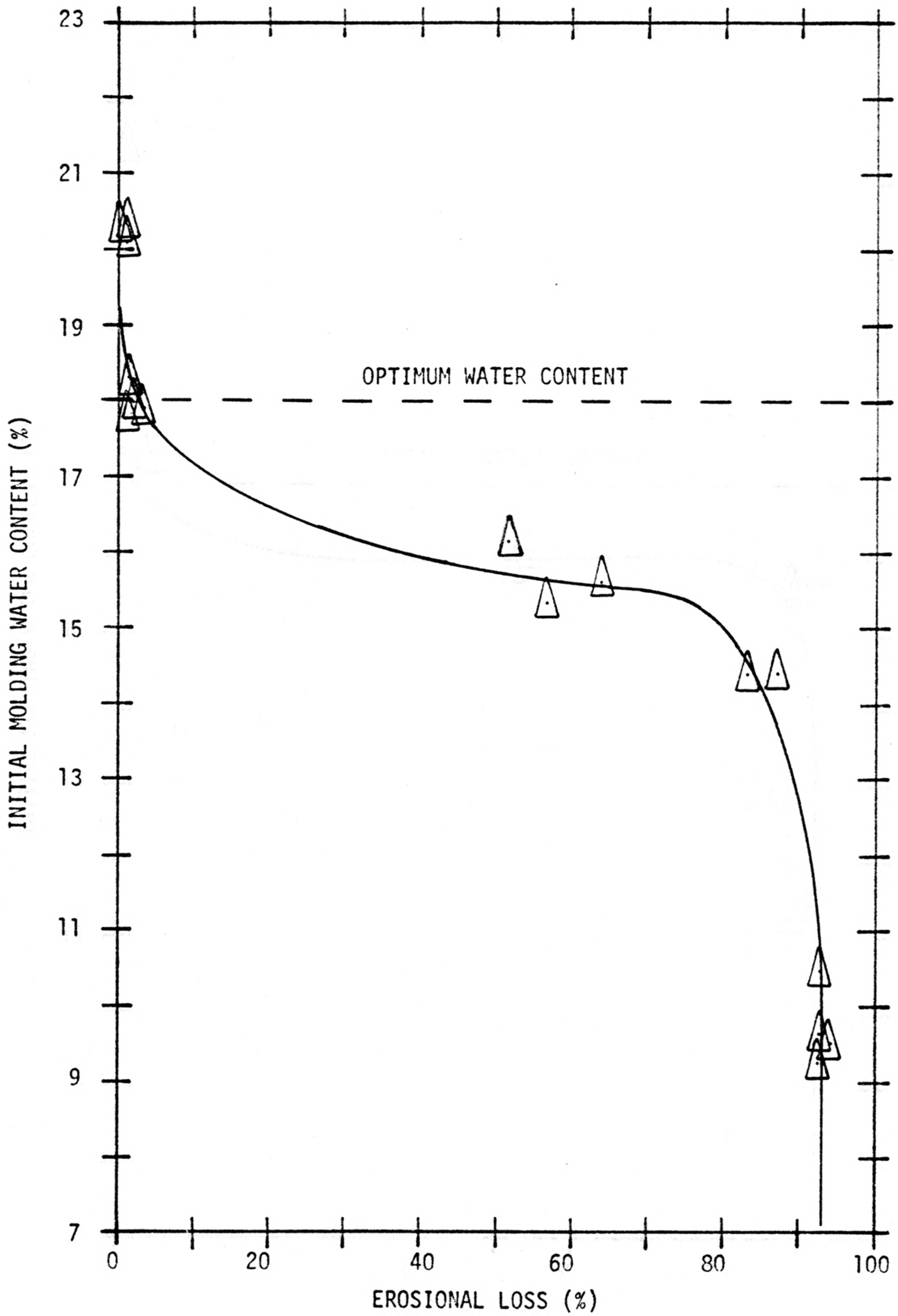

Figure 6. The Relationship Between Initial Molding Water Content and Erosional Loss for Sogn Clay (Dry)

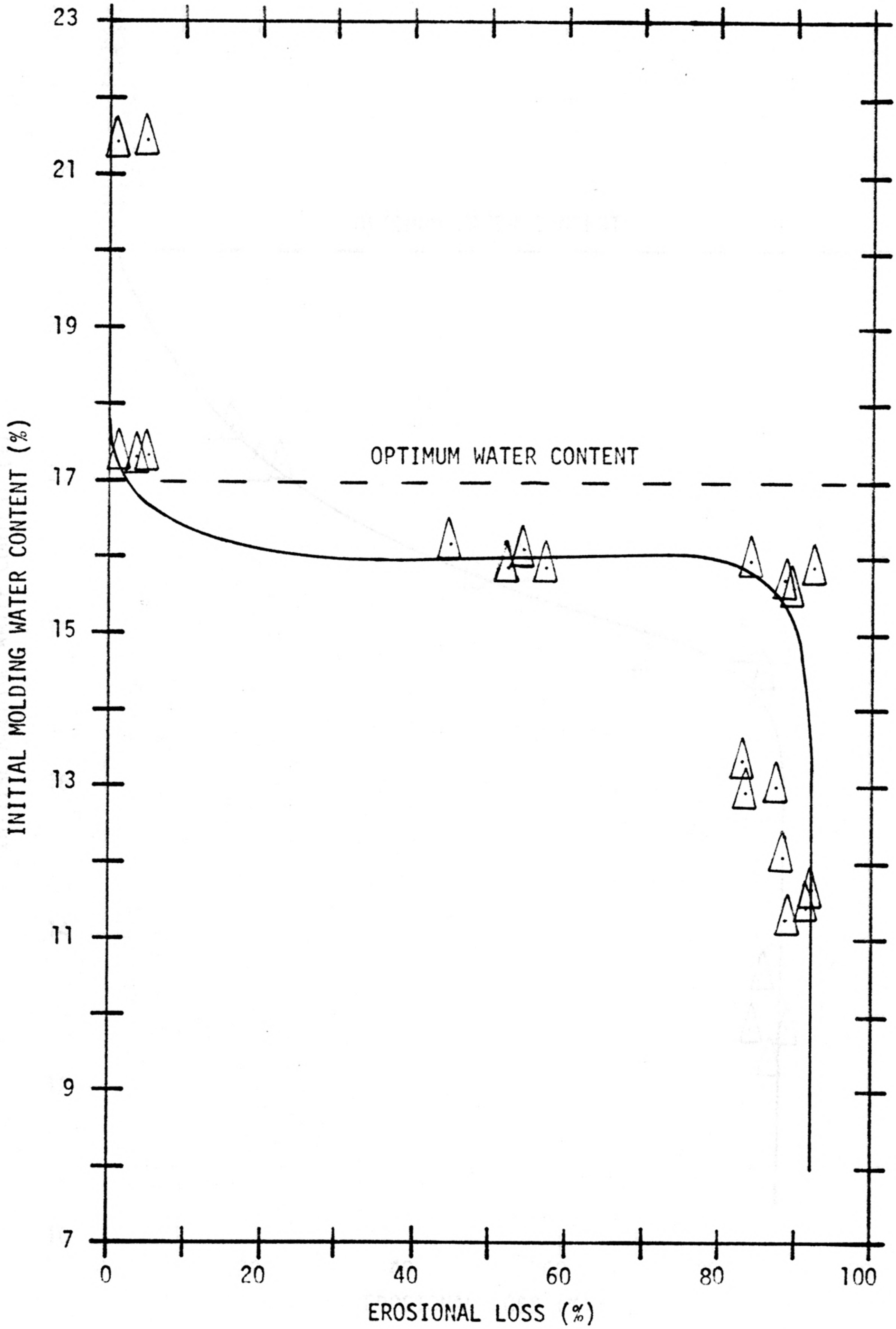

Figure 7. The Relationship Between Initial Molding Water Content and Erosional Loss for Wamego Clayey Silt (Dry)

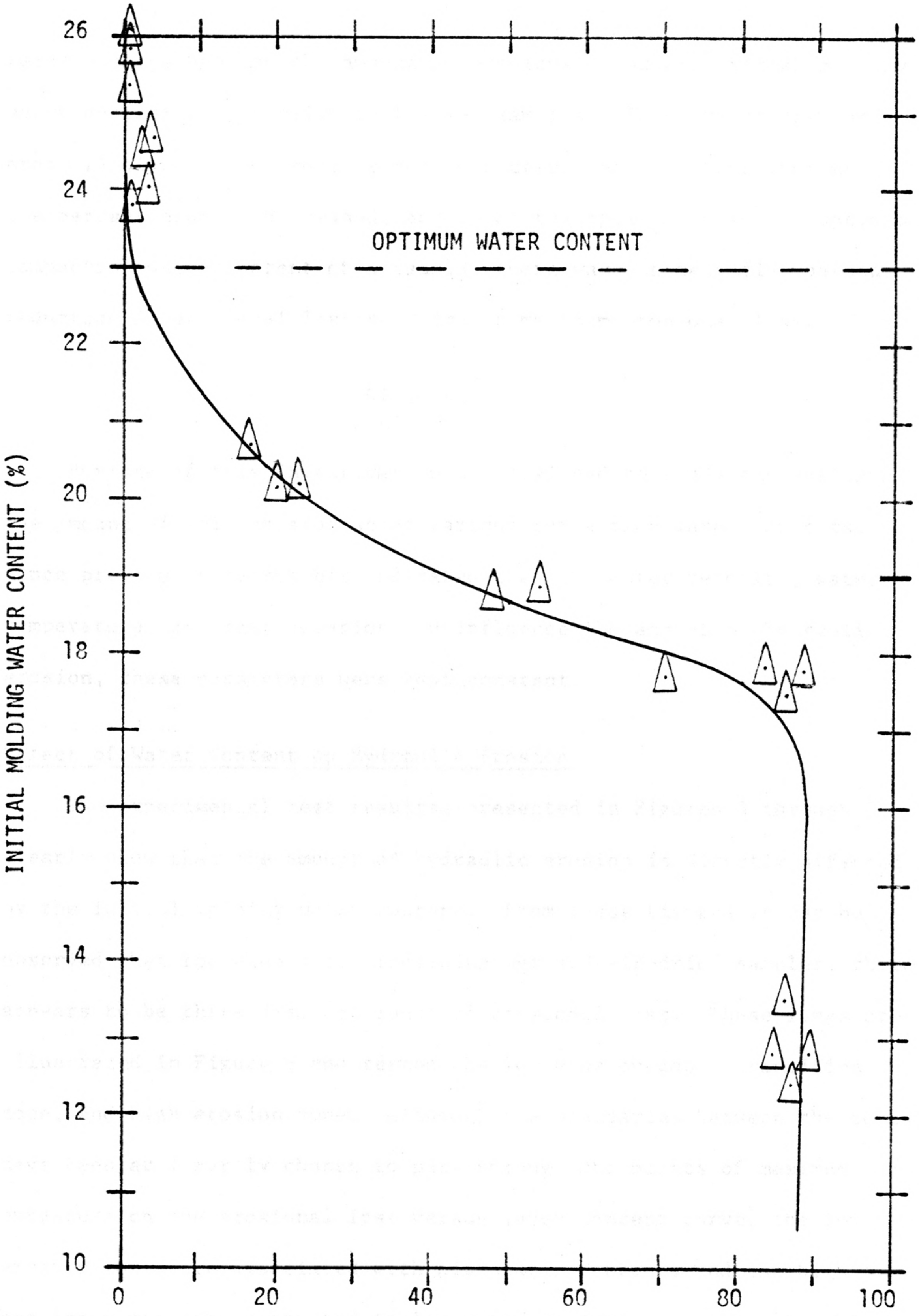

Figure 8. The Relationship Between Initial Molding Water Content and Erosional Loss for Wymore Clay (Dry)

relationships between the amount of erosional loss and initial molding water content were similar to the wet samples. These relationships are: 1) close to optimum, as the compaction water content increased the percent erosion decreased, and 2) at the optimum or wet of optimum compaction water content of a sample, there was a ninety-five percent reduction in erosional loss relative to maximum erosional loss.

Discussion

Purpose of this investigation was designed to study and evaluate the amount of soil erosion under various compaction water contents. Since previous research has indicated that the water velocity, water temperature, and test duration can influence the amount of hydraulic erosion, these parameters were kept constant.

Effect of Water Content on Hydraulic Erosion

The experimental test results, presented in Figures 3 through 8, clearly show that the amount of hydraulic erosion is directly affected by the initial molding water content. From these figures it can be observed that for each soil, including wet and air-dried samples, there appears to be three distinct zones of erosional loss. These zones are illustrated in Figure 9 and termed the low erosion zone, transition zone, and high erosion zone. Although the boundaries between the zones have been arbitrarily chosen to pass through the points of maximum curvature on the erosional loss versus water content curve, the low erosion zones are associated with high water contents and the high erosion zones are associated to low water contents. Between the high and low erosion zones is a transition zone.

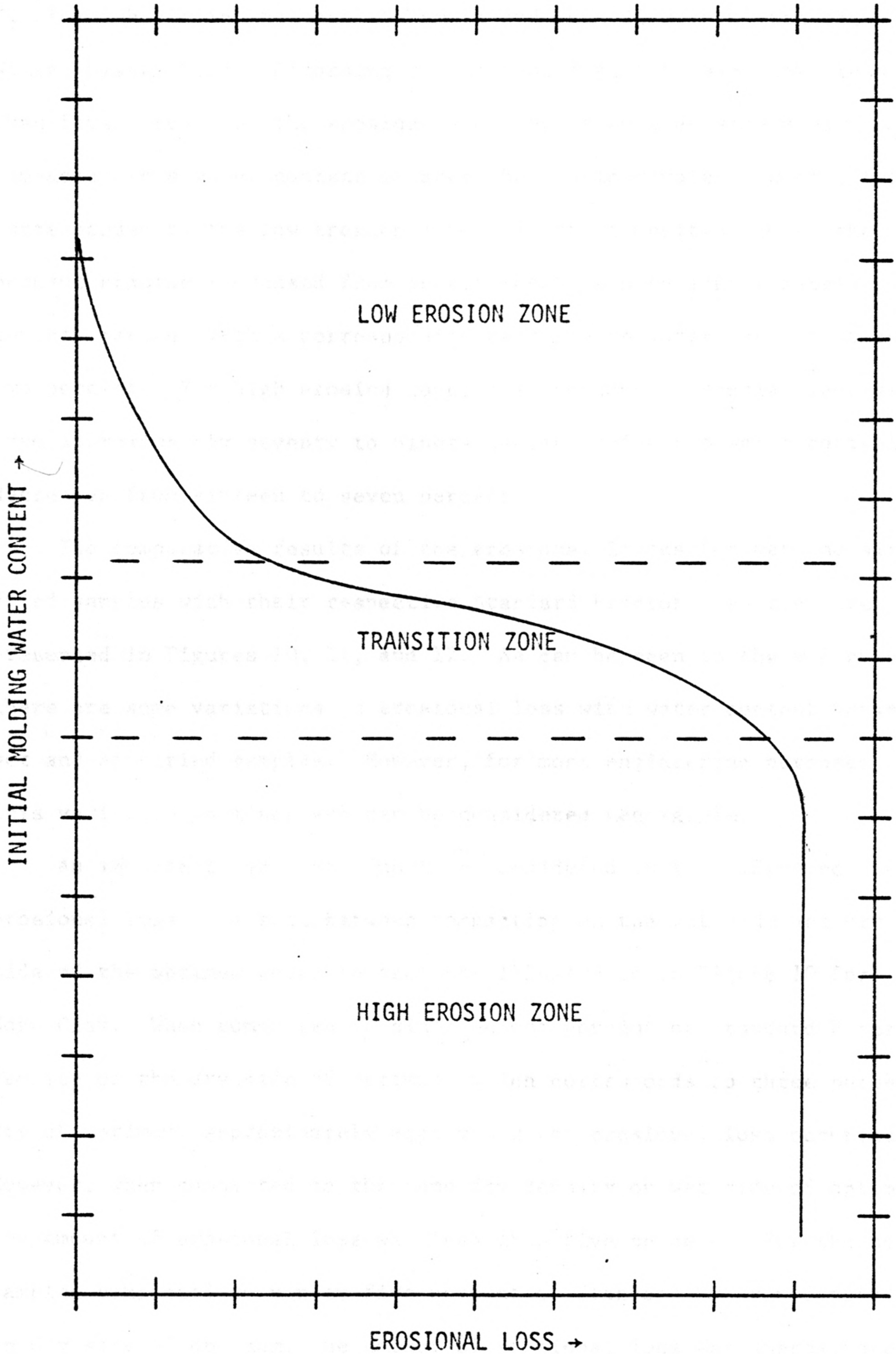

Figure 9. Characteristics of Initial Molding Water Content on Erosional Loss

The three erosion zones illustrated in Figure 9 are more distinguishable in the case of Wymore and Sogn Clay than with the Wamego Clayey Silt. According to the test data for Sogn Clay, less than five percent of the erosional loss occurred when sample was compacted at a water content greater than optimum water content, this corresponded to the low erosion zone. In the transition zone, the percent erosion increased from approximately ten to approximately seventy percent with a corresponding decrease in water content of only two percent. For high erosion zone, the erosional potential increased from approximately seventy to ninety percent while the water content decreased from sixteen to seven percent.

The comparative results of the erosional losses for wet and air-dried samples with their respective Standard Proctor densities are presented in Figures 10, 11, and 12. As can be seen in these figures, there are some variations in erosional loss with water content between wet and air-dried samples. However, for most engineering purposes this variation is minor and can be considered negligible.

An important fact which must be considered is the difference in erosional loss of a soil between compacting on the wet side and dry side of the optimum water content, as illustrated in Figure 10 for Sogn Clay. When compacted to ninety-eight percent of Standard Proctor density on the dry side of optimum, which corresponds to three percent dry of optimum, approximately eighty percent erosional loss occurred. However, when compacted to the same dry density on wet side of optimum, the amount of erosional loss was less than five percent. For the soil samples compacted to ninety-five percent of Standard Proctor density on dry side of optimum, the amount of erosional loss was approximately

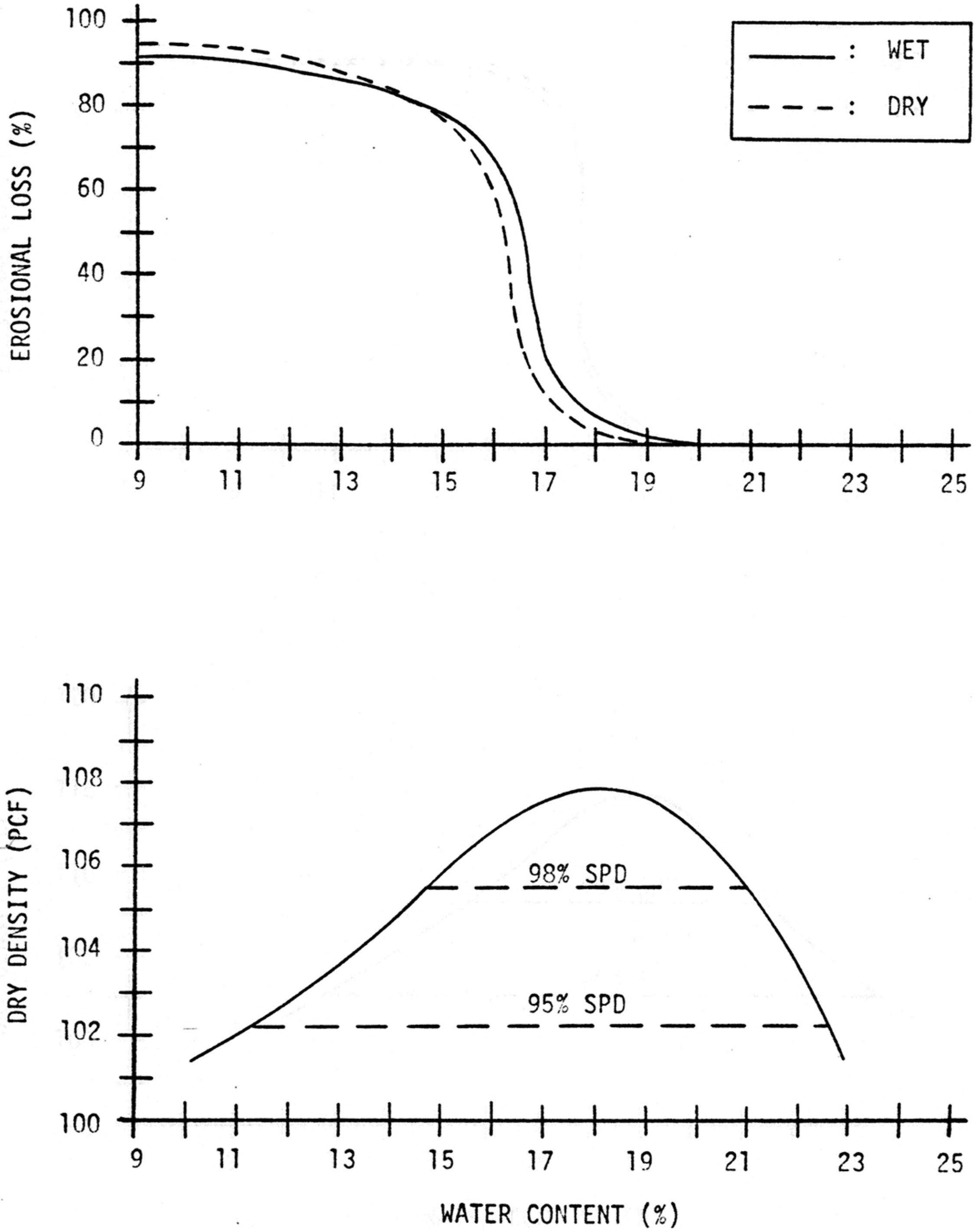

Figure 10. Comparison Between Standard Proctor Density (SPD) and Erosional Loss for Sogn Clay (1 pcf = 16.018 kg/m^3)

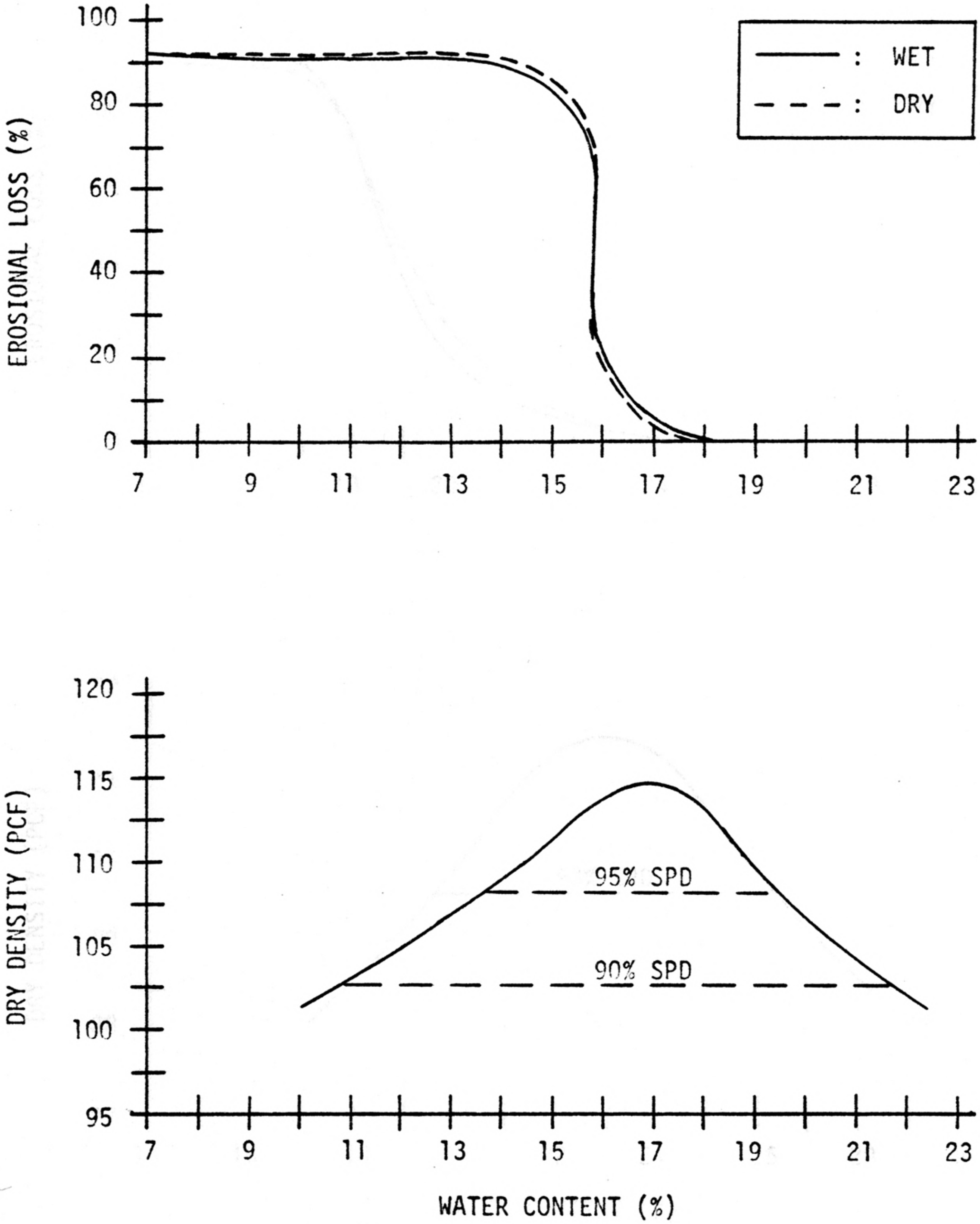

Figure 11. Comparison Between Standard Proctor Density (SPD) and Erosional Loss for Wamego Clayey Silt (1 pcf = 16.018 kg/m^3)

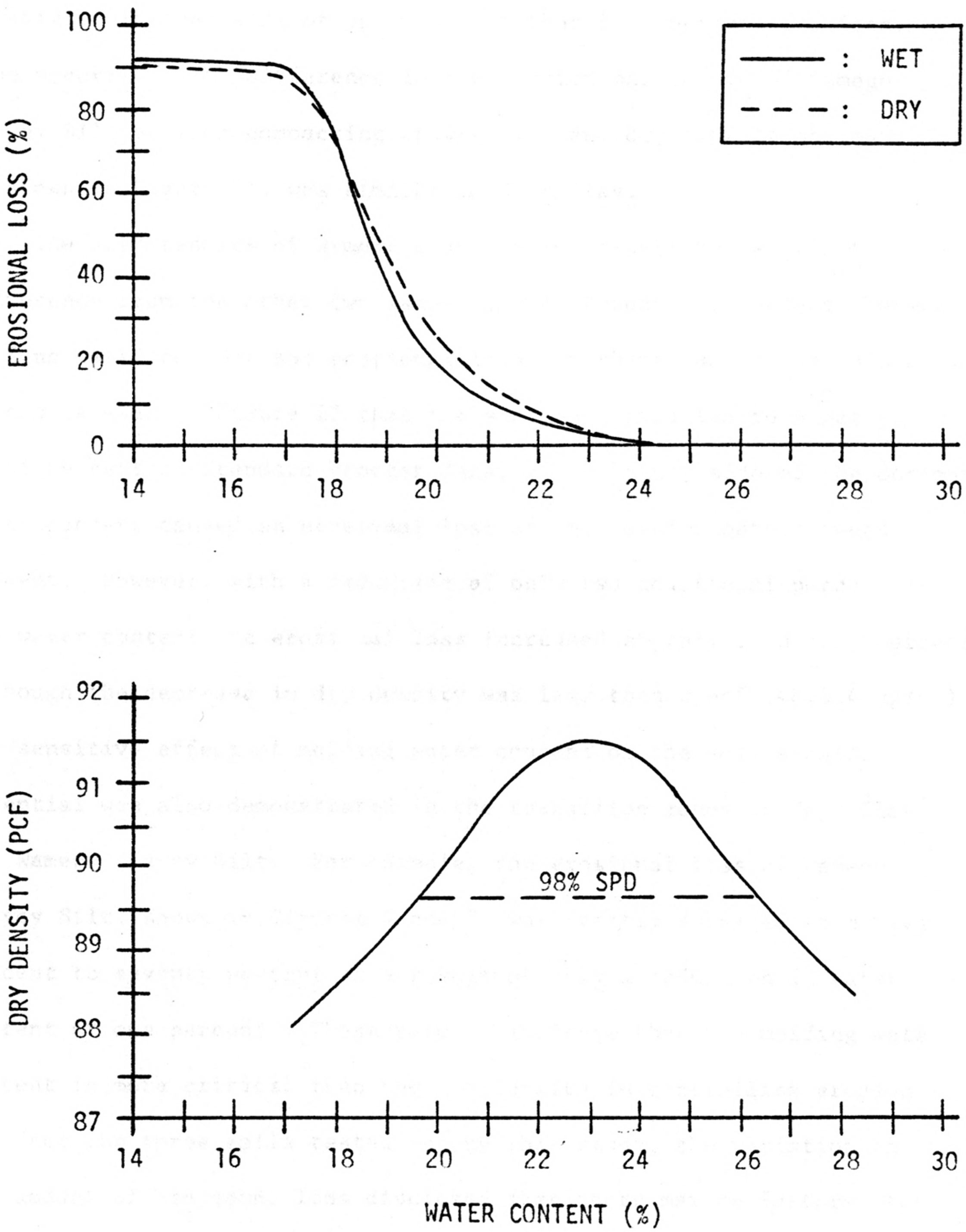

Figure 12. Comparison Between Standard Proctor Density (SPD) and Erosional Loss for Wymore Clay (1 pcf = 16.018 kg/m^3)

ninety percent. However, for the same soil compacted to the same dry density on the wet side of optimum less than five percent erosional loss occurred. The difference in the erosion percentage of Wamego Clayey Silt between compacting on wet side and dry side of optimum, as shown in Figure 11, was similar to Sogn Clay.

The test results of Wymore Clay sample illustrated a slight difference from the other two samples, even though the tendency between molding water content and erosional loss for three samples was similar. It can be seen in Figure 12 that the specimen compacted to ninety-eight percent of Standard Proctor density on the dry side of the optimum water content caused an erosional loss of only approximately twenty percent. However, with a reduction of only two additional percent in the water content the erosional loss increased sharply to ninety percent, although the decrease in dry density was less than 3 pcf (48.054 kg/m^3). The sensitive effect of molding water content on the soil erosion potential was also demonstrated in the transition zones of Sogn Clay and Wamego Clayey Silt. For example, the erosional loss of Wamego Clayey Silt, shown in Figures 4 and 7, was greatly enlarged from five percent to seventy percent as a result of only a reduction in water content of one percent. These results indicate that the molding water content is more critical than the dry density in controlling erosion.

For the three soils tested during this study, the variation in the amount of erosional loss disclosed that there may be factors other than water content which influence the potential erosion of a soil. It is believed by this researcher that further study is necessary to identify these factors. However, it can be concluded that soil compacted on wet side of optimum can increase the resistance of soil to erosion.

Tractive Stress

The soil erosion problem considered in this study is a surface erosion phenomenon. Surface erosion will occur when the fluid flow-induced tractive stress, termed hydraulic tractive stress, on the soil-water interface is greater than the interparticle shear strength. The hydraulic tractive stress is a function of the flow velocity, frictional factor, and fluid density. For a given soil, the greater the hydraulic tractive stress the greater the erosional loss.

In this research study, the hydraulic tractive stress and frictional factor were kept constant for each soil under consideration. The frictional factor was calculated to be 0.0424 using Equation 2. The hydraulic tractive stress was calculated to be 0.0255 psf (1.220 Pa) using Equation 1.

As previously described, the test data revealed that there was a large change in erosional loss with only a minor change in the molding water content for each of the soils in the transition zone. These three zones can be explained if the critical hydraulic tractive stress is a function of water content. The experimental test results indicated that the critical tractive stress was greater than applied hydraulic tractive stress (1.220 Pa) in the low erosion zone. In the transition zone the increase in erosional loss implied a decrease in critical tractive stress of compacted soils. In the high erosion zone the large amount of erosion implied that the critical tractive stress was less than the applied hydraulic tractive stress.

The conspicuous differences in soil erosional loss between a soil compacted wet of optimum and that compacted dry of optimum were presented in Figures 3 through 8. The considerable variance in the erosional loss with changes in water content shown in these figures supports the premise that water content is an important parameter which affects the critical hydraulic tractive stress. It is believed that soil compacted on wet of optimum possess a greater critical hydraulic tractive stress than those compacted dry of optimum.

Shear Strength

The shear strength of a cohesive soil not only depends on soil type but also on ambient conditions. Normally, for a given compactive effort, the shear strength of a cohesive soil compacted on the dry side of optimum is greater than the soil compacted on the wet side of optimum to the same density. Under saturated conditions at very low confining pressure, the shear strength of soils compacted on the dry side of optimum may be less than that compacted wet of optimum for the same initial dry density.

In this investigation, it was considered that surface hydraulic erosion is a form of shear failure within soil. According to this assumption, the hydraulic tractive stress acts as a shear stress, which is applied on the interface between soil and water. For a given hydraulic tractive stress, the greater the shear strength the greater the resistance to erosion.

For the soils tested, the erosional losses were greater for the samples compacted dry of optimum compared to those compacted wet of optimum. This fact implies that the shear strength for the samples compacted dry of optimum must have been less than that of the samples compacted wet of optimum to the same dry density. Therefore, under the saturation conditions at very low confining pressure, soil compacted wet of optimum may produce a greater shear strength than that compacted on dry side of optimum to the same dry density. Conclusive results are not yet available to confirm this.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

The primary objective of this study was to determine the effect of molding water content on the hydraulic erosion of cohesive soils. This objective was accomplished by evaluating the erosional potential of three different soil samples using different molding water contents. From the knowledge gained during this study, the following conclusions were made:

1. Compaction water content is an important parameter in predicting the erosional losses of cohesive soils.

2. Soil samples compacted on the wet side of the Standard Proctor optimum water content exhibited significantly less erosion than soils compacted to the same dry density on the dry side of optimum.

3. A comparison of the results for the percentage of erosional loss versus molding water content for the wet and air-dried soil samples tested, indicated that the amount of erosional loss is independent of the change in water content after compaction prior to testing.

4. The experimental data indicates that the critical hydraulic tractive stress for a cohesive soil is affected by the molding water content.

Recommendations

In the course of this research study, several areas were identified which need future study. These areas were:

1. Determine the erosion potential of cohesive soils compacted to different densities using different compactive efforts while holding the molding water content constant.

2. Investigate the effect of molding water content on the compacted shear strength under saturated conditions at very low or no confining pressure.

3. Study the influence of the molding water content on the critical hydraulic tractive stress.

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APPENDIX A

Sample Preparation and Testing Procedure

1. Thoroughly mix the soil with sufficient distilled de-ionized water to obtain the desired water content. After mixing, the sample should be broken down such that all particles pass the U. S. No. 10 sieve.

2. Compact the sample according to the Harvard Miniature compaction technique (35).

3. After compaction, partially extract the soil cylinder from the mold using the small spacing block (t = 0.406 in. [10.312 mm]). Trim the cylinder level with top of the mold and use a representative sample from the trimmings for initial water content determination. Record all data on data sheet.

4. Place the compacted soil cylinder into the assigned test cell (Figure 2), orienting the cylinder such that the top of the cylinder is at the top of the cell.

5. Place the cell, cylinder and compression blocks in a hydraulic press with the top of the cell up. Provide sufficient compression so that the blocks are completely seated into the test cell.

6. After compression, remove the blocks and mark the longitudinal hole locations in the top of the soil cylinders. Drill three 0.125 in. (3.175 mm) holes in the samples at a speed such that minimal sample disturbance will result. A drill press should be used to insure proper alignment.

7. Carefully clean each hole with a pipe cleaner. Then weigh each cell and cylinder to the nearest .01 gm.

8. The apparatus should be prepared for conducting the Physical Erosion Test by using the following procedure:

a) Each settling basin should be cleaned and filled with water.

b) Fill the primary holding tank with sufficient distilled water for a complete test (at least 12 gallons).

c) Connect the air pressure supply line to a source capable of supplying at least 20 psi. (1.4×10^5 Pa) pressure.

d) The air pressure input line should be connected from the air pressure regulator to the primary holding tank. The pressurized water line should be connected to the secondary holding tank from the primary holding tank.

e) The tank should be pressurized such that 15 psi. (1.0×10^5 Pa) minimum is available to each test cell.

f) Place the outflow lines in the proper wastewater container.

9. Place the sieve discs, spacer ring and support ring in the bottom of the cell.

10. Connect each cell to the device by pushing the cell end pieces into their cells and rotating them, to ensure proper seating of the "O" rings. The cells are then placed in their "C" brackets and secured to prevent any movement of the cell during testing.

11. The secondary holding basin should be filled and pressure vented. Five minutes prior to the beginning of testing, open the shut-off valves to each cell and allow the sample to saturate (for dry samples, it would take 15 minutes to saturate). The secondary holding basin should be kept at least half full of water by intermittent filling from the main tank as needed.

12. After a fifteen minute (900 sec.) saturating period, each cell should be pressurized to the desired water pressure 15 psi. (1.0×10^5 Pa) for standard testing.

13. The test is started by switching on the timer for each channel at 15 second intervals. The timers are set to open each solenoid valve at six-minute (360 sec.) intervals for approximately nine seconds, thus providing a system to flush out any soil suspended in the soil cylinder holes and cells (if particles would pass a U. S. No. 40 sieve), and provide fresh distilled water.

14. After four hours (1.4×10^4 sec.) of elapsed testing time each unit is turned off. Prior to the last time each solenoid valve opens, its corresponding shut-off valve is closed. The power switches are then shut off as soon as each solenoid valve closes.

15. The cylinder is removed and each cell is disconnected. The soil remaining in the cell should be completely washed into a pre-weighed dish. The dish and sample are then dried in an oven at 105°C for 24 hours (8.6×10^4 sec.). After drying, the sample should be placed in a dessicator to cool, after which it is weighed to the nearest 0.01 gm. The dry weight of the soil is then used to determine the soil erodibility, expressed as a percentage of the weight loss.

For dry sample, the testing procedure is almost the same as previously described with the following two exceptions:

Step 3. In order to determine the sample's initial water content before drying, partially extract each cylinder from the mold using the small spacing block. Trim the cylinder level with top of the mold and use a representative of the sample trimmings for water content determination.

Step 7. After carefully cleaning each hole and weighing each cell and cylinder, the five samples are dried in the air at least for twenty-four hours (8.6×10^4 sec.). Then, one of the five is broken and partial samples are extracted around its three holes to determine the air-dry water content.

APPENDIX B

STANDARD PROCTOR COMPACTION CURVES FOR TESTING SAMPLES

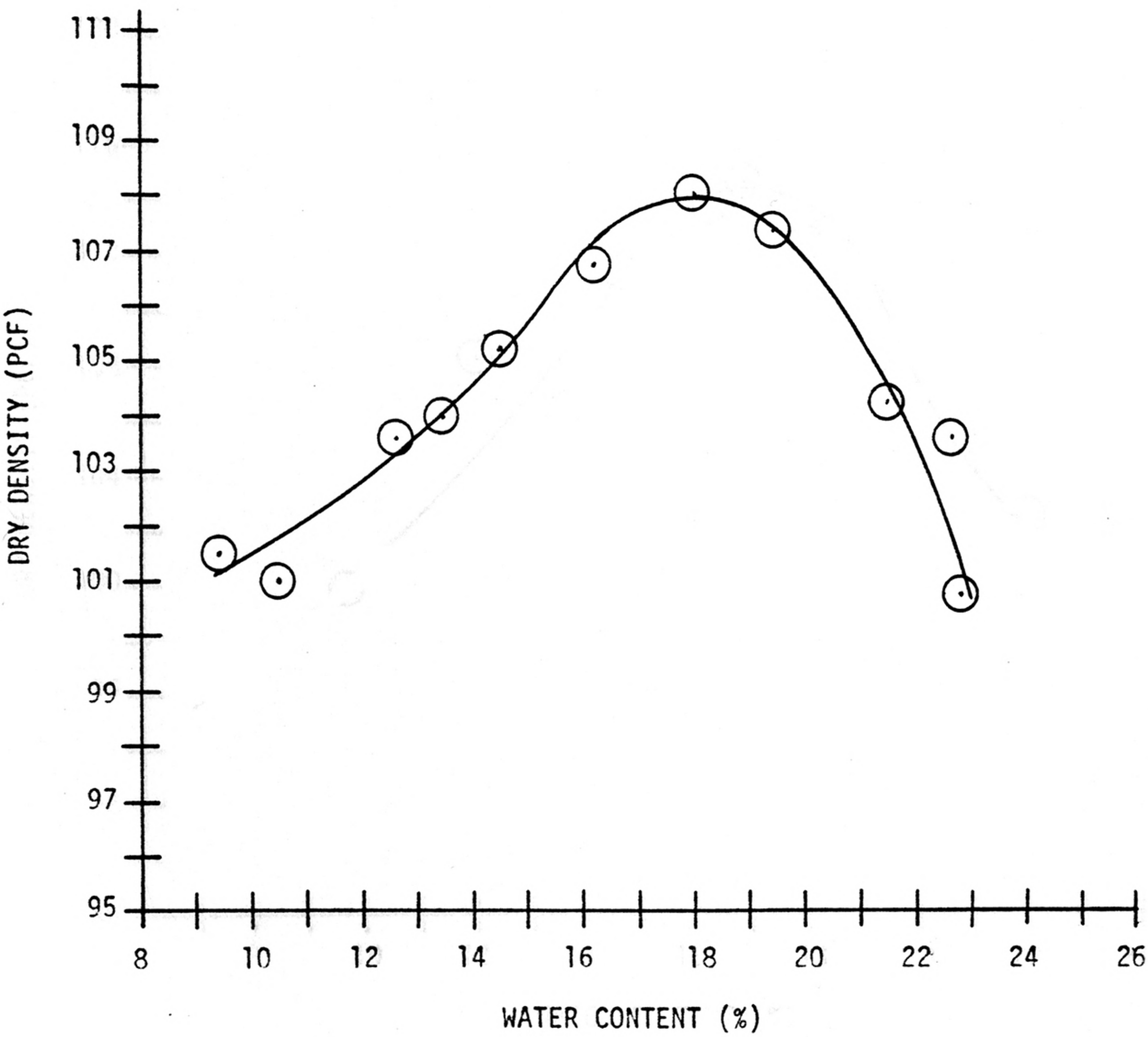

Figure 13. Standard Proctor Compaction Curve for Sogn Clay (1 pcf = 16.018 kg/m^3)

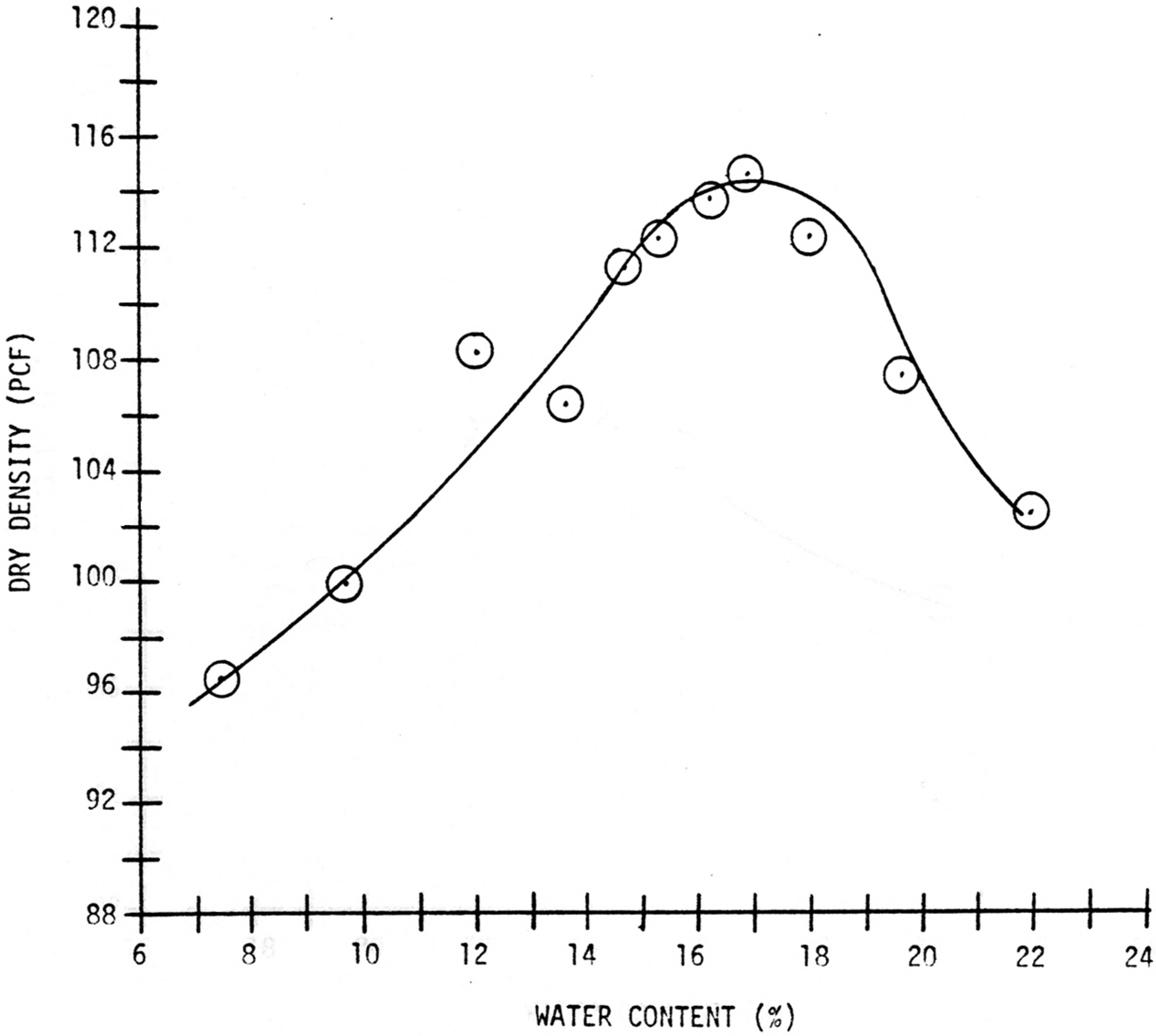

Figure 14. Standard Proctor Compaction Curve for Wamego Clayey Silt (1 pcf = 16.018 kg/m^3

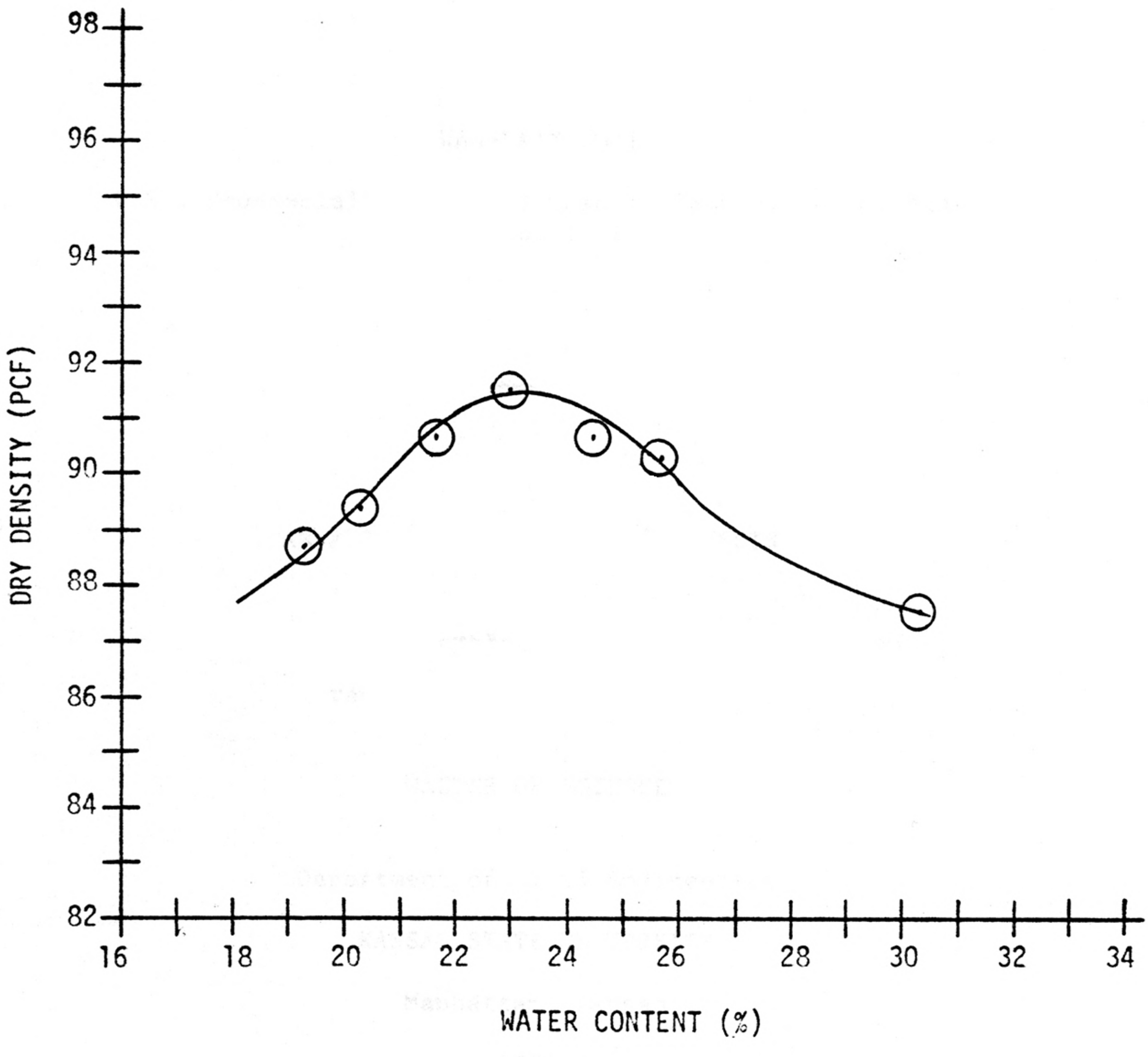

Figure 15. Standard Proctor Compaction Curve for Wymore Clay (1 pcf = 16.018 kg/m^3)

THE EFFECT OF MOLDING WATER CONTENT ON THE HYDRAULIC EROSION POTENTIAL OF COHESIVE SOILS

by

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Taiwan, 1971

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements of the degree

MASTER OF SCIENCE

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Manhattan, Kansas

1981

ABSTRACT

This study was undertaken to gain a better understanding of the erosional characteristics of cohesive soils and to determine the relationship between the amount of erosional loss and the variation in molding water content. Laboratory samples were compacted, saturated, and tested under controlled laboratory conditions using an erosion test apparatus. Erosion tests on both wet and air-dried samples were carried out under the same conditions. It was concluded that the amount of erosional loss is affected by the compacting water content. The soil samples compacted on the wet side of the Standard Proctor optimum water content resulted in a significant reduction in erosional loss of the soil when compared to the same dry density compacted dry of optimum. The test results clearly show that the amount of erosional loss was dependent upon the initial compaction water content and independent of any change in water content after compaction prior to testing. Data also indicated that the critical hydraulic tractive stress for a cohesive soil is significantly affected by changes in the molding water content.