THE UNIVERSITY OF ALBERTA

AN EVALUATION OF DIFFERENTIAL HEAVING IN RAILWAY ROADBEDS

BY

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "AN EVALUATION OF DIFFERENTIAL HEAVING IN RAILWAY ROADBEDS" submitted by JOHN SHYMONIAK in partial fulfilment of the requirements for the degree of Master of Science.

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ABSTRACT

Differential frost heaving of roadbeds has been of major concern in railroad operation. The procedure used to maintain a level track consists of insertion of hardwood shims between the rail and the tie. This is a tedious and expensive process and has prompted the search for more economical methods to reduce or eliminate differential heaving. This thesis attempts to clarify the reason for some observed heaves in the field and also embarks on a preliminary program of assessing the value of three chemical admixtures to the soil as a method of reducing differential heaving.

A subsurface investigation of the subgrade soils in two areas with differentially heaved track was conducted by means of auger borings and block sampling. The data showed that a variation in soil type is a major factor in causing differential heave. Secondary factors are location of the water table and the density of the soil mass.

Laboratory freezing tests were conducted on compacted specimens two inches in diameter and four inches long. Three additives were used, namely, sodium chloride, calcium chloride and a sodium polyphosphate. Four soil types varying from a clay-silt-till to a silty fine sand were obtained from two differentially heaved areas in the field. The results showed that all the additives are effective in reducing both the total and differential heave with sodium chloride being the most effective. The effect of the salts was most pronounced at concentrations up to approximately 0.15 percent, based on the dry soil weight. Higher concentrations than this showed a lesser effect in reducing heaving.

The migration of sodium and calcium chloride due to movement of water in the pores in a number of the laboratory soil specimens was investigated by conductivity measurements. The data obtained indicated that salts migrate readily with moisture movement in the soil.

It is recommended that field trials of uniformly applied brine solution to an area with differential heaving be carried out. Further and more detailed studies of some differentially heaved areas are recommended to explain the field anomalies observed in a few instances in this study.

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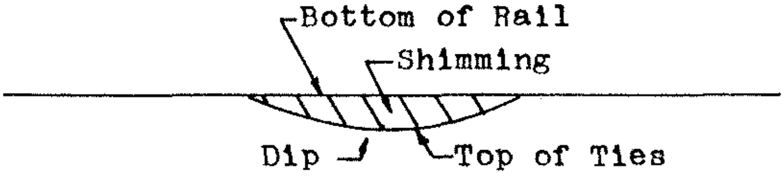
EXPLANATION OF TERMS

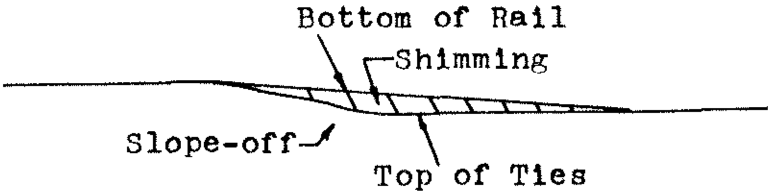
The frost action terminology as used in this thesis is in accordance with the list of terms and definitions as prepared by the Highway Research Board Committee on Frost Heave and Frost Action in Soil (Frost and Permafrost Definitions, 1956). The following terms have been adopted by the Canadian National Railways to describe the different types of differential heave.

Lump: A central part of track heaves more than the adjacent areas.

Dip: The adjacent areas heave more than a central portion.



Slope-off: One area of track heaves more than an adjacent area.



CHAPTER I

INTRODUCTION

1.1 General

Ground freezing and heaving has been of observational and practical interest for many years. Its effects were not of great concern until the development of rapid transportation by railroads, highways and airports. Frost action then became an important problem to be considered by engineers, from a technical as well as an economical viewpoint.

The oldest concept of frost action suggested that all heaving was due to expansion when the water contained in the voids changed to ice upon freezing (approximately 9 percent volume increase). This concept was disproved by Taber and Beskow with the publication of their studies that frost heaving is due to the growth of ice crystals and the formation of ice lenses. It is from these works that the modern concept of frost action has emerged. Since that time much effort has been spent in studying the fundamentals of frost action and their application to roads, railroads and airports. This thesis will concentrate on some aspects of the frost heaving problems associated with railroads.

The problems caused by frost action in railroads are somewhat different than those in flexible pavements used on highways and airports. In the latter two the principal concern is a reduction in bearing capacity during the frost melting period and subsequent damage to the pavement structure caused by the loads imposed by traffic. In railroads the major problem is differential heave which results in an uneven track. The most common method presently used to remedy the uneven track is to place variable heights of wooden shims between the rail and the ties thus providing gradual approaches to and departures from the differentially heaved locations. According to Yalcin (1963)*, the most frequent height of shims used by the Canadian National Railways are between 3/4 and 1-1/2 inches. In the spring of 1965, shimming records were made in the Telkwa Subdivision in British Columbia on a 120 mile length of track. This section has been observed to require as much shimming as any other Canadian National Railways subdivision in Canada. The records indicated that 98 percent of the shimmed locations had maximum shim heights of 2 inches or less and 42 percent 1 inch or less. Therefore, the major problem of undulating track is caused by differential heaves two inches or less in height.

FIGURE 1.1 is a photograph taken with a telephoto lens of a portion of unshimmed track near Camrose, Alberta, taken in mid-April just before spring thaw. It clearly illustrates the uneven track which can result due to differential heave.

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*References listed alphabetically in "List of References".

FIGURE 1.1 DIFFERENTIALLY HEAVED TRACK AT CAMROSE, ALBERTA, MID-APRIL, 1965

Frost heaves on tracks are considered to be a more serious problem than frost heaves on highways. Smooth track is not only desirable for passenger comfort and economical operation but is a necessity for the safe operation of modern high speed trains. A small differential heave on a highway might be just a minor nuisance to motor traffic; on a railway track it becomes a menace calling for immediate correction with the possibility of a derailment and human life being endangered.

The present method of maintaining heaved track by shimming is a slow, tedious procedure requiring a large labour force and obviously has to be done during the coldest time of the year. Cost analyses by the CNR have shown this method to be expensive and to require a high proportion of the total expenditure for maintenance of track. An estimate of annual cost for labour and material for shimming alone for the CNR system mileage in Canada is in the order of $3,800,000 (Yalcin and Peckover, 1963). With the sharp increase in labour costs during the past few years shimming is becoming increasingly more expensive and uneconomical.

Many phases of railroad maintenance are being automated, with accompanying reduction in manual labour and a consequent saving in costs. Shimming is an operation which cannot be easily and economically automated.

Due to the high and increasing costs of shimming, the CNR began an intense investigation of the problem of differential heave, commencing about 1959.

Excavation of frost susceptible soil and replacement with non-frost susceptible granular materials is a method often used for eliminating detrimental frost heaving. This method has been used by the CNR in locations with excessive heave. However, it is a method which cannot be economically applied to areas with numerous small differential heaves requiring shims less than 2 inches. This method would almost necessitate the construction of a side track to keep the traffic in operation and would therefore be a very expensive undertaking.

Since the problems due to frost action in railroads affect many miles of existing track, the CNR engineering staff are attracted by the reduction in differential heaving resulting from the surface application of inexpensive chemicals either in powder form or in solution. Sinclair and Hemstock (1947), Yurkiw (1952) and Luck (1953) showed that lignosol was very effective in reducing heave in laboratory freezing studies. From field tests on sections of track, Hardy (1953) noted that lignosol eliminated track shimming at two treated locations for two winters. A number of test sections have been experimentally injected with lignosol by the CNR. Although very effective in reducing heave, lignosol was found unsatisfactory because it requires an elaborate injection procedure and its effectiveness is only short term due to leaching by rain, and water migration in the soil.

Numerous field test sections have been experimentally treated by the CNR with many different admixtures. The effectiveness of the chemicals in the majority of the test sections was evaluated by noting the reduction in height of shimming required the following winters. To date, the field tests indicate that sodium chloride and calcium chloride are effective in reducing differential frost heaving. They have the further advantage of being easily applied.

1.2 Statement of the Field Problem

The major problem is the reduction or elimination of differential heaving of the track. In the past shimming has been used, but the increasing labour costs and the desire for automation have necessitated the search for other solutions. Surface applied chemicals, particularly sodium and calcium chloride brines, have shown some promise.

1.3 Purpose of Investigation of this Thesis

The work on which this thesis is based may be considered in two parts. The first consists of a preliminary field study to more clearly define some of the causes of differential heaving of railroad track. The second part consists of a laboratory study of the influence of chemicals on heaving.

The field work consisted of a subsurface investigation of several differentially heaved sites and subsequent laboratory classification of soil samples obtained from the boreholes. The laboratory phase attempted to assess the reduction in frost heaving of soil samples brought about by three chemical additives. These chemicals are calcium chloride, sodium chloride and a sodium polyphosphate. The latter is sodium hexametaphosphate, $Na\ (PO_3)_6$, sold under the trade name "Calgon".

1.4 Résumé of Thesis

In order to provide a background Chapter II briefly outlines theories of frost action and discusses some factors affecting the amount of heave.

The field investigations are presented in Chapter III. The procedures are given and the field and laboratory data are discussed. Tentative conclusions arising from this phase of the work are proposed.

The work of the second phase, which consists of the laboratory investigations is detailed in Chapter IV. The data are presented in the form of tables and graphs and the results of this work are discussed.

The conclusions and recommendations arising from this study are presented in Chapter V.

CHAPTER II

THEORETICAL CONSIDERATIONS AND SOME FACTORS AFFECTING FROST HEAVE

2.1 Short Outline of Theories

The oldest concept considered that frost heaving is due to the volume change of the water contained in the voids when it freezes. This misconception arose from experiments in which soil samples were frozen under closed system conditions.

The present concept that frost heaving is due to the growth of ice crystals into ice lenses within the soil mass was originated by Taber in 1916 when he experimentally showed that ice lens formation can occur in soil. He later formulated a theory explaining the mechanics of freezing and heaving (Taber 1929, 1930). Growing ice crystals remove molecules of water from the film of water on soil particles. As these molecules are removed, new molecules are drawn to the film. Water is supplied through small capillary passages in the soil to the partly depleted water films. As the new molecules are attached to the ice crystal, it grows in size displacing the soil above it. Taber's reason why ice layers do not form in coarse grained soils was due to the rapid conductivity of the particles which caused ice to form around them, not permitting film moisture flow to ice crystals.

According to Johnson (1952), Beskow's statements explaining the mechanics of frost heaving differed little from those of Taber. "At the frost line a drying out occurs, a squeezing together of the adsorption films, which spread further and further, causing a shrinkage. If the freezing zone spreads to a place of contact with a free supply of water . . ., the water begins to flow upward from this point and the fundamental requirement for . . . a subsequent frost heave is fulfilled". His explanation for the lack of heaving in coarse grained soils was due to the thin and long films with low molecular mobility on the coarse particles which do not permit free passage of water to the ice crystal. The ice grows into the pore space, surrounds the particles and no ice segregation occurs. On the other hand, a fine grained soil has thick adsorbed water films through which flow of water molecules can occur much more rapidly. In saturated heavy clays the amount of mobile water is large, however, the permeability is so low that water supply for ice lenses is limited to local flow from the soil close to the ice lens. In silts and silty sands, the thickness of the water film is small, however, the permeability is large. When in contact with water, the silts and silty sands will allow considerably more water to flow to the frost line than the heavy clay, and thus the silts and silty sands heave to a considerably greater degree.

Two modern contributors to the theory of frost action are Penner and Martin. Penner (1957) measured moisture tensions for different soil types. He suggested that the freezing point depression at the ice-water interface determines the moisture tension which acts as the driving force during frost heaving. The freezing point depression is induced, at least in part, by the dimensions of the soil pores, when a saturated soil specimen is frozen unidirectionally. Thus, higher tensions are developed in soils with small pores than with large pores.

Penner (1959) applied the formulas for the size of a stable spherical crystal in its own melt, and pressure - freezing point depression equations to describe a mechanism of ice lens growth together with the development of heaving pressures and suction in the soil moisture.

Martin (1958) presented a theory to explain rhythmic ice banding which produces frost heaving in soil. The discussion of his theory was divided into four stages: a) nucleation of ice at some distance from an existing ice front, b) rapid growth of this nucleus into an ice lens, c) termination of crystal growth, and d) heat and water flow between the end of stage (c) and the beginning of a new cycle at stage (a).

Nucleation occurs at a supercooled temperature. Supercooling provides the energy to draw water to the ice front and to raise the overburden. After start of nucleation, there is a rapid growth of ice crystals, with water being drawn through the pores to the ice crystal. The larger the crystal becomes, the faster it tends to grow and the more the amount of water that is required. With increased demand for water, the ability of the soil to supply water is decreased because of an increase in negative pressure which decreases the unsaturated permeability of the soil. The decrease of water supply reduces the amount of water being converted to ice and the heat of fusion per unit time; therefore, the rate of heat extraction exceeds the rate of heat supply and the temperature decreases. When the actual temperature is lowered to the nucleation temperature, ice nucleates at a small distance ahead of the existing ice front, and the cycle starts again.

2.2 Some Factors Affecting Frost Heave

2.2.A Grain Size and Gradation.

Early investigators of frost action in soils noted that certain types of soil exhibited more heave and more numerous and larger ice lenses than others. Beskow (1935) demonstrated, by using Atterberg soil fractions, that maximum heaving occurred with grain sizes from 0.002 to 0.005 mm. Taber (1929) demonstrated the influence of fine particle size on ice segregation by using various fine-grained and coarse-grained soils and soil mixtures. Casagrande (1931) from experiments on natural soils under natural freezing conditions concluded that with sufficient water supply one could expect considerable ice segregation in non uniform soil containing more than 3% smaller than 0.02 mm. and in very uniform soils containing more than 10 percent smaller than 0.02 mm. No ice segregation was observed in soils containing less than 1 percent smaller than 0.02 mm.

The Corps of Engineers (Linell and Kapler, 1959), conducted tests to check the validity of the Casagrande criteria and to determine the relationship between the 0.02 mm. size and the amount of heave produced by soils of various gradations ranging from well graded sandy gravel to uniform fine sand. These materials were combined with fines to observe the effect of various soil fines on frost behavior. They showed that accurate prediction of relative heave rate cannot be made simply from general soil type and percent finer than 0.02 mm. Soils of even similar gradation may vary significantly in frost behavior. Factors not apparent from a gradation analysis affect the behavior.

Field observations have definitely established that excessive frost heaving is not restricted to soils of any particular gradational characteristics. Heaving has been observed to occur in clays, silts, very fine sands and in textures approaching the grading of gravels (Johnson, 1952).

Ducker (1956) stated that in nature there is no sharp boundary between frost-susceptible and non-frost susceptible soils, as outlined by the Casagrande criteria. Some soils showed frost susceptible properties even when they had no sizes below 0.02mm. He noted that test results clearly indicate that the decisive factor determining the behavior of a soil with respect to frost is not the percentage passing 0.02 mm. but rather the mineralogical and chemical nature of the fine grained component.

The Department of Highways of Ontario (Townsend and Csathy, 1963) analyzed the field frost performance of 126 highway subsoils and applied some of the most widely accepted frost susceptibility criteria to this field performance. The results indicated serious limitations of these criteria. They found the Casagrande criteria highly conservative in that it appeared to reject a relatively high percentage (84%) of the frost susceptible soil, but accepted only a relatively low percentage (20%) of the non-susceptible soils. They developed a simple method to determine the pore size distribution of the soils, using a capillary rise type of test procedure, and established a frost susceptibility criterion. This criterion rejected 75 percent of the frost susceptible soil and accepted 79 percent of the non-frost susceptible soil.

2.2.B Mineral Type

Grim (1952) analyzed the possible effects of clay mineral composition on frost action in soils. He reasoned that clay minerals which adsorb a quantity of oriented immobilized water on the clay surface, reduce the permeability and thus the ability of the soil to supply water for ice segregation.

In sodium montmorillonite, there are thick highly oriented water hulls in which the water is immobile. Such clays are essentially impervious and cause little or no ice segregation. In montmorillonite carrying calcium, magnesium or hydrogen as the exchangeable ion, the water hulls are thinner and ice concentration may develop at high moisture contents.

Kaolinitic soils have small surface area and thus very little rigid water. At relatively small water contents kaolinite soils would contain free water. Since they are not particularly impervious, segregation may readily occur.

Illite soils have characteristics between those of kaolinite and those of montmorillonite. Grim considers the illites to be closer to the former, hence, ice segregation may take place.

The Corps of Engineers in cooperation with Lambe (Linell and Kapler, 1959) performed freezing tests in which clay mineral and non clay mineral fines were added to a clean cohesionless sand, to demonstrate the influence of soil fines on frost behavior. From the tests some of the conclusions drawn were:

(a) At low concentrations of fines, the clay minerals produced higher heave than non-clay minerals. At higher concentrations the clay mineral effect varies over a wide range.

(b) Heave varied considerably, over a hundredfold, with montmorillonite as the soil fines, depending on the nature of the exchangeable ion. Sodium gave the lowest heave, while ferric iron gave the highest heave.

(c) The increase in concentration of fines above a certain minimum can result in a decrease of frost heave rate for some of the more plastic clays.

2.2.C Density

The effective pore or channel size is a major factor in governing frost action in soils since it governs the amount and rate of water available, to the frost line. It follows, therefore, that any factor that affects pore space or the voids in the soil mass will also affect the frost heave potential.

Density is one factor which affects pore size, and hence influences the amount of heave. Taber (1930) observed that higher remolded densities reduced the amount of heave in a Cretaceous clay. Winn (1940) made laboratory tests on a natural sandy clay and on admixtures of the clay with other materials. The results showed a trend of increasing heave with increasing density until a maximum was reached and then a decrease in heave with increase in density.

Johnson and Lovell (1953) reported an increase in ice segregation with an increase in compacted density for open system laboratory tests on a well graded soil containing fine sizes. The increase in ice segregation increased to a critical density then decreased. This critical density for this particular soil was in the order of 95% of that achieved by the modified AASHO Compactive Effort. In inorganic silty soils, ice segregation increases up to 100 percent AASHO Modified density. Uniformly graded frost susceptible sands are little affected by variations in degree of compaction.

The Corps of Engineers conducted extensive investigations on the influence of initial density on frost heave (Linell and Kaplar, 1959). Many different soil types from a clay to sandy gravels were used. The results showed density to produce a quite responsive and variable effect on heave depending on the soil type. With the absence of experimental data, it is not necessarily obvious whether an increase in density in a soil should result in an increase or a decrease in the rate of frost heave, or that soils of similar gradation characteristics will show similar trends of rate of heave versus dry unit weight.

2.2.D Moisture Content

Soil moisture is a dominating influence in determining the magnitude of freezing and thawing effects. The moisture content of soil at the beginning of freezing largely determines the amount of segregated ice and the heaving of the soil on freezing (Johnson and Lovell, 1953). The increase in moisture content and change in distribution of moisture in the soil in addition to changes in density and soil structure after ice segregation determine the amount of reduction in load carrying capacity after thaw.

The increase in moisture content in a soil during freezing is dependent on the initial moisture content. The higher the initial degree of saturation, the greater the heave and reduction in load carrying capacity on thawing.

The magnitude of the initial degree of saturation necessary to cause ice segregation and reduction in load carrying capacity differs with soil type, water availability, and climatic influences. Meager data show no detrimental frost action if the initial moisture content is less than 65 percent of that required for saturation (Johnson and Lovell, 1953). From a survey of subgrade and base moisture contents beneath paved runways and highways, the normal moisture contents ranged from 50 percent saturation for coarse grained gravelly and sandy soils to almost 100 percent for fine grained silty and clayey soils (Kersten, 1944, 1945).

Closed system tests by the Corps of Engineers (Linell and Kaplar, 1959) indicated that a reduction in degree of saturation to the order of 70 percent does not eliminate ice segregation and heave but does reduce it substantially.

2.2.E Pressure at Frost Line

Pressure at the frost line is made up of two components, the external load and capillary pressure. The capillary pressure is negative and acts in such a way that it tends to compress the soil. The external load consists of the weight of overburden material above the frost line.

Beskow (1935) concluded from his experimental work that the rate of frost heaving for a given soil is inversely proportional to the square of the pressure at the frost line.

Surcharge loads influence the extent of heaving with an increase in load causing a decrease in amount of heave. The effect of surcharge on reducing heave varies with soil type. Taber (1930) found that a relatively small load which prevented heaving in a coarser textured soil did not greatly effect the heaving of clay soils.

2.2.F Structure

Structure, as it pertains to frost action, not only includes an arrangement of soil particles into forms as blocky, prismatic, etc. but includes large irregular masses of different soil horizons.

Structure in clayey soils may be evident in the form of fissures. Such fissures provide channels for the ingress of free water into the soil mass and hence aid appreciably in intensifying frost action.

Non uniformity in structure may also influence the amount of heave. Small variations in average grain size or in grading may cause large differences in pore volume and can influence the water content before freezing. The relative differences in pore sizes may influence the rate of water movement to the freezing zone and thus result in differential heave. The occurrence of thin layers of silt or clay in the order of one to two millimeters in a sand mass, textural differences from one soil horizon to another, pockets of sand, silt or clay, contact boundaries between deposits of different texture or porosity are examples where soil structure results in differential heave. The occurrence of ledge, boulders, and stumps in or near the frozen zone have been noted to produce local and often intense frost action (Johnson and Lovell 1953). Stratification and lamination in soils has been noted to produce high heaves. Finely laminated soils can be made many times more frost heaving than a corresponding homogeneous soil. This is especially true for the finer grained sediments. The increase in heave was found to be greater with a decrease in the thickness of the laminations (Beskow, 1935).

A few investigators have correlated frost heaving with pedological soil type. Some have noted soil series which are susceptible to frost action. Other investigators have correlated the occurrence of frost heaves according to geologic land forms. Burton and Benkleman (1930) made a detailed study of 156 heaved areas in Michigan. They found that 65 percent of heaves occurred in moraines, 15 percent in shallow outwash, 12 percent in till plain and 8 percent in lake bed and deep outwash.

2.2.G Climate

Climate is another factor of considerable importance in influencing the nature of frost action and reduction in bearing capacity following thaw. The significant elements of climate in order of relative importance in their influence are temperature, precipitation and humidity, sunshine and wind.

Several investigators have found a relationship between climate, magnitude of heave and depth of frost penetration by expressing temperature and time in terms of degree-days or degree-hours (Johnson, 1952). The cumulative curve of degree-hours of freezing against time provides a qualitative measure of the increase in heave with time. The extent of damage resulting from frost action is usually associated with a fairly long cold period provided the moisture conditions in the soil are adequate.

The increase in the depth of frost penetration results in the frost line approaching the water table hence providing easier access of water to the freezing zone. In this way greater heaves are often associated with deeper depths of frost penetration.

The rate of freezing is controlled to a large extent by climate and temperature. Beskow (1935) concluded that the rate of frost heaving is, for practical purposes, independent of the rate of freezing. Rate of freezing, however, effects the distribution of water and consequently the bearing capacity of a soil on thawing. A slow rate of freezing, associated with slowly dropping average ground surface temperatures results in thicker, more concentrated ice segregation than a rapid rate of freezing. On thawing, the concentrated ice lens results in a higher moisture content in a lesser thickness of soil and thus a more unstable condition.

The number of freeze thaw cycles is largely controlled by surface temperatures. There is complete agreement that frost action is more severe with a greater increase in moisture content resulting from several cycles of freezing and thawing. The effects of refreeze after a thaw are accentuated because the first freeze leaves the soil in a more expanded and an increased moisture condition.

Many cases are cited by Johnson (1952) in which the most severe spring breakup in roads was associated with high precipitation the previous fall. Rainfall exerts a strong influence on the quantity of moisture in the soil and thus the amount of heave when frozen. Another factor associated with rain water percolation in soil is the influence of the heat it carries and its effect on conductivity and diffusivity due to the change in moisture content of the soil.

Insolation influences soil temperatures; for instance, under a black asphalt surface the soil temperatures are higher due to absorption of solar radiation. Frost penetration under northern exposures is deeper due to this insolation effect. Another important climatic factor which effects ground temperatures is snow cover. A thick blanket of fresh snow acts as an insulation blanket which slows the conductivity of heat from the ground and deters the frost line from penetrating down with decreased air temperatures.

2.3 Summary

The oldest concept of frost heaving suggested ice segregation was due to the expansion of water as it freezes. Subsequent work by Taber and Beskow showed experimentally that ice segregation occurs in a soil mass and the ice lenses so formed are responsible for the heaving.

Taber hypothesised that a molecule of water drawn from the adsorbed water film around the soil particle to form the ice lens was replaced by a water molecule drawn from an adjacent water source. It was shown that pore size and permeability of the soil mass exerted a considerable influence on ice segregation. The more recent work of Penner and Martin was reviewed briefly.

Consideration was given to seven factors that have an important influence on the frost heaving phenomena. In order of presentation these are grain size and gradation, mineral type, density, moisture content, pressure at the frost line, structure and climate. Normally the various factors act simultaneously and the evaluation of their individual effects is difficult. Frost action can occur only when the soil type, the associated water conditions and the temperatures are favorable for a sufficient length of time.

CHAPTER III

FIELD INVESTIGATION

3.1 General

A subsurface investigation was carried out during the spring and summer of 1965 on a number of the differentially heaved locations on the Canadian National Railroad. The first investigation was conducted in mid April just prior to ground thaw in order to observe the ice formation in a lump.* During the summer a more detailed subsurface exploration was carried out in order to determine some of the possible reasons for the differential heaving. At Mile 202, in the Wainwright subdivision in Alberta, a series of analyses were conducted on block samples from one lump and one dip,* supplemented with auger borings in four additional differentially heaved locations. Finally an extensive subsurface exploration by means of auger borings was conducted in the Telkwa Subdivision in British Columbia.

3.2 Investigation at Camrose

This investigation was conducted on April 15, 1965, at the time of maximum heave just before thaw of the ground at a site located on the southern outskirts of the town of

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*Refer to "Explanation of Terms"

Camrose, Alberta. Test holes, twenty-four inches in diameter, were bored by means of a disc auger in the centre of the railroad bed, one hole located in the centre of a two to three inch lump, and a second hole on a nearby stretch of level track with no differential heave. The large diameter was chosen in order that an observer could descend below the surface and note any ice formation in the frozen zone.

The investigation revealed no distinct ice lens formation in the walls of the test hole. In the centre of the lump, a few patches of ice were noted which formed in discontinuities in the soil. Minute crystals of ice were also noted by observing the reflection of light from pieces of frozen soil held in the sunlight. The frozen soil had a structure consisting of very fine, short, hairline partitions which could be noted in pieces of the soil when broken apart. In the test hole on the level track ice was not observed. The frozen soil from this location did not reveal the structure noted from the heaved site.

FIGURE 3.1 is a log of the two test holes drilled at Camrose. The moisture content data reveals that the water content in the frozen zone in the centre of the lump, test hole 'S', was higher than in the unfrozen zone below the frost line. A study of the hole log shows the moisture content in the frozen zone to be 21.1%. Approximately one foot above the frost line the moisture content increased to

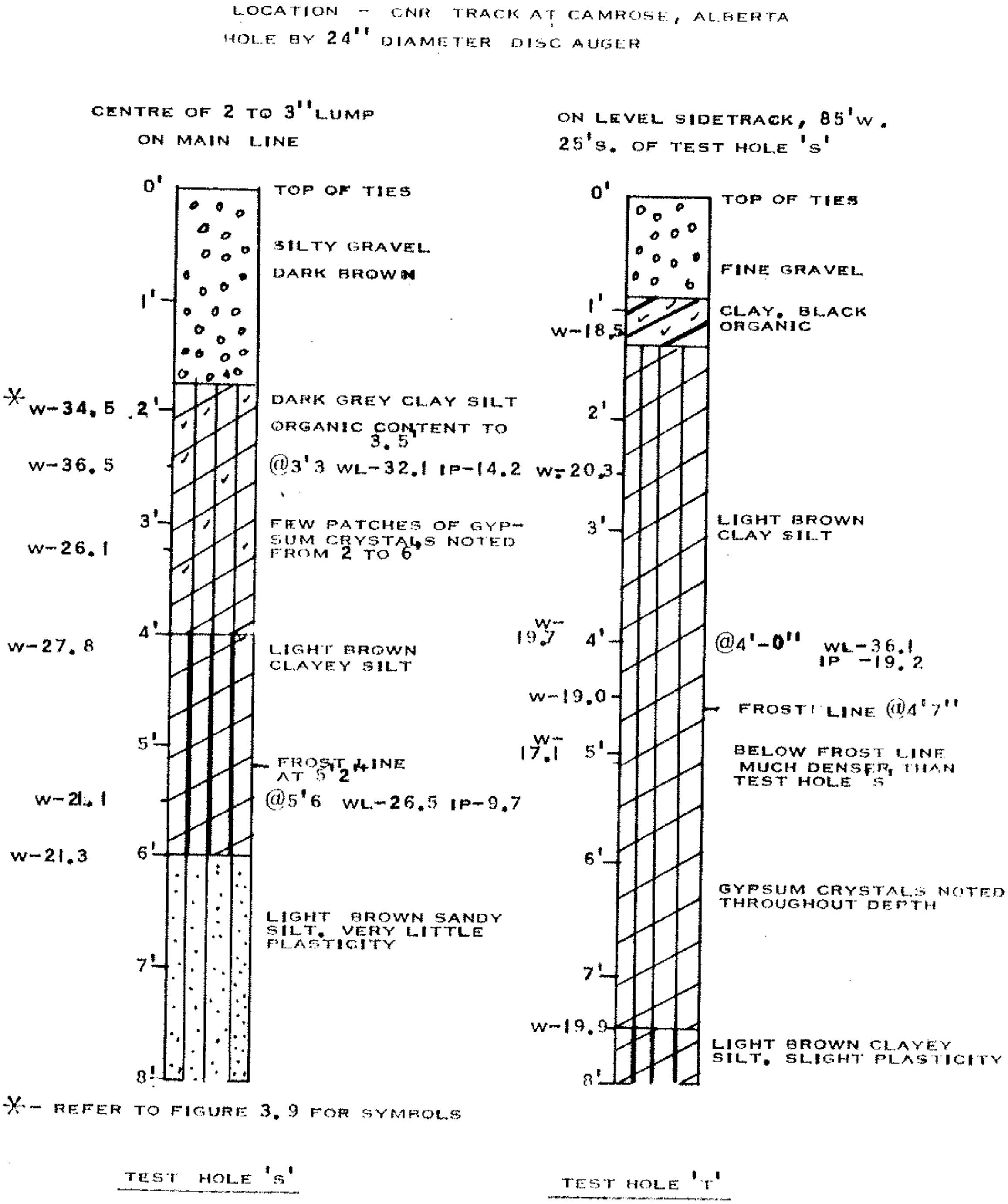


FIGURE 3.1 TEST HOLE LOGS, CAMROSE, ALBERTA, 15 APRIL, 1965

27.8% and two and one half feet above the frost line the moisture content was 36.5%. The increase from 27.8% to 36.5% may be partly due to the increased organic content of the soil.

Test hole 'T' on level track did not show an increase in moisture content in the frozen zone.

The results of this preliminary field investigation and the associated laboratory testing indicate that there was moisture migration to the frost line and that ice segregation did occur. The ice segregation was discontinuous and took the form of small granular masses.

3.3 Block Sample Analysis

One $1\frac{1}{2}$ inch lump and $1\frac{1}{4}$ inch dip at mile 202 in the Wainwright Subdivision (approximately 60 miles southeast of Edmonton) were analysed in detail for soil properties. Test pits were excavated both in the centre and off the lump and dip. Block samples were obtained from the test pits. These samples were analysed in the laboratory for moisture content, Atterberg Limits, degree of saturation, density and void ratio. The detailed procedure of the block sampling and laboratory analysis is given in Appendix A. The logs for the test pits are shown on FIGURE 3.2.

FIGURE 3.3 shows the results of the laboratory

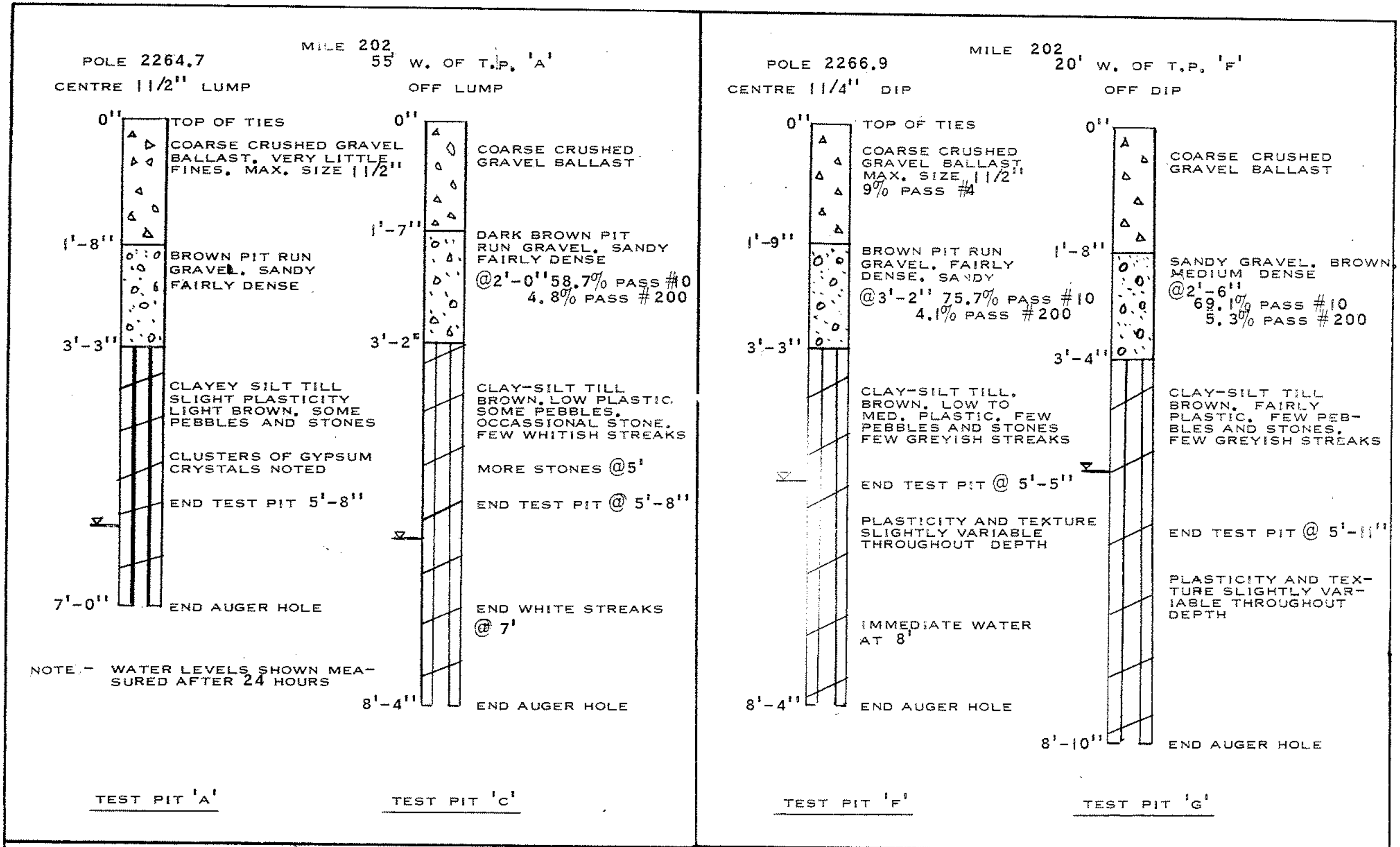


FIGURE 3.2 LOGS FOR TEST PITS A, C, F, AND G, WAINWRIGHT SUB.

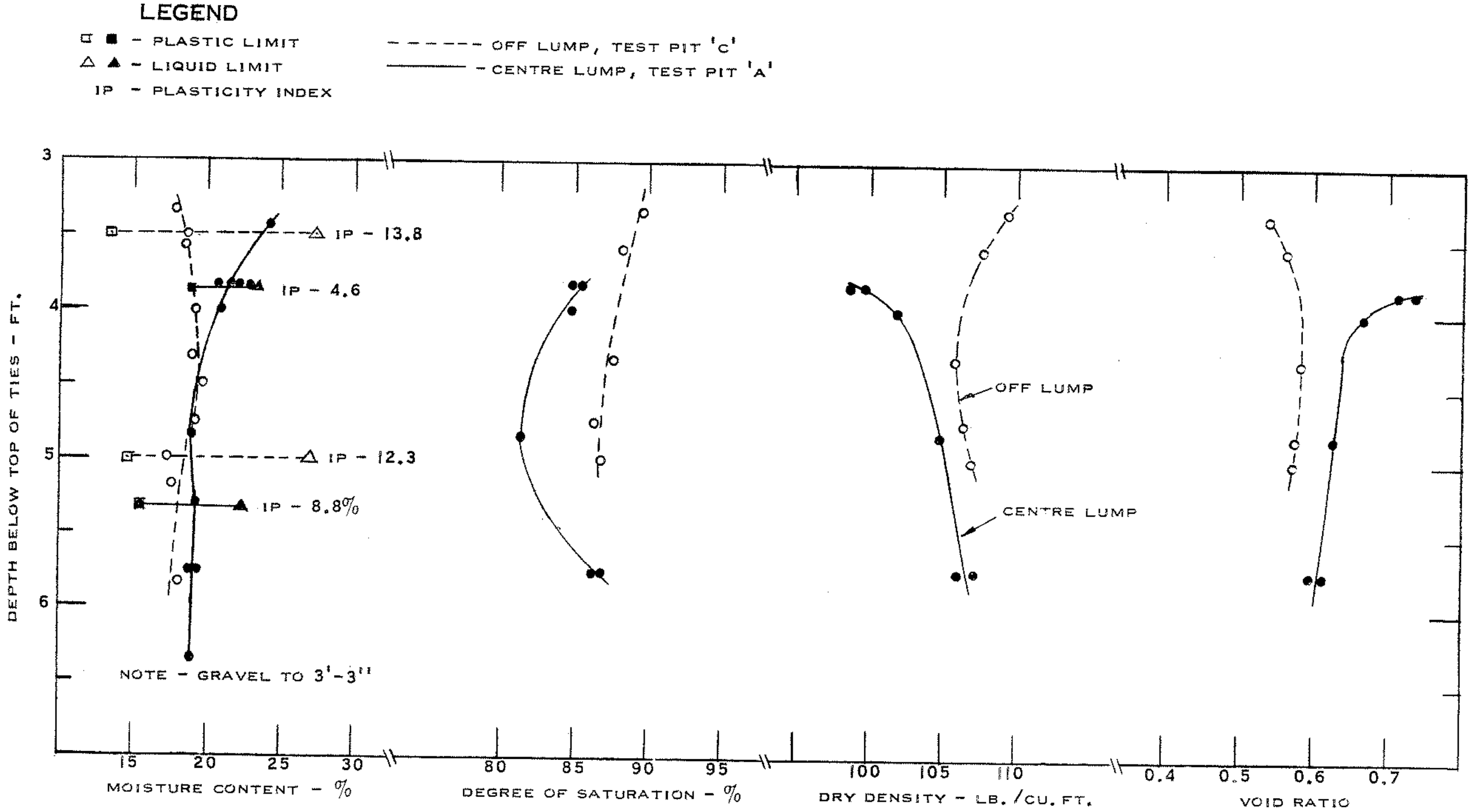


FIGURE 3.3 RESULTS OF ANALYSIS OF BLOCK SAMPLES FOR A LUMP, WAINWRIGHT SUB.

analysis for the block samples obtained from the test pits in the centre and off the lump.

The Atterberg Limits show a less plastic soil in the centre of the lump (plasticity indices of 4.6% and 8.8% at 3'-10" and 5'-4" respectively) than off the lump (plasticity indices of 13.8% and 12.3% at 3'-6" and 5'-0"). Soils with a lower plasticity are, in general, more permeable. This greater permeability would result in a higher rate of moisture migration to the frost line and hence more ice segregation which in turn would result in more heave at the surface. Therefore, at this site, the frost heaving can be explained by the difference in soil type as evidenced by the difference in plasticity.

In addition to the plasticity differences, the curves for dry density and void ratio show an overall lower density and higher void ratio in the centre of the lump. Generally, one would expect a higher density to be associated with the lower plastic material. This trend, however, is reversed when the data of FIGURE 3.3 are compared. A soil with a lower density or higher void ratio has a higher permeability. Again, a higher permeability would permit faster migration of water to a frost line, and thus the density and void ratio are another factor which contributed to more heave in the centre of this lump. Further considerations concerning the effects of density on frost heaving are presented in the portion of this thesis dealing with the laboratory investigations.

Hamilton (1964) conducted closed system freezing tests on remolded clay specimens. The results showed that expansion or shrinkage can occur depending on the degree of saturation. A high degree of saturation resulted in expansion and a low degree of saturation resulted in contraction. The intermediate point at which no volume change occurred was at a degree of saturation of approximately 90%. It was felt that some of the lumps and dips could be explained by a variation in degree of saturation, with the dips having a lower degree of saturation in the centre than adjacent areas. The reverse would be the case for the lumps.

From FIGURE 3.3, the centre of the lump had a lower degree of saturation than the soil off the lump. This condition is contrary to Hamilton's postulate as previously noted. In order to resolve this apparent anomaly, the following reasoning is suggested. Since the water table was approximately 6 feet below the top of the ties it was close enough for moisture migration to the frost line to have occurred, that is, the field condition in this particular instance is not duplicated by a closed system laboratory test. Hamilton's results are, therefore, considered not to be applicable in this case.

According to Johnson (1952), the degree to which a subgrade soil or base coarse is saturated depends on the texture and composition of the soil, the nature of the subgrade soil profile, the density and the climatic conditions including seasonal effects. These items need to be taken into consideration to evaluate the frost susceptibility of any soil for any given locality.

It is felt that little reliance can be placed on moisture content and degree of saturation data obtained during the summer in analysing its effect on frost action. Railroads contain a porous ballast below the ties, through which rain can easily permeate down to the subgrade soil. Also, most of the existing railroad subgrades which were constructed many years ago are lower in the centre than at the shoulders due to the repeated loading and to subsidence. Some of the moisture permeating downward through the ballast is trapped by this concave upward surface resulting in a high degree of saturation in the subgrade. The moisture contents and degree of saturation at the time of sampling could thus vary considerably, depending on the length of time since precipitation occurred. It is suggested that a more appropriate time to obtain moisture content would be after a few inches of frost penetration had occurred which would prevent further moisture movement downward and upward moisture movement due to evaporation.

In FIGURE 3.4 are shown the results of the

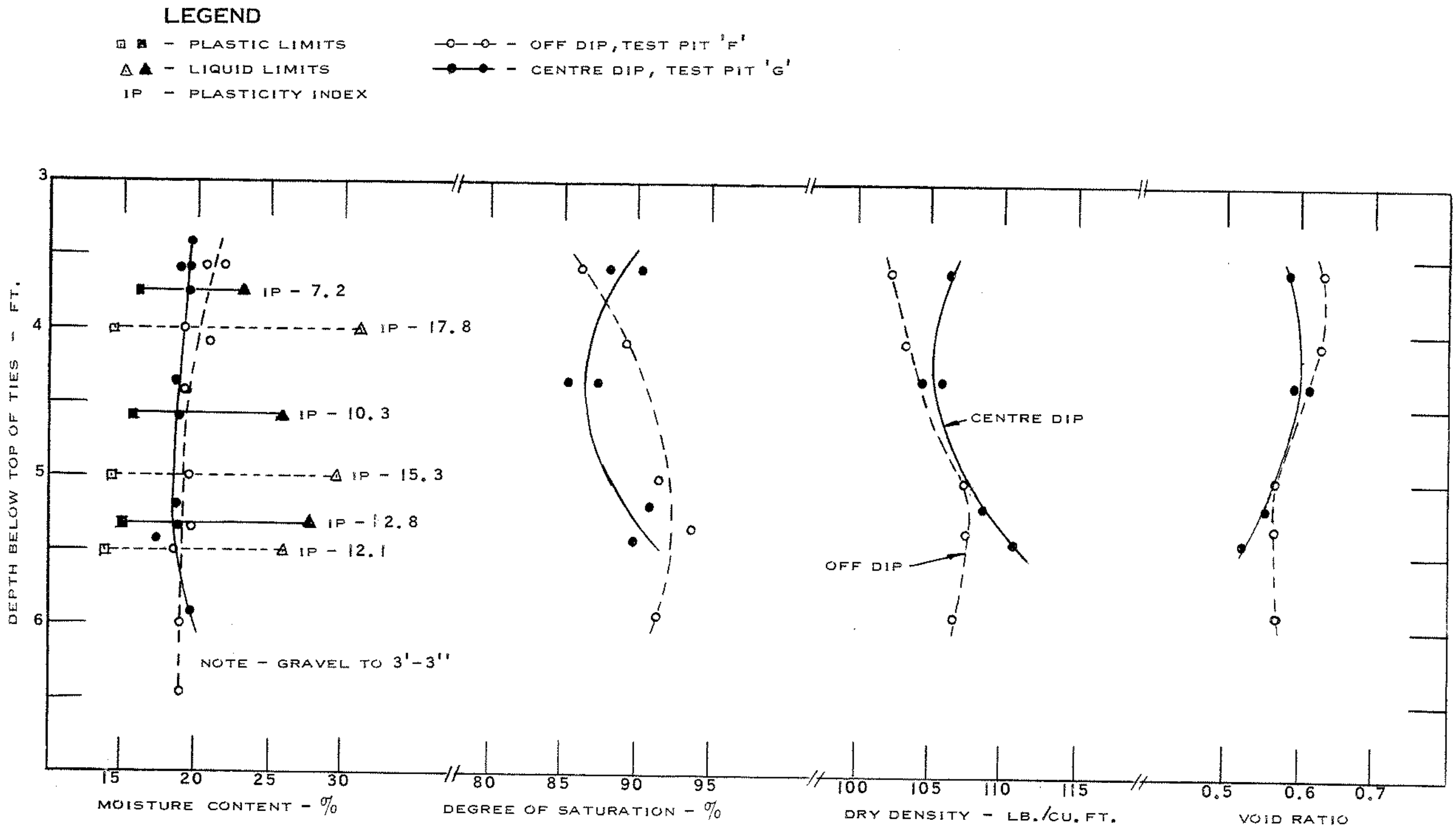


FIGURE 3.4 RESULTS OF BLOCK SAMPLE ANALYSIS FOR A DIP, WAINWRIGHT SUB.

laboratory analysis on the block samples from a $1\frac{1}{4}$ inch dip located at mile 202 in the Wainwright subdivision, pole number 2266.9. The Atterberg Limits did not show a more plastic soil in the centre of the dip. The only reason for differential heave is indicated by the dry density and void ratio curves. A substantially higher density or lower void ratio is shown below the five foot depth in the centre of the dip. The difference between the centre and off the dip increases with depth. A higher density in the centre of the dip would result in a lower rate of migration of moisture to the frost line due to a lower permeability of the soil. This would result in less ice segregation and therefore less heave in the centre of the dip.

The moisture content and degree of saturation data is of little value in analysing the effect on heave for similar reasons as previously noted in analysing the data for the lump.

3.4 Auger Borings

3.4.A General

At mile 202, Wainwright Subdivision, four additional differentially heaved locations were investigated by auger borings. This data, together with the results of the previously discussed block sampling analysis from the lump, indicated that a difference in soil type is an important factor in causing differential heave. With the indication that a difference in soil type is a predominant reason for differential heave, further subsurface exploration by means of auger borings was carried out in the Telkwa Subdivision to substantiate this. The Telkwa Subdivision is located in British Columbia, approximately 150 miles west of Prince George, between the towns of Endako and Smithers, and includes approximately 120 miles of track. This subdivision, in the experience of the CNR, requires the highest amount of shimming in Canada.

The data from the auger borings is presented in the form of test hole logs. Some of the visual analyses of the soil types are supplemented by laboratory analyses which consist of liquid and plastic limits, and washed sieve analysis. The test holes on FIGURES 3.5 and 3.6 were located at mile 202 in the Wainwright Subdivision. The remaining test holes were located in the Telkwa Subdivision. The height noted for each differential heaved location is the maximum height of shims installed as logged in the spring of 1965. In the Telkwa Subdivision, the location of the test holes is noted by pole numbers. One pole length is approximately 140 feet.

The general procedure in this field study was to auger a test hole in the centre of the lump or dip and a companion hole off the lump or dip. The following paragraphs compare the results of sets of holes and attempt to determine the reason for the differential heave at each site investigated.

3.4.B Test Holes 'P' and 'Q' (FIGURE 3.5)

The centre of this 1¼ inch lump, test hole 'P', contains a low plastic clayey silt till subgrade which must be more frost susceptible than the sandy soil below the 3'-3" depth in test hole 'Q' off the lump. The sieve analysis at a depth of 5'-2" in test hole 'Q', shows 31.5 percent passing No. 200 sieve and the Atterberg Limits show the soil to be non plastic. This combination suggests that, under normal conditions this soil should be frost susceptible. It is noted that at 5'-9" the texture changes abruptly to a clean uniformly graded medium sand. This uniform sand may act as a capillary cutoff layer above the water table and prevent or deter moisture migration to the frost line.

3.4.C Test Holes 'R' and 'S' (FIGURE 3.5)

The centre of this 1½ inch dip contains a medium textured sand at 3'-2" which becomes coarser with depth. This sand is less frost susceptible than the clayey silt-till in test hole 'S' off the dip and thus would result in little or no moisture migration to the frost line, resulting in less or no heave in the centre of this dip. The free water level is approximately 1'-3" higher in the auger hole off the dip, which would be another factor contributing to more heave.

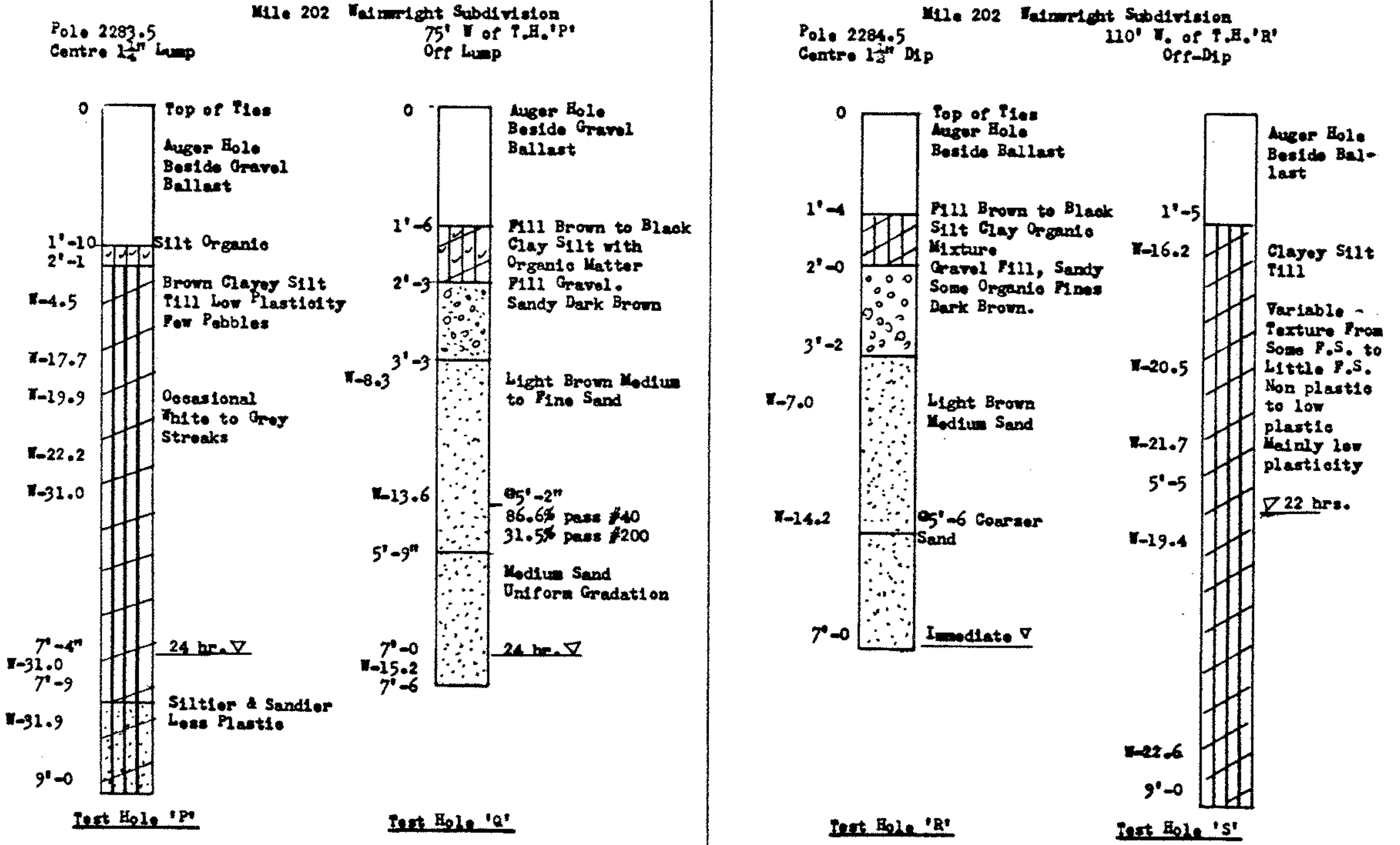


FIGURE 3.5 LOGS FOR TEST HOLES P, Q, R, AND S, WAINWRIGHT SUB.

3.4.D Test Holes 'K' and 'L' (FIGURE 3.6)

Test hole 'L', located in the centre of a 1 inch lump, contains a low plastic clayey silt-till below the fill. Test hole 'K' has a layer of fine to medium sand with some silt from 2'-9" to 5'-2". A descending frost line would draw moisture at a different rate in the different soil types, resulting in more heave at test hole 'L'.

3.4.E Test Holes 'M' and 'N' (FIGURE 3.6)

Very little difference in soil type is shown by these two test holes on centre and off a 1 inch dip. The test hole in the centre of the dip has a slightly less plastic soil, however, the difference is very small. The reason for differential heave at this location is a factor other than a difference in soil type. From the field data available further reasons for this differential heaving cannot be specified.

3.4.F Test Holes 1 and 2 (FIGURE 3.7) Telkwa Subdivision

This portion of track is located in a cut 10 feet deep, and in this instance has poor drainage and a high water table. The differential heave at this location was logged as a slope-off but it was not noted in which area the higher heave occurred. The two test holes show a marked difference in soil type hence a descending frost line would result in a different rate of ice segregation, and thus result in a differential heave.

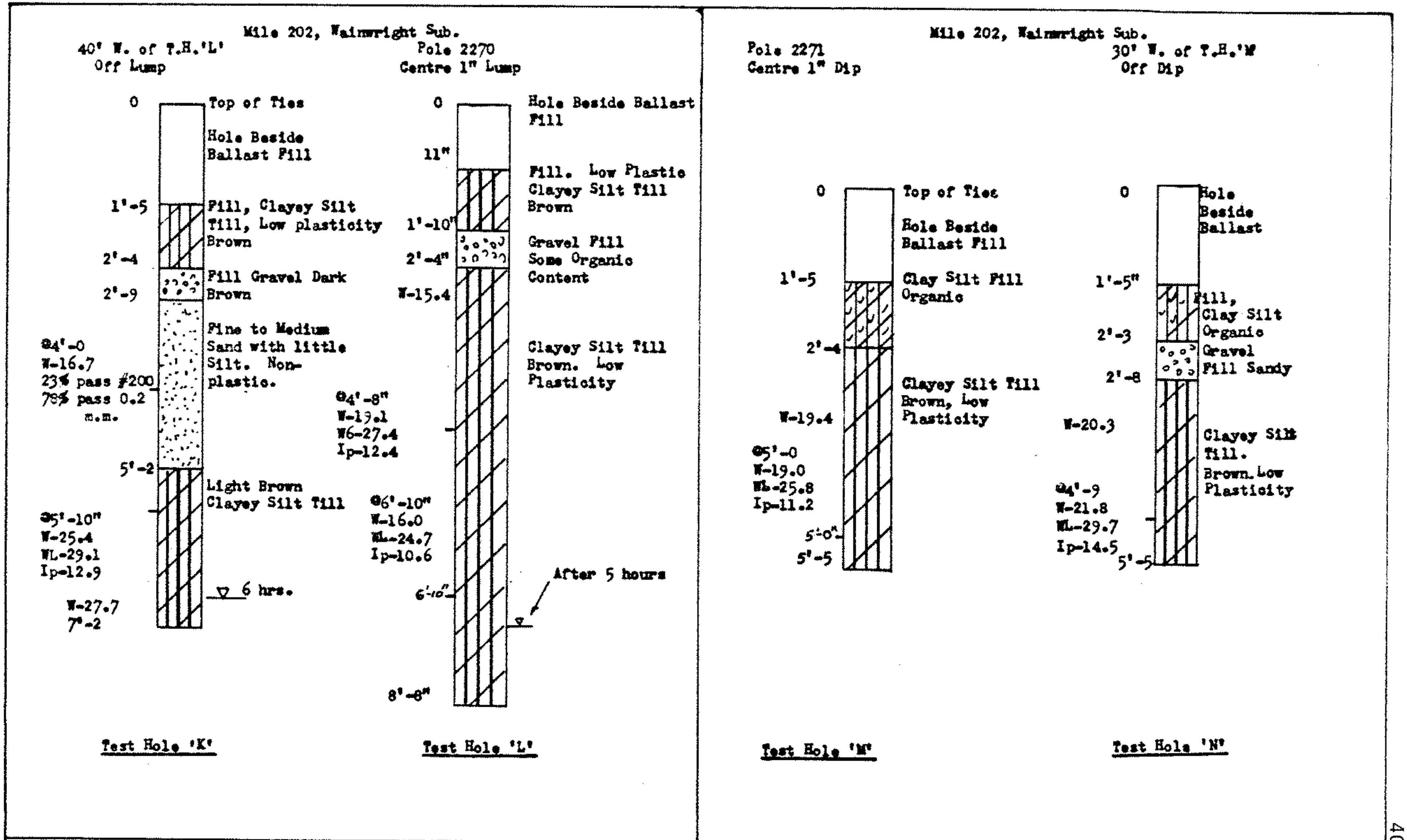


FIGURE 3.6 LOGS FOR TEST HOLES K, L, M, AND N, WAINWRIGHT SUB.

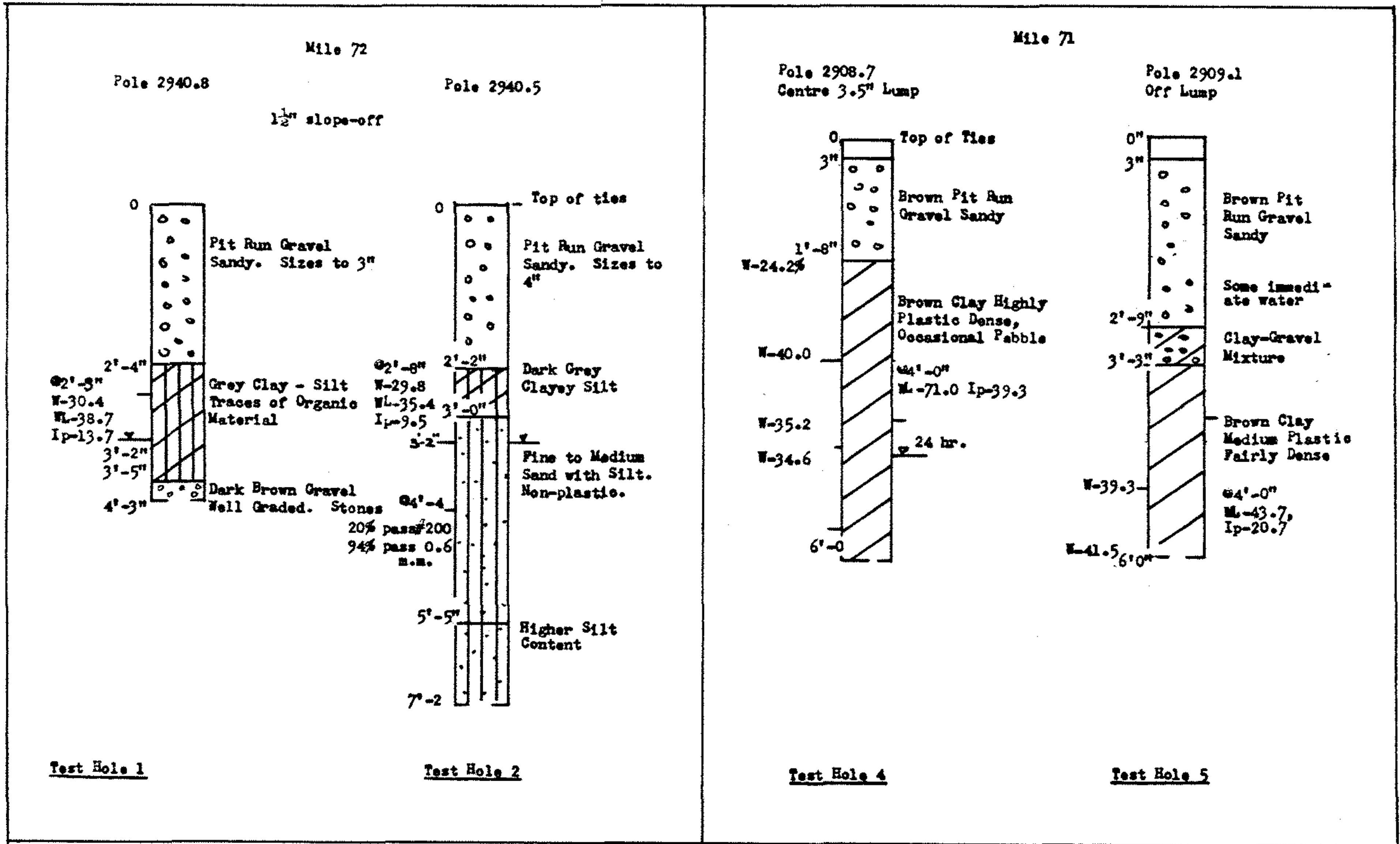


FIGURE 3.7 LOGS FOR TEST HOLES 1, 2, 4, AND 5, TELKWA SUE.

3.4.G Test Holes 4 and 5 (FIGURE 3.7)

The reason for the differential heave at this location is not apparent. The centre of the lump contains a lesser thickness of gravel which is a factor that may contribute to higher heave. On the other hand, the clay located below the gravel is more plastic and one would anticipate a slower rate of moisture migration to the frost line and thus one would anticipate a dip instead of the lump that in fact occurred. Some free water was encountered at the bottom of the pit run gravel in test hole 5. This is most likely water which was trapped above the clay. One would expect this trapped water to saturate the clay beneath and provide moisture conditions conducive to higher heave. This area was approximately 30 feet south of the edge of a slough in which the water level was 4'-8" below top of ties, indicating undesirable water conditions are present.

Frost studies by Minnesota Highway Department showed that cohesive subgrades seldom develop detrimental heaving (Fordyce, 1963). The reason for higher heave at test hole 4 may be due to a fissured structure despite the fact that the soil is a dense, highly plastic clay. Whether a fissured structure was present was not determined in this investigation due to method of augering.

3.4.H Test Holes 6 and 7 (FIGURE 3.8)

Test hole 6, located in the centre of a 3.5 inch

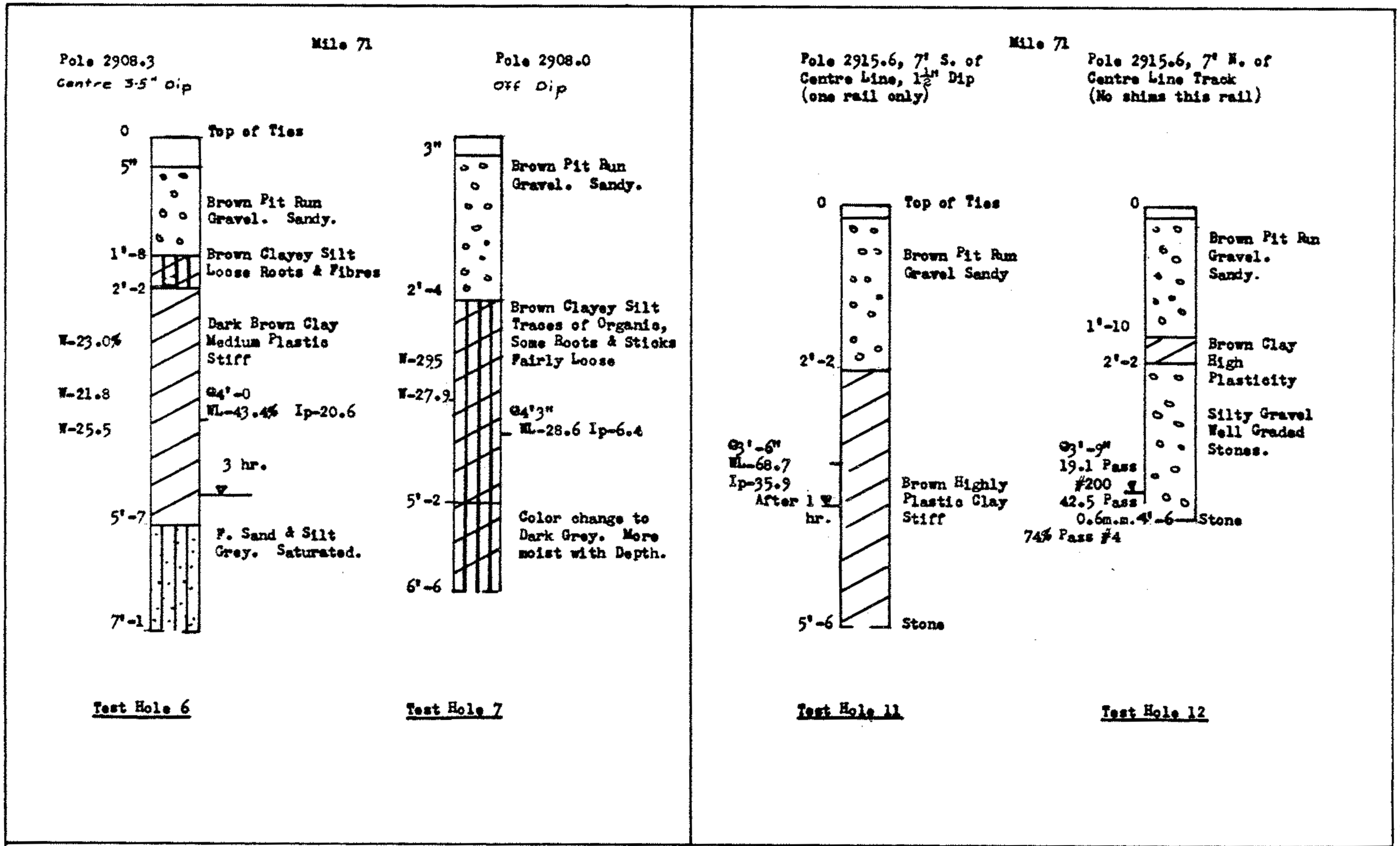


FIGURE 3.8 LOGS FOR TEST HOLES 6, 7, 11 AND 12, TELKWA SUB.

dip, has a more plastic, dense clay which would permit less moisture migration to a frost line due to its low permeability, than the more frost susceptible, loose clayey silt in test hole 7, off the dip.

3.4.I Test Holes 11 and 12 (FIGURE 3.8)

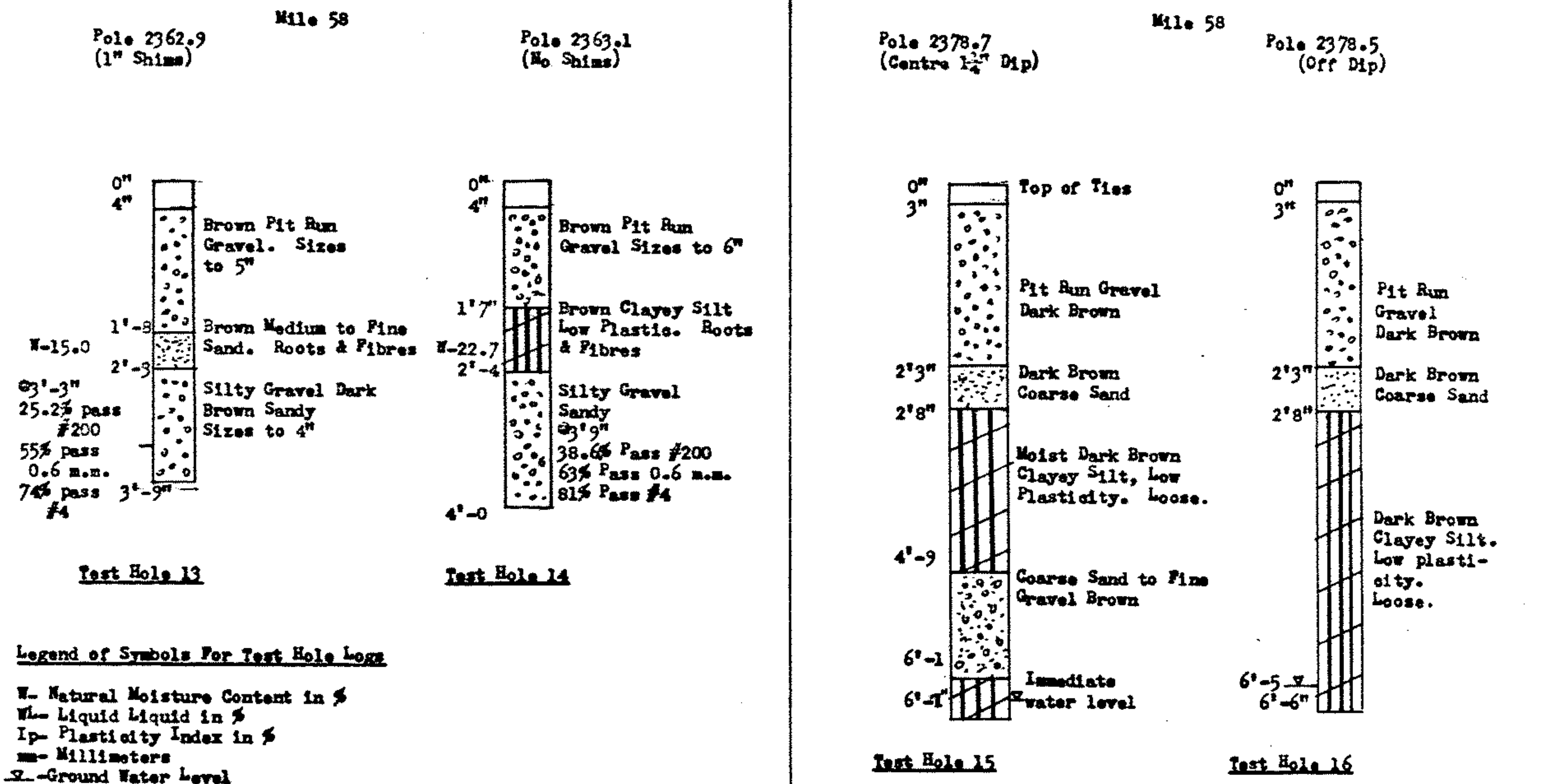
The differential heave at this location was a dip on one rail only. The test holes showed a large difference in soil type, with a 3'-4" layer of clay on one side of the track and predominately gravel with silt on the other side. The highly plastic clay resulted in less heave than the gravel.

3.4.J Test Holes 13 and 14 (FIGURE 3.9)

These test holes are located on a section of track which was treated with calcium chloride applied in granular form between the ties in the fall of 1964. Test hole 13 is on an area with 1 inch less heave than test hole 14. The reason for more heave at test hole 14 is due to a higher content of fines in the gravel below 2'-4". A wash sieve analysis resulted in 38.6 percent passing No. 200 sieve at test hole 14 compared with 25.2 percent at test hole 13. It has been shown by the Corps of Engineers (Linell and Kaplar, 1959) that an increase in the rate of heave results from an increase in the fines in a gravelly soil.

3.4.K Test Holes 15 and 16 (FIGURE 3.9)

The reason for less heave in the centre of this



Legend of Symbols For Test Hole Logs

W- Natural Moisture Content in %
WL- Liquid Liquid in %
Ip- Plasticity Index in %
mm- Millimeters
▽ -Ground Water Level
#200- U. S. Seive Size
T.H.- Test Hole

FIGURE 3.9 LOGS FOR TEST HOLES 13, 14, 15, AND 16, TELKWA SUB.

1¼ inch dip is apparently due to a 1'-4" coarse sand to fine gravel layer acting as a capillary cut-off above the water table, as indicated by a study of test hole 15.

3.4.L Test Holes 19 and 20 (FIGURE 3.10)

Test hole 19 is located in the centre of a 2 inch dip. The log shows a much less frost susceptible coarse sand to fine gravel, and clayey silt layers in the centre of the dip compared with a more frost susceptible silt for the same depth, off the dip. This location also has a high water level. With a descending frost line, the coarse sand to fine gravel and clayey silt would heave much less than the silt, resulting in a depression at test hole 19.

3.4.M Test Holes 21 and 22 (FIGURE 3.10)

Test hole 21 contains a highly frost susceptible silt in the centre of the lump, below the 2'-4" depth. This soil will obviously heave more than the gravel in test hole 22, resulting in a lump at test hole 21.

3.4.N Test Holes 32 and 33 (FIGURE 3.11)

Test hole 32 is located on the high part of a slope-off which required 3 inch shims to level out the abruptness of the differential heave. It is seen that in test hole 32 the silty soil has 85.2 percent pass No. 200 sieve, compared with 17.5 percent passing No. 200 sieve in test hole 33. The soil in test hole 32 with the high

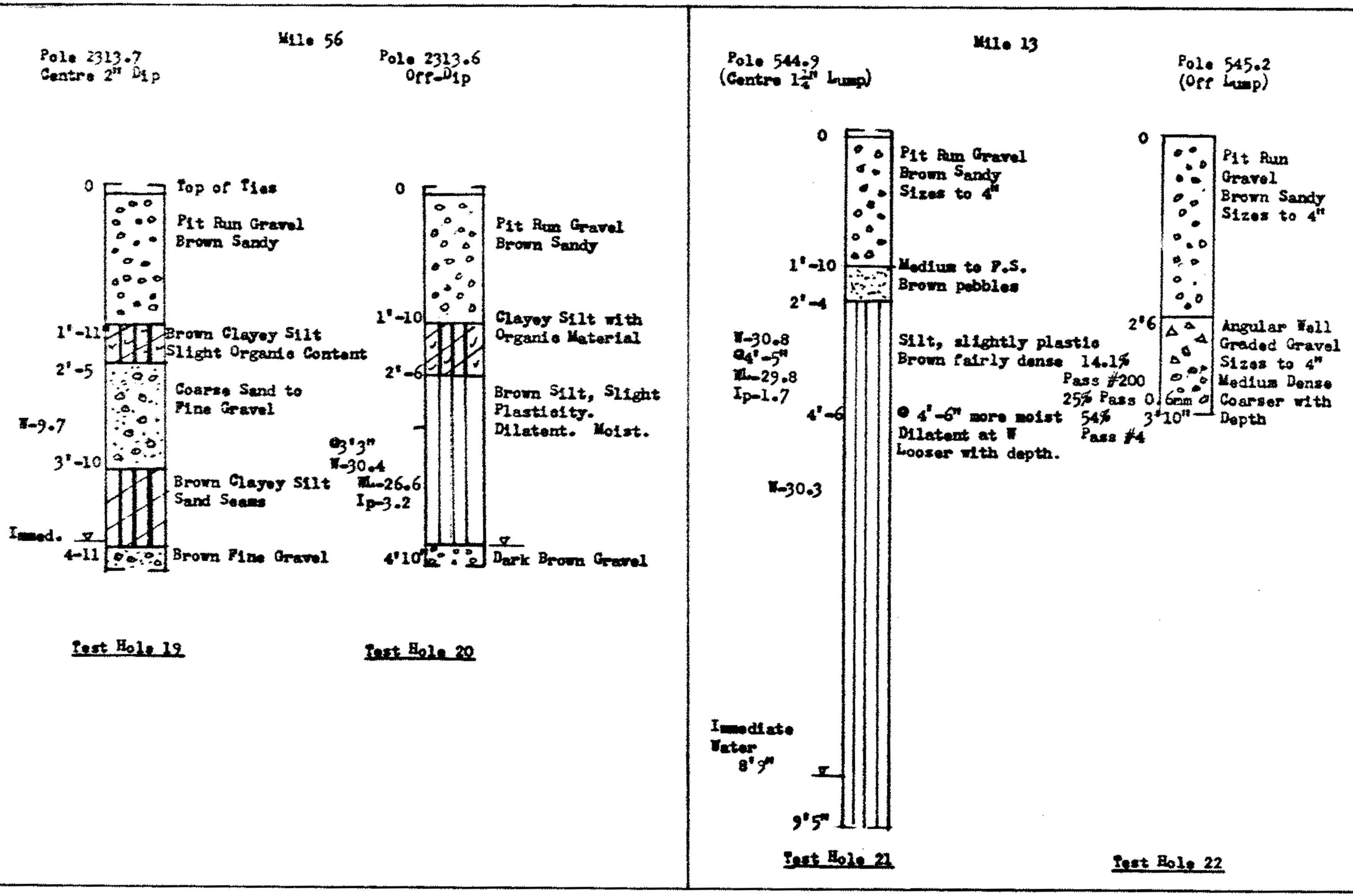


FIGURE 3.10 LOGS FOR TEST HOLES 19, 20, 21 AND 22, TELKWA SUB.

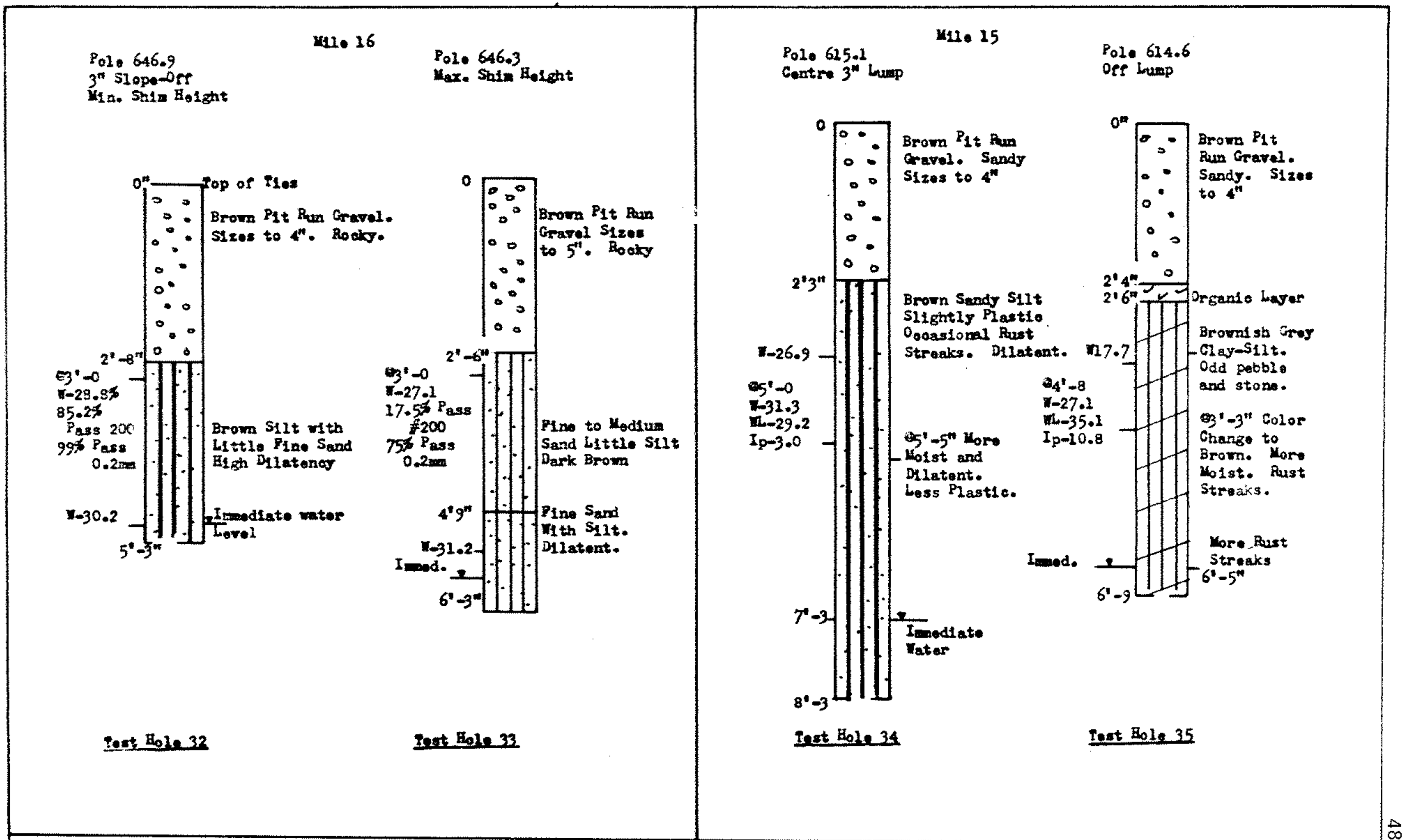


FIGURE 3.11 LOGS FOR TEST HOLES 32, 33, 34 AND 35, TELKWA SUB.

proportion of fines is more frost susceptible and will result in a higher heave.

3.4.0 Test Holes 34 and 35 (FIGURE 3.11)

Test hole 34 in the centre of a 3 inch lump contains a less plastic silty soil (plastic index 3.0%) than test hole 35 off the lump with a clay-silt soil (plasticity index 10.8%). The less plastic silt in the centre of the lump would permit a faster migration of water to a frost line due to its lower permeability, resulting in more heave in the centre of the lump.

3.4.P Test Holes 40 and 41 (FIGURE 3.12)

Test hole 40, located on the centre of the lump contains a less plastic silt and fine sand with silt layer which will permit faster migration of moisture to a frost line than the more plastic clayey silt off the lump in test hole 41.

3.4.Q Test Holes 44 and 45 (FIGURE 3.12)

The soil types from these two test holes were used in the laboratory study. The frost room tests showed the non-plastic fine sand and silt in the centre of the lump (test hole 44) to heave more than the slightly plastic brown silt off the lump (test hole 45).

3.4.R Test Holes 23 to 28 (FIGURE 3.13)

At this location is a lump which required 4 inches

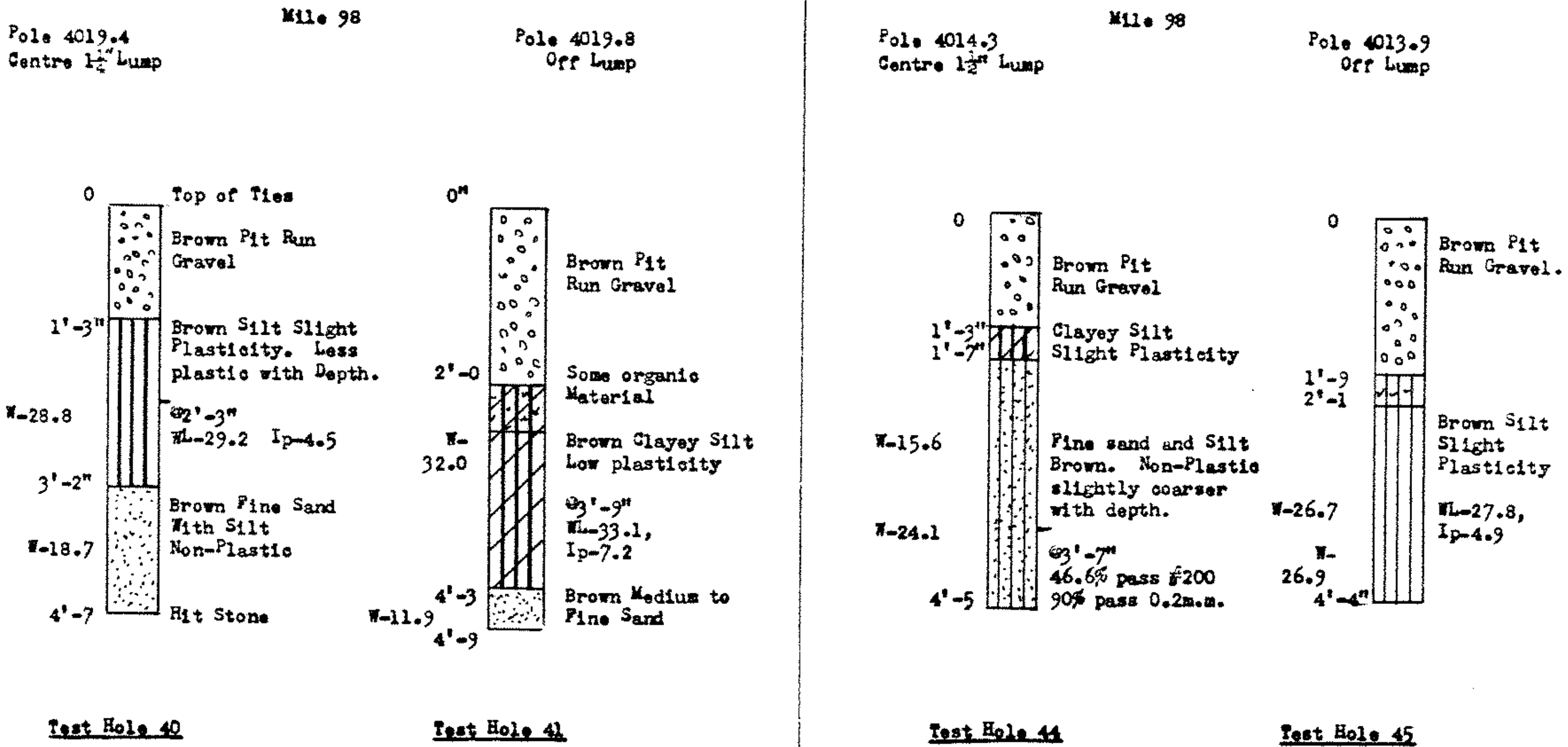


FIGURE 3.12 LOGS FOR TEST HOLES 40, 41, 44 AND 45, TELKWA SUB.

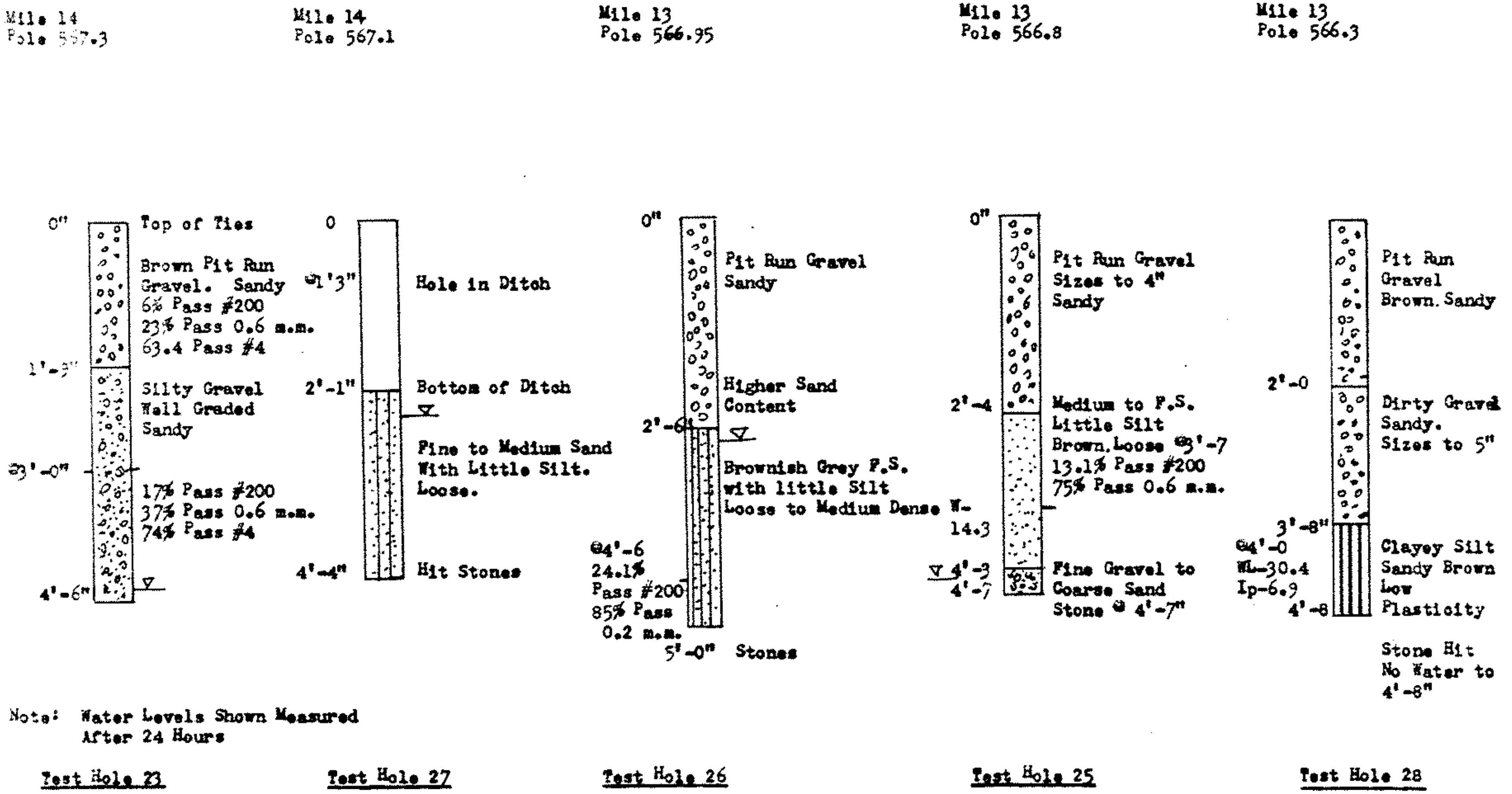
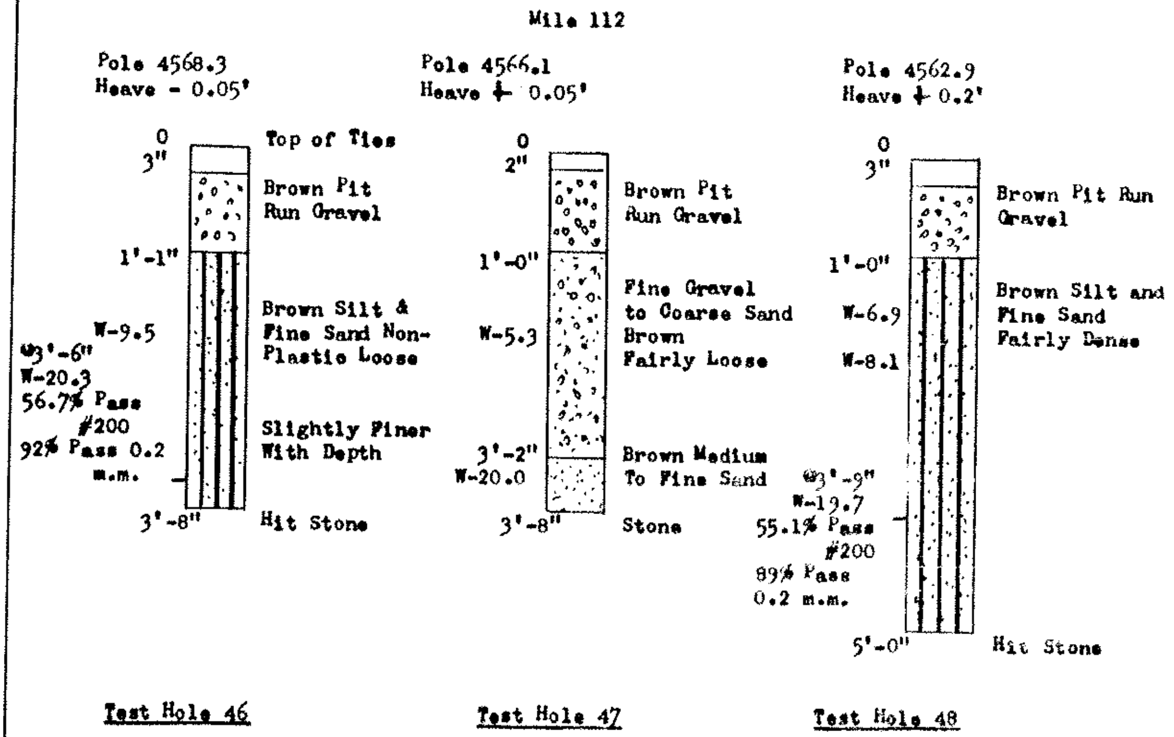


FIGURE 3.13 LOGS FOR TEST HOLES 23, 25, 26, 27 AND 28, TELKWA SUB.

of shimming to level the abruptness of the differential heave. It is an area in which the highest shimming was logged in the Telkwa Subdivision in the spring of 1965. The location of the centre of the lump was not known with certainty hence five test holes covering a distance of 140 feet along the track were dug to obtain a soil profile. The logs indicate that test hole 26 in the centre of the area has a higher ground water level and the most frost susceptible soil, and one would expect the centre of the lump at this location. In any event, the main reason for the heave at this site would appear to be due to the high water table.

3.4.S Test Holes 46, 47 and 48 (FIGURE 3.14)

These test holes are located in an area of the track treated with chemicals in the fall of 1964. The test area consisted of alternate 35 foot lengths of treated and untreated sections. The test holes are located in the centre of three untreated sections. Survey elevations were taken by CNR personnel on the top of ties to record the heave in the spring just before thaw. The heave is shown above each test hole log in FIGURE 3.14. Test hole 46 shows a contraction after freezing. A decrease in the surface elevation may not have actually occurred because movement of the bench mark was noted in the survey notes from a tie to a similar bench mark a short distance away. However, the relative heave between the three test holes is acceptable. Test hole 47 has a



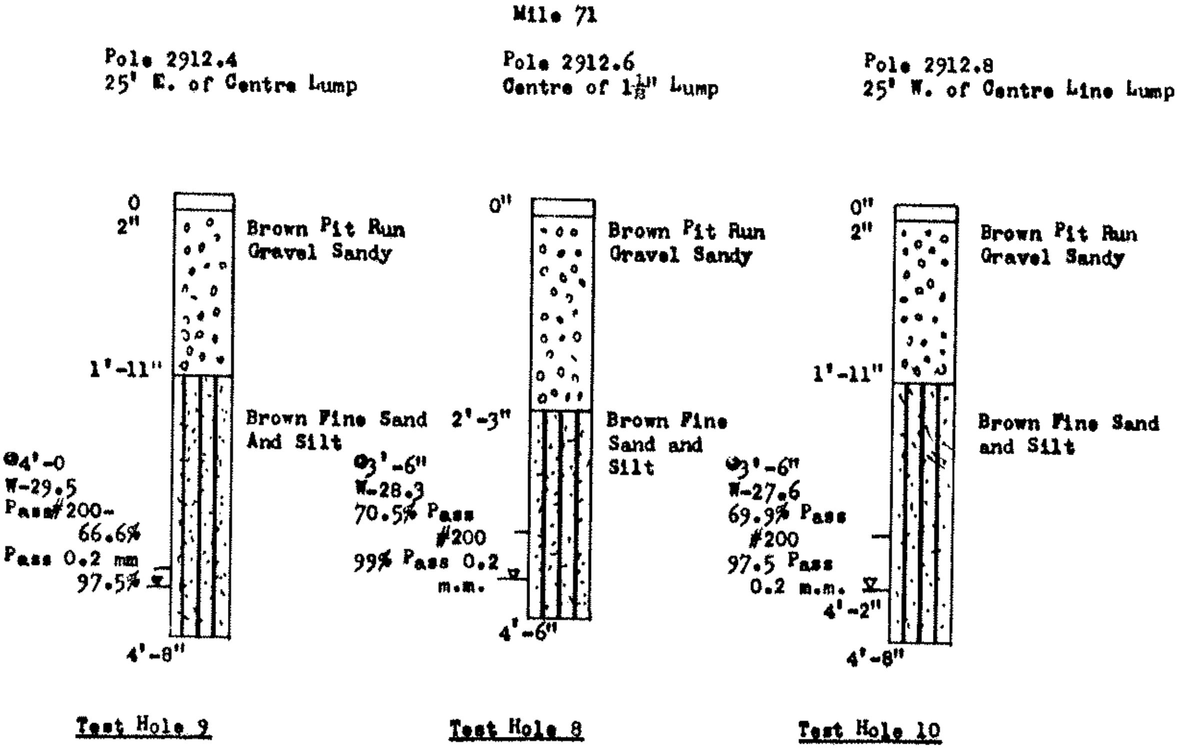


FIGURE 3.14 LOGS FOR TEST HOLES 46, 47, 48, 8, 9, AND 10, TELKWA SUB.

different soil type than test holes 46 and 48, and the difference in heave is probably due to the difference in soil type. Test holes 46 and 48, however, have the same soil type and resulted in a relative difference in heave of 3 inches. From the "feel" of the auger, the soil in test hole 49 was much denser than test hole 46. The difference in heave is probably due to the difference in density. The Corps of Engineers (Haley, 1953) showed that an increase in density in an inorganic silty soil results in an increase in heave.

At the end of each auger hole a stone was encountered, indicating the presence of a gravel layer. Approximately 2000 feet west of this location there is a gravel pit, indicating that the area is underlain by a gravel deposit. The water level could not be established at the test holes. In the gravel pit, the water level was approximately 10 feet below the top of the ties.

3.4.T Test Holes 8, 9 and 10 (FIGURE 3.14)

Test hole 8 is located in the centre of a 1½ inch lump and test holes 9 and 10 are located off the lump, on either side. The three test holes shows a negligible difference in soil type and water level, and the reason for differential heave is not due to these two factors. At the 3.5 to 4 foot depth, the percent passing the No. 200 sieve was 70.5%, 66.6% and 69.9% for test holes 8 to 10 respectively. The reason for differential heave is some other factor than a difference in soil type or depth to water table at this location.

3.4.U Test Holes 30 and 31 (FIGURE 3.15)

Test hole 30 is located in the centre and test hole 31 off a 3 inch lump. There was no apparent difference in soil type in the two test holes. The plasticity index is 4.4 percent and 4.3 percent respectively at the 4.5 foot depth. The soil type is a highly frost susceptible silt. Except at the 2.5 foot depth, the moisture content difference was within 1.5 percent at equal depths in the two test holes. The test holes extended to 9 feet and no water was encountered within this depth at that time of the year. The differential heave at this location is due to some factor other than a difference in soil type.

3.4.V Test Holes 42 and 43 (FIGURE 3.15)

Test hole 42 is located in the centre of a $1\frac{1}{2}$ inch dip and test hole 43 off the dip. Again there was very little difference in soil type in the two test holes. At 4'-6" and 4'-1" the percentage passing No. 200 sieve was 40.5 percent and 43.1 percent respectively. Test hole 42 indicates a water table near 4'-10". The reason for differential heave at this location is not apparent from the field data.

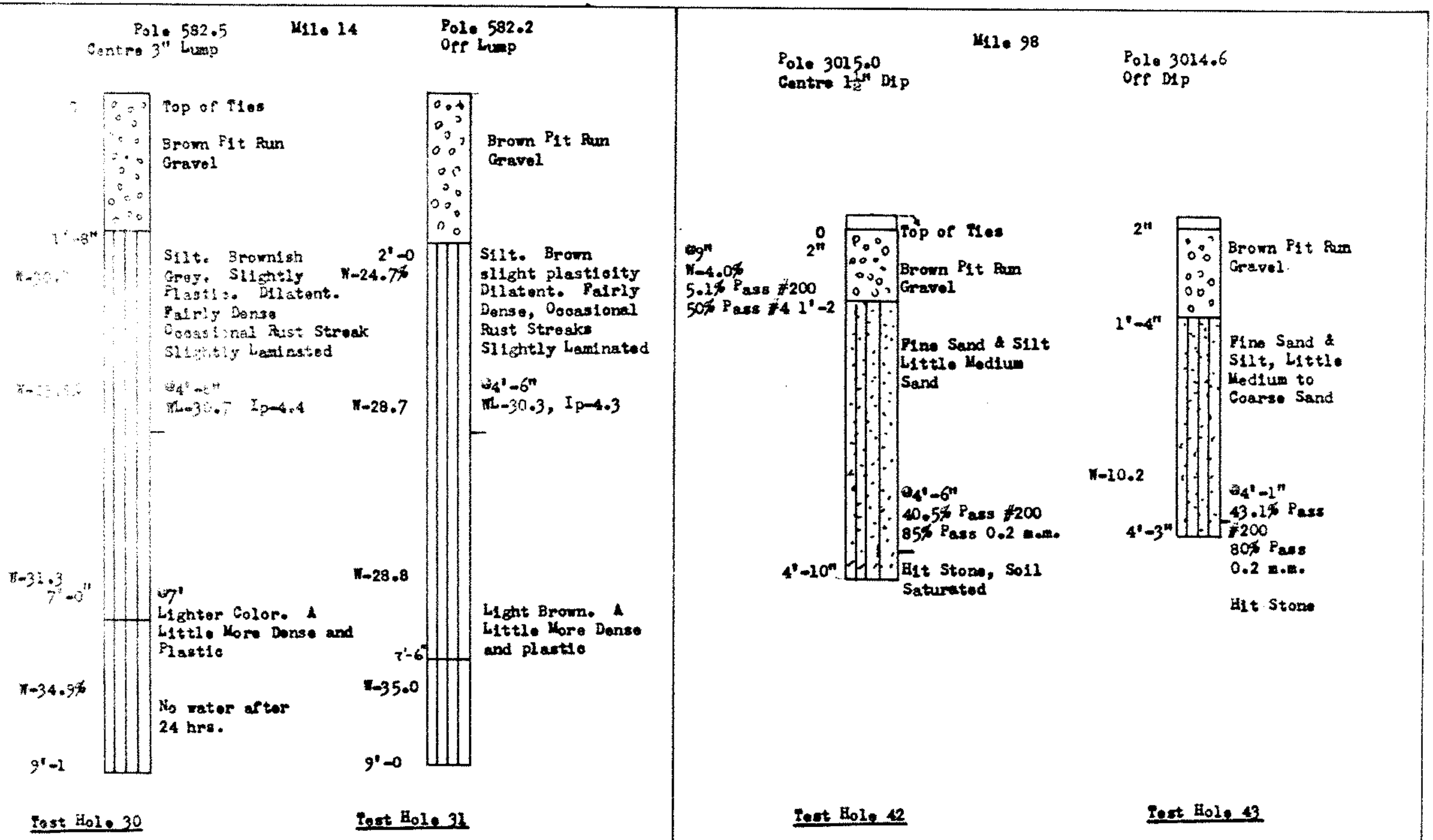


FIGURE 3.15 LOGS FOR TEST HOLES 30, 31, 42 AND 43, TELKWA SUB.

3.5 Summary

The subsurface investigation before ground thaw at Camrose indicated that some moisture migration to the frost line had occurred and ice segregation had taken place in the centre of the lump. The block sample analysis at mile 202, Wainwright Subdivision, indicated that a difference in density or void ratio is a factor in causing differential heave at this site. The data derived from the hole logs and discussed in the preceding pages has been briefly summarized in TABLE 3.1. From a study of this Table, the following tentative conclusions are suggested:

1. The causes for approximately 80% of the differential heaves can be reasonably determined by the simple techniques used in this phase of the investigation.

2. More than 50% of differential heaves appear to be caused by a variation in soil type.

3. The reason for almost 20% of differential heaves investigated could not be determined using the procedures employed. It is suggested that undisturbed soil samples should be obtained before further analyses are conducted.

4. Other factors, such as high water table, density and natural capillary cut-offs account for some 30% of the differential heaves.

TABLE 3.1

SUMMARY OF FIELD INVESTIGATIONS

Serial	Test Holes	Type of Differential Heave	Remarks
1	A,C	1½" lump	Block samples, less plastic and less dense soil in centre.
2	F,G	1¼" dip	Block samples, lower density in centre.
3	P,Q	1¼" lump	More frost susceptible soil in lump (silty till) capillary cut-off layer off lump.
4	R,S	1½" dip	More frost susceptible soil off dip area (silty till).
5	K,L	1" lump	More frost susceptible soil in lump (silty till)
6	M,N	1" dip	Reason not apparent.
7	1,2	1½" slope-off	More frost susceptible soil on high side, high water table.
8	4,5	3½" lump	Anomaly, more plastic soil in centre of lump, perhaps fissures.
9	6,7	3½" dip	More frost susceptible and less dense soil off dip, (silty soil).
10	11,12	1½" dip (one rail only)	Frost susceptible soil off dip.
11	13,14	1" dip	Treated area, more frost susceptible soil off dip (fines in gravel).
12	15,16	1½" dip	Capillary cut-off layer.

TABLE 3.1 Cont.

SUMMARY OF FIELD INVESTIGATIONS

Serial	Test Holes	Type of Differential Heave	Remarks
13	19,20	2" dip	More frost susceptible soil off dip (silty).
14	21,22	1¼" lump	Frost susceptible soil in lump (silt).
15	32,33	3" slope-off	More frost susceptible soil on high side (silt).
16	34,35	3" lump	More frost susceptible soil in lump (silty).
17	40,41	1¼" lump	More frost susceptible soil in lump (silty).
18	44,45	1½" lump	More frost susceptible soil in lump (silty fine sand).
19	23,25,26 27,28	4" lump	High water table, higher proportion of fines passing #200 sieve in centre of lump.
20	46,47,48	heave differences from survey levels	Density and soil type differences.
21	8,9,10	1½" lump	Reason not apparent.
22	30,31	3" lump	Reason not apparent.
23	42,43	1½" dip	Reason not apparent.

5. Judging from soil type and the particular field environment, it is felt that at least 60% of the differentially heaved locations noted would be improved by salt treatment. In addition, those locations listed as "no apparent reason" would also probably show beneficial results from chemical treatment. Overall, some 80% of the differentially heaved areas should show improvement after salt treatment. The beneficial effects of the salts is based on a consideration of the results from field trials carried out by the CNR mentioned in Chapter 1 and on the results of the laboratory work that forms the second part of this thesis. This conclusion is presented at this time in order to complete the field work portion and also since such a conclusion appears to be more appropriately included with field considerations than with the laboratory study.

The preceding is, perhaps, oversimplified. Undoubtedly, in many cases, several factors contribute to the heaving phenomena. However, it is believed that the major cause has been singled out.

The soil types in which differential heaving was noted to occur varied from highly plastic clays to gravels. According to Johnson (1952), "Field observations have definitely established the fact that excessive frost heaving is not restricted to soils of any particular grading or characteristics. Heaving was observed to occur in clays, silts, very fine sands and in textures approaching the grading of gravel." In general, however, the field investigation of this thesis showed that a majority of the differentially heaved locations were in a fine sand to a clayey silt soil type.

CHAPTER IV

LABORATORY STUDY

4.1 Introduction

The present program of the Canadian National Railways deals primarily with laboratory and field experiments with inexpensive chemicals which are known to reduce heave and can be easily applied on the ground surface. To date, their field tests indicate that sodium chloride and calcium chloride are highly suitable. This portion of this thesis deals with a laboratory study in which these two additives were investigated to determine their relative effects in reducing differential heave under controlled laboratory conditions. Due to the many variables in the field, such as soil type, density, degree of saturation, depth of water table, temperature and snow cover, the practical relative effects of the two admixtures is difficult to determine. The optimum amount to be applied in the field is also difficult to establish. It was felt that some of these factors could be more fully investigated under controlled conditions in the laboratory in order to assess more clearly their effects under field conditions of frost heaving.

Lambe (1956) tested various additives in an effort to discover one which would inhibit ice segregation and could be economically used in field applications. His experiments showed that polyphosphate dispersing agents proved to be very promising. This work prompted the inclusion of a polyphosphate in this program, thus the sodium polyphosphate "Calgon" was added as the third admixture.

The basic scheme involved in the testing program may be outlined as follows. The soils selected were compacted to a density determined by a preliminary testing program. Concentrations of 0, 0.05, 0.15, 0.25 and 0.50 percent by dry weight of soil of sodium chloride, calcium chloride and calgon were chosen on the basis of field applications of the salts used by CNR. Batches of 24 samples were made up consisting of soil samples from the lump and off the lump having salt concentrations as noted. Four batches in addition to preliminary tests were required to include all the combinations of soil type, salt and variations of salt concentration. The details of each batch and each specimen are given in Tables 4.2 to 4.8 inclusive.

4.2 Soils Used

The soils used in this laboratory analysis to determine the relative effect of the admixtures were obtained from the field from two lumps during June and July, 1965. Two soil types were obtained from the test pits on centre and off a $1\frac{1}{2}$ inch lump at mile 202, pole location 2264.7, in the Wainwright Subdivision. The soils are designated as Test Hole "A" from the centre of lump and Test Hole "C" off the lump. These soils are from the same test pits at which block samples were obtained and analysed as previously shown on FIGURE 3.3. The soils were obtained from a depth between 4 to 5.5 feet below the top of ties. The other two soils were obtained from a $1\frac{1}{2}$ inch lump, located at pole 3014.3, mile 98 in the Telkwa Subdivision. The soils are designated Test Hole 44, centre of the lump, and Test Hole 45, off the lump. The soils were obtained from a depth of 3 to 4 feet.

The soils were classified in accordance with standard ASTM procedures except for the following deviations:

a) The fraction passing the No. 10 sieve was used for Atterberg Limits instead of the fraction passing the No. 40 sieve.

b) Oven dried soils were used.

c) The liquid limit was determined using the one point method.

The material passing the No. 10 sieve (2 mm. openings) was chosen for Atterberg Limit tests in order that the results could be considered as reflecting the plasticity characteristics of the entire sample but recognizing the necessity for removing the larger sizes. These latter particles would have unduly influenced test results. Oven dried soils were used for convenience and since the organic content and the proportion of clay minerals are both reasonably low, it was considered that the Atterberg Limits would not be significantly influenced. The one point method for determining the liquid limit was a matter of convenience and of saving time.

The properties of the four soils have been summarized on Table 4.1.

4.3 Laboratory Procedure

A detailed laboratory procedure and description of the equipment is given in Appendix A. A brief outline of these procedures is as follows:

Two inch diameter by four inch high soil specimens were used enclosed in rubber membranes. The samples were formed in a split mold and compacted in four lifts using a Standard Proctor hammer. Admixtures were introduced into the specimens by dissolving them in the molding water. A frost box was made in which 24 specimens were frozen at one time under open system conditions. The warm side temperatures were provided by a constant temperature bath and maintained at 46.5°F. The cold side temperatures were obtained by placing the apparatus in a frost room. The temperatures were lowered in decrements every 24 hours from 25°F to -15°F in a one week period. Heave measurements were taken three

TABLE 4.1

SUMMARY OF CLASSIFICATION TESTS

TEST HOLE	A	C	44	45
Location	Centre Lump	Off Lump	Centre Lump	Off Lump
Description	Clayey Silt Till	Clay Silt Till	Silty Fine Sand	Silt
Classification (Unified)	CL	CL	SM	ML
Liquid Limit - %	29.9	29.5	Non-Plastic	27.8
Plastic Limit - %	21.1	14.7	Non-Plastic	22.9
Plasticity Index - %	8.8	14.8	Non-Plastic	4.9
Specific Gravity	2.74	2.69	2.75	2.75
Standard Proctor Dry Density-#/ft^3	109.5	117	109	104.5
Optimum Moisture Content - %	17	13.5	15.5	20
Grain Size - M.I.T. Scale				
Sand - %	47	39	62.5	17
Silt - %	44	37	31.5	70.5
Clay - %	9	24	6	12.5
Pass 0.02 mm - %	35	45	17.5	55

times a day with a moveable .001" dial gauge resting on a straight edge.

Seven different batches were tested. The variables between the seven batches and the specimens within the batches are outlined in TABLES 4.2 to 4.8.

4.4 Discussion of Procedure

According to Penner (1958) simulation in the laboratory of the complex natural field conditions is at best an approximation. Many differences exist between the laboratory procedure and actual field conditions, in this program. The water level throughout the duration of the test was from 4 inches to approximately one inch below the frost line. This is a severe condition which normally does not exist in the field. Frost room temperatures were varied from 25°F to -15°F in a one week period but such a temperature range is not uncommon in the interior parts of Canada. However, this temperature drop was imposed over a four inch specimen, resulting in a very high temperature gradient which is not present under field conditions. The samples were remolded and thus the soil structure or the pore structure may or may not be comparable to that of the same soil in the field. The laboratory test conditions are, in general, more severe than those encountered in the field. However, this may be used to advantage in that differences in frost action will be more pronounced and therefore more easily measured.

TABLE 4.2

BATCH NO. 1 VARIABLES

Compactive Effort - 14,100 ft.#/ft.^{3}
Specimens 1 to 8 - Open System
Specimens 9 to 12 - Closed System

Specimen No.	Soil	Molding Moisture %	Molded Dry Density #/ft.^{3}	Sat. Dry Density #/ft.^{3}
1,2	T.H."A"	20.2	106.7	105.4
3,4	T.H."C"	20.1	107.8	107.5
5,6	T.H. 44	15.4	106.6	106.8
7,8	T.H. 45	19.7	107.6	107.6
9	T.H. 45	19.7	108.6	--
10	T.H. 44	15.4	107.2	--
11	T.H."A"	20.1	107.2	--
12	T.H."C"	19.3	106.4	--

TABLE 4.3

BATCH NO. 2 VARIABLES

No Admix

Specimen Numbers	Soil	Compactive Effort ft.#/ft.^{3}	Molding Moisture %	Dry Density #/ft.^{3}	After Saturation Moisture Content %	After Saturation Dry Density #/ft.^{3}	After Saturation Void Ratio	After Saturation Degree Sat. %
1	T.H.45	3,000	20.3	97.8	24.8	98.5	.74	92
2	T.H.45	3,000	20.3	99.8	23.5	100.1	.71	91
3	T.H.45	6,700	20.3	104.7	21.3	102.9	.67	87
4	T.H.45	6,700	20.3	105.7	--	--	--	--
5	T.H.45	10,400	20.2	106.8	21.2	106.4	.61	95
6	T.H.45	10,400	20.2	106.2	20.7	106.1	.62	92
7	T.H.45	14,100	20.2	107.6	20.3	107.8	.59	94
8	T.H.45	14,100	20.2	106.9	21.6	106.4	.60	98
9	T.H.45	14,100	24.0	99.3	23.6	102.3	.68	96
10	T.H.45	14,100	24.0	99.2	--	--	--	--
11	T.H.45	14,100	22.1	104.4	22.4	104.8	.64	97
12	T.H.45	14,100	22.1	103.3	22.3	103.5	.66	93
13	T.H.44	3,000	15.1	98.4	--	--	--	--
14	T.H.44	3,000	15.1	98.5	22.3	98.5	.71	87
15	T.H.44	6,700	15.1	103.3	21.4	104.0	.63	92
16	T.H.44	6,700	15.1	103.8	--	--	--	--
17	T.H.44	10,400	15.4	106.0	19.5	105.9	.59	89
18	T.H.44	10,400	15.4	105.5	19.4	105.4	.61	89
19	T.H.44	14,100	15.1	107.2	19.0	106.8	.58	88
20	T.H.44	14,100	15.1	107.5	--	--	--	--
21	T.H.44	14,100	17.7	106.7	20.6	105.1	.61	92
22	T.H.44	14,100	17.7	106.8	19.2	106.2	.59	88
23	T.H.44	14,100	21.1	102.3	--	--	--	--
24	T.H.44	14,100	21.1	103.8	--	--	--	--

TABLE 4.4

BATCH NO. 3 VARIABLES

No Admix
Even Numbers Saturated

Specimen Numbers	Soil	Compactive Effort ft.#/ft.^{3}	Molding Moisture %	Dry Density #/ft.^{3}	After Saturation Moisture Content %	After Saturation Dry Density #/ft.^{3}	After Saturation Void Ratio	Degree Sat. %
1	T.H."A"	3,000	16.5	92.7	--	--	--	--
2	T.H."A"	3,000	16.5	93.2	28.4	91.4	.872	89
3	T.H."A"	6,700	16.6	101.9	--	--	--	--
4	T.H."A"	6,700	16.6	102.0	24.7	99.5	.706	96
5	T.H."A"	10,400	16.6	107.5	--	--	--	--
6	T.H."A"	10,400	16.7	107.5	22.5	104.4	.642	96
7	T.H."A"	14,100	16.7	111.0	--	--	--	--
8	T.H."A"	14,100	16.7	110.5	21.6	106.9	.598	99
9	T.H."A"	14,100	21.8	104.4	--	--	--	--
10	T.H."A"	14,100	21.8	104.4	22.6	104.4	.638	97
11	T.H."A"	14,100	19.5	108.2	--	--	--	--
12	T.H."A"	14,100	19.5	108.1	21.2	107.4	.594	98
13	T.H."C"	3,000	12.9	91.6	--	--	--	--
14	T.H."C"	3,000	12.9	91.5	27.0	90.3	.863	84
15	T.H."C"	6,700	12.9	104.1	--	--	--	--
16	T.H."C"	6,700	12.9	103.3	24.0	99.7	.683	95
17	T.H."C"	10,400	13.0	113.1	--	--	--	--
18	T.H."C"	10,400	13.0	112.7	20.4	108.4	.547	100
19	T.H."C"	14,100	13.0	118.7	--	--	--	--
20	T.H."C"	14,100	13.1	119.3	17.0	115.0	.458	100
21	T.H."C"	14,100	15.9	115.8	--	--	--	--
22	T.H."C"	14,100	15.9	115.3	17.8	112.9	.489	98
23	T.H."C"	14,100	19.1	109.0	--	--	--	--
24	T.H."C"	14,100	19.1	108.9	20.3	107.7	.560	98

TABLE 4.5

BATCH NO. 4 VARIABLES

Admix - Sodium Chloride
Compactive Effort - 10,400 ft.#/ft.^{3}

					After Saturation			
Specimen Numbers	Soil	Admix Conc.%	Molding Moisture %	Dry Density #/ft.^{3}	Moisture Content %	Dry Density #/ft.^{3}	Void Ratio	Degree Sat. %
1,2,3	T.H."A"	0.05	16.6	107.1	22.5	104.5	.638	97
4,12	T.H."A"	0.25	17.0	107.1	22.3	104.4	.640	96
5,6	T.H."A"	Nil	16.9	106.6	22.8	103.6	.647	97
7,8,9	T.H."A"	0.15	16.9	105.9	22.6	102.5	.667	93
10,11	T.H."A"	0.5	17.0	106.9	23.2	102.1	.648	98
13,14,15	T.H."C"	0.05	13.4	112.8	20.2	106.2	.564	95
16,17	T.H."C"	0.25	13.4	112.8	20.5	106.3	.579	95
18,24	T.H."C"	Nil	13.3	113.3	20.0	107.0	.570	94
19,20,21	T.H."C"	0.15	13.2	112.9	20.9	106.0	.593	95
22,23	T.H."C"	0.5	13.2	112.6	20.7	105.1	.596	93

TABLE 4.6

BATCH NO. 5 VARIABLES

Admix - Calcium Chloride
Compactive Effort - 10,400 ft.#/ft.^{3}

					After Saturation			
Specimen Numbers	Soil	Admix Conc.%	Molding Moisture %	Dry Density #/ft.^{3}	Moisture Content %	Dry Density #/ft.^{3}	Void Ratio	Degree Sat. %
1,2,3	T.H."A"	0.05	16.5	105.5	22.4	102.6	.653	95
4,12	T.H."A"	0.25	16.2	104.8	22.8	102.3	.671	94
5,6	T.H."A"	Nil	16.3	105.3	23.3	102.1	.675	93
7,8,9	T.H."A"	0.15	16.4	105.6	22.5	103.0	.662	93
10,11	T.H."A"	0.5	16.4	105.0	23.0	102.1	.675	93
13,14,15	T.H."C"	0.05	13.4	111.6	20.9	105.3	.594	95
16,17	T.H."C"	0.25	13.1	111.8	20.7	105.6	.589	94
18,24	T.H."C"	Nil	13.3	111.3	21.1	104.7	.603	94
19,20,21	T.H."C"	0.15	13.3	111.3	20.9	105.0	.587	96
22,23	T.H."C"	0.5	13.0	110.9	20.6	104.5	.595	93

TABLE 4.7

BATCH NO. 6 VARIABLES

Admix - Calgon
Compactive Effort - 10,400 ft.#/ft.^{3}

Specimen Numbers	Soil	Admix Conc.%	Molding Moisture %	Dry Density #/ft.^{3}	After Saturation Moisture Content %	After Saturation Dry Density #/ft.^{3}	After Saturation Void Ratio	After Saturation Degree Sat. %
1,2,3	T.H."A"	.05	16.5	105.5	24.1	101.1	.691	95
4,12	T.H."A"	.25	16.65	108.5	22.5	104.3	.640	96
5,6	T.H."A"	Nil	16.4	102.3	24.8	99.2	.724	94
7,8,9	T.H."A"	0.15	16.5	107.5	24.1	103.0	.659	99
10,11	T.H."A"	0.50	16.6	112.3	20.8	108.5	.576	99
13,14,15	T.H."C"	0.05	13.4	111.7	21.3	105.4	.593	97
16,17	T.H."C"	0.25	13.5	110.0	23.2	102.8	.633	96
18,24	T.H."C"	Nil	13.5	112.4	20.6	106.1	.579	95
19,20,21	T.H."C"	0.15	13.5	111.4	21.5	104.0	.615	94
22,33	T.H."C"	0.50	13.4	107.5	16.0	105.4	.593	73

TABLE 4.8

BATCH NO. 7 VARIABLES

Compactive Effort - 10,400 ft.#/ft.^{3}

Specimen Number	Soil	Admix	Admix Conc. %	Molding Moisture %	Dry Density #/ft.^{3}	Moisture Content %	After Saturation Dry Density #/ft.^{3}	Void Ratio	Degree Sat. %
1,2	T.H.44	Nil	Nil	15.0	106.2	19.9	106.5	.611	90
4	T.H.44	NaCl	.05	15.0	106.1	20.1	106.6	.610	91
7,8	T.H.44	NaCl	0.15	15.0	106.7	19.9	107.0	.603	91
10	T.H.44	NaCl	0.25	15.1	106.7	20.0	107.0	.603	91
12	T.H.44	NaCl	0.5	14.8	107.1	19.7	107.2	.603	90
3	T.H.44	Calgon	0.05	14.9	106.7	19.7	107.1	.602	90
5,6	T.H.44	Calgon	0.15	15.0	106.1	19.9	107.2	.601	91
9	T.H.44	Calgon	0.25	14.9	106.4	19.9	106.6	.603	90
11	T.H.44	Calgon	0.5	14.9	106.3	20.4	106.6	.611	92
13,14	T.H.45	Nil	Nil	19.9	108.5	20.6	107.6	.595	95
16	T.H.45	NaCl	0.05	20.6	108.4	20.7	108.4	.584	97
19,20	T.H.45	NaCl	0.15	20.0	108.2	20.6	107.3	.599	94
22	T.H.45	NaCl	0.25	19.9	107.9	21.2	108.0	.590	99
24	T.H.45	NaCl	0.5	20.0	108.8	20.2	108.8	.578	96
15	T.H.45	Calgon	0.05	19.7	108.6	20.5	108.2	.571	99
17,18	T.H.45	Calgon	0.15	19.9	109.2	20.6	108.5	.582	97
21	T.H.45	Calgon	0.25	20.2	107.2	21.4	106.9	.607	97
23	T.H.45	Calgon	0.5	20.0	107.5	20.5	107.1	.602	94

Rubber membranes were used to enclose the soil specimens, rather than lucite rings or a greased cylinder as have been used by other investigators. One advantage of using rubber membranes is that wall friction is overcome. Also heave is not confined to any specific plane such as in the immediate vicinity of the joints in lucite rings. One disadvantage of using rubber membranes is lateral expansion. In natural ground the sidewise expansion is prevented by adjacent soil pressure. The amount of expansion was checked by measuring the diameter before and after freezing of a number of specimens in each batch. The average increase in diameter for the soil types from test holes 44 and 45 was 3% and 1% respectively. The average increase for the soil types from test holes "A" and "C" was 0.5%. This increase in diameter is small and has been considered to have a negligible effect on vertical heave of the specimens. Most of the increase in diameter was subsequently found to be due to a thin coating of ice that formed between the membrane and the soil.

Except for Batch No. 7, two or three duplicate samples were made for each variable tested. According to Lovell (1957), the preparation of samples to achieve a given moisture density with precision, to achieve a uniform moisture density throughout the sample and to reproduce a uniform moisture density condition between a number of samples is a problem that has never been completely solved. In order to reduce the effects of this problem great care was used to assure uniformity among samples. All the specimens were compacted and stored in the moisture room to avoid evaporation before placing in the frost box. Each lift of soil was weighed before compacting in the mold, to provide a uniform thickness of lifts. With this procedure dry densities varying by only one pound per cubic foot were obtained among specimens for the same soil type and compactive effort. Despite these precautions the occasional sample showed an erratic behavior as evidenced by a substantially higher or lower rate of heave. Luck (1953) mentions occurrences of similar, unexplainable erratic heave of some samples. Individual specimens which displayed an erratic behavior inconsistent with the average trends were disregarded. In general duplicate specimens displayed a similar behavior.

A low surcharge equal to 0.15 psi consisting of a 2 inch diameter by 1 inch aluminum disc was used on top of each specimen. This is much less than the estimated field surcharge of up to 5 psi assuming a frost line depth of 5 feet. A high surcharge could not be used because the specimens were only supported laterally by rubber membranes and zonolite insulation, hence a high surcharge might have caused the specimens to flow laterally or to shear. A low surcharge results in a higher rate of heave (Beskow, 1935).

Three thermocouples were inserted in each of two specimens in each batch. The thermocouples did not appear to affect heave since no consistently high or low heave was recorded for these specimens.

Most of the areas investigated as outlined in the previous chapter had a fairly high water table, indicating that the field conditions more closely approached the open system rather than closed system conditions. The locations from which the soil types were obtained used in the freezing tests came from areas of high water table. Therefore, the open system conditions as used in this investigation are felt to be acceptable.

The capillary saturation to which some of the specimens were subjected prior to freezing (see Appendix "A" for detail) resulted in an overall increase in moisture content. In Batches No. 4 to 7 (excluding Batch #6) a reasonably constant moisture content after saturation was attained by the different specimens. (Refer to TABLES 4.5 to 4.8). The degree of saturation attained varied from 93 to 98 percent for test holes "A" and "C", and 90 to 99 percent for test holes 44 and 45. Batch No. 6, with Calgon as the admix, displayed different density and moisture characteristics due to the dispersing effect of the additive. This will be discussed subsequently in this chapter.

An increase in moisture content caused the samples to swell during saturation. This generally resulted in a decreased dry density as shown in TABLES 4.2 to 4.8. The silt, and silty fine sand in test holes 44 and 45 exhibited very little swell compared with the more clayey soils in test holes "A" and "C". In a few cases the specimens from test holes 44 and 45 showed an increase in dry density after saturation, due to contraction.

Some additional specimens for the soil from test hole "C" were made up and saturated for an additional two days beyond the standard 24 hours to check the change in density, moisture content, and degree of saturation. The data showed an average decrease in density of 0.3 lb. per cu. ft., an average increase in moisture content of 0.7% and in degree of saturation of 3.5%. When compared to the standard test they indicate that these changes were almost complete during the first 24 hours, and little change resulted with the additional saturation.

4.5 Presentation and Discussion of Laboratory Data and Results

4.5.A Temperature versus Time

FIGURE 4.1 is a typical plot showing the frost room temperatures used and the advance of the 32 degree isotherm in the specimens. The frost room temperatures shown were kept constant for Batches No. 4 to 7 in which admixtures were used. In general, the temperature was lowered from 25°F to 17°F in two decrements during the first 40 hours,

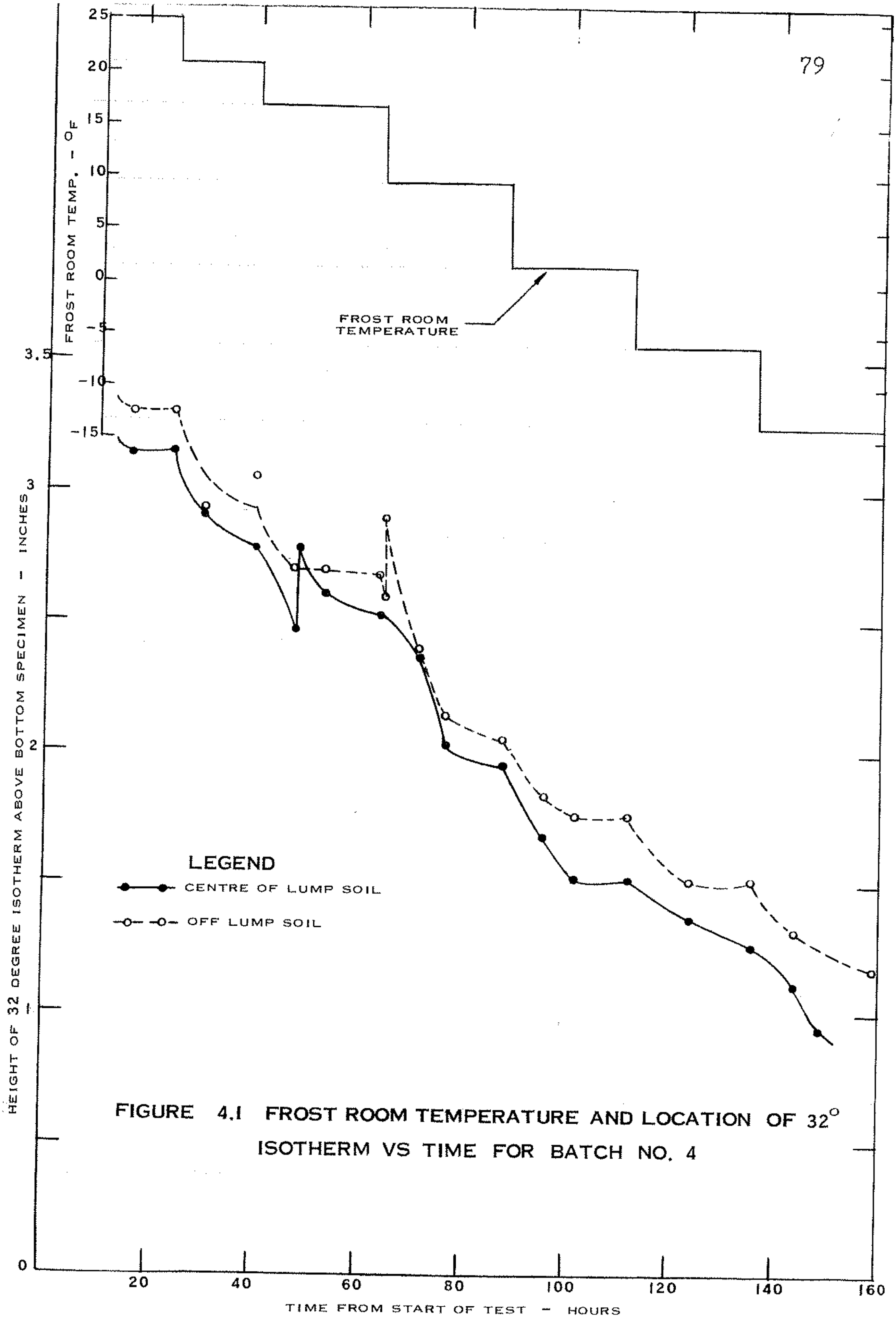


FIGURE 4.1 FROST ROOM TEMPERATURE AND LOCATION OF 32° ISOTHERM VS TIME FOR BATCH NO. 4

then lowered in approximately 8 degree decrements every 24 hours to -15°F.

The lower curves on FIGURE 4.1 show the location of the 32°F isotherm above the bottom of the specimen. The points for the curves were obtained from three thermocouples spaced one inch apart in two specimens in each batch. The temperatures were recorded by a continuous "Brown" recorder. The location of the 32° isotherm was obtained by interpolating the temperature between the thermocouples assuming a linear distribution, and correcting for heave between thermocouples.

The penetration of the 32° isotherm, generally followed the frost room temperature decrements. With a decrease in temperature, there was a more rapid rate of downward movement at the start, decreasing to a lower rate of penetration or stationary location of the 32° line towards the end of the 24 hour interval before the frost room temperature was again lowered. The ice formation in the specimens appeared to follow the fluctuations in rate of frost line penetration. Thicker and more concentrated bands of ice were observed in the specimens when the rate of frost penetration was slow.

The fluctuations in the lower curves illustrate the occurrence of supercooling. The 32 degree isotherm, after penetrating some distance into the sample, suddenly receded before readvancing. A similar occurrence has been observed by the Corps of Engineers (Haley and Kaplar, 1952). This phenomenon is due to the release of the latent heat of fusion, after the water in the soil pores has been cooled below the freezing point. It was noted that the heaving of specimens began about the time when this supercooling effect occurred. In general, supercooling and thus the beginning of heave did not occur until the frost room temperature was lowered to 17 or 9 degrees Fahrenheit. The soils from the centre of the lump tended to heave sooner than the soils off the lump. The addition of sodium chloride and calcium chloride tended to delay the start of heaving with an increase in concentration.

The data shown in FIGURE 4.1 when applied to subsequent sample observations indicate that heave did not commence until the frost line had penetrated approximately 1 to 1.5 inches below the top of the sample. This upper 1 to 1.5 inches of the specimens were homogeneously frozen. From measurements after removing the specimens from the frost box, an average of 1 inch of the bottom of the specimen was unfrozen. Thus ice segregation took place in only an average length of 1.5 to 2 inches of the specimens.

4.4.B Heave versus Time Plots

Batch No. 1 was essentially intended as a pilot test to check the suitability of the apparatus. The four soil types were compacted using a constant compactive effort close to that used in the Standard Proctor test. The specimens for test holes "A" and "C" were compacted at approximately the field moisture content. The specimens from test holes 44 and 45 were compacted at a moisture content near optimum. Eight specimens were tested under open system conditions and four specimens under closed system conditions in this batch. The heave versus time results are plotted on FIGURE 4.2. The rate of heave curves shown are not representative of the curves for the other batches. This is believed to be due to a defective thermostat as described in the following paragraph.

At 95 hours the thermostat setting had to be changed to raise the temperature from 44.5 to 46.5°F, which was the warm side temperature which had to be maintained for all the batches. This increase in temperature must have raised the frost line and melted some of the previously formed ice lenses resulting in a decrease in heave during the subsequent 16 hours. This experience indicated that heave of the specimens is very sensitive to increases in the warm side temperature.

Since all the specimens were frozen under the same conditions, this data indicates the relative frost susceptbility of the four soil types at the particular densities andcompaction moisture contents for the open system conditions. From the data, it is seen that the Telkwa soils,

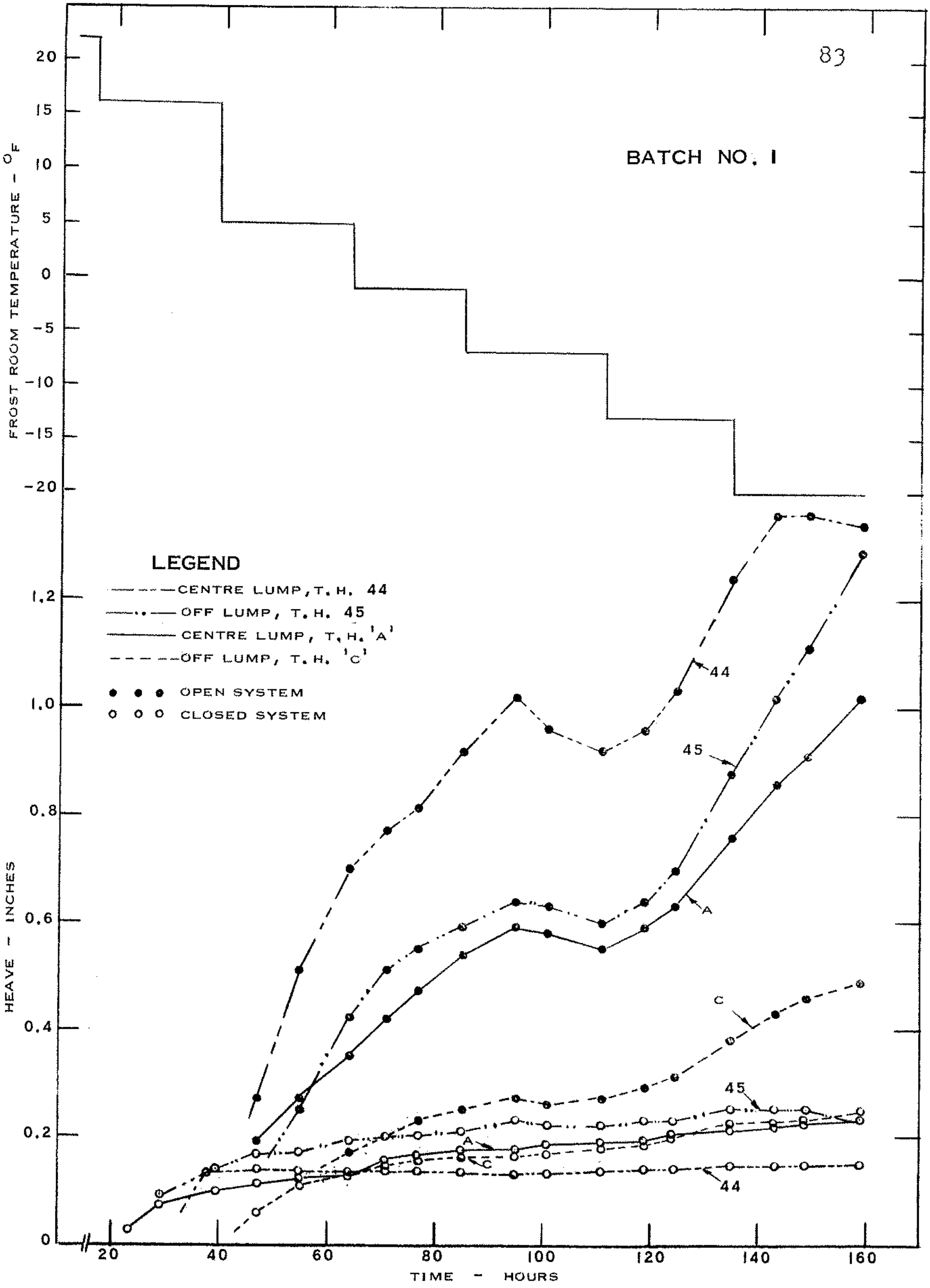


FIGURE 4.2 FROST ROOM TEMP. AND HEAVE VS TIME FOR BATCH NO. I

test holes 44 and 45, are more frost susceptible than the Wainwright soils represented by test holes "A" and "C". All the soils from the centre of the lump heaved more than the soils off the lump thus laboratory observations are broadly similar to those in the field.

The specimens tested under the closed system conditions resulted in a rapid heave at the start and tapered off to a low rate of heave. The total heave under closed system was much smaller than under open system conditions. This is considered due to the lack of a continuous supply of water to the frost line under the closed system conditions. Test hole 45, off the lump, showed a higher heave than test hole 44, on the centre of the lump which is not representative of field conditions. The specimen for test hole 45 was molded at a moisture content of 19.7% compared with 15.4% for test hole 44. Test hole 45 resulted in more heave due to the higher initial moisture content. Samples from test hole "A" and "C" were molded at moisture contents of 19.3% and 20.1% which resulted in a similar amount of heave for both soils.

The data from Batch No. 1 indicated that open system conditions are more representative of the heave occurring under field conditions. Therefore, the subsequent batches were tested under open system conditions.

FIGURE 4.3 is a plot of heave versus time for the

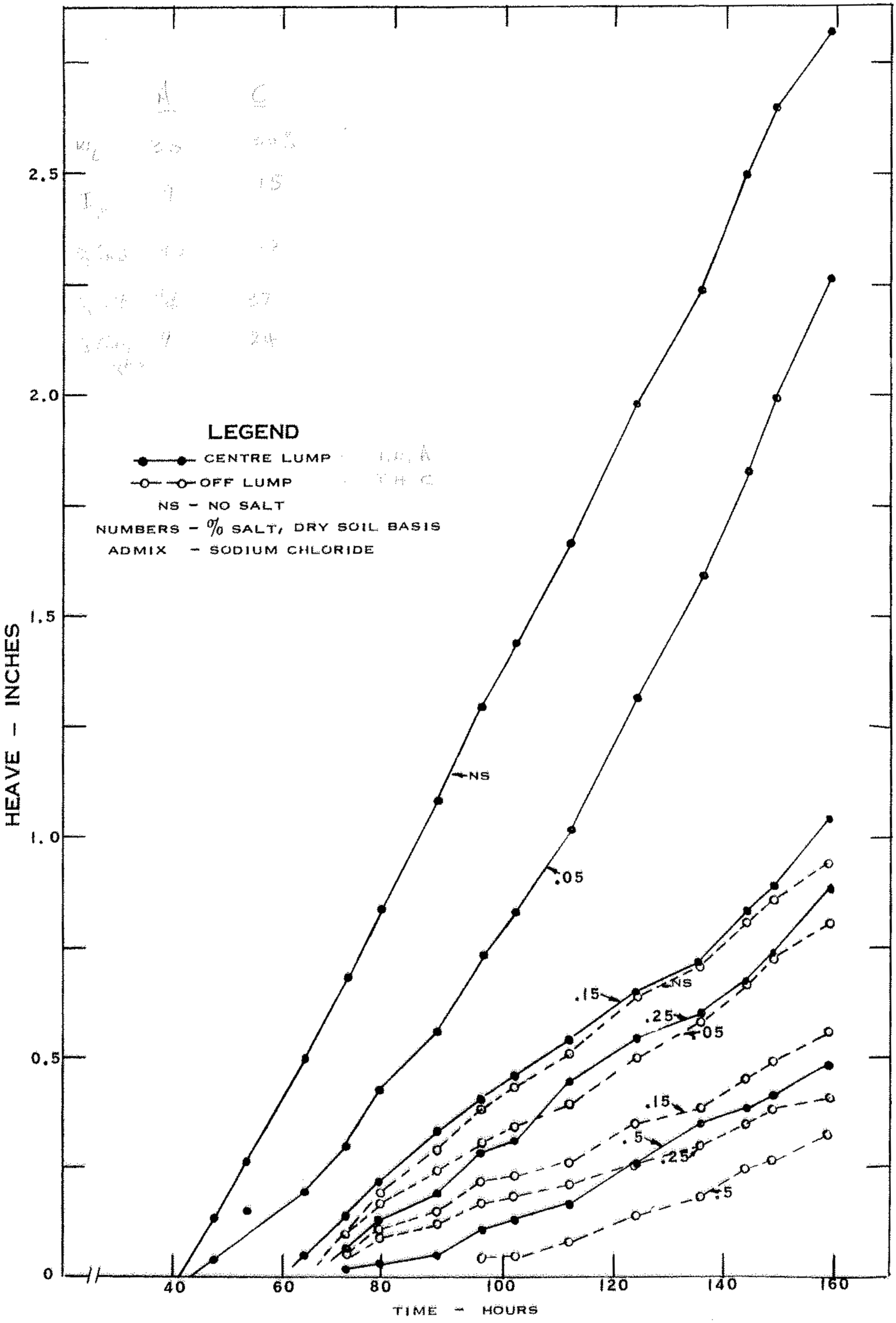


FIGURE 4.3 HEAVE VS TIME FOR BATCH NO. 4

specimens tested in Batch No. 4. This plot is typical of the curves obtained for the other Batch Numbers 2 to 7 inclusive. The admix used in Batch No. 4 was sodium chloride. The numbers beside the curves are the percentage of admixture introduced based on the dry weight of soil. Two soil types from the centre and off the lump were tested in the frost room in each batch under the same warm and cold side conditions.

From FIGURE 4.3 it is seen that the heave for the different concentrations and soil types showed an approximate linear relation with time. The fact that rate of heave is essentially independent of the rate of frost penetration or fluctuations in the cold side temperature has been experimentally shown by Beskow (1935). Some irregularities are noted in the curves of FIGURE 4.3. This was probably caused by a non-homogeneous soil density of the specimens in the vertical direction due to compaction in lifts. The effect of an increasing concentration of the admix is to decrease the slope of the curve or the rate of heave. The decrease in rate of heave is much greater for the soil from the centre of the lump. The graphs also illustrate another effect of the salt additive, that is, an increase in salt concentration showed a trend toward delaying the time of start of heave. This delay is most likely due to a depression of the freezing point of pore water by the presence of the salt.

The plots of heave verus time as shown in FIGURE

4.3 for Batch No. 4 are representative of curves obtained for the other Batch numbers 2 to 7 inclusive. These curves are included in Appendix B. An approximate linear relationship resulted. In Batch No. 2, the curves showed many more irregularities. This is believed to be due to the defective thermostat controlling the warm side temperature which fluctuated within three degrees. In the batches with Calgon as an admixture, there was no freezing point lowering effect as was noted in the specimens with salt as an additive. The specimens with different concentrations of Calgon started to heave at approximately the same time. In Batch No. 3, an increase in density showed a slight trend in delaying start of heave, similar to the effect of salt, except to a smaller extent. This probably illustrates that the freezing temperature of the water decreases as the size of the voids decreases.

4.4.C Heave versus Density

When remolded samples are used, there are three factors which affect the amount of heave when the specimens are subjected to freezing with a constant surcharge. These are density, moisture content during compaction and the degree of saturation. Batches Nos. 2 and 3 were an attempt to study the effect of these variables on heave. In order to investigate the effects of these variables the following samples were prepared from the material from a lump at mile 202, Wainwright Subdivision:

a) Specimens 1 to 8 and 13 to 20 were compacted at optimum moisture content but at various compactive energies. This would allow assessment of density variation.

b) Specimens 9 to 12 and 21 to 24 were molded at a moisture content higher than optimum but using a compactive effort near Standard Proctor effort. This would allow assessment of an increase in moisture content.

c) Specimens 7, 8, 19 and 20 were compacted near optimum moisture content and using a compactive effort near Standard Proctor effort.

All the even numbered samples were saturated for 24 hours by allowing the bottoms of the specimens access to water. The odd numbered specimens were subjected to freezing in the as-compacted condition.

The results of this test are plotted on FIGURE 4.4. For the specimens compacted near optimum moisture content by varying the compactive effort, the soil from the centre of the lump showed an increase in heave with decrease in density. The more plastic soil off the lump showed a slight increase in heave with increase in density up to 108 lbs. per cu. ft., then a decrease in heave above this density.

The specimens compacted at a moisture content above optimum showed a much lower heave for both soils on centre and off the lump. The reason for this marked decrease in

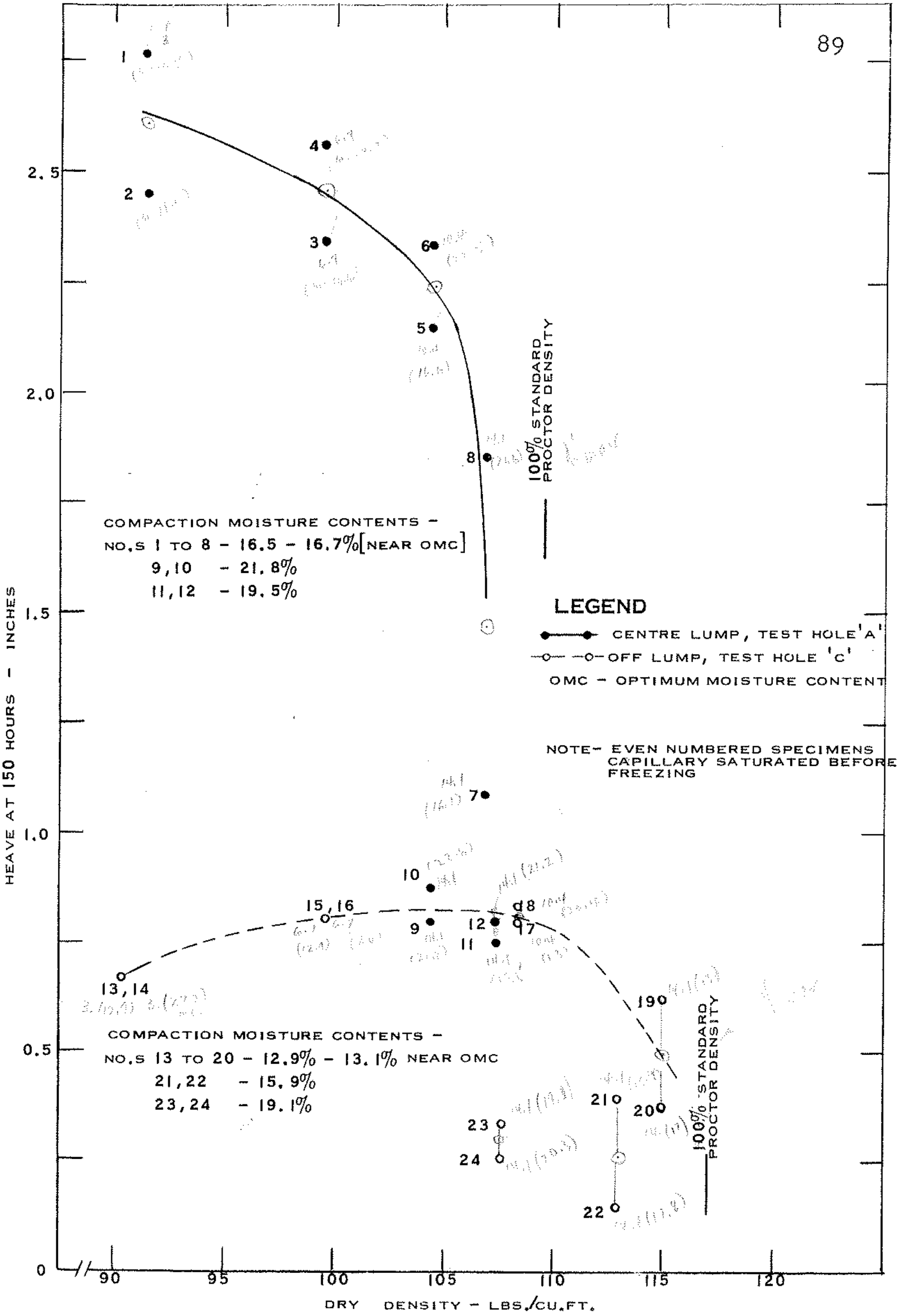


FIGURE 4.4 HEAVE VS DENSITY FOR BATCH NO. 3

heave may be explained by reference to work by Seed (1959) on compaction and soil structure. Seed noted that clay soils compacted wet of optimum have a dispersed structure, and a flocculated structure when compacted dry of optimum moisture content. Since a dispersed structure results in a more impermeable soil, the specimens compacted wet of optimum resulted in less heave due to a lower rate of moisture migration to the frost line.

The effect of capillary saturation on heave was quite variable. Nearly all the saturated samples for the centre of the lump soil showed a higher heave. This difference was highest at the maximum compactive effort as shown by specimens 7 and 8, FIGURE 4.4. The samples compacted at a moisture content above optimum showed a small difference in heave due to saturation. These samples would have an initially higher degree of saturation and this is probably the reason why saturation showed a smaller difference in heave. For the specimens off the lump, there was little or no difference in heave due to saturation for specimens 13 to 18 and a lower heave for the remaining saturated samples.

When the unsaturated samples are placed in the frost box, they will absorb water and swell before heave commences, resulting in an unmeasured density but which is known to be less than the molded value. When plotting the heave for the unsaturated specimens on FIGURE 4.4, the density of the saturated duplicate specimen was used.

From the data in FIGURE 4.4 a compactive effort was chosen which resulted in a dry density of the remolded specimens close to field value as determined from the block sample analysis reported in FIGURE 3.3. This compactive effort was 10,400 ft. lbs. per cu. ft. and is represented by specimens 6 and 18 in FIGURE 4.4. This compactive effort was maintained throughout the remainder of the testing program. All the specimens were saturated.

The preceding investigation was repeated for the Telkwa Subdivision soils. FIGURE 4.5 is a plot of heave versus density for test hole numbers 44 and 45, showing the effect on heave of density, molding moisture content and saturation. As before, specimens 1 to 8 and 13 to 20 were molded near optimum moisture and the compactive effort varied, specimens 9 to 12 and 21 to 24 were compacted at a higher than optimum moisture content and at the compactive effort of specimens 7, 8, 19 and 20. The unsaturated samples are noted on FIGURE 4.5.

The soil off the lump showed an increase in heave with a decrease in density. For compaction at higher moisture contents the Telkwa soils did not result in a marked decrease in heave as did the Wainwright clayey till discussed previously. The two unsaturated samples resulted in a higher heave than the saturated samples.

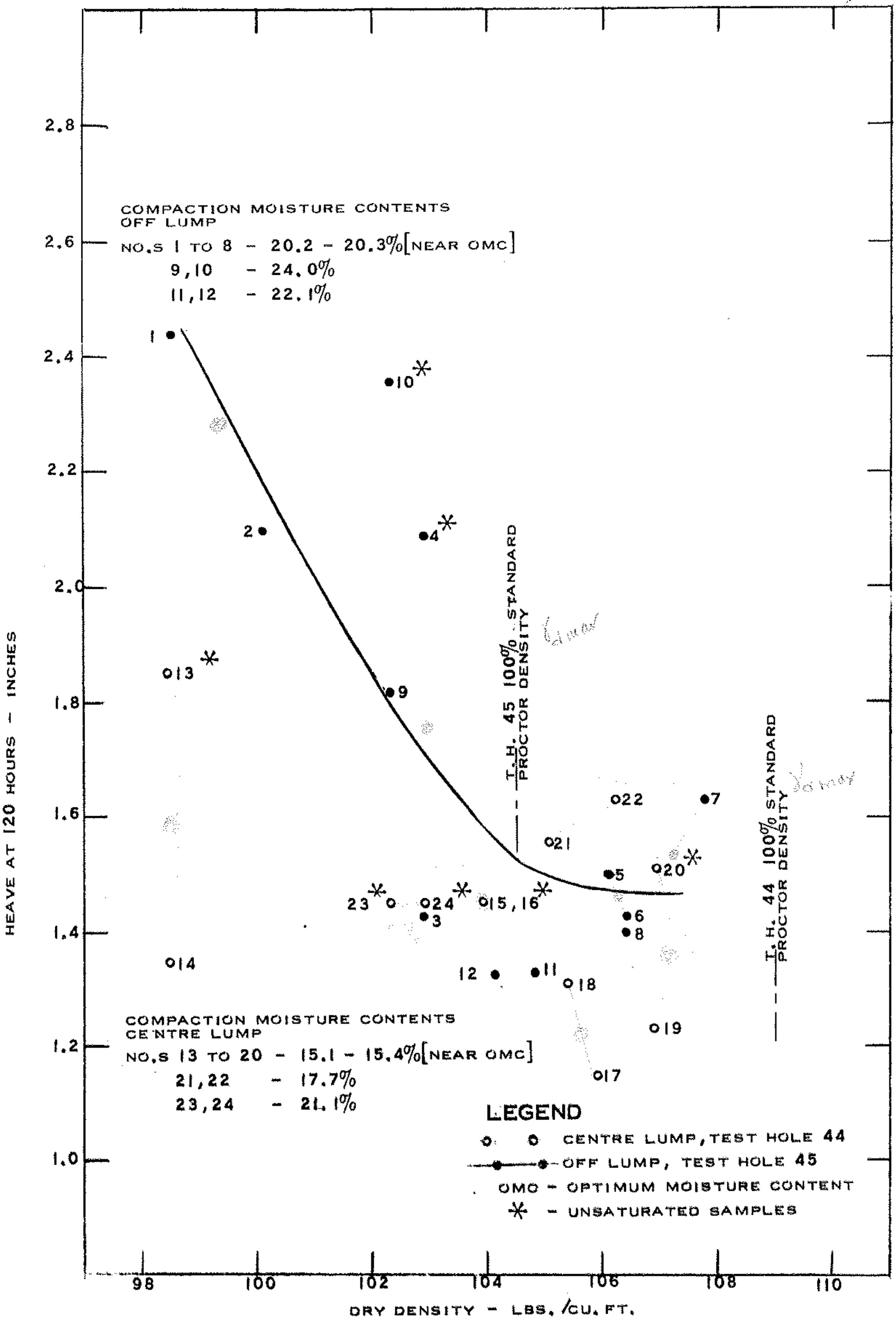


FIGURE 4.5 HEAVE VS DENSITY FOR BATCH NO. 2

From FIGURE 4.5 it will be noted that the soil type from the centre of the lump at Telkwa resulted in a considerable scatter of the points hence no specific trend in heave could be established for the different densities. The majority of the specimens from the centre of the lump showed less heave than the soil off the lump. Subsequent testing of Batches Nos. 1 and 7, which contained untreated specimens of soil from this lump, showed the soil from the centre of the lump to heave more than the soil off the lump. This anomalous behavior of Batch No. 2 may be explained by a defective thermostat which fluctuated within 3 degrees Fahrenheit. This fluctuation may have affected the silty fine sand from the centre of the lump more than the slightly plastic silt off the lump, giving the erroneous results.

4.4.D Heave versus Admix Concentration

Since it appeared desirable to determine a concentration of the proposed admixtures to be used in subsequent comparative tests, a test was carried out to enable a suitable concentration to be chosen. This test comprised of specimens containing percentages of admix ranging from 0 to 0.5% by weight of dry soil. The results of these tests are plotted in FIGURE 4.6 which shows the relative effect of the three admixtures on heave for the soils from the centre and off the lump at mile 202 in the Wainwright Subdivision. All three admixes were more effective in reducing the heave in

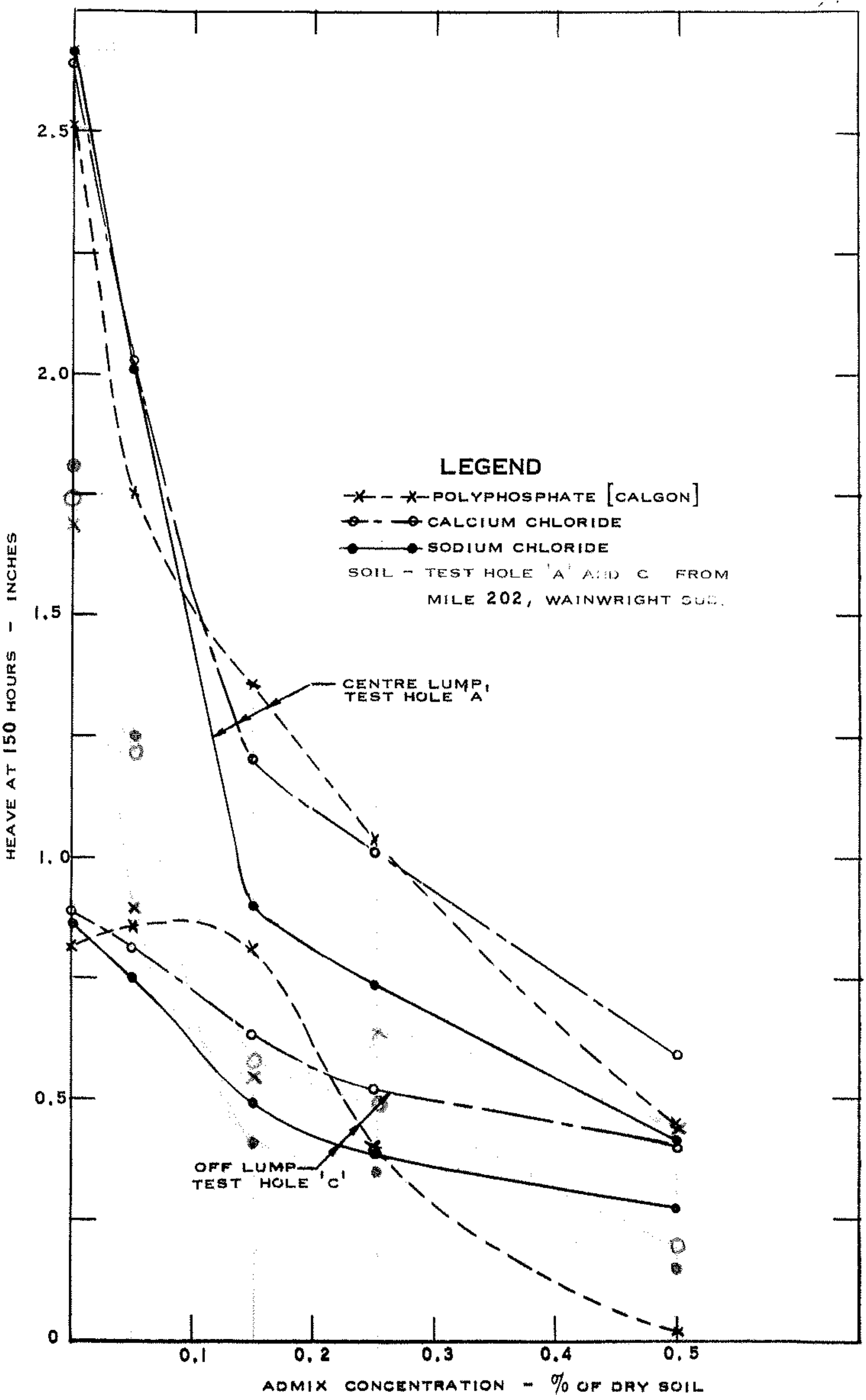


FIGURE 4.6 HEAVE VS ADMIX CONCENTRATION

the soil from the centre of the lump, that is, differential heaving is reduced. The most effective additive in reducing total heave and differential from this data is sodium chloride. An increase in concentration of sodium and calcium chloride added increased the effectiveness in reducing differential heave, however, an 'optimum' is indicated at 0.15 percent, with concentrations higher than this value showing a lesser effect in decreasing heave. The break in the curves is probably due to physical-chemical influences whose explanation is beyond the scope of this thesis.

The latest field tests conducted by the Canadian National Railways in the Mountain Region consist of an application of a concentrated salt solution on the surface of the railroad ballast by means of a track mounted spray truck in areas of extensive differential heave. The results in FIGURE 4.6 indicate that a constant application will not completely eliminate the differential heave on the lumps, and some shimming may still be required. This application of the laboratory results is based on the assumption that field treatment will result in a distribution of the salt throughout the depth of frost penetration.

A method of treatment which may eliminate differential heave, is by treating the heaved portion of the lump only. An application of 0.15% of sodium chloride on the centre of the lump would appear to eliminate the differential heave, as indicated in FIGURE 4.6. The concentration of salt used is important. This indicates a disadvantage of spot treatment which will present difficulties during field application. Too high a sodium chloride concentration will result in a dip and too low an application will result in a lump. The optimum quantity will be difficult to estimate and will vary with each location due to differences in soil properties. Also the correct concentration the first year, which will eliminate differential heave, may change the following years due to a possible decrease in concentration by leaching.

Other types of differential heaves in railroads are dips and slope-offs. From the logs of shimming occurrence in the spring of 1965 in the Telkwa Subdivision, the data showed that 60 percent of all differential heaves were dips, 34 percent were lumps and 6 percent were slope-offs. The majority of the dips required shim heights of 1½ inches or less. From the field investigation in the previous chapter, it was shown that a dip or the lower part of a slope-off generally contained a less frost susceptible soil or a higher density. It is inferred from this laboratory data that a uniform application of salt will decrease the differential heave due to dips and slope-offs; however, some differential heave will still remain which may require some shimming. The only feasible method of treatment with admixes to eliminate all the shimming is by applying an increasing or tapered concentration of salt on either side of the dip or on the high part of the slope-off, to provide a gradual reduction in heave to the dip or lower part of the slope-off.

The polyphosphate admixture displayed a different effect on heave for the soil off the lump. Up to a concentration of 0.15%, a slight increase in heave resulted, then a rapid decrease in heave to almost zero at 0.5%. The behavior of Calgon for the soil from the centre of the lump was similar to the sodium and calcium chloride.

Lambe (1956) describes the mechanism by which polyphosphate dispersing agents reduce frost heave. He postulates that a cation exchange and an anion adsorption of the polyphosphate with the soil mineral surface, expands the diffuse double layers around the soil colloids which increases the interparticle repulsion. A disperson of soil particles results from this increase in interparticle repulsion, hence it permits them to be orientated into a more orderly and dense structure. This results in a higher density, lower permeability and higher stability in the presence of water. The alteration of these soil properties results in a change in their frost susceptibility characteristics. Dispersants also tend to lower the freezing temperature of soil moisture by decreasing the size of soil voids.

FIGURE 4.7 is a plot which illustrates the effect of calgon on the density of the soil from test holes "A" and "C". All specimens were molded near optimum moisture content

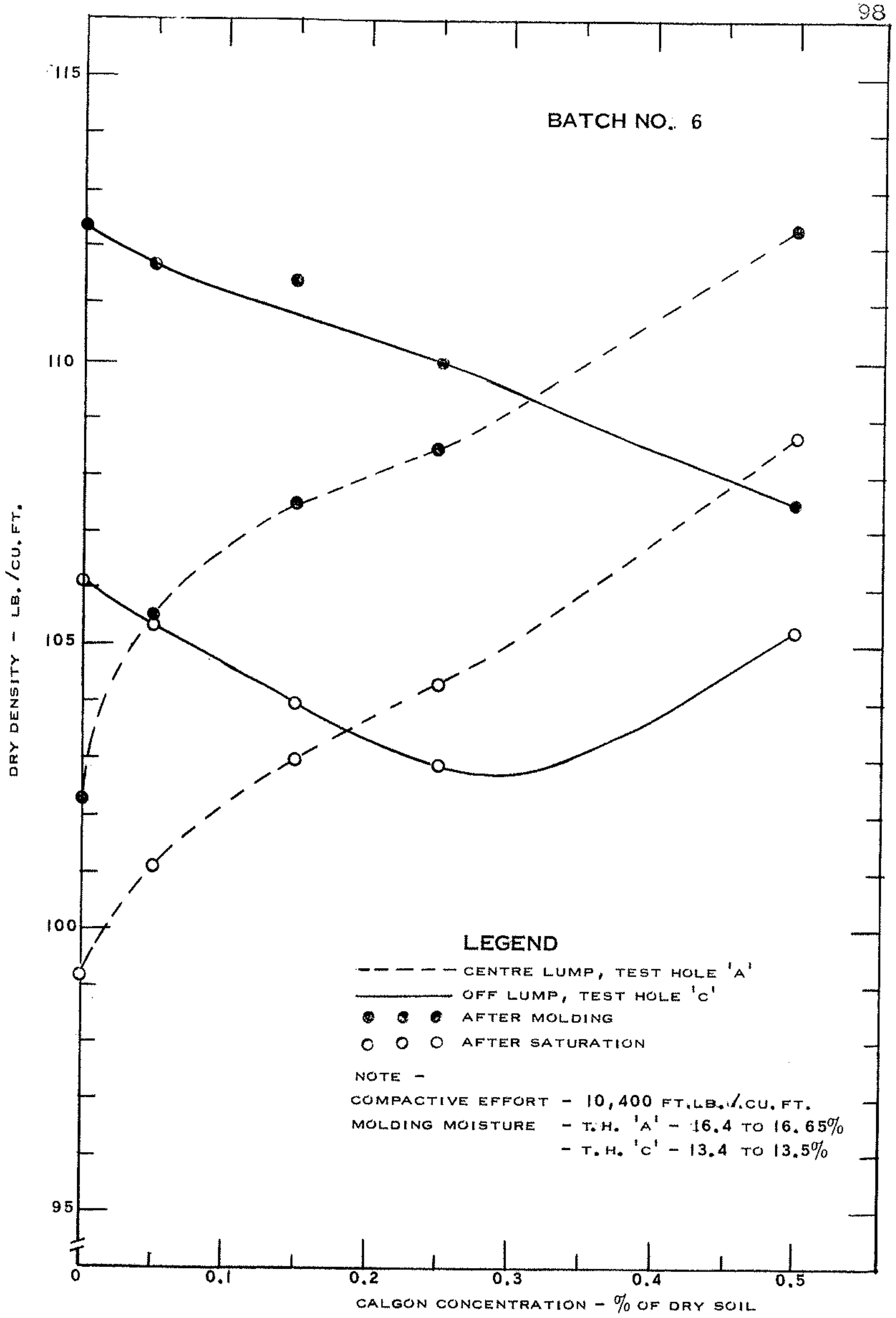


FIGURE 4.7 DRY DENSITY VS CALGON CONCENTRATION FOR BATCH NO. 6

using the same compactive effort. They are the specimens used in the frost room tests for Batch No. 6. The plot illustrates the different effect of calgon on the density of the two soil types. An increase in calgon concentration resulted in an increase in density for the soil from the centre of the lump. The soil off the lump showed an opposite effect of a decrease in molded density with increase in calgon concentration. After saturation, this soil showed a decrease in density to 0.25% concentration and then an increase in density to 0.5% concentration. The specimen at 0.5% (test hole "C") showed a much smaller increase in moisture content during saturation than the specimens at lower concentration indicating that the calgon imparted hydrophobic characteristics to the soil particles.

The decrease in heave with increasing calgon concentration for the soil from test hole "A" is partly due to an increase in density due to the calgon. The decrease in heave being only partly due to density can be shown by comparing the change in density from FIGURE 4.7 with FIGURE 4.4 and noting the relative decrease in heave. It may be noted that the decrease in heave due to calgon as shown in FIGURE 4.6 is much larger than can be attributed solely to density.

The very low heave for the soil from test hole "C" at 0.5% calgon concentration is probably due to the hydrophobic nature imparted by the calgon, causing the soil to have a repulsion to water and decreasing its upward migration from the water source.

According to Lambe (1956), the mechanism by which sodium and calcium chloride reduces frost action is by lowering the freezing temperature of the water in the soil pores. From FIGURE 4.3, the data shows that an increasing concentration of salt also alters the rate of heave. This indicates that some other mechanism in addition to lowering of freezing point, must be taking place. In a discussion on a publication by Woods and Yoder (1952), R. M. Hardy notes that the effect of calcium chloride was to eliminate migration of water to the frost line rather than to lower the freezing point of the soil water.

FIGURE 4.8 is a composite plot showing the effect of varying concentrations of admix on heave for the Telkwa soils (test holes 44 and 45). Only sodium chloride and calgon were evaluated with these soils in one batch. The sodium chloride was more effective in reducing heave than calgon. Also a uniform concentration of sodium chloride is more effective in reducing differential heave at high concentrations than calgon. At a low concentration of sodium chloride, differential heave may be eliminated by treatment of the heaved portion only. The calgon showed a slight increase in heave at low concentration for the soil off the lump. No trends of an increase or decrease in density were

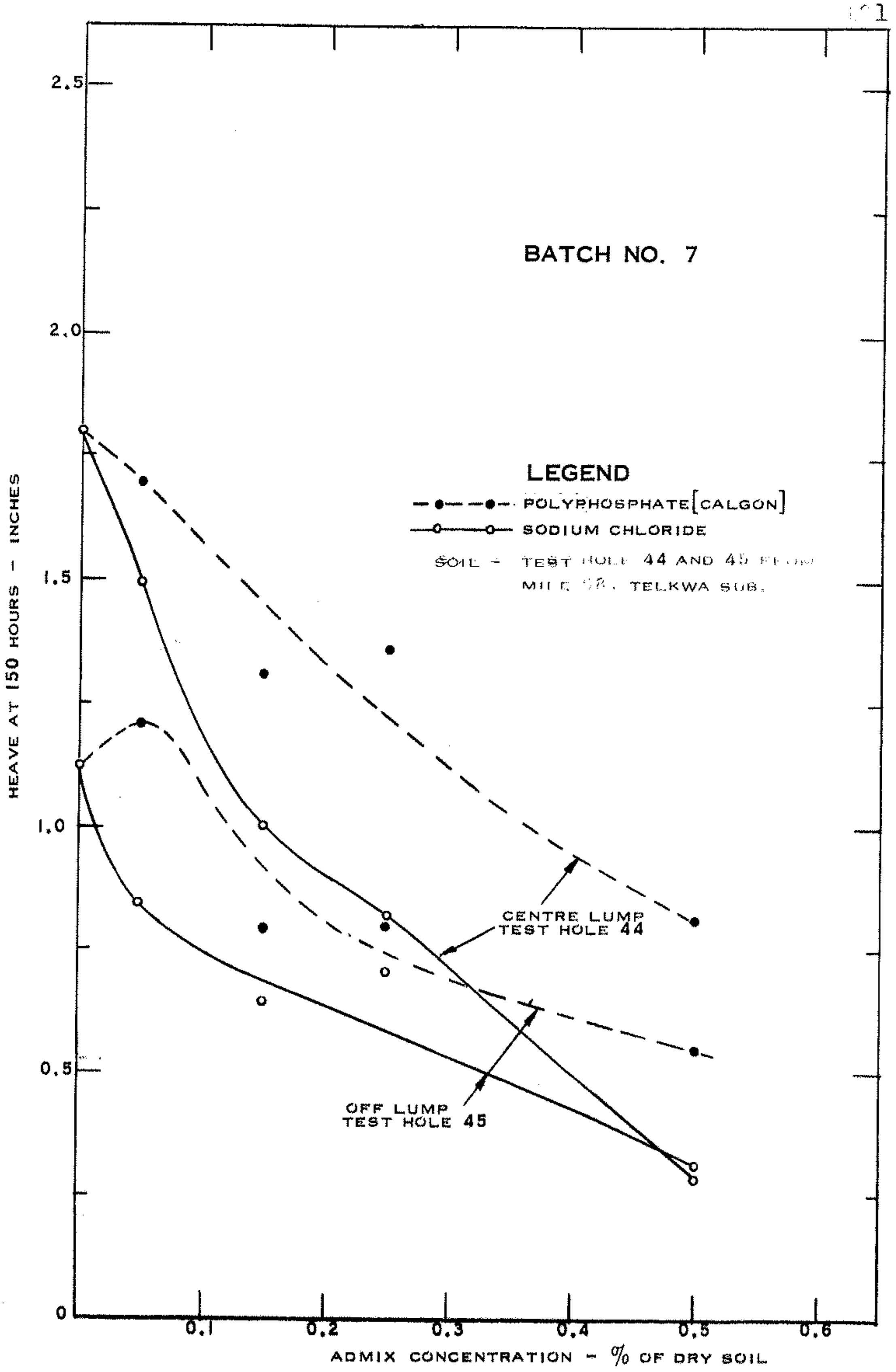


FIGURE 4.8 HEAVE VS ADMIX CONCENTRATION FOR BATCH NO. 7

noted with increase in calgon concentration, as for the clayey soils from test holes "A" and "C" previously discussed. This data again shows that the polyphosphate admix is less effective in reducing differential heave than sodium chloride.

4.4.E Admix Migration

One of the disadvantages often quoted when using sodium and calcium chloride as an additive is their impermanence due to leaching by moisture migration in the soil. The movement of the salts in a number of specimens was checked in this laboratory program by the conductivity method. A detailed procedure of the method used is given in Appendix A.

The apparatus is an electrical device which measures the conductance of a solution. The conductance reading is proportional to the ionic strength or the salt concentration in the solution. FIGURE 4.9 is a plot of conductivity readings of a fixed volume of water with a fixed quantity of soil into which increasing quantities of salt were added, as a percentage of the dry weight of soil. A linear relationship resulted between conductivity and percent salt. Thus the relative salt distribution can be determined by slicing a specimen horizontally and immersing a fixed weight of the oven dried soil from each slice in a fixed volume of water and obtaining the conductivity reading.

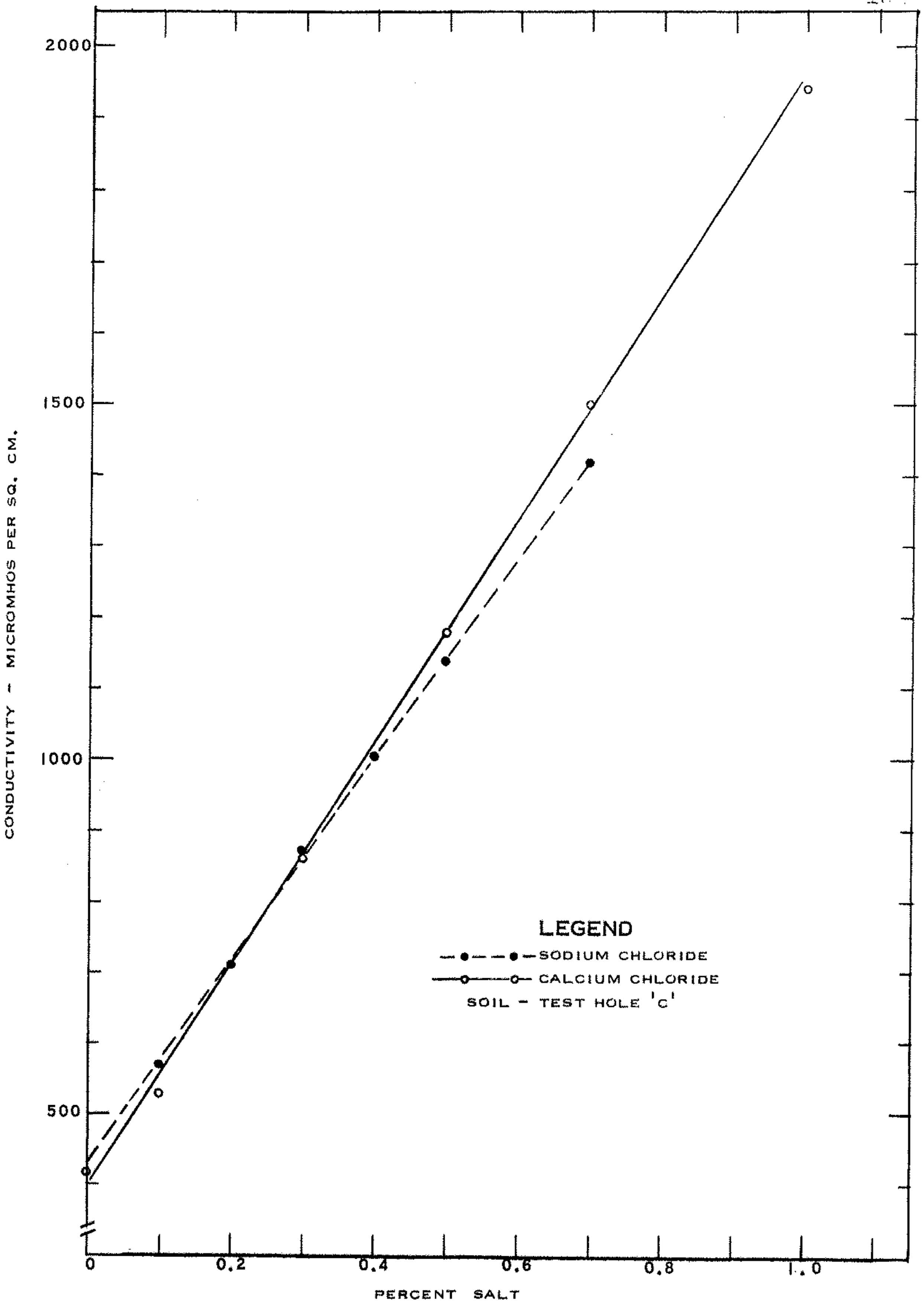


FIGURE 4.9 CONDUCTIVITY VS SALT CONCENTRATION

FIGURE 4.10 is a combined plot showing the migration of calcium chloride in specimens molded at three different concentrations. An initial movement of calcium chloride resulted from the lower to the upper part of the specimen due to upward movement of water during saturation. The amount of salt that migrated increased as the initial molding salt concentration increased. Further movement of salt from the lower to the upper part of the specimens resulted as water was drawn to the frost line during freezing. After freezing, all three concentrations showed approximately the same conductivity in the unfrozen part of the specimen and also a residual unleached salt content is indicated. The actual amount of added salt remaining in the unfrozen part of the specimen cannot be determined accurately by the conductivity method. As shown by the curve with no admix after freezing, the existing total salts in the specimens also migrate. The apparatus measures the conductivity of the existing total salts and the salts added and therefore the actual quantity of the added salts that migrate is not known.

FIGURE 4.11 is a plot showing the migration of sodium chloride in the same soil (test hole "C"). Only specimens with two salt concentrations were checked in this case. This plot indicates that similar to calcium chloride, sodium chloride also displays a high amount of migration in the pore voids of the soil due to saturation and ice segregation. The 0.15% concentration of sodium chloride showed

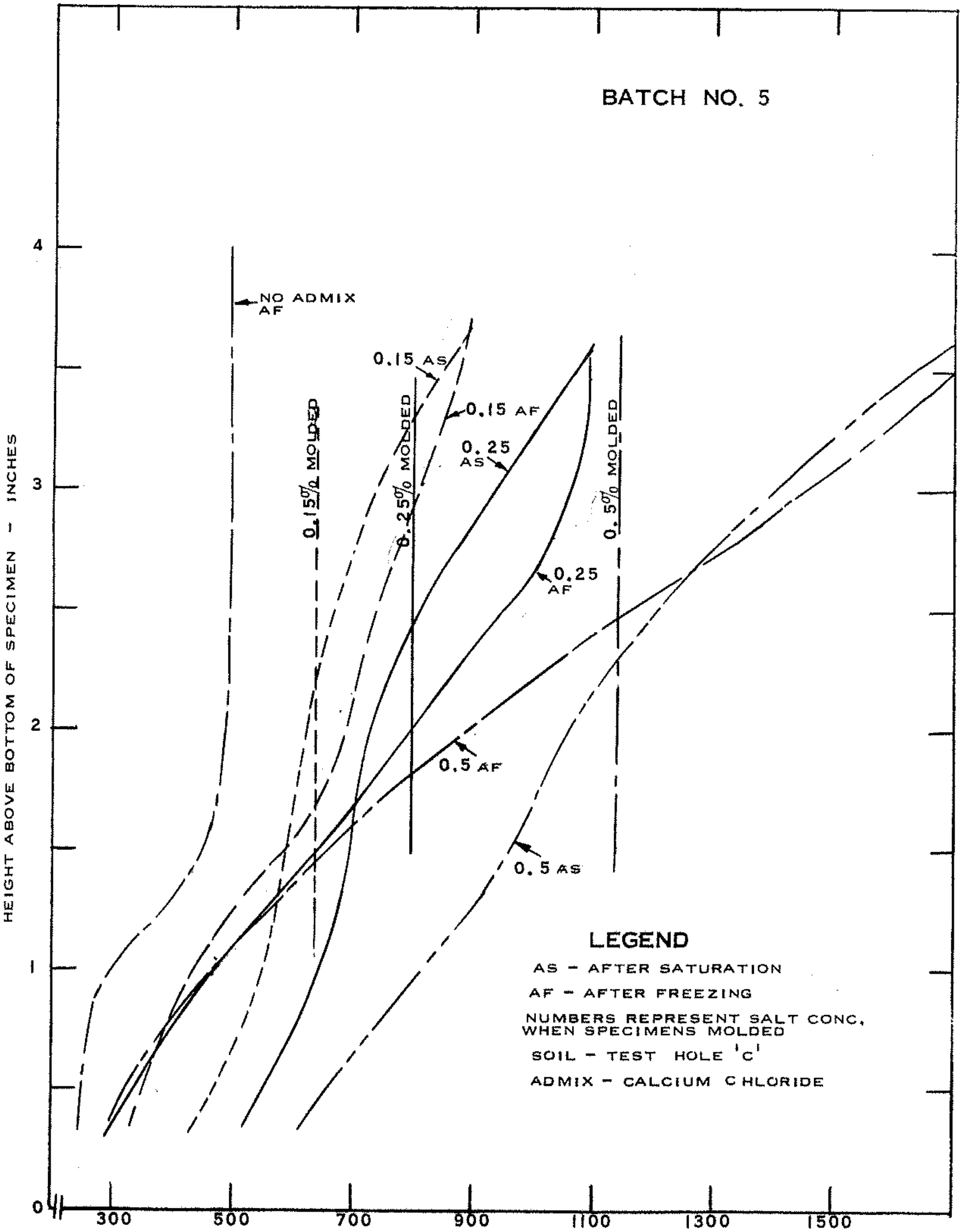


FIGURE 4.10 CALCIUM CHLORIDE MIGRATION BY CONDUCTIVITY MEASUREMENTS

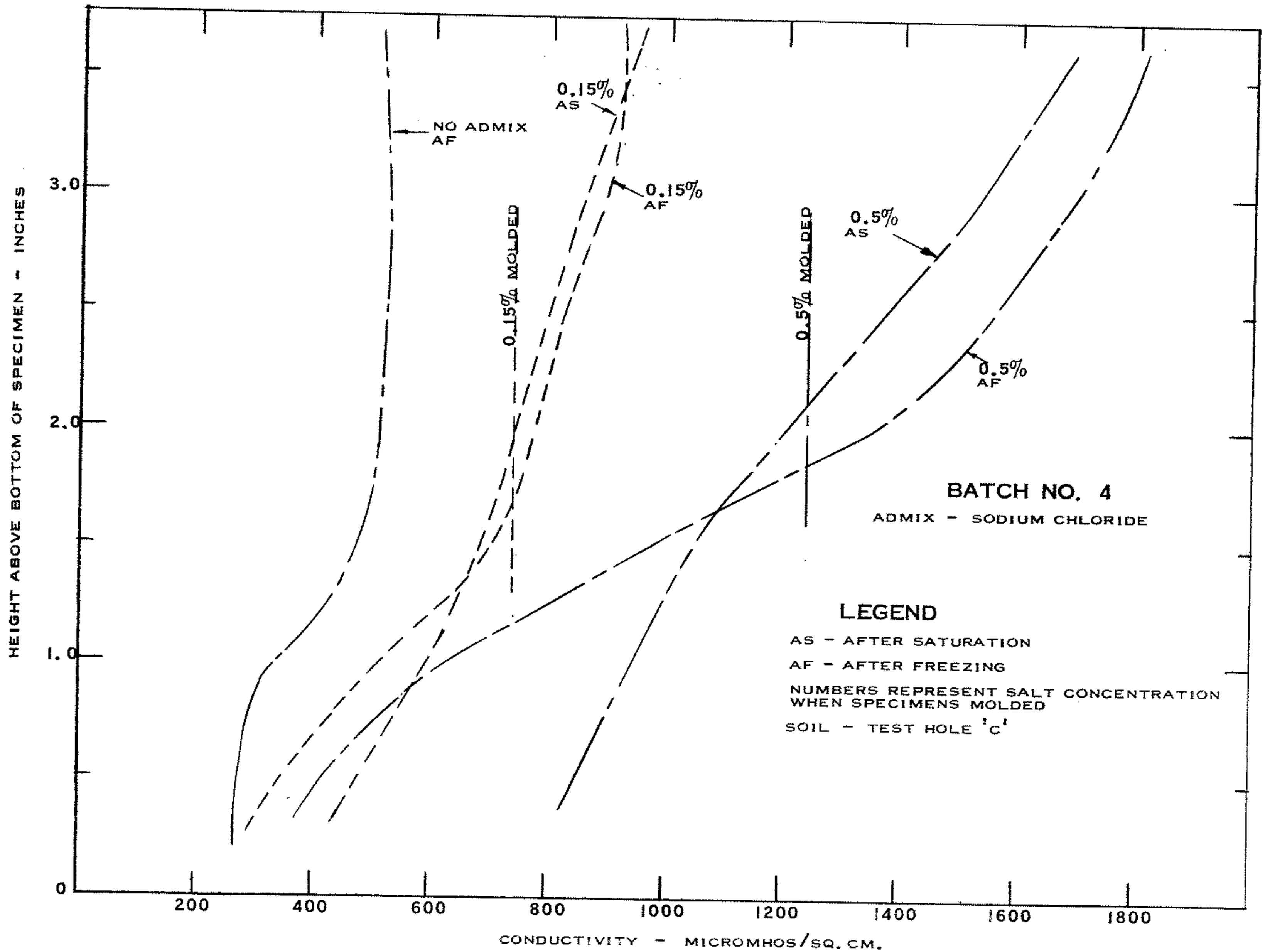


FIGURE 4.11 SODIUM CHLORIDE MIGRATION IN SPECIMENS BY CONDUCTIVITY MEASUREMENTS

a similar migration and distribution in the specimens as the calcium chloride.

The 0.5% concentration of sodium chloride showed a higher salt content at the lower part of the specimen than calcium chloride, indicating that sodium chloride tends to have a lower rate of migration at high concentrations. Slesser (1943) showed that calcium chloride tends to migrate more readily in soil than sodium chloride.

The conductivity method has a number of disadvantages which make its use unsuitable for the accurate determination of the migration of salt admixtures in a soil, in laboratory as well as under field conditions. It cannot be used with a soil having a natural high content of total salts. A low concentration of added salt does not produce a significant increase in reading with these soils.

As an example, the soil in the centre of the lump (test hole "A") has a high total natural salt content equal to 4,900 micromhos per square centimeter. From FIGURE 4.9, an increase in sodium chloride concentration of 0.15% would increase the conductivity reading approximately 200 micromhos per sq. cm. This increase is very small compared with 4,900 and the increase can hardly be read on the logarithmic conductivity scale of the apparatus.

A migration of pore water results in the migration of the salt additive and the original total salts in the soil. Since the conductivity apparatus measures the content of both the original salts and the salt added, the net movement of the additive only is not known.

If an accurate analysis of the migration of salt admixtures is required, some means other than the conductivity method is necessary. Slesser (1943) describes a method of pore water extraction and chemical analysis to determine the calcium and sodium content.

Unlike the salts, the presence of calgon did not show a significant increase in conductivity with an increase in calgon concentration in the soil. Hence the migration of calgon in the specimens could not be determined by the conductivity method.

4.4.F Literature Review Concerning Migration of Salts

The migration of sodium chloride and calcium chloride has been studied by a number of investigators. Slate (1942) conducted field studies by application of calcium chloride in 6 inch deep pockets in the road surface. He concluded that calcium chloride will migrate laterally but is slow for silty clay soils under pavements. In the laboratory, Slate studied the effect of height to water table, rainfall and evaporation on migration of calcium chloride in a silt soil. He found that a high water table caused faster migration. When calcium chloride was carried upward by evaporation or downward by rainfall, there was very little lateral movement of the salt. A simulated 8 inches of rainfall washed away 80 percent of the salt originally present in the silt.

Slesser (1943) studied the migration of sodium and calcium chloride under field and laboratory conditions. He found that under the influence of capillarity and evaporation, sodium chloride tends to move upward and crystallize on the surface and may be lost by being washed laterally by rainfall. Calcium chloride did not accumulate on an unpaved road surface in this manner. A high ground water table accelerates the downward movement of the salts, with calcium chloride being more effected than sodium chloride. He found that the important variables affecting the movement of water soluble chemicals in soil are evaporation, soil texture, percolating water and soil cover. The depletion of sodium and calcium chloride in silty soils by percolating water is very rapid.

On an experimental test section in a highway project in Massachusetts, calcium chloride was incorporated in the surface of the subgrade (Yoder, 1955). The pavement surface of this road was noted as being sufficiently porous to permit water to percolate to the subgrade. There was also horizontal flow of water which caused additional leaching of the calcium from the subgrade. The effective life of the calcium chloride was noted as 3 years. No calcium chloride remained in the subgrade after 6 years on the experimental test section.

The Canadian National Railways conducted surveys in five subdivisions in Northern Ontario to evaluate the effect of salt treatment on frost heaving of track (Yalcin and Peckover, 1964). The data showed salt to be effective in reducing shimming in all cases and in a number of cases the shimming was completely eliminated by the salt application up to 4 to 6 years after treatment. Generally, treatment was most effective up to 3 years, after this showing a decreased effectiveness. In a few cases in clay and muskeg areas, the treatment had little effect.

Rowat (1939) described the use of salt in the prevention of heave on railroad tracks. He noted that the length of time over which treatment continued to be effective cannot be predicted accurately, since soil conditions vary from place to place. He concluded from records kept that two years is the minimum expectation of effectiveness.

Smith (1952) noted that permanency tests on chloride treated aggregate bases showed that after a period of 5 to 10 years, one-third to one-half of the chemical originally placed still remained. Almost all the loss occurred during the first five years.

4.6 Frozen Structure of Specimens

A number of specimens were split open after removal from the frost box to note the ice formation. The upper part of the untreated specimens from approximately 1 to 1.5 inches were homogeneously frozen and revealed no ice lensing or ice segregation. Below this portion, ice crystals and ice lenses were formed to a level approximately one inch above the bottom. The ice generally formed in three or four bands or clusters, with the spacing between the bands decreasing towards the bottom of the samples. This banding is considered due to the lowering of the frost room temperature in approximate 8°F decrements. Each time the frost room temperature was lowered, the descent of the frost line was rapid at the start and then gradually diminished to a lower rate of penetration or to a stationary position. At the low rate of penetration a higher concentration of ice formed. The occasional sample in a batch showed no banding, the ice formation being uniformly dispersed except that these specimens generally terminated in a thick ice lens at the bottom. Samples that displayed this behavior showed a high heave. This is interpreted as indicating a uniform penetration of the frost line.

In the soils from test holes "A" and "C", the ice occurred as many hairline lenses separating soil granules. These lenses were approximately parallel to the surface and increased in thickness toward the bottom of the sample. The more plastic soil off the lump (test hole "C") showed thicker ice lenses spaced further apart than the soil in test hole "A". The silt soil in test hole 45 showed a similar structure to test hole "A". The fine sand with silt from test hole 44 had a different structure and consisted of a more homogeneous mixture of ice and soil, with no layers of ice.

4.7 Summary

In this chapter a brief description of the laboratory procedure and apparatus is given. The properties of the four soil types used in the freezing tests are described. They varied from a clay silt till to a silty fine sand. Although the laboratory conditions are considered severe and not directly comparable to the field, the laboratory conditions may be used to advantage to show more clearly the relative effect of the admixtures on heave. Density is shown to have a variable effect on heave depending on the soil type. The amount of heaving showed an approximately linear relationship with time. The effect of the salt additives was to decrease the rate and amount of heave and to delay the onset of heaving with an increase in salt concentration. The results show that the three admixes investigated are effective in reducing differential heave. With the soil types used, sodium chloride is the most effective additive in reducing total and differential heave. The data indicates that a uniform application of the admixture on and off a lump may not eliminate differential heave. The data further suggests reduction of differential heave by treating the heaved portion of a lump only.

Migration of sodium and calcium chloride in the soil specimens was checked by conductivity measurements. The data indicates that salts are very mobile and migrate readily with moisture movement in the soil.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1 General

A field investigation was conducted in an attempt to more clearly define some of the reasons for differential heave. A laboratory study was carried out primarily to determine the relative effect of three admixtures on differential heave. In this chapter, some of the conclusions and recommendations arising from this study are presented. Remolded laboratory specimens and only soil types from two lumps were used hence the results are not fully representative of all field conditions.

5.2 Conclusions

From the results of the field and laboratory study on which this thesis is based, it appears that the following conclusions are justified:

1. Based on the analysis of one lump, there is moisture migration to a frost line and ice segregation in the frozen zone of a lump.
2. The major factor in causing differential heave in railroads is a difference in soil type. A different soil type will possess a different pore structure and moisture conditions. A frost line penetrating a subgrade under these soil conditions will

result in a different rate of moisture migration and thus a different magnitude of heave.

3. A difference in density of soil deposits and variable depth to water table are also factors which result in differential heave.
4. Calcium chloride, sodium chloride and calgon are effective in reducing differential heave.
5. An increased concentration of the admixtures tested results in an increased effectiveness. However, the reduction in differential heave is more pronounced at lower concentrations and lesser decrease in heave occurs at higher concentrations.
6. For the freezing tests conducted in this laboratory program, heave showed an approximate linear relationship with time.
7. Of the three admixes evaluated using the specific soil types, this laboratory program shows that sodium chloride is the most effective in reducing differential heave, with calcium chloride and calgon following in order of effectiveness.
8. The effect of an increasing concentration of salt in laboratory specimens is to delay the time at which start of heave occurred and to decrease the rate of heave. Calgon showed a decrease in the rate of heave only.

9. Salts migrate very readily in the pores of a soil due to moisture movement.

5.3 Recommendations

From the field and laboratory study comprising this thesis, the following recommendations are offered:

1. Based on the results of this test program, which was carried out on remolded soil samples from the centre and off a lump, and assuming that these results are also applicable to dips and slope-offs, it is recommended that a uniform brine treatment be applied on the surface of the ballast by means of a track mounted spray truck. This procedure will be most effective on those portions of the track having a porous ballast. This method of treatment may not eliminate shimming but should reduce it considerably.

2. In order to ascertain the effectiveness, economics and duration of a treated section of track, it is recommended that records of amounts and location of shimming be maintained for subsequent analysis.

3. Based on the data presented in FIGURE 4.6, it is recommended that consideration be given to selective treatment of heaved locations. The reason for this recommendation is that FIGURE 4.6 indicates that treatment of this particular lump with an admix concentration of approximately 0.15% sodium chloride (based on dry soil weight) results in a heave that is

in the same order of magnitude as the heave of the untreated soil off the lump, that is differential heave is virtually eliminated.

4. In order to obtain further information regarding the general depth of the heaving zone, it is recommended that records be kept concerning the time (day, month) of installation of the shims. This is based on the generality that a deeper heaving zone will heave later in the season. It is recognized that other factors, for example climate, will influence the observations but a consistent pattern may be observed.

5. It is recommended that subsurface soil data be obtained in order that the most value may be derived from heave observations. Such data is essential when dealing with causes, effectiveness of treatment and migration of salts.

6. There is some question as to whether or not the dips are due to shrinkage or a lesser amount of heave. It is recommended that a series of levels be maintained to determine absolute movements of the track. These surveys should be tied into deep bench marks that are unaffected by frost penetration into the ground.

7. During the field studies it was observed that several heaves were associated with high water tables, hence it is recommended that surface drainage be improved where feasible.

8. Since the permanence or migration of salts in the soil mass appear to have a pronounced effect on heaving, it is recommended that field checks be made over a period of years to ascertain the distribution of the salts. Such information may be obtained by laboratory analysis of soil samples taken in the field.

9. From the log of shimming occurrence in the Telkwa Subdivision, 60 percent of the differential heaves were dips, with a majority of these located in fill sections, and having shim heights of 1½ inches or less. In the field investigation no dips in fill were analysed since none of these were marked and thus could not be accurately located in the field. It is recommended that a number of these dips in fill be investigated to establish if they are similarly caused by a difference in soil type.

10. As was noted in Table 3.1, a number of differentially heaved locations were investigated that showed little or no difference in soil type and/or depth to the water table, and at this time the causes of differential heave at these locations is unknown. Therefore, it is recommended that some of these locations be investigated in more detail by sub-surface exploration of the soil on the centre and off the lumps or dips. A laboratory analysis for Atterberg Limits and grain size distribution should be performed on samples obtained at one foot intervals. A check should be made for variation in

density on undisturbed block samples for cohesive soils or by an in-place method for cohesionless soils. A record should be kept of the depth to water table during the penetration of the frost line on the centre and off the lump or dip. An analysis of mineralogical and natural salt content should be obtained to check for any differences which may cause differential heave.

11. Lambe (1956) indicated that polyphosphates have a low mobility, hence, if they are more permanent than salts in the soil, they may be a more economical admixture to use. It is recommended that the mobility of polyphosphates in soil samples be investigated in the laboratory. Since the conductivity method cannot be used, other chemical or physical tests must be employed. One suggested test may be based on leaching duplicate samples for equal lengths of time and comparing the difference in heave after leaching from freezing tests.

12. It is recommended that consideration be given to a laboratory program designed to provide more basic information on the role played by physical chemical phenomena in frost action. Such a program may take the form of investigating the effects of specific cations, such as sodium and calcium, and anions, such as the carbonate or sulphate radical, on heaving. In addition the soil types may be analysed for clay minerals and cation exchange capacity.

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APPENDIX A

DETAILED PROCEDURES

A.1 Block Sample Analysis

a) Field Procedure

The test pits were dug by spade to required depth to obtain the desired block samples and the bottom of the pit was levelled. At first the soil was scooped out with the spade to the bottom of the block sample, excavating an area approximately four inches larger than the required surface area of the block sample. The remainder of the soil was carefully trimmed with a knife and a small scoop to the required surface area. The bottom of the sample was cut with the knife and carefully lifted out of the pit. The sample was further trimmed and tightly wrapped with three layers of "Saran" polythene wrap. The final surface wrap was made with about two layers of paper towels dipped in hot wax. The samples were transported and stored in a moisture room until testing.

b) Laboratory Procedure

The wrap was removed, and the exterior of the sample trimmed to remove any disturbed surface soil. The weight of the sample was obtained. The sample was then dipped in wax, and the sample plus wax was weighed. The buoyant weight was then obtained of the sample plus wax. The wax was then removed and the soil sample placed in a drying oven to obtain the moisture content. Knowing the unit weight of the wax, the moisture content, and specific gravity of the soil solids; the dry density, degree of saturation and void ratio were calculated for each block sample.

The specific gravity of soil solids was determined for a representative sample from each test pit. ASTM procedures were used as outlined in Designation D854-54.

A.2 Auger Borings

From the auger borings, disturbed samples were obtained and placed in two polythene bags to prevent loss of moisture. The samples were analysed for moisture content, liquid and plastic limit, and/or wash sieve analysis. The plastic limit was determined in accordance with ASTM Designation D 424-54T, except that it was run on the undried soil sample. The liquid limit was determined using the one point method as outlined by Eden (1959) on the undried soil samples from their natural state. The value of tan B used was 0.1. The wash sieve analysis was performed by first determining the material finer than No. 200 sieve in accordance with ASTM designation C 117-49 and then performing a sieve analysis on the material coarser than the No. 200 sieve. In gravel soil, only the fraction passing the one inch sieve was analysed.

A.3 Laboratory Frost Room Tests

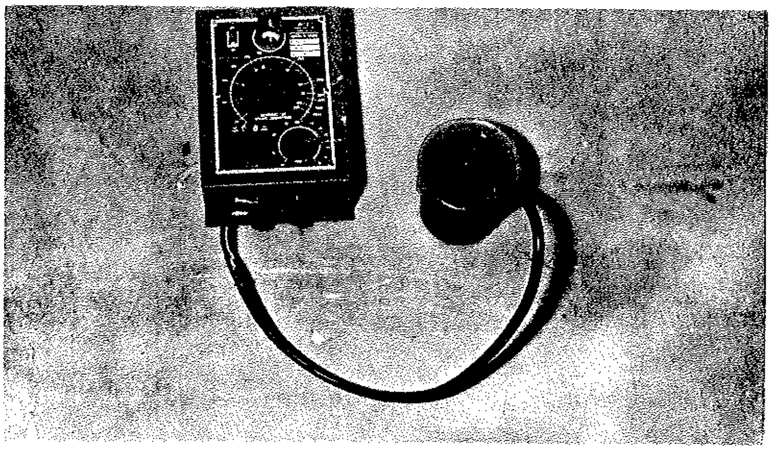
a) Apparatus

The apparatus used in this laboratory program is shown in FIGURES A.1 and A.2. A cross-sectional drawing of the frost box is shown on FIGURE A.3.

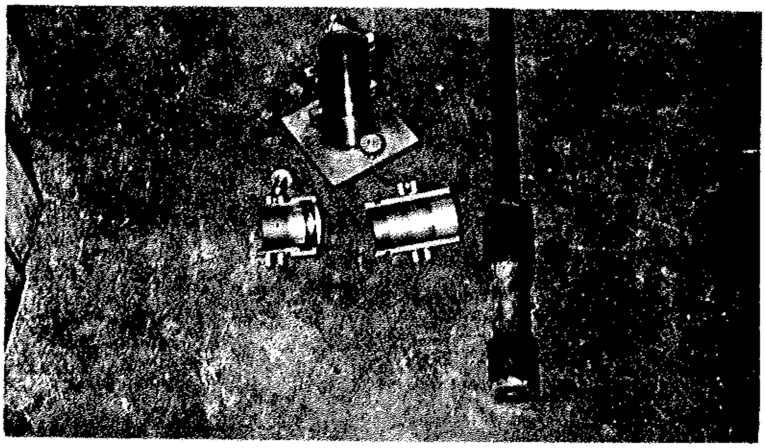
The specimens were compacted in four lifts in a two inch diameter split mold, using a standard Proctor hammer. Rubber membranes were used to enclose the specimens. An aluminum cap was placed at the top and a wooden perforated plate at the bottom of each specimen. Volume measurements after molding and saturation were made with calipers and .001" dial gauges. The specimens were placed in a frost box which held 24 samples at one time. The warm side temperature was provided by a constant temperature bath, Blue M, Model No. MV 1130 and was maintained at $8^{o}C \pm 0.5^{o}$. This temperature was chosen as representative of ground water conditions (Jumikis, 1956). The existing constant temperature bath thermostat would not function at this low temperature and a Fisher, Cat. No. 15178 flange head type thermostat was adapted to control the warm side water temperature. The cold side temperatures were obtained by placing the apparatus in the frost room. Temperatures were measured with iron-constantin thermocouples and a continuous "Brown" recorder. Heave measurements were taken by a moveable 0.001" dial gauge mounted on an angle bar straight edge.

b) Materials

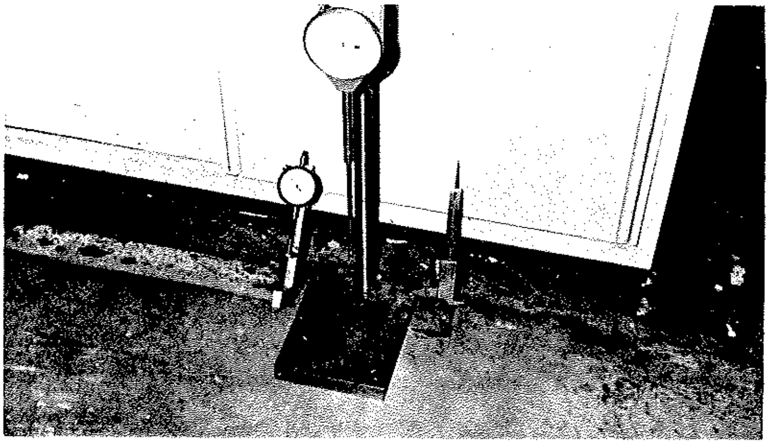
The soils used have been described in Chapter IV.



[A] CONDUCTIVITY APPARATUS

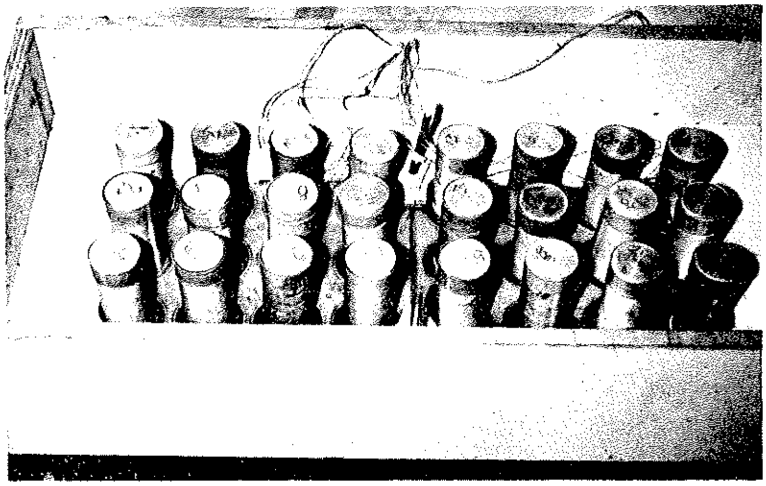


[B] MOLDING EQUIPMENT

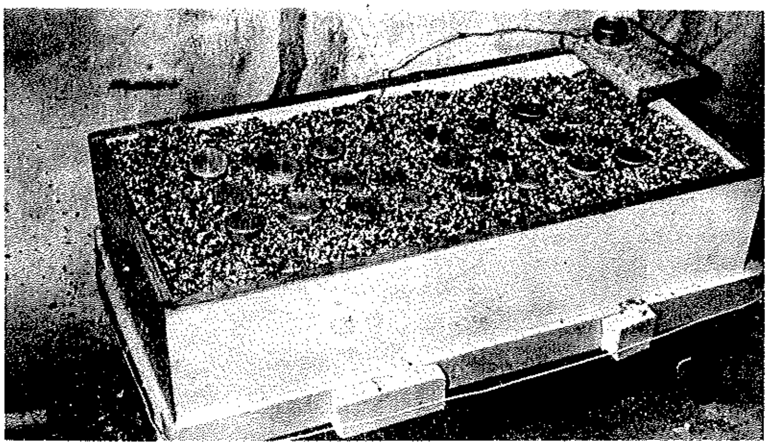


[C] VOLUME MEASURING EQUIPMENT

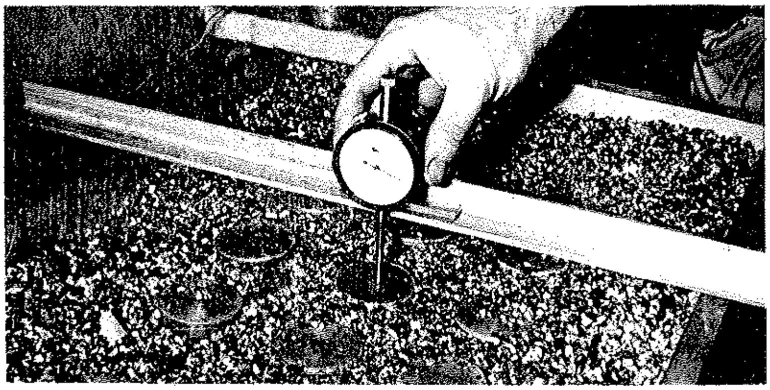
FIGURE A.1 LABORATORY APPARATUS



[A] SPECIMENS IN PLACE



[B] TEST IN PROGRESS



[C] MEASURING HEAVE

FIGURE A.2 FROST ROOM EQUIPMENT

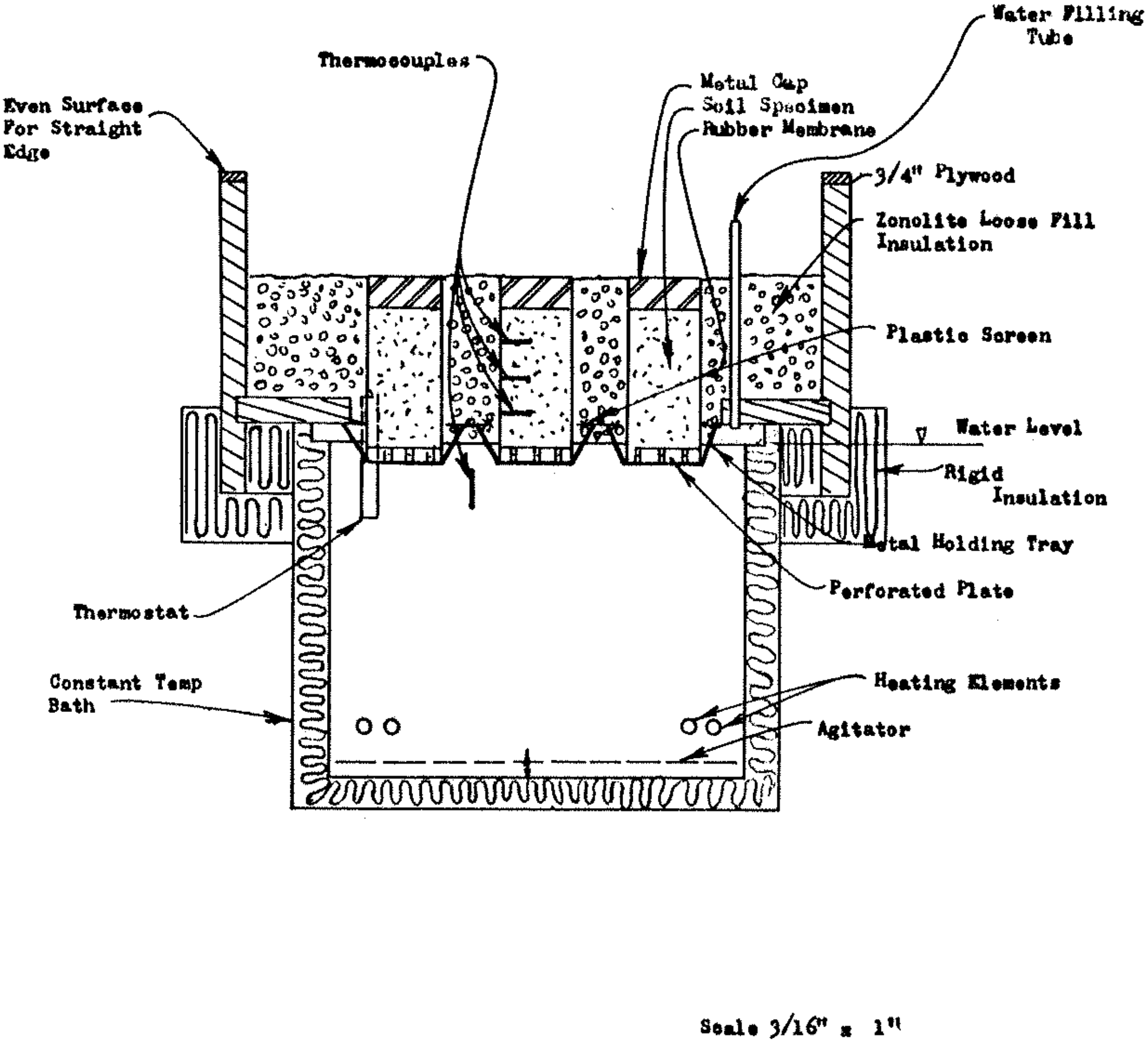


FIGURE A.3 CROSS SECTION DRAWING OF FROST BOX

The admixtures used were sodium chloride, calcium chloride and calgon. All admixtures were oven dried before introducing into the soil to eliminate water of hydration.

c) Specimen Preparation

1. The oven dried soils were ground in a motorized mortar and pestle to pass the No. 10 sieve. Pebbles retained on the No. 10 sieve were discarded.

2. In each batch a number of variables were investigated, such as admix concentration and molding moisture content. The different variables and the number of specimens for each variable are listed in Tables 4.2 to 4.8. The dry soil required for the specimens for each variable tested was weighed separately. The molding water was also weighed and thoroughly mixed with the dry soil. When admixtures were used, these were dissolved in the molding water. All mixing and specimen preparation was done in the moisture room to reduce loss of water by evaporation. After mixing, the soil was placed in polythene bags and stored in the moisture room for a minimum of 24 hours.

3. The wet soil was then forced through a No. 4 sieve to break up the agglomerations and to yield a more uniform soil-water mixture.

4. The soil for each lift was weighed, introduced into the oiled mold and compacted. The top of each lift was scarified to break up the compaction planes. A representative

sample of soil was taken from different parts of the polythene bag for a molding moisture content determination.

5. The top collar of the mold was removed and the surface trimmed with a straight edge. The specimen was removed from the split mold and weighed. Two measurements to 0.001 inches were taken of length with the calipers and six measurements of diameter with an .001" dial gauge adapted to measure diameters.

6. The membrane and aluminum top cap were installed and all three items were weighed. Three readings were then taken of the diameter at marked locations on the membrane. The bottom perforated plate was installed and the overall length, including perforated plate, sample and cap was observed and recorded.

7. After all twenty-four specimens were molded, measured and weighed, they were saturated for a minimum period of 24 hours, by immersing the porous plate in water. A space was provided at the top of each specimen by inserting a match between the cap and the membrane, to allow escape of air during capillary saturation. Some of the specimens were not saturated in Batches Nos. 2 and 3, as noted in Tables 4.3 and 4.4.

8. After saturation, measurements were made of diameter at the marked locations and length. These measurements were necessary in order that the new density after saturation could be calculated. The bottom perforated plate was

removed, and the sample, membrane and top weighed to determine the increase in moisture content due to saturation. The perforated plate was replaced and the samples were then ready for placing in the frost box.

d) Frost Room Procedure

1. The constant temperature bath was filled with tap water so that the level was approximately 0.1 inches above the bottom of the specimen after they were in place. The temperature of the water was lowered to approximately 46.5°F with ice.

2. Three thermocouples were inserted into each of two specimens in each batch. Three holes were made in the side of each specimen spaced at 1 inch intervals above the bottom. The thermocouples extended approximately 3/4 inch into the specimens.

3. All twenty-four specimens were placed in the frost box. Loose fill "zonolite" insulation was used around the specimens to the level of the top of the top caps. An initial zero reading was recorded for heave measurements. The frost room freezer unit was turned on and set for an initial temperature of 25°F.

4. The frost room temperature was lowered every morning. Measurements of heave were taken three times a day. The water level was checked once a day and water was added if necessary. The duration of the test for each batch was 160 hours.

A.4 Conductivity Measurements

a) Apparatus

A Conducto-Bridge Model X50 was used for conductivity measurements. (Refer to FIGURE A.1 for a picture of the apparatus). A high speed dispersion mixer was used to dissolve the soil salts, and salt additive in the water.

b) Procedure

1. The calibration of the meter was the first step. From preliminary checks it was found that 20 gms. of dry soil in 200 c.c. of water gave readings at a sufficiently low range on the meter scale. To 20 gms. soil and 200 c.c. of water, weighed quantities of salt were added, mixed with the dispersion apparatus, and conductivity readings were taken. From this a graph of conductivity versus salt concentration was plotted. (Refer to FIGURE 4.9)

2. Extra specimens were made at the time the specimens for frost room testing were being molded. These specimens were used for determining the salt distribution after saturation. At the end of the saturation period, the extra specimens were cut into four or five equal segments. Each segment was oven dried. After drying and cooling in a dessicator, each segment of soil was ground and thoroughly mixed. Twenty grams of this soil were dissolved in 200 c.c. of water by mixing with the high speed dispersion apparatus for a minimum of one minute. The temperature of the soil

and water mixture was taken and the meter set for this temperature. The soil and water was further stirred with the meter probe until a constant reading was attained. This reading was recorded. This procedure was repeated for the other segments of soil and for different specimens.

3. For determination of salt movement due to water migration after freezing, the frozen soil specimens removed from the frost box were cut into segments. The segments were oven dried and the same procedure used for determining the conductivity as previously outlined.

APPENDIX B

RATE OF HEAVE PLOTS

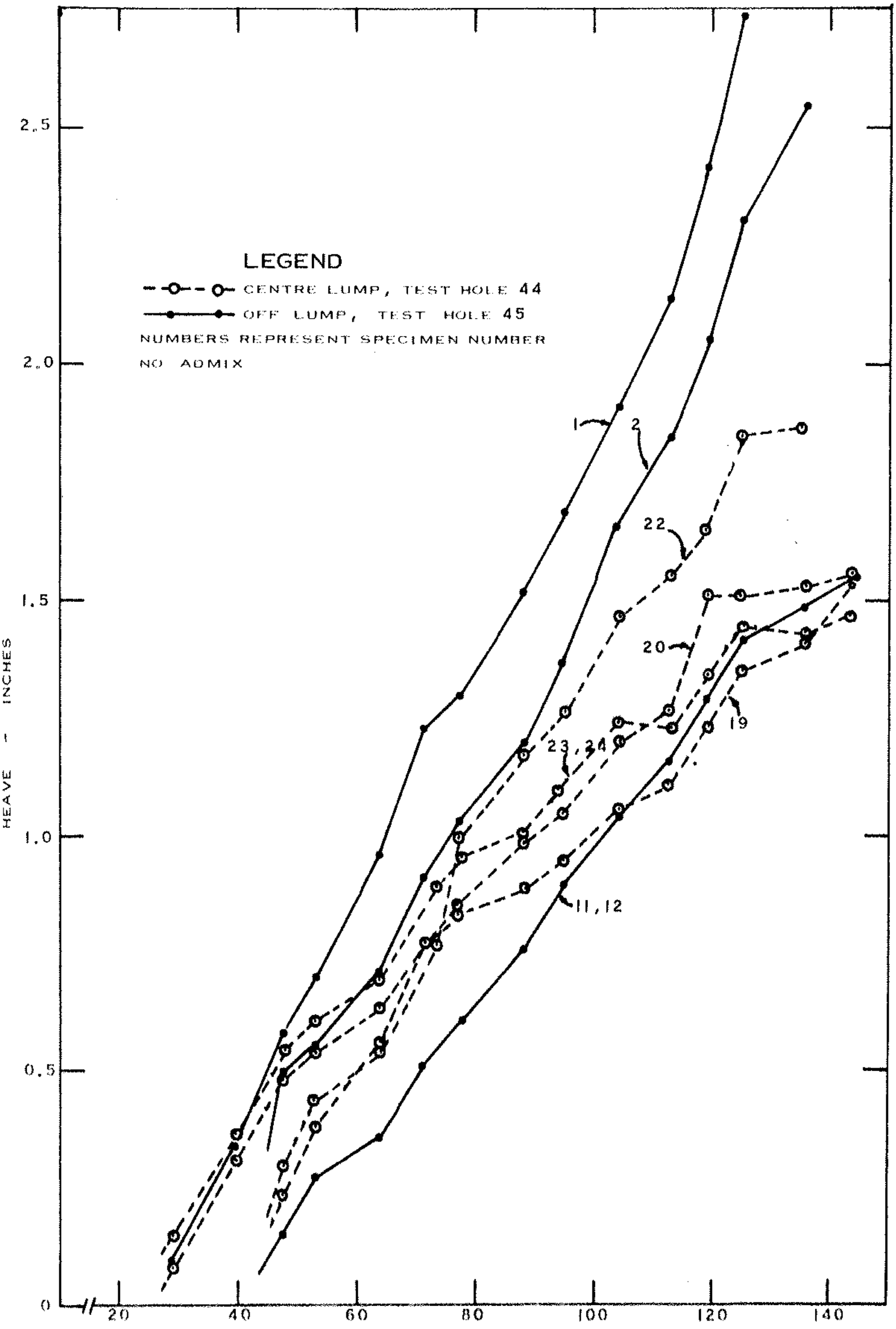


FIGURE B.1 HEAVE VS TIME FOR BATCH NO. 2

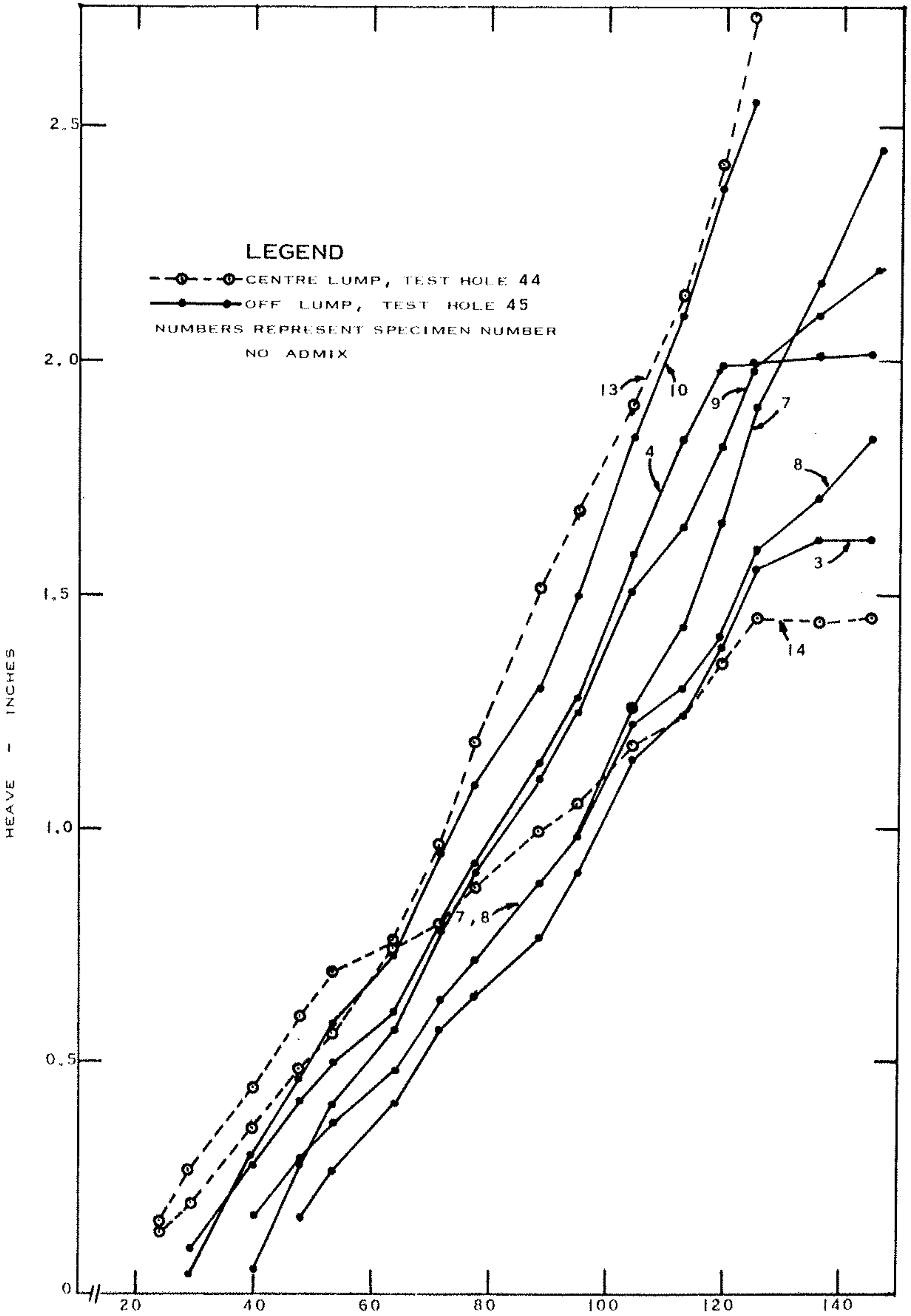


FIGURE B.2 HEAVE VS TIME FOR BATCH NO. 2 [CONTINUED]

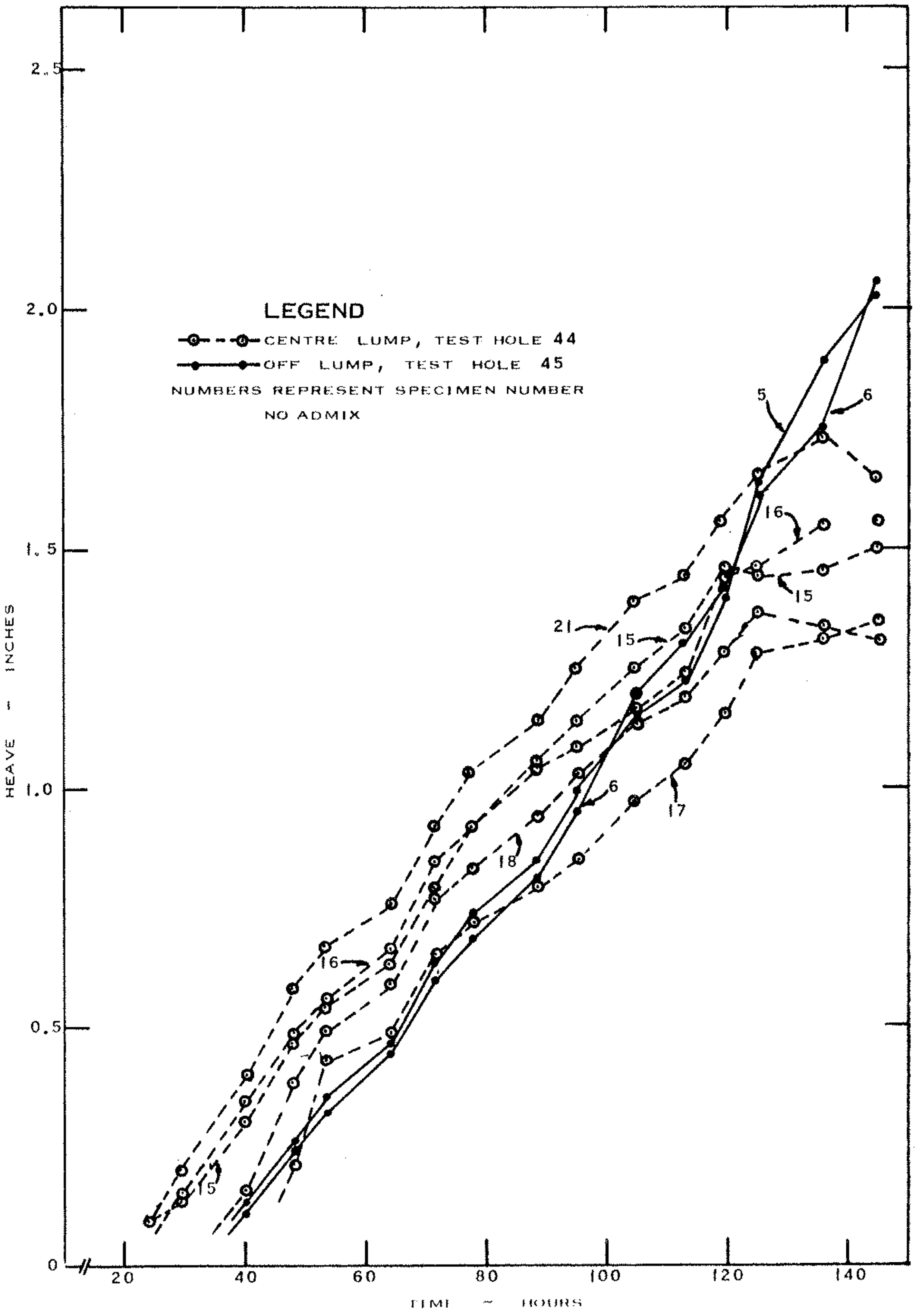


FIGURE B3 HEAVE VS TIME FOR BATCH NO. 2[CONTINUED]

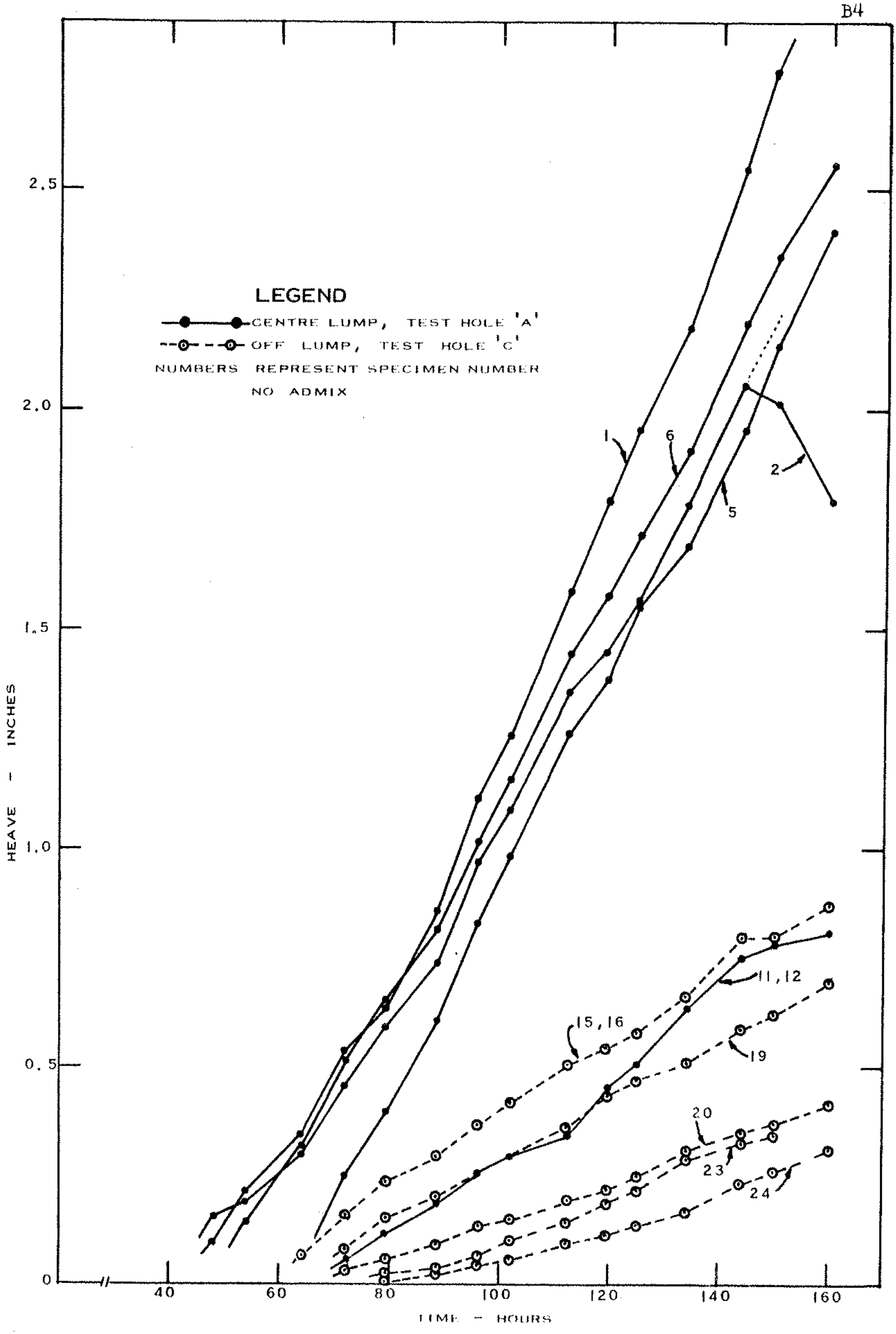


FIGURE B.4 HEAVE VS TIME FOR BATCH NO. 3

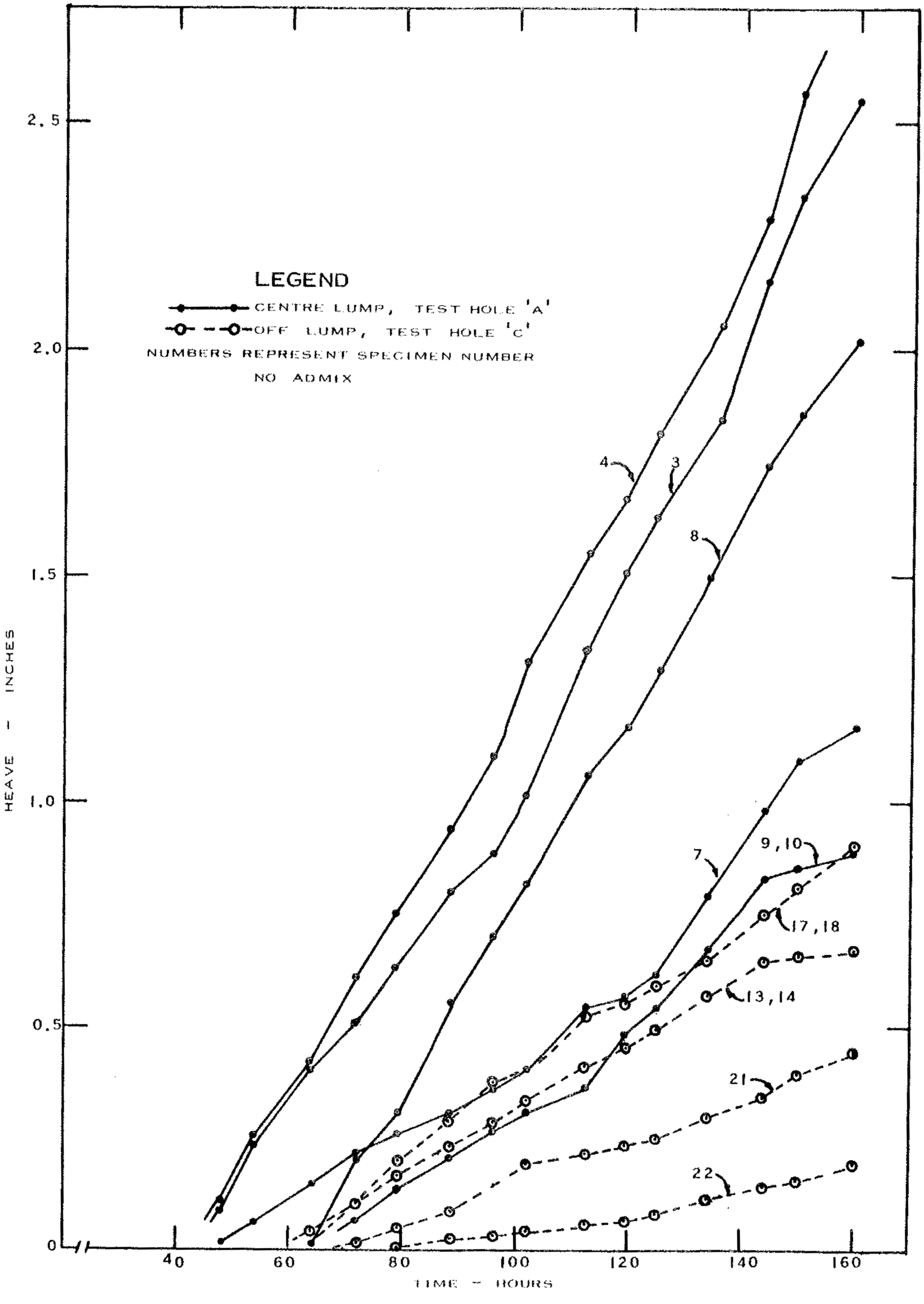


FIGURE B.5 HEAVE VS TIME FOR BATCH NO. 3 [CONTINUED]

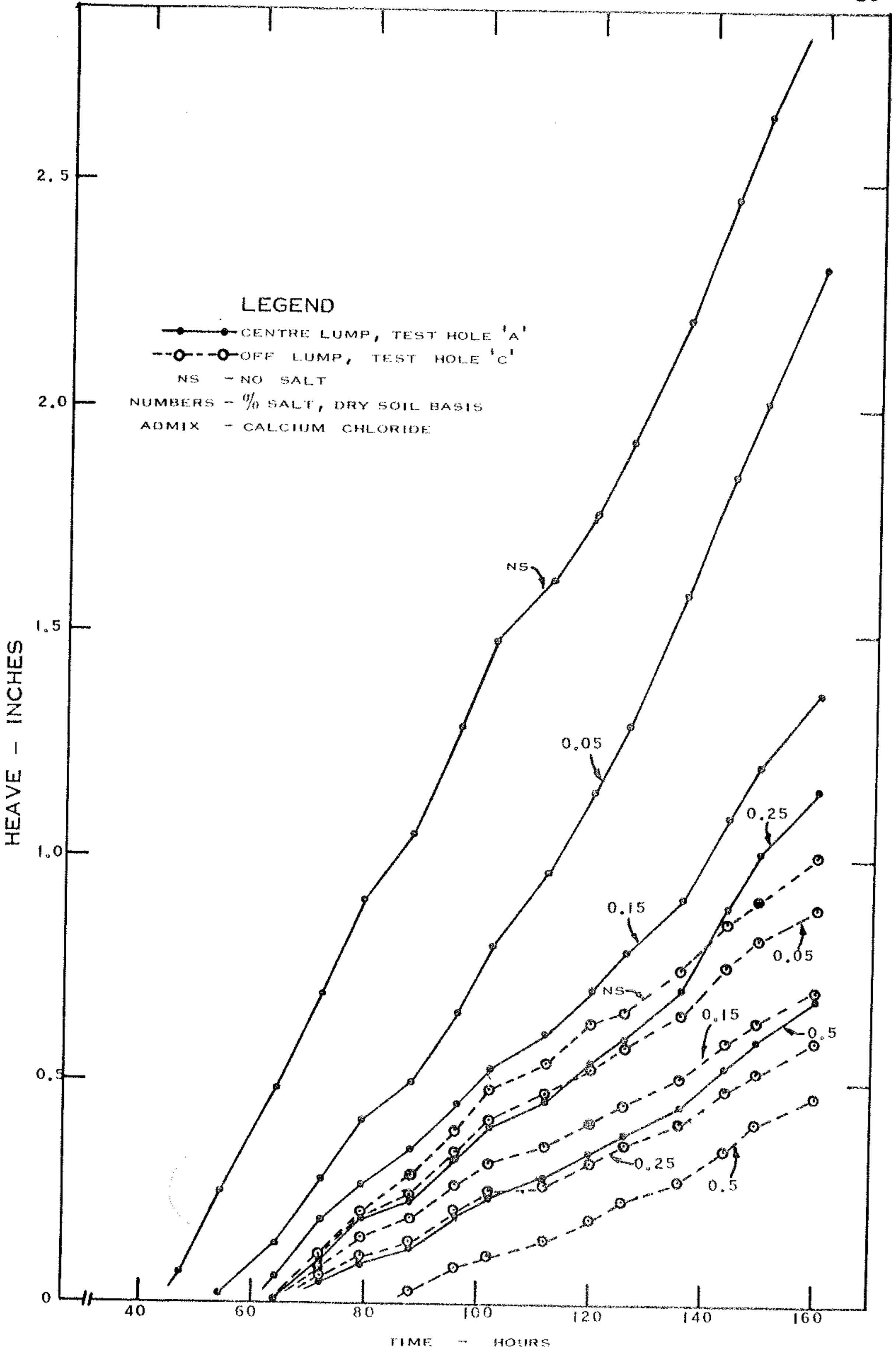


FIGURE B.6 HEAVE VS TIME FOR BATCH NO. 5

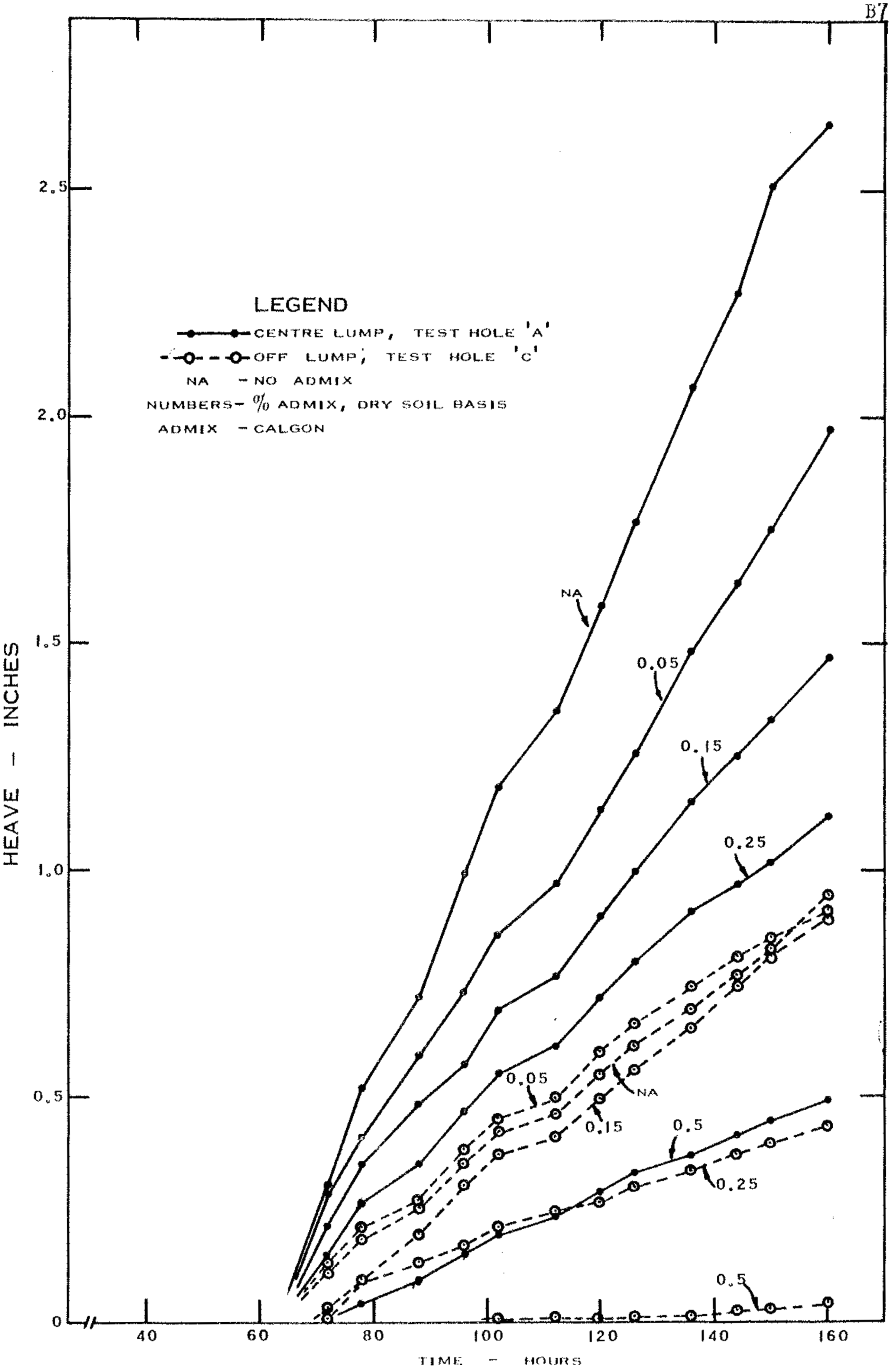


FIGURE B.7 HEAVE VS TIME FOR BATCH NO. 6

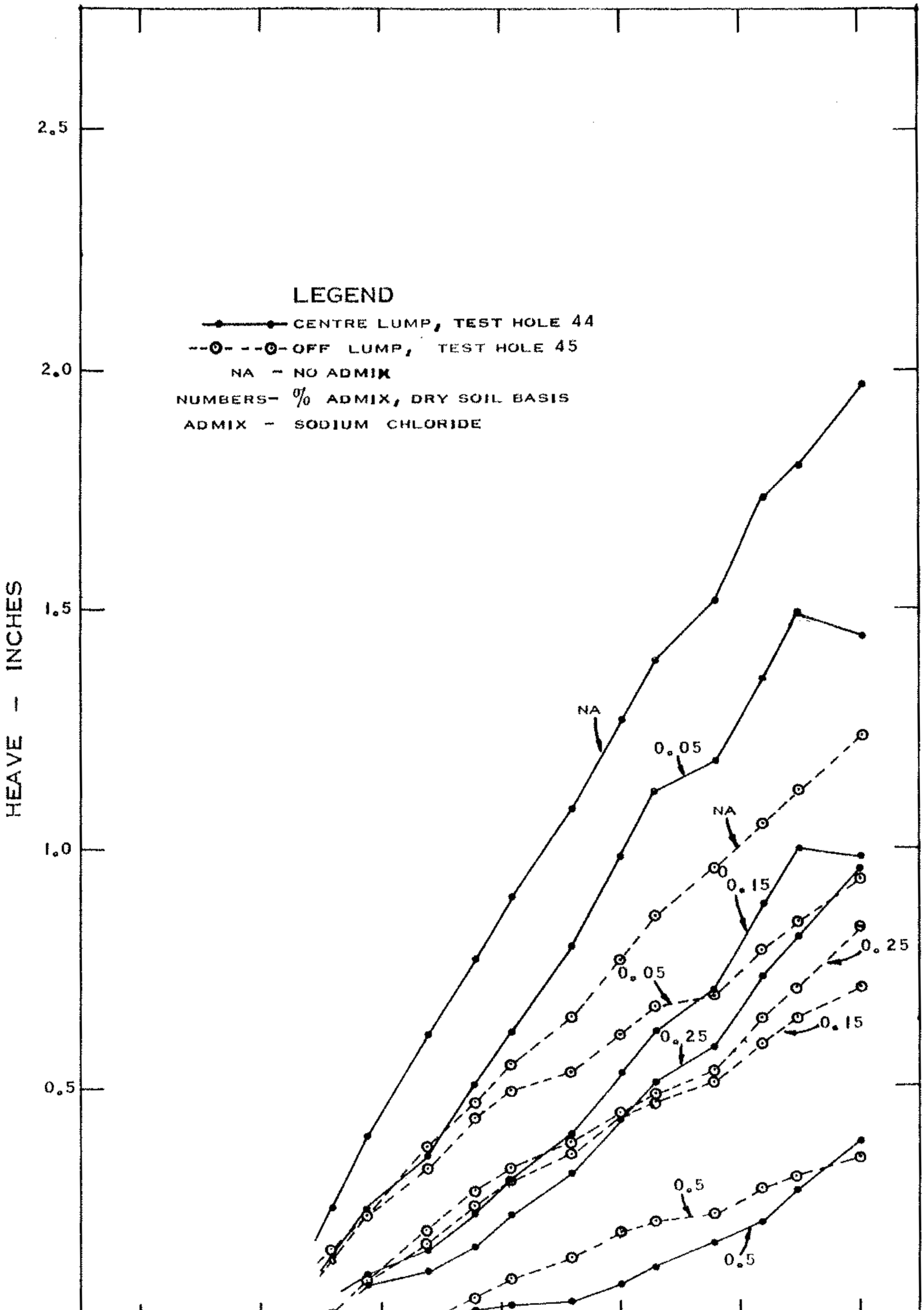


FIGURE B.8 HEAVE VS TIME FOR BATCH NO.7

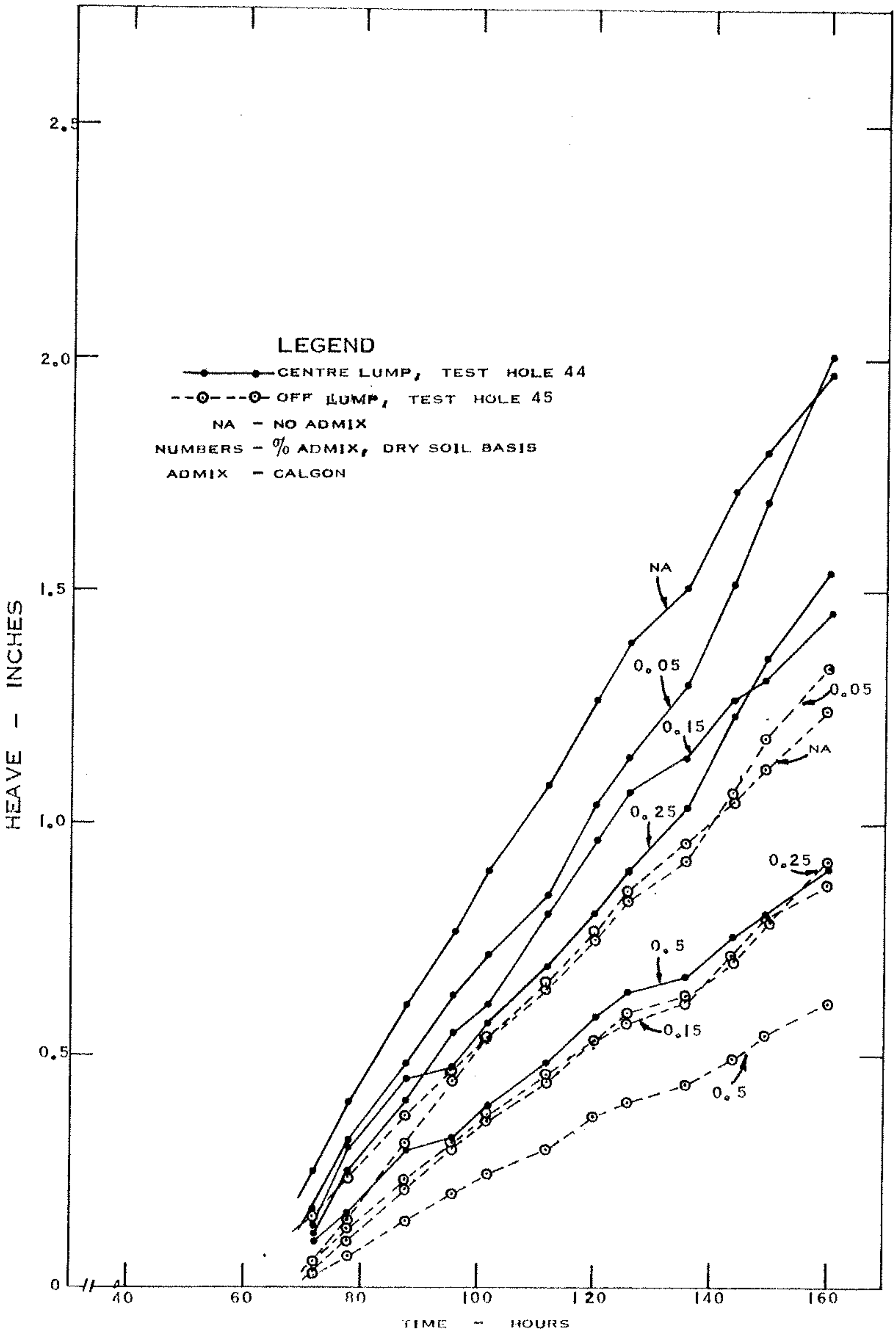


FIGURE B.9 HEAVE VS TIME FOR BATCH NO. 7 [CONTINUED]

Mile 202, Wainwright Sub.

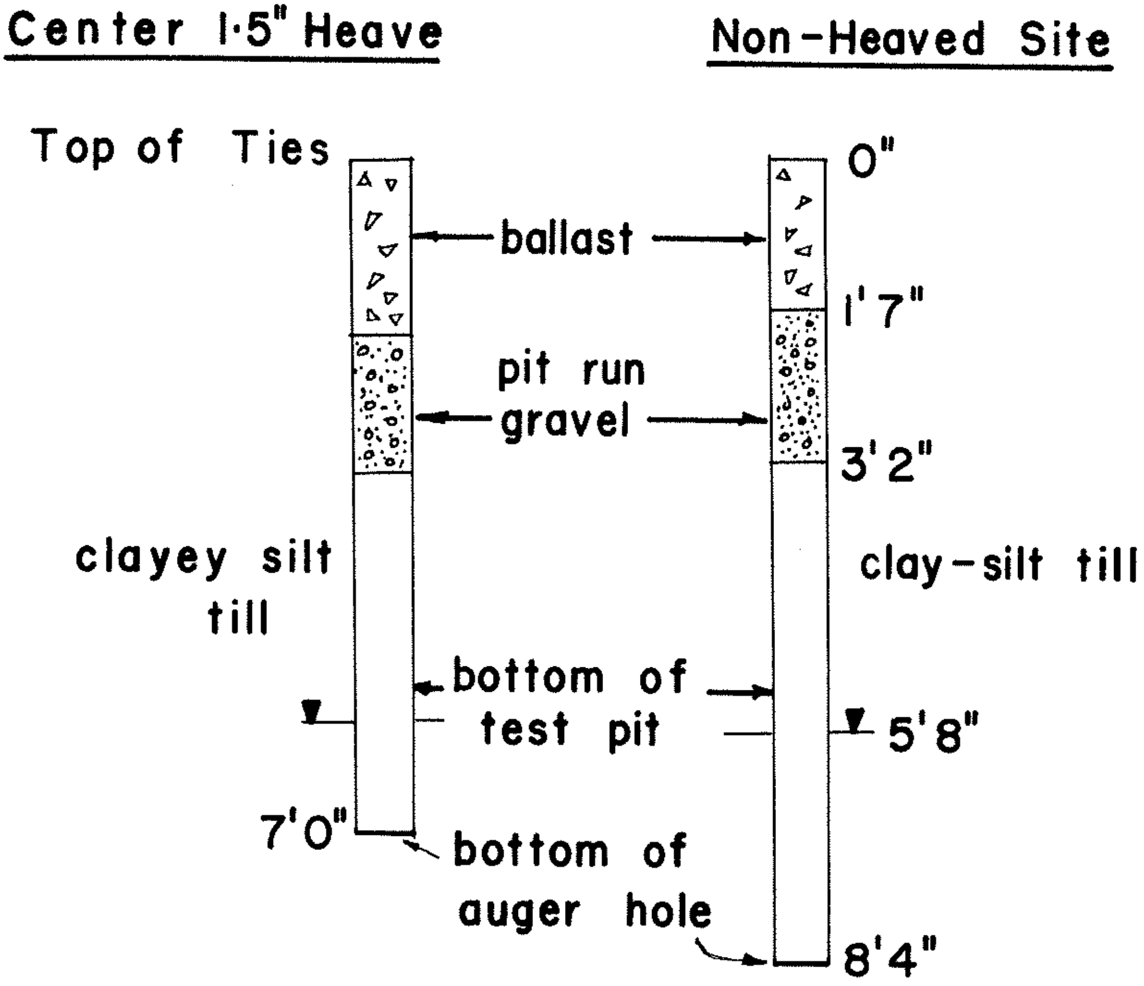


FIG I HOLE LOGS MILE 202

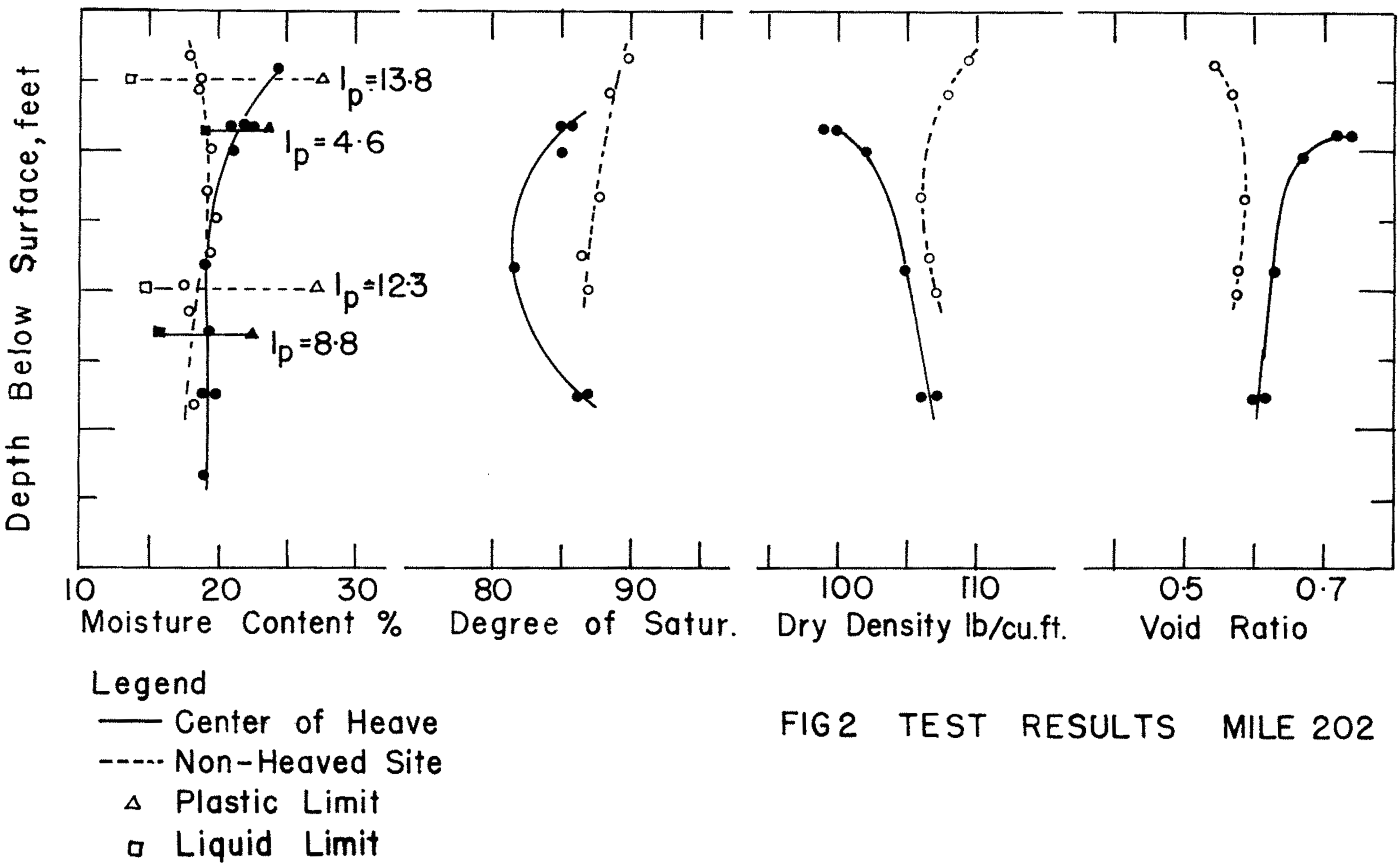


FIG 2 TEST RESULTS MILE 202

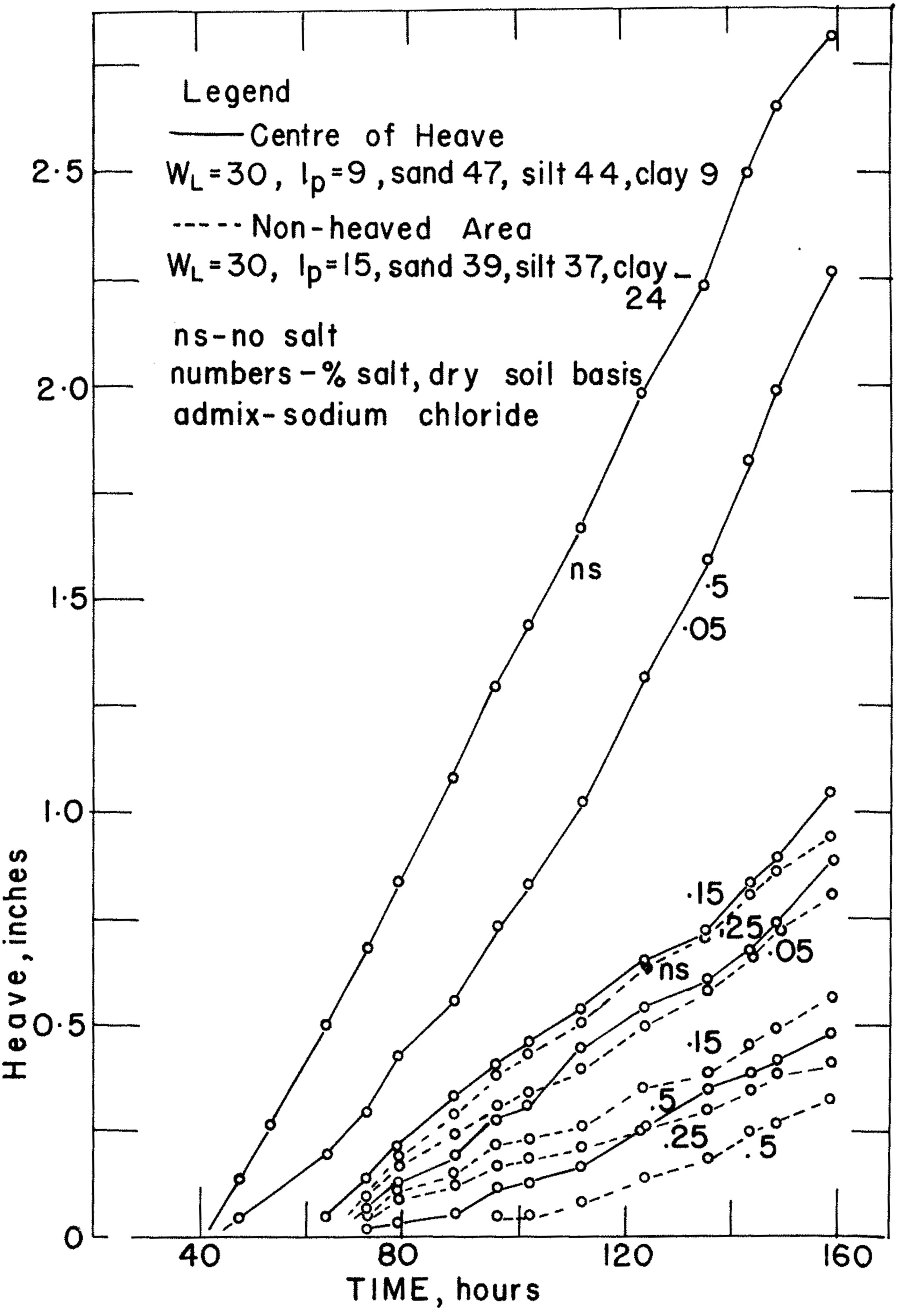


FIG 3 HEAVE VS TIME

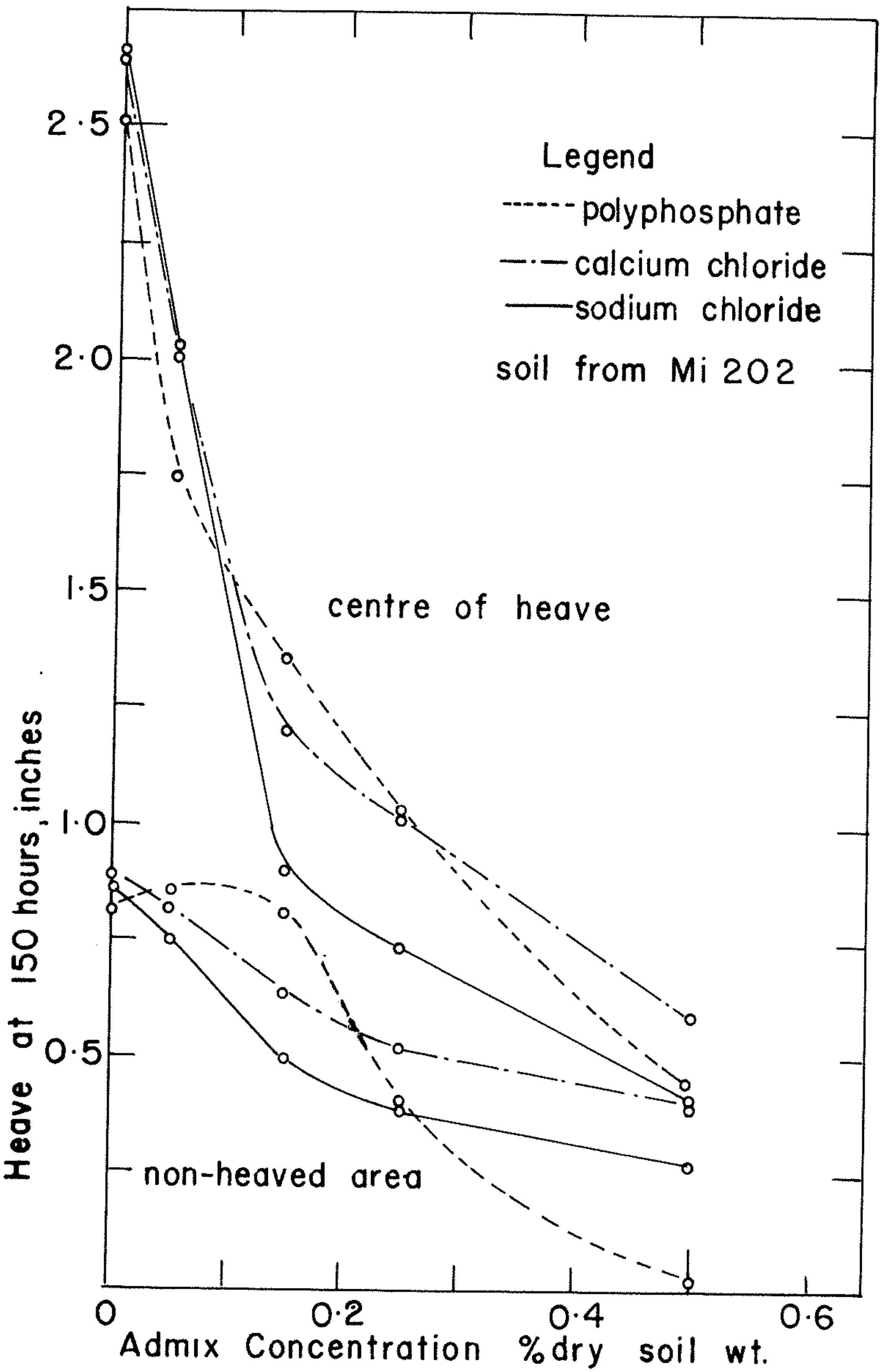


FIG 4 HEAVE VS ADMIX CONCENTRATION

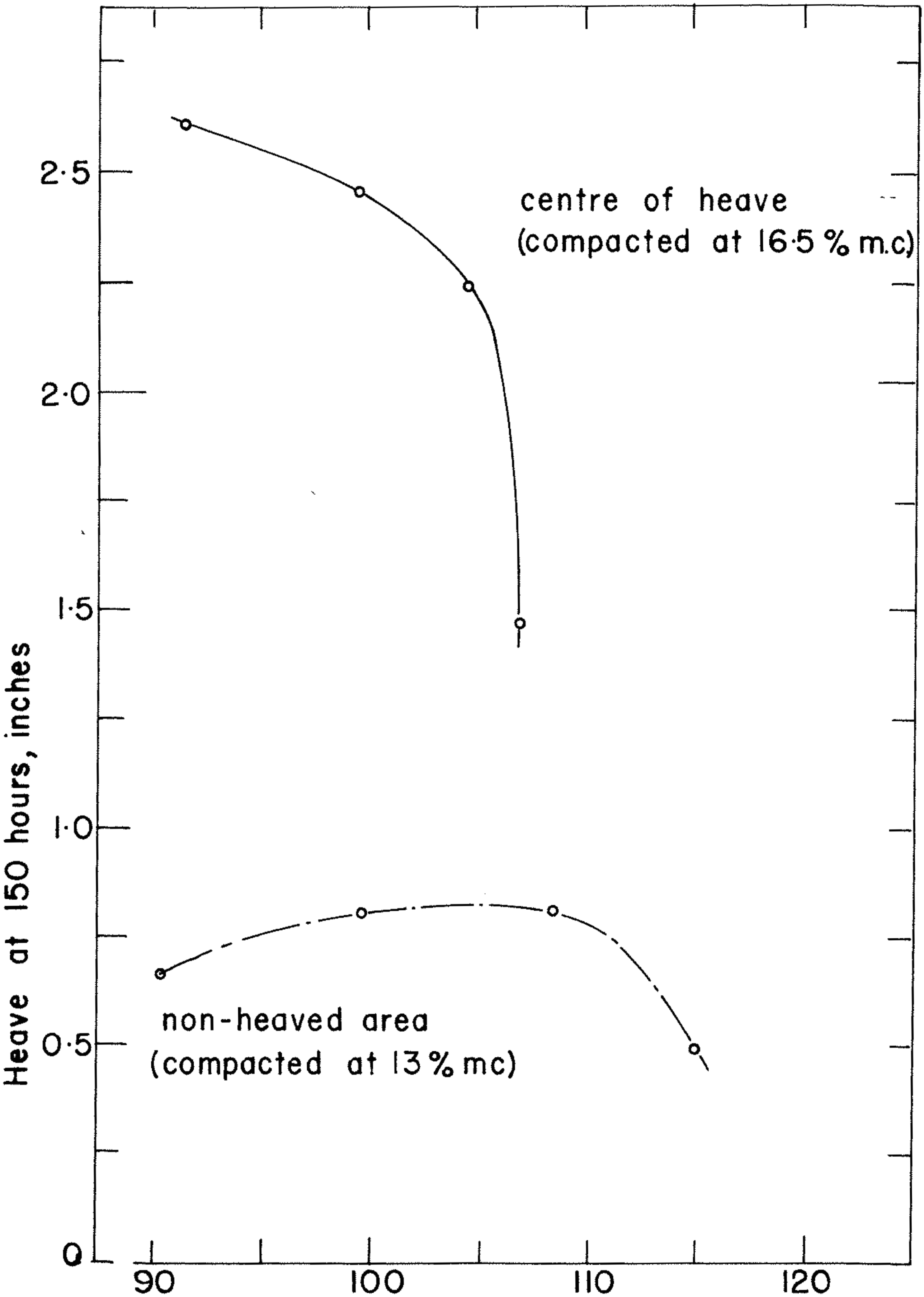


FIG 5 HEAVE VS DENSITY

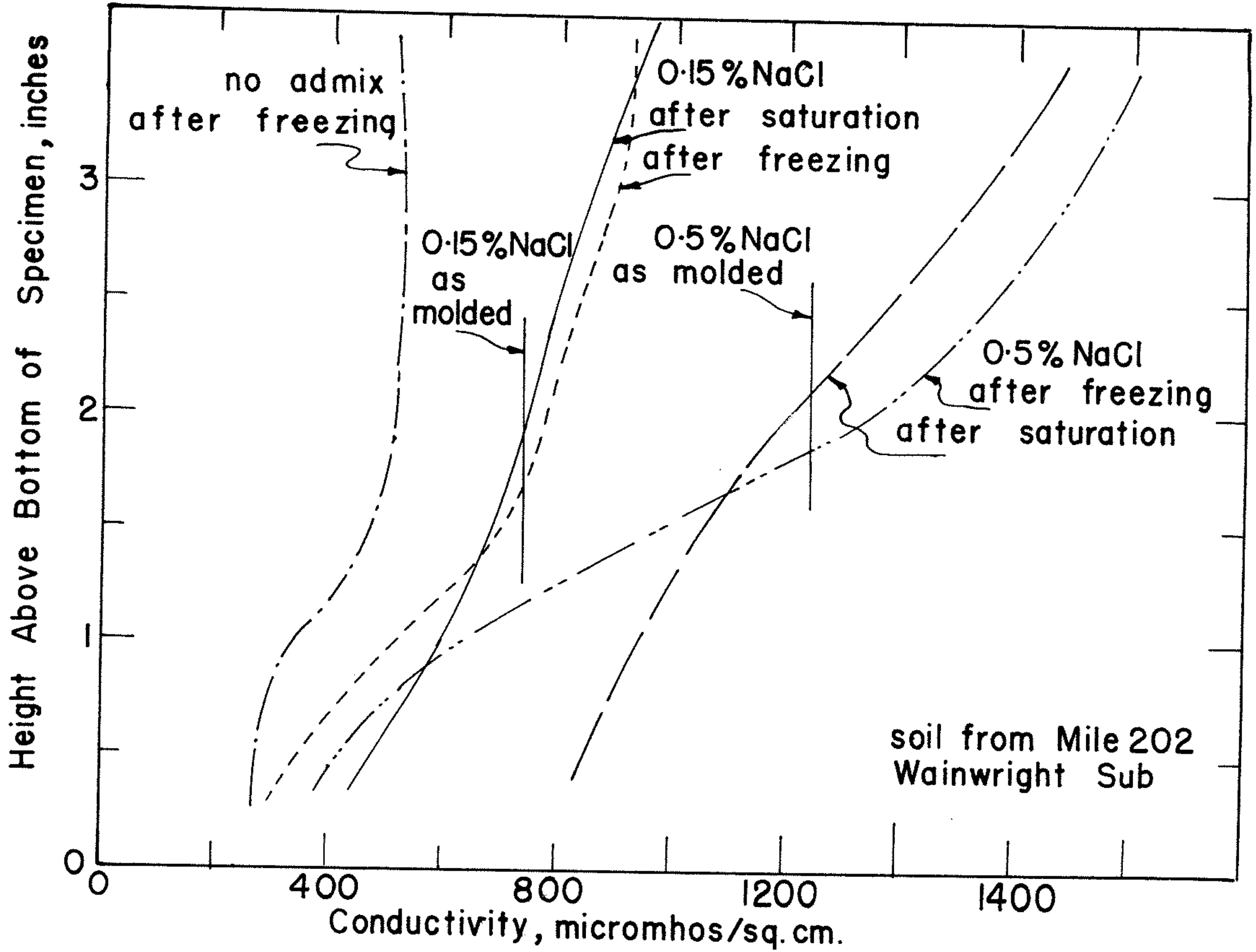


FIG 6 SALT MIGRATION IN SPECIMENS