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Waterjetting as a method of compacting native trench backfill.

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WATERJETTING AS A METHOD OF COMPACTING NATIVE TRENCH BACKFILL

by

Mohamed Aly Fahmy Sheta

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of
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of the requirements for the Degree
of Master of Applied Science at
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Windsor, Ontario, Canada

1977

To my Parents

ABSTRACT

WATERJETTING AS A METHOD OF COMPACTING NATIVE TRENCH BACKFILL

by

Mohamed Aly Fahmy Sheta

Engineers who are associated with trenching in public thoroughfares have been striving for many years to find better and more economical construction methods and procedures for backfilling these trenches. The use of waterjetting to compact native trench backfill has long been known among engineers and contractors. The importance of waterjetting comes into view because of the possible savings which might be derived from the use of this method. Unfortunately, the lack of research and field data in waterjetting makes it difficult to evaluate this method properly.

In this study, results of a monitoring experimental programme that had been initiated to study the effect of relevant selected parameters on the backfill behaviour during and after jetting are presented. These parameters are: lump size and gradation, initial trench depth, jetting water pressure, seepage force, soil rejetting, jetting the backfill in layers, soil area per jet, trench drainage conditions, and backfill soil type.

A separate comparative study is carried out on each parameter to examine its effect on the backfill behaviour. The behaviour of a backfill is governed in this research work by the degree of compaction, the average change in void ratio, the settlement and the change in backfill moisture content with time after jetting. Curves are drawn for each of the selected parameters to show their effect on the aforementioned backfill behaviour. Based on the analysis of the experimental data obtained, a general compaction mechanism of the waterjetting process is also presented.

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INTRODUCTION

1.1 General

The use of waterjetting to compact native trench backfill has long been debated among engineers and contractors in many areas and for example, the Windsor area (1). The available information on waterjetting as a compaction method for native trench backfills pertains mainly to the performance of the method rather than its fundamental principles of compaction. Unfortunately, the lack of research studies on waterjetting makes it difficult to evaluate this method properly.

1.2 Definition of the Problem

A typical urban street has at least one backfilled trench underlying the limits of the pavement. The existence of such a trench is essential for placement of services such as sanitary and storm sewers, electrical and telephone cables, water and gas lines, runoff culverts and oil pipelines. In order to repair a pavement through which a cut has been made, it is necessary to compact the trench backfill. Two procedures can be employed for backfill trench compaction; namely, using mechanical equipment such as sheepsfoot rollers, pneumatic wheel rollers, etc., and using water as in the case of puddling, ponding or waterjetting the soil (2).

1.3 Motivation

Increased attention is being paid by engineers and contractors who are associated with trenching problems to find optimum economical methods and procedures for backfilling and compacting these trenches. The use of waterjetting as a compaction method in lieu of mechanical compaction results in significant savings, especially when native materials are used.

To the author's knowledge, no attempt has been made previously to discuss the basic concepts of compaction by waterjetting or to clarify its mechanism. The lack of literature on this problem was in fact the principal motivation for this work.

1.4 Objectives and the Approach in General

The main objective of this investigation was to study the effect of relevant selected parameters on the behaviour of the backfill during and after jetting. These parameters are: lump size and gradation, initial trench height, jetting water pressure, seepage force, soil rejetting, jetting in layers, soil area per jet, drainage conditions and soil type. The above mentioned behaviour of backfill is presented in this study in terms of degree of compaction, average change in voids ratio, settlement, and time dependent moisture content and degree of saturation. Based on the analysis of the experimental data obtained, an attempt was also made to conclude a general compaction mechanism of the waterjetting process.

The experimental study was carried out on a model which consisted of a plexiglass box where the different backfill samples were placed and jetted. Jetting was conducted using a brass pipe connected to the water supply.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

2.1 Introduction

A survey of the literature revealed that virtually no research has been undertaken to study the behaviour of native cohesive backfill compacted by the waterjetting method under the effect of the parameters considered in this study. Most of the investigators appear to be concerned with comparing the use of waterjetting with mechanical compaction methods (1) and (8).

This chapter presents a review of the available literature on issues related to the current research; namely, basic concepts of backfill compaction, service trench backfills and the selection of its material, specifications and design of service trench backfill, and finally, waterjetting as a method of compacting native trench backfills.

2.2 Basic Concepts of Backfill Compaction

Compaction is the process of applying energy to soil, e.g. backfills, to pack its particles more closely through a reduction in voids. Proper backfill compaction improves its load carrying capacity, reduces settlements, prevents collapse or deformation of structures built over the soil, reduces volume change and reduces water infiltration and frost damage.

2.2.1 Compaction Mechanism of Trench Backfill

a) Granular materials

To simply illustrate the mechanism of compaction of granular material, a diagram is shown on Figure 2.1 for a uniform granular material. In this classic example, the soil particles are represented as glass marbles, all of the same size. The loosest configuration of the marbles occurs where they are in vertical stacks with each marble directly on top of the one below. The densest configuration is obtained when the layers of marbles move laterally and drop into the space between the underlying marbles (Figure 2.1) (3).

b) Cohesive materials

With a backfill consisting of cohesive soils, a different mechanism of compaction occurs. The cohesive soil is invariably broken into lumps during excavation.

In order to compact cohesive backfill having a lumpy structure, it is necessary to use a method which applies vertical forces and kneading process to squeeze the lumps together (Figure 2.1). The distortion of the shape of the lumps of clay to fill the voids necessitates each lump to fail in shear and remould into a new shape (3).

2.2.2 Measurement of Soil Compaction

Compaction is measured quantitively in terms of the dry density of the soil, which is the weight of soil solids per unit volume of the soil in bulk. The density is chosen because it is an easily determined characteristic, and its variation reflects the variation of those important soil properties such as strength, freedom from additional densification under natural forces, water-tightness, and many other relevant characteristics of great interest in trenching operations (4).

A common practice in earthwork construction is to control compaction by specifying dry densities equal to or greater than some arbitrary percentage of the maximum dry densities obtained by standard laboratory tests. Laboratory tests used as guides for field compaction are the standard Proctor test (AASHO T-99 and ASTM A-698) and the modified Proctor test (AASHO T-180 and ASTM D-1557). The standard Proctor test is best suited as the control test for normal earthwork construction which includes compaction of trench backfill (5).

2.3 Service Trench Backfill

A great number of services requires trenching for their placement such as sanitary and storm sewers, electrical and telephone cables, etc. (see Section 1.2). Engineers who are associated with trenching in public thoroughfares have been striving for many years to find better and economical construction methods and procedures for backfilling these trenches. The essence of the problem of controlling backfill materials in general is to repair a pavement, through which a cut has been made, in as permanent a manner as possible, consistent with reasonable economy and a minimum of public inconvenience.

2.3.1 Selection of Service Trench Backfill

The selection of service trench backfill is primarily a matter of economics, availability of materials and local municipal policy as in Southwestern Ontario (3). The selection of backfill material is normally a choice between native excavated (mostly cohesive) or imported granular material. It is widely acknowledged that granular materials are preferred. However, with the increasing scarcity and cost of granular materials coupled with a rising public concern for the conservation of valuable natural resources, a choice of alternative backfill material is not always available. Hence, it is becoming increasingly important that native backfill be used wherever possible in service trenches.

To determine basic soil class division between granular and cohesive materials for compaction purposes, it has been suggested (6) that all soils with less than 15 per cent of their mass made up of material smaller than 0.06 mm be classed as granular soils. A soil is cohesive (2) when it contains a fair proportion (approximately 10 per cent or more) of the clay fraction.

2.3.2 Characteristics of Native Cohesive Backfills

Native cohesive backfill materials have a number of advantages; namely, they are available in places of cohesive soil nature at no cost, most stable in its natural state, able to bond with adjacent similar materials, easily re-excavated and available for relative compaction tests. On the other hand, cohesive backfills have the following disadvantages: they are difficult to handle, especially under adverse weather conditions, difficult to compact properly and require close inspection to verify the required state of compaction (5).

2.4 Specifications and Design of Service Trench Backfill

One of the primary purposes of a road is to enable traffic to proceed with comfort. To do this, the road surface must be free from irregularities, cracks, and other defects which interfere with the smooth travel of a vehicle and cause discomfort to the passengers and possible danger to the vehicle or the goods it is carrying (2). Many of the defects in road surfaces are attributed to the soil foundation on which the road is built. Moreover, these defects are often more serious than those resulting merely from faults in the surfacing.

A typical urban street has at least one backfilled trench running within the limits of the pavement. In order to illustrate the behaviour of pavement structure and the subgrade when a wheel load is applied to the top of the pavement, a simplified distribution for a typical 9 kip wheel load is shown in Figure 2.2 which demonstrates that the applied stress decreases from 9 kips/square foot at the surface to 0.25 kips/square foot at a depth of five feet. The subgrade below this depth experiences little or no stress increase from the applied wheel loadings, but merely has to be stable under the stresses induced by its own weight. On normal municipal streets this five foot thickness usually consists of two feet of asphalt and granular materials in various proportions and the upper three feet of the service trench backfill. Below a depth of five feet the backfill does not substantially contribute to the strength of the pavement (3).

In order to examine the functions of and design criteria for the backfill, it is convenient to divide it into three distinct zones as shown in Figure 2.3

Zone A: This backfill, usually a select granular material, is required for bedding and backfilling around the buried service. Its specification and degree of compaction is controlled by the type of underground service and its specific support requirements.

Zone B: The backfill fills the zone between the pavement structural beam and the underlying service bedding. Its main requirement is to be stable under its own weight, traffic vibrations, and downward water seepage forces.

Zone C: This backfill forms a part of the pavement structure. It must be capable of distributing part of the traffic wheel loading and remain stable under the weight of the overlying backfill and the applied pavement loads. The actual specifications vary with the type of soil and the pavement loading conditions. They are rarely less than 95 per cent of the standard Proctor maximum density at a water content of about 2 per cent less than the optimum to the optimum water content (3). This zone extends to different depths depending upon the weight of the traffic using the road and the thickness and type of road structure (2).

2.5 Waterjetting as a Method of Compacting Native Trench Backfills

The method of waterjetting to compact native trench backfill is known among engineers and contractors, although its mechanism of compaction is not. In "waterjetting," the trench is filled nearly to the top with relatively dry, loose soil, and then with a water supply turned on, the jetting pipes are slowly inserted by hand into the backfill until the granular material (Zone A, Figure 2.3) is reached. The pipes are usually left in this position for a period of time (15-20 minutes), after which time the pipes are progressively withdrawn a foot or two at a time (1). The pipes are completely removed when water begins to appear at the top of the backfill (1 and 7) (see Photos 2.1 to 2.3).

Based on field results (1) a number of advantages and disadvantages associated with the use of waterjetting are described below.

2.5.1 Advantages

Waterjetting of a trench backfill in lieu of mechanical compaction can result in significant savings (see Section 2.5.3). Narrow trenches can be used resulting in less excavation, less excess material to dispose of, shorter crossing utility supports and less surface restoration requirements. This method also has an advantage in terms of construction safety (1), as men and machinery are not required to enter the trench behind the service pipe laying operation. In the case of mechanical compaction, the trench backfill is compacted relatively dry, and hence further settlements occur after periods of successive rainfall and ground water infiltration, even though the compaction meets the required specifications. This is not the case when waterjetting is used, since the backfill material is entirely saturated and further settlement due to water infiltration is less likely. In most cases where mechanical compaction is used with native trench backfills, proper compaction is not achieved immediately adjacent to the trench walls. It is possible for the water to permeate at the backfill during waterjetting.

In existing built-up areas, frequent utility crossings make it impossible to construct proper ramps down to the bottom of the trench for use by mechanical equipment. As a result, the use of sheeps-foot rollers, for example, are impossible in these areas and smaller hand operated plate tampers must be used to compact native materials around existing utilities and manholes. Such a problem does not exist when waterjetting is employed.

When waterjetting is used, the initial backfilling operation can be completed quickly. Temporary gravel driveways can be quickly constructed across the backfill to service existing homes. Generally, when carefully applied, waterjetting can be an effective method of compacting free draining trench backfill materials.

It may be of interest to mention that, although waterjetting increases the backfills' moisture content, a significant reduction in this water content within a few percentage points of the Proctor optimum value could occur after periods of time (28 to 43 days, for example, at Sandwich South Provincial Sewage Works, Ontario (8)). This reduction in water content is always accompanied by an increase in dry density to about or in excess of 95 per cent of the standard Proctor maximum value (8).

2.5.2 Disadvantages

Some delay is generally experienced from the time that the utility is installed until the waterjetting can be carried out and a proper road can be reconstructued. Since the jetting water interferes with the utility installation, it is generally preferable to carry out the jetting after fairly long sections have been completed.

Prior to jetting, the level of the backfill materials should be kept below grade to prevent the saturated backfill from spilling onto areas adjacent to the trench (1).

The use of waterjetting causes a significant increase in the water content (1); it is common practice to leave the top of the trench open for one to several weeks to permit the drainage of excess water (7). Free draining pipe bedding must be used in conjunction with waterjetting to permit the water to drain out of the backfill material through the bedding into openings left in the manholes. Also, considerable testing is required with waterjetting to ensure that no significant settlement will occur after the complete restoration of the trench is carried out.

2.5.3 Cost Study

It appears that the contract cost of placing backfill by mechanical tamping is approximately three times the cost of using water (7). This comparison is based on the average basis and on the assumption that native excavated material is satisfactory for backfilling. If selected material is brought, the relative cost may be in a 5 to 1 ratio (7).

Based on detailed cost estimates prepared by M. M. Dillon Limited (1), it appears that savings from 5 to 15 percent of the lineal foot price for the installation of sanitary sewers can be achieved through the use of waterjetting rather than mechanical compaction.

CHAPTER III

EXPERIMENTAL SET-UP AND TEST PROCEDURE

3.1 Soils

Most of the tests were carried out on Soil No. 1, obtained from East Windsor (Table 3.1). This soil was generally classified as cohesive soil according to the suggestions made in Section 2.3.1, Ref. (2) and (6).

To study the effect of soil type, Soil No. 1 was mixed with Soil No. 5 (Erie Sand) to obtain five different soil types. The properties and classification of all five soils are summarized in Table 3.1. The grain size distribution curves for all soils and the standard Proctor Compaction test results (AASHO T-99 and ASTM A-698) are shown in Figures 3.1 and 3.2 respectively.

3.2 Test Apparatus

The main apparatus used in this research work consisted of a transparent plexiglass box 30.7 inches long, 7.9 inches wide and 19.7 inches high (78 by 20 by 50 cm.), 0.6 inches (1.5 cm.) thick walls, as shown in Figure 3.3. Plexiglass was chosen to minimize the friction of soil against the walls of the apparatus and to allow visual observation and photography during testing.

In order to obtain samples of identical initial conditions and for comparison purposes, the apparatus was divided into essentially three water-tight compartments each of 9.8 inches long, 7.9 inches wide, and 19.7 inches high (25 by 20 by 50 cm.). This was done using two movable plexiglass partitions 0.6 inches (1.5 cm.) thick.

To simulate field conditions and to drain the excess water out of the soil during and after jetting, a 2 inch layer of uniform gravel (0.5 inches diam.) was placed on the bottom of the apparatus as shown in Figure 3.3 and Photo 3.1. This layer was covered by a window screen of 0.078 by 0.078 inch (2 by 2 mm.) openings to prevent the soil from mixing with the gravel. Three water outlets, one for each compartment as shown in Figure 3.3, were used to permit water drainage and were secured with valves.

3.3 Measurement of Settlement

In order to determine the settlement occurring in each sample at different depths, steel settlement plates 1.0 inch by 1.0 inch (2.5 by 2.5 cm.) were used and installed inside the soil samples at various depths. Steel rods, 1/8 inch (.32 cm.) in diameter, were attached to the settlement plates and extended vertically up through the top steel guide plates (see Photo 3.2), which were used to position the settlement rods during and after soil placement (Photo 3.3). A typical soil sample layout in a compartment is shown in Figure 3.4.

The settlement of the steel rods, which represent the settlement of the soil sample itself at various elevations were measured using Mercer dial gauges of 0.001 inch accuracy (Photo 3.4). The tips of the dial gauges rested on aluminum caps placed on top of the settlement rods as shown in Figure 3.4 and Photo 3.2. To facilitate the measurement of soil surface settlement and to determine the actual sample heights, a set of horizontal lines 1.0 cm. apart was inscribed on both sides of the plexiglass box (Figure 3.3 and Photo 3.4).

3.4 Waterjetting Technique

Waterjetting of the soil was carried out using a brass pipe 19.7 inches (50 cm.) long and 0.4 inches (1.0 cm.) I.D. The lower end of the pipe was machined to form a conical nozzle with eight 0.08 inch (2.0 mm.) diameter holes around the sides and one at the top (Figure 3.5). The upper end of the brass pipe was connected via a reinforced plastic hose of 0.5 inches (12.5 mm.) I.D. to the water supply through a water pressure regulator (Figure 3.5 and Photo 3.5). To measure the jetting water pressure, an Ashcroft pressure gauge was used and connected to the water regulator as shown in Figure 3.5 and Photo 3.5.

In a few tests, in order to study the effect of seepage force after jetting on soil behaviour, a means of achieving various seepage rates was required. Since pumping was judged less convenient than applying negative water heads at the water exits, the latter method was adopted/ A constant water level at the initial soil surface was maintained and different negative water heads were applied at the exits to create different water heads. This was achieved using the vacuum system shown in Figure 3.6 and measured using an Ashcroft vacuum gauge.

3.5 Preparation of Samples

To prepare the samples for jetting, the required moist weight of soil to fill each compartment was first determined. In order to achieve uniform initial conditions for the study of each parameter, the dry density was kept constant. Thus, the moist weight of the samples required were determined from the knowledge of the initial moisture content. This was done by taking three moisture content samples for oven drying before each experiment, while the rest of the soil was protected with plastic sheets to prevent evaporation of water.

During soil placement, settlement plates were embedded inside the soil, two at each specific depth to obtain average readings, as illustrated in Figure 3.4 and Photo 3.3. The top guide plates were used to position the settlement rods during soil placement (Photo 3.3), then were screwed to the aluminum channels surrounding the top of the box to act as bases for the dial gauges. Aluminum caps were then placed on the tips of settlement rods and dial gauges with bases resting on the top of the guide plates were installed and zeroed.

3.6 Test Procedure

When soil placement was completed, waterjetting was carried out. With the water flowing, the jetting pipe was lowered through the soil until the gravel layer was reached. The pipe was lowered mainly under its own weight, occasionally additional hand pressure was required to aid impeded progress or restraint when progress was judged to be too rapid. The water supply was closed when water reached the soil surface. The time of jetting and the actual jetting water pressure were recorded for each experiment. Essentially, all the water outlet valves were opened during jetting to simulate field conditions and to obtain free drainage conditions.

Immediately after jetting, and every 24 hours for a fifteen day period, dial readings were recorded to determine the soil settlements at the various elevations. This fifteen day period was assumed to be long enough to give an adequate determination about soil behaviour. A study was always carried out after this period of time to show the effect of the selected parameters. The same time period was also considered short enough to enable the study of several parameters within a convenient time span.

To study the change in soil moisture content with time, samples were taken from the top of each soil compartment every five days for moisture content determinations. Care was taken not to disturb the soil masses.

To calculate the fifteen day average dry density, the following steps were taken upon completion of the test period:

1. The dial gauges and top steel guide plates were removed.

2. The total soil volume was determined as follows:

   a. In the case of a smooth soil surface, the average top soil elevation was observed using the lines inscribed on the box sides. With the knowledge of the soil area, the volume was calculated.

   b. In the case of an irregular soil surface, a thin plastic sheet was used to cover the surface to prevent soil contamination, and a known volume of sand was added to bring a level surface to a known elevation. Thus the actual volume of soil was calculated.

3. Before removing the soil, and as a check of the average density, soil samples were cut from different depths using an Hvorslev Pocket Piston Sampler (Photos 3.6 and 3.7) and weighed. The volume of each sample was determined by knowing the area of the sampler and measuring the penetration of the sampler in the soil mass (actual height of sample) using a dial caliber 0.001 inch accuracy, 6.0 inch travel and manufactured by Mitutoyo (Photos 3.6 and 3.8). The sampler penetration in the soil mass was used for volume determination rather than the samples' lengths in order to eliminate the effect of friction densification during driving and sample extraction.

4. The entire soil mass from each compartment was then removed, weighed and three samples were taken for moisture content determinations.

5. Knowing the total weight, moisture content (step 4) and total volume of soil (step 2), the average dry density was

then calculated.

All water outlets, valves, hoses and the gravel used were flushed after each experiment to prevent any entrapped soil from impeding water outflow during subsequent experiments. More than thirty samples were used and several tests were carried out with samples for the study of each parameter to minimize the experimental errors.

CHAPTER IV

ANALYSIS AND DISCUSSION OF TEST RESULTS

This chapter includes two parts. Presented in the first part, section 4.1, are the factors governing soil behaviour and how they are determined. This is followed in the second part, section 4.2, by the experimental results, plus an analysis and discussion of these results.

4.1 Introduction to the Factors Governing Soil Behaviour

The main purpose of this research work was to study the behaviour of native cohesive backfills when waterjetting is used as a compaction method. The behaviour of the backfill was studied under the effect of several selected parameters; namely, lump size and gradation, initial soil height (H), jetting water pressure (P), soil rejetting, seepage force (J), drainage conditions, soil area per jet (As), jetting in layers and soil type.

In this study, the behaviour of the backfill was evaluated in terms of the average degree of compaction, the average change in void ratio, the variation of settlement with depth, soil's moisture content and degree of saturation. A brief explanation of the factors describing the soil behaviour and their relevance are shown below.

4.1.1 Degree of Compaction

The degree of compaction, which is the main concern in earth work studies, is defined in this study as:

$$(D.C)_{15} = (\gamma d)_{15} \,/\, (\gamma d)_{max} \tag{4.1}$$

where $(D.C)_{15}$ = average degree of compaction, fifteen days after jetting;

$(\gamma d)_{15}$ = average dry density, fifteen days after jetting;

and $(\gamma d)_{max}$ = standard Proctor maximum dry density.

For each parameter studied, the average degree of compaction is calculated considering two cases. In the first case, Case A, $(\gamma d)_{15}$ is calculated considering the soil loss with water outflow. In the second case, Case B, $(\gamma d)_{15}$ is calculated assuming no soil loss (based on the initial dry soil weight before jetting). This is done to illustrate the effect of the selected parameters on the amount of soil loss. The latter can be represented by the differences in the degree of compaction values given by Cases A and B.

4.1.2 Average Change in Void Ratio

If a cohesive soil is excavated and then replaced in trenches, it retains a lumpy structure. In this case, the behaviour of cohesive backfill can be evaluated by the reduction in voids between the lumps. Hence, a new term "average change in void ratio," Δe, is introduced; defined as:

$$\Delta e = e_i - e_{15} \tag{4.2}$$

where e_i = average initial void ratio;

and e_{15} = average void ratio, fifteen days after jetting.

The average change in void ratio is also calculated based upon two cases (as mentioned in Section 4.1.1); first, considering soil loss with water outflow (Case A), and second, assuming no soil loss with water outflow (Case B). The value of the average change in void ratio, Δe, is in general a measure of the backfills' compactability. It is worthy to note that soil densification can be represented by the increase in the "degree of compaction" $(D.C)_{15}$, as well as the increase in "average change in void ratio," Δe.

4.1.3 Settlement

Total settlement occurring after jetting represents one of the principal measures by which the effectiveness of water jetting can be judged. In this research work, settlement values were obtained by recording the dial readings at various sample depths. Surface settlements were also determined using the set of lines inscribed on the sides of the test apparatus (Section 3.3). Hence, it is possible to trace the average settlement profiles and to note those layers where greater settlement occurred. All settlement profiles are studied immediately after jetting and fifteen days after jetting to ascertain the effect of jetting only.

For comparison purposes, the change in volume for different soil samples at different layers can be represented by the slopes of the depth-settlement curves. Accordingly, the effect of the different parameters on soil behaviour represented by the settlements occurring and the change in volume can be established.

4.1.4 Moisture Content

The waterjetting method produces an excess of free moisture in cohesive soils (65). In terms of moisture content, w, an idea about the backfills' behaviour can be given by tracing the moisture content values and their change with time after jetting. The test period (fifteen days) is considered long enough to give a fair impression about the decrease in moisture content with time as mentioned before (Section 3.5). With the small soil heights used in this experimental work, the top soil moisture content is considered to be an indication of the sample's moisture content. This assumption was adopted to avoid disturbing the soil by taking moisture content samples and hence affecting its density. Moreover, in the field it is of great value to know the top soil moisture content when placing pavement on top of the jetted trenches.

4.1.5 Degree of Saturation

The degree of saturation is another measure of the water entrapped inside the backfill after jetting. The degree of saturation is defined as the ratio of the volume of water to the volume of voids. The average degree of saturation, S, is calculated in this study according to the empirical formula (10);

$$S = G_s \, w/e \tag{4.3}$$

where, S = average degree of saturation;
w = average soil moisture content;
e = average void ratio;
and G_s = specific gravity of soil particles.

It can be noted (Eq. 4.3) that the average degree of saturation, S, is a function of the average moisture content, w, as well as the void ratio occurred after jetting, e, as G_s is constant for the soil type. The average void ratio, e, at a time, t, after jetting is calculated by the equation:

$$e = (1 + e_{15}) \, (1 + \Delta H/H) - 1.0 \tag{4.4}$$

where, H = total soil height, fifteen days after jetting;
ΔH = difference in total soil heights, between time t and fifteen days after jetting;
and e_{15} = average void ratio fifteen days after jetting.

4.2 Analysis and Discussion of Test Results

4.2.1 Effect of Lump Size and Gradation

To study the effect of lump size and gradation on soil behaviour, Soil No. 1 was placed in the three apparatus compartments under three conditions of varying lump size and gradation. The lumps used to fill the first and second compartments were "uniform" of one inch and one half inch in diameter respectively (will be referred to as Cases I and II). The soil sample in the third compartment, Case III, had mixed (non uniform) lumps of different sizes up to one inch in diameter. These lump sizes were considered to reasonably represent the field conditions. The different lump sizes were prepared by breaking the big lumps obtained from the field (East Windsor, Ontario) into the required sizes.

Table 4.1, Appendix C, shows the initial conditions for the three different cases. Listed also in the same table are the period of jetting, t_j, required to saturate each of the three soil samples (see section 3.6), and the total applied energy due to waterjetting per unit volume of soil, Ea, for each sample (sample calculation is shown in Appendix D).

a) The degree of compaction and change in void ratio

Figures 4.1 and 4.2 show the variation in the average degree of compaction, $(D.C)_{15}$, and the average change in void ratio, Δe, respectively, versus the different lump sizes. The A Curves on the graphs show the $(D.C)_{15}$ and Δe values considering soil loss with water drainage (Case A, Sec. 4.11), while the B curves represent the $(D.C)_{15}$ and Δe values assuming no soil loss, Case B (sample calculation is given in Appendix D).

It can be seen that curves A and B, Figures 4.1 and 4.2, show the greatest $(D.C)_{15}$ and Δe values (most compaction) for the mixed lump size, Case III, while the smallest values are obtained for Case I (uniform lump size, D ≃ 1.0 inch) even though the applied energy was about the same for all cases, Table 4.1. This may be attributed to the greater effect of waterjetting in densifying backfills containing smaller lump sizes which expose greater surface area to the jetting action.

It can be noted that curves B show steeper slopes than curves A indicating the greatest difference in the $(D.C)_{15}$ and Δe values to be associated with Case III, while the smallest is with Case I. This difference indicates the amount of soil loss with water drainage.

b) The Settlement

The variations in settlement with depth are shown in Figure 4.3 for the three cases. The dotted lines on the graph indicate the total settlement immediately after jetting, while the total settlement fifteen days after jetting are shown in solid lines. All settlement values are listed in Table 4.2 as well as the difference in settlement values immediately and fifteen days after jetting (net settlement occurred in fifteen days), at various depths.

From Figure 4.3 and Table 4.2 it can be noted that the major part of settlement occurred immediately after jetting for all three cases. The greatest total settlement of soil surface was for Case III, while the smallest was for Case I. This resulted from the difference in volume change caused by waterjetting. The net change in volume for different soil layers in each sample can be judged by the slope of the depth-settlement lines. Employing this technique, it can be noticed that at the top layers the greatest change in volume occurred for Case III while the smallest was for Case I. This may be due to the migration of the soil particles from the soil in the top layers, with the flow of water, to be deposited at the lower layers (as illustrated by Figure 4.4). These particles may also leave the soil mass causing the soil loss. This mechanism is most pronounced with the greatest lumps surface area, Case III (mixed lumps).

c) Water Content and Degree of Saturation

Figures 4.5 and 4.6 show the correlations between the average top soil moisture content, w, and the average degree of saturation, S, respectively, versus the time after jetting, t, for the three different cases. It can be seen from the graphs that Case III shows the greatest w and S values at all times after jetting. On the other hand, Case I (uniform lump size, D ≈ 1.0 inch) shows the lowest values at all t valves. Case II shows always an intermediate value between

Case I and III. It can also be noted that all w and S values decrease, with a decreasing rate, with time after jetting.

4.2.2 Effect of Soil Height

To study the effect of soil height on its behaviour after jetting, Soil No. 1 was placed in the three compartments in three different heights; namely, 4, 8 and 12 inches (10, 20 and 30 cm.), and jetted. The initial conditions for the three samples, the time of jetting, t_j, and the total applied energy due to jetting per unit volume, Ea, are listed in Table 4.3. The difference in Ea values is small, hence it can be assumed that it has ~~a~~ minor effect on the forthcoming results.

a) The Degree of Compaction and Change in Void Ratio

Figures 4.7 and 4.8 show the relations between the average degree of compaction, $(D.C)_{15}$, and the average change in void ratio, Δe, respectively, versus the initial soil height, H. As can be noted, curves A and B on both graphs show an increase in the average degree of compaction and the average change in void ratio with an increase in initial soil height, H. This can be seen by studying the settlement profiles for the three samples.

b) Settlement

Figure 4.9 and Table 4.4 show the settlement profiles and values respectively for the three samples immediately after and fifteen days after jetting. The figures indicate that the settlement profiles for each sample show an increase in slopes with height, except for the sample of H = 12 inches at the uppermost 2 inch layer. It can also be noticed that the greater the initial soil height, H, the greater are the average settlement values either immediately after or fifteen days after jetting at the different soil heights. The height-settlement lines for the different samples at different soil layers show steeper slopes for samples of smaller initial soil heights. This, in general, indicates less change in volume with the decrease in initial height, i.e. decrease in the overburden pressure after jetting which results in less degree of compaction and change in voids ratio (see Figures 4.7 and 4.8).

c) Water Content and Degree of Saturation

Figures 4.10 and 4.11 show the average top soil moisture content, w, and the average degree of saturation, S, respectively versus the time after jetting, t. It can be noticed from the graphs that the highest w and S values are associated with the sample of H = 12 inches, while the smallest values are for the samples of H = 4 inches, for all t values. All samples show a decrease in w and S with time. The sample of H = 4 inches shows the highest rate of decrease in w values as can be seen in Figure 4.10.

4.2.3 Effect of Jetting Water Pressure

To study the effect of jetting water pressure, P, on the soil behaviour, Soil No. 1 was used and placed in the three apparatus compartments under the same initial conditions (Table 4.5). The samples were waterjetted under three different applied pressures, P, of 20, 40 and 55 p.s.i. respectively. The water pressure was controlled by using the water regulator (Chapter III, Section 3.4). Table 4.5 shows the initial soil conditions for the three samples, the time of jetting t_j and the total energy applied due to waterjetting per unit volume, Ea.

a) Degree of Compaction and Change in Void Ratio

Figures 4.12 and 4.13 show an increase in the average degree of compaction, $(D.C)_{15}$, and the average change in void ratio, Δe, with the increase in jetting water pressure, P, for Cases A and B. This reflects the increase in soil densification with higher water pressures, since a higher amount of energy was applied (Table 4.5). Figure 4.14 shows the direct relationship between the average degree of compaction $(D.C)_{15}$ versus the applied energy, Ea.

b) Settlement

Figure 4.15 shows the total settlement profiles for the three samples immediately after jetting, represented by the dotted lines, and fifteen days after jetting by solid lines. All the total settlement values and the net settlements occurring in the fifteen days after jetting are listed in Table 4.6. As can be seen, larger settlements which occurred at different depths immediately after jetting, are generally associated with higher jetting water pressure, P. This relation also holds for the total settlement values fifteen days after jetting. By comparing the slope of the settlement profiles at various depths for the three samples, one can generally notice that the greater change in volume is associated with the higher jetting water pressures, P. The net settlements occurring in the fifteen days following jetting (Table 4.6) show a decrease with depth for all samples.

c) Moisture Content and Degree of Saturation

The average top soil moisture content, w, and the average degree of saturation, S, versus the time after jetting are shown in Figures 4.16 and 4.17 respectively for the three soil samples. The greatest w values are shown for the sample of P = 55 p.s.i., while the smallest are for the sample of P = 20 p.s.i. All w values decrease with time after jetting. The same trend of the w-t curves can be noted for the S-t curves, Figure 4.17, for the three samples.

4.2.4 Effect of Rejetting the Soil

To study the effect of rejetting the soil, three samples of Soil No. 1 were placed in the apparatus under identical conditions, Table 4.7. All the three samples were jetted in a normal fashion. Sample II was jetted once again, five days after the first jettings. Sample III was rejetted twice, five and ten days after the first jettings.

a) Degree of Compaction and Change in Void Ratio

Figures 4.18 and 4.19 show an increase in $(D.C)_{15}$ and Δe valves with rejetting (as expressed by the number of jettings, N) for Cases A and B. Both curves A and B, Figure 4.18 ($(D.C)_{15}$ vs. N), start from a degree of compaction of 63.6 per cent at $N = 0$ which represents the initial degree of compaction before jetting. Similarly, curves A and B, Figure 4.19 (Δe vs. N) starts from $\Delta e = 0$ at $N = 0$. This was done to compare the effect of the first jettings with the second and third jettings. A decrease in the slope of the curves on both graphs (Figures 4.18 and 4.19) is noted with an increase of N . The steepest slope was from $N = 0$ to $N = 1$. This indicates the greatest efficiency for the first jettings in densifying the backfills. With further rejettings (greater N value), a smaller increase in $(D.C)_{15}$ and Δe values is obtained since the change in soil structure after first jetting decreases its compactability, even though the energy applied due to jettings, Ea, increase linearly with N, Figure 4.20 and Table 4.7.

b) Settlement

Figure 4.21 shows the settlement profiles for the three samples immediately after first jettings and fifteen days later. All settlement values for the various depths are shown in Table 4.8. The additional settlement occurring due to rejetting during the fifteen days, for samples II and III, are included in the net settlement values shown in Table 4.8. These values illustrate that the effect of rejetting is more pronounced in the upper soil layers.

c) Water Content and Degree of Saturation

Figures 4.22 and 4.23 show the w vs t and s vs t curves for the three samples respectively. A decrease in w and S with time for all three samples in the first five days can be noted. The w and S values for Sample I (no rejetting) continue to decrease with time. Rejetting Sample II at t = 5 days and Sample III at t = 5 and 10 days causes a sudden increase in w and S as can be noted (Sample III shows 95 per cent degree of saturation after second rejetting).

4.2.5 Effect of Seepage Force

To study the effect of water seepage force after jetting, required applying various seepage rates inside the soil samples. This was done to simulate the in-field practice of pumping the water out of the trenches after jetting, and was adopted in this experimental work by applying negative water heads at the water exits, since pumping was considered less convenient (see Section 3.4 and Figure 3.7). Three different water heads, H_w, of 12, 80 and 194 inches (30, 203 and 492 cm.) were applied on three different soil samples after jetting. The three water heads correspond to seepage forces, J, of 75, 500 and 1,260 pcf (11.8, 78.4 and 198 N/cm^3) respectively (sample calculation is given in Appendix D, while the initial soil conditions are given in Table 4.9).

a) Degree of Compaction and Change in Void Ratio

Figures 4.24 and 4.25 show an increase in the average degree of compaction, $(D.C)_{15}$, and the average change in void ratio, Δe, with the increase in seepage force for Cases A and B as noted. Curves B on both graphs show steeper slopes than curves A, indicating a greater difference in $(D.C)_{15}$ and Δe values with increasing J values. This illustrates the greater amount of soil loss with higher seepage forces.

b) Settlement

The variation of settlement with depth for the three samples are shown in Figures 4.26, 4.27 and 4.28. Settlement curves are shown for each sample at three stages: immediately after jetting (curves 1), after jetting and seepage of water (curves 2), and fifteen days after jetting and seepage (curves 3). The difference in settlements occurring after jetting due to seepage of water. These net settlements at various depths increase with the increase in seepage force, as can be noted by comparing the graphs for the three samples.

The slopes of curves 2 and 3 are similar for each sample, with a slight decrease in settlement with depth, due to the net settlements occurring in the fifteen days.

c) Water Content and Degree of Saturation

The variations in moisture content, w, and degree of saturation, S, with time after jetting for the three samples are shown in Figures 4.29 and 4.30, respectively. A decrease in w and S values accompanied by a decrease in slope of the w-t and s-t curves with time for the three samples can be noted. The highest w and S values are associated with the sample subjected to a water head of 12 inches, while the smallest values are generally for the sample subjected to a water head of 194 inches.

4.2.6 Effect of Drainage Conditions

To evaluate the influence of drainage conditions on soil behaviour when waterjetted, it was first decided to investigate two samples placed with and without the usual underlying 2 inch (5 cm.) gravel layer (will be referred to as samples I and II respectively). In both cases, the drainage valves attached to the apparatus were left open during and after jetting to drain the excess water. However, a great similarity in drainage conditions was noted for both samples. Then, it was decided to test a third soil sample (sample III), which was placed on top of a compacted 2 inch (5 cm.) thick soil layer (Soil No. 1). The aforementioned three cases simulate the following field conditions: permeable granular layer underlying the excavation, gravel filter provided under backfill and no special drainage provided, respectively. All initial conditions were kept constant as listed in Table 4.10. Listed also in Table 4.10 are the required jetting times for each sample and the applied energy per unit volume due to jetting, Ea.

a) Degree of Compaction and Change in Voids

Table 4.11 was prepared by listing the values of the average degree of compaction, $D.C_{15}$, and the average change in void ratio, Δe, for three samples. All $D.C_{15}$ and Δe values are shown for case A (considering soil loss) and B (assuming no soil loss) as noted. By comparing the $D.C_{15}$ and Δe values shown in the table, it can be noted that the smallest $D.C_{15}$ and Δe values correspond to Sample III (with underlying 2 inch compacted soil layer), while no practical differences are apparent between the $D.C_{15}$ and Δe values for samples I and II.

b) Settlement

Figure 4.31 and Table 4.12 show that the smallest settlements were for Sample III in general except at the lower most 3 inch soil layer. The settlement profiles for the three samples, Figure 4.31, show variation in slope of the depth-settlement lines at various depths. Samples I and II show a similar trend regarding the depth-settlement curves in general, while sample III shows a lower rate of increase in settlement with depth than that exhibited by the other two samples. This indicates that the lowest average volume change is associated with sample III. Table 4.12 indicates that the greatest net settlements occurred in the fifteen days after jetting being for sample III at all depths. This appears to be due to the greater deformation of the lumps, Sample III, under its own over-burden since more water was absorbed by the soil sample III (Section C).

c) Moisture Content and Degree of Saturation

Figures 4.32 and 4.33 show the relationships between the top soil moisture content, w, and the average degree of saturation, S, respectively versus the time after jetting, t, for the three samples. The greatest w and S values are for sample III as noted, while the smallest values are for sample I. All the w and S values for the three samples show essentially a decrease in values together with a decrease in slope of the w-t and S-t curves with time.

It is worthy to mention that the placement of a granular layer under the trench backfill to surround the service utilities is recommended by specifications (see Chapter II, Section 2.4). Moreover, the presence of this layer allows pumping of the excess water out of the trench backfill after jetting, if desired.

4.2.7 Effect of Soil Area per Jet (A_s)

The effect of soil area per jet, which simulates the effect of distance between jets in the field, on soil behaviour was studied in this research. This was done using four different compartment sizes which were filled with Soil No. 1 to the same initial height, H, and jetted using one jet for each sample. The movable plexiglass partitions (Section 3.2) were used to separate the compartments and to obtain areas of 242, 160, 77.5 and 38.8 square inches (1560, 1030, 500 and 250 cm^2). All other initial conditions were constant as listed in Table 4-13 which also shows the time of jetting, tj, and the applied energy per unit volume, Ea, which is nearly the same for the four backfill samples.

a) Degree of Compaction and Change in Void Ratio

Figures 4.34 and 4.35 show the effect of soil area per jet, A_s, on the average degree of compaction, $(D.C)_{15}$ and the average change in void ratio, Δe, respectively.

In the graphs, an increase in $(D.C)_{15}$ and Δe values with the decrease in soil area per jet, A_s, is shown by curves A and B. This may be explained by the localized effect of jetting forces since the total energy applied per unit volume is almost the same for all samples (see Table 4.13).

b) Settlement

Figure 4.36 shows the settlement profiles for the four samples. All settlement values are listed in Table 4.14. Higher total settlement values can generally be noticed (Table 4.14) for samples of smaller A_s . Comparing the slopes of the depth-settlement curves for the different samples, it can be generally concluded that less volume change (steeper slopes), occurs at the upper layers with an increase in soil area per/jet, A_s. This fact is most pronounced at the uppermost 2.0 inch layer.

c) Moisture Content and Degree of Compaction

The moisture content and the degree of saturation values, Figures 4.37 and 4.38 show a decrease with time as expected to confirm the general trend. Also the w-t and S-t curves for all four samples show a decrease in slope with time. Generally, it can be noted that the samples of smaller soil area per jet show greater degrees of saturation and water contents.

4.2.8 Effect of Jetting in Layers

It is common practice in the field, when mechanical compaction is applied, to compact the backfill in layers to improve its compaction. To evaluate the influence of compacting the backfill in layers using waterjetting, two samples of Soil No. 1 were used. Sample I was jetted in three layers: 4.0 inches (10 cm.) thick each with a five day period between placing and jetting each layer. Sample II was jetted in one layer 12 inches (30 cm.) thick. The initial conditions for both samples are shown in Table 4.15.

a) Degree of Compaction and Change in Void Ratio

Table 4.16 shows the average degrees of compaction, $(D.C)_{15}$, and the average change in void ratios, Δe, for both samples, I and II. As can be noted, jetting the soil in layers (Sample I) results in a marginal decrease in $(D.C)_{15}$ and Δe values although more energy per unit volume was applied to sample I with placing and jetting the subsequent layers (Table 4.15). However, a greater amount of soil loss can be noticed by the difference in $(D.C)_{15}$ and Δe values between cases A and B for each sample.

b) Settlement

Figure 4.39 shows the settlement profiles for both samples. Curves 1, 2 and 3 represent the settlement profiles immediately after placing and jetting the first, second and third layers of Sample I, respectively. Curve 4 shows the settlement profile fifteen days after jetting of the first layer of sample I. Curves 5 and 6 show the settlement profiles immediately after jetting and fifteen days after jetting Sample II, respectively. It can be noted that the first 4 inch layer, sample I, shows less settlement and volume change compared to the lowermost 4 inch layer of sample II, immediately after jetting (see curves 1 and 5). Although an additional settlement occurs after jetting the second and third layers, Sample I (curves 2, 3 and 4), the total settlement fifteen days after jetting, Sample I (curve 4), shows marginally smaller values than those associated with sample II, curve 6.

c) Moisture Content and Degree of Saturation

Figures 4.40 and 4.41 show the moisture content w and the degree of saturation, S, respectively versus the time after jetting, t, for both samples I and II. The w and S values for sample II show the normal decrease in values and slope of the curve with time. On the other hand, w and S values, sample I, show a significant increase after jetting the second and third layer. This resulted in greater w and S values for sample I and t=15 days as shown.

4.2.9 Effect of Soil Type

In order to study the effect of soil type on the behaviour of waterjetted backfills, the five different soil types listed in Table 3.1 were tested. The initial conditions for the different soils are listed in Table 4.17. Listed also in the same table are the time of jetting, t_j, and the values of the total applied energy due to jetting, Ea, which apparently does not significantly vary for the different samples.

a) Degree of compaction and change in void ratios

Table 4.18 shows the average dry density values fifteen days after jetting, γd_{15}, for the different soils. Because of the variations in soil type and laboratory compaction test results, it would be impractical to compare γd_{15} values for the five soil samples. Soil behaviour would be better illustrated by comparing the average degree of compaction fifteen days after jetting based on both the maximum Proctor density (the common practice) and Proctor density at an identical moisture content. Due to the difference in initial dry density, γd_i, for the different soils (Table 4.17), a new term was introduced and defined as the ratio $\gamma d_{15}/\gamma d_i$. This term represents the soil's compactability for different soil samples (see Table 4.18). All γd_{15}, $(D.C)_{15}$, $\gamma d_{15}/\gamma d_i$ and Δe values are shown in Table 4.18 for cases A (considering soil loss) and B (assuming no soil loss).

Comparing the results obtained for soils 1 to 4, it can be noted that, the average degree of compaction, $(D.C)_{15}$ decreases with an increase in sand content as shown in Table 4.18. This is more pronounced with the $(D.C)_{15}$ values based on Proctor density at an identical moisture content. The same phenomenon can be observed for $\gamma d_{15}/\gamma d_i$ and Δe values for the different soil samples. This phenomenon bears out the fact that waterjetting is more effective in soils having greater cohesive fractions.

In the case of pure sand, a different compaction mechanism occurs (see Chapter II, Section 2.2.1), and hence it is not comparable to other soils (see Section d).

b) Settlement

The settlement profiles are shown in Figure 4.42 for all soil samples. It can be noted that soil samples of greater cohesion show in general a greater settlement at different depths as well as greater change in volume.

c) Moisture Content and Degree of Saturation

Figures 4.43 and 4.44 show the top soil moisture content, w, and the degree of saturation, S, respectively versus the time after jetting, t, for all samples. It can be noted from the graphs that the greater the cohesive fraction, the greater the w and S values.

d) Soil No. 5 (Pure Sand)

It can be seen, Table 4.18, that the backfill sample made of soil No. 5 (pure sand) shows the highest γd_{15} and $(D.C)_{15}$ values. However, a clearer concept is given by noting the $\gamma d_{15}/\gamma d_{initial}$ and Δe values for the same sample. This shows that no significant change occurred in either the dry density or the voids ratio of the sandy sample due to jetting. It is obvious that pure sand shows the smallest w and S values compared to other soils as shown in Figures 4.43 and 4.44.

CHAPTER V

DISCUSSION OF THE WATERJETTING MECHANISM OF COMPACTION

Upon examination of the problem and the analysis of test results presented in the previous chapters, a description of the waterjetting mechanism of compaction can be drawn as follows:

1. Before jetting, the soil lumps (which exist after excavating cohesive soils) placed in the trenches are initially stable with each lump resting on the underlying lumps with a certain area of contact.

2. When waterjetting starts, the jetted water washes some soil particles from the lumps' surface. These soil particles migrate with the flow of water and become deposited in the voids between the lumps or leave the soil sample with the drained water causing soil loss.

3. The remaining lumps become softer and of a greater bulk density, due to water absorbtion. Because of the jetting forces, seepage force and the increase in overburden, the lumps tend to soften at the points of contact. In addition, these forces would squeeze the lumps and lead to significant distortion of these lumps. This process continues until the bearing surfaces at the points of contact in the deformed lumps are large enough to support the applied forces.

Successive settlements occur at various elevations. These settlements essentially represent the volume change due to the distortion of the backfill.

4. After jetting, the deformed lumps become packed more densely due to reduction in voids with the remaining voids between the lumps filled with air, water and/or soil particles. More settlement continues to occur after jetting since the soil lumps which remain soft adjust themselves under their own overburden.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 The effectiveness of waterjetting for compacting trench backfills which can be judged by the increase in degree of compaction and decrease in voids ratio is found to be dependent upon the parameters studied as follows:

a) Waterjetting is more effective in backfills with mixed lump size.

b) Waterjetting is more effective in deeper trenches.

c) Waterjetting is more effective with higher jetting water pressures.

d) Waterjetting effectiveness improves marginally with further rejettings.

e) Waterjetting is more effective if accompanied by higher seepage forces.

f) Waterjetting effectiveness improves with the placement of a granular soil layer under the backfill.

g) Waterjetting effectiveness improves with a smaller jetted area per jet.

h) Waterjetting effectiveness decreases marginally when jetting in layers.

i) Waterjetting effectiveness decreases as the amount of granular material in the backfill increases, i.e. waterjetting is more effective with more plastic soils.

6.2 Waterjetting causes an increase in the backfill moisture content and degree of saturation after jetting, followed by a decrease with time. An increase in the moisture content and degree of saturation after jetting are associated with backfills having the following characteristics:

a) Containing mixed lump sizes
b) Placed in deeper trenches
c) Jetted under high water pressure
d) Rejetted
e) Compacted under small seepage forces
f) Placed without an underlying gravel layer
g) Having small area per jet
h) Placed in layers
i) Containing less granular material.

6.3 Recommendations for Further Work

Field study is recommended to verify and compare the research results obtained under ideal laboratory conditions with the less controlled field conditions.

APPENDIX A

PHOTOGRAPHS

PHOTO 2.1 Service Trench Before Backfilling

PHOTO 2.2 Trench Backfill During Waterjetting

PHOTO 2.3 Water Begins to Appear at Top of Backfill

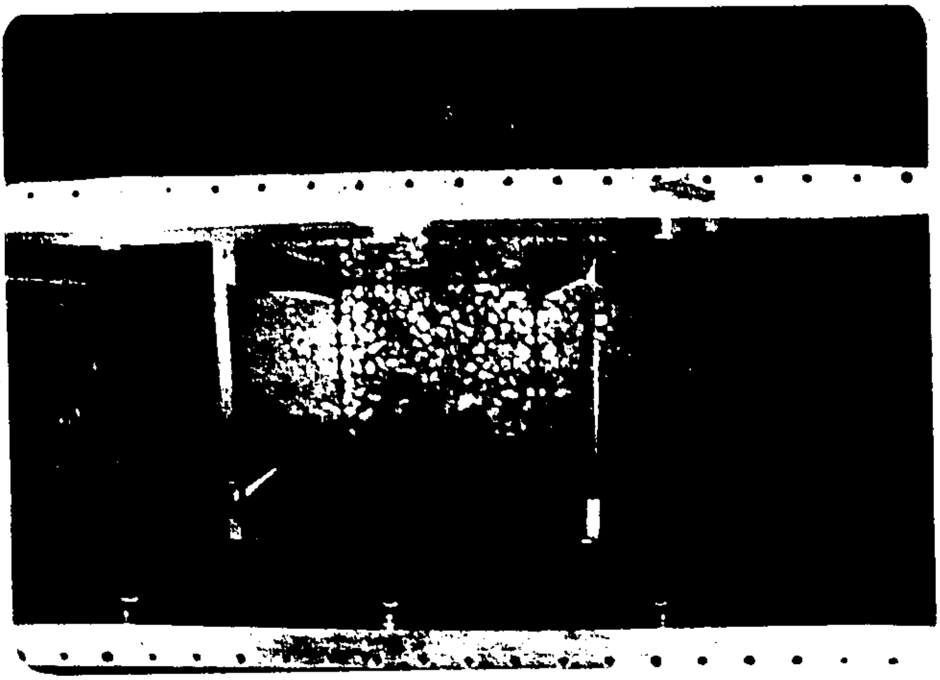


PHOTO 3.1 Gravel was Placed on the Bottom of the Apparatus

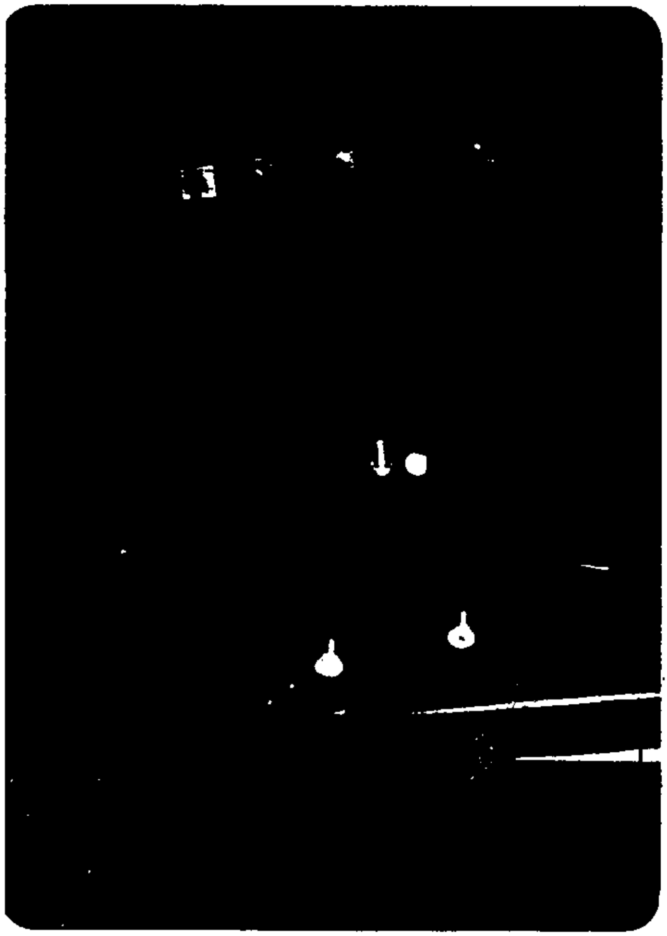


PHOTO 3.2 Settlement Plates, Top Steel Plates and Aluminum Caps on Top of Two Steel Rods

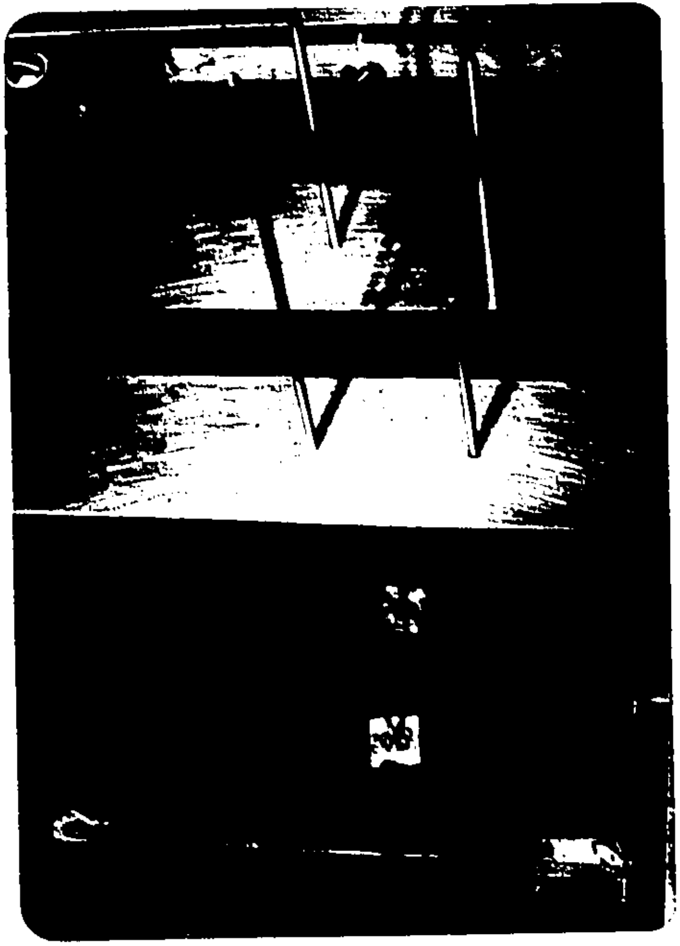


PHOTO 3.3 Top Steel Plates Were Used to Position Settlement Plates During Soil Placement

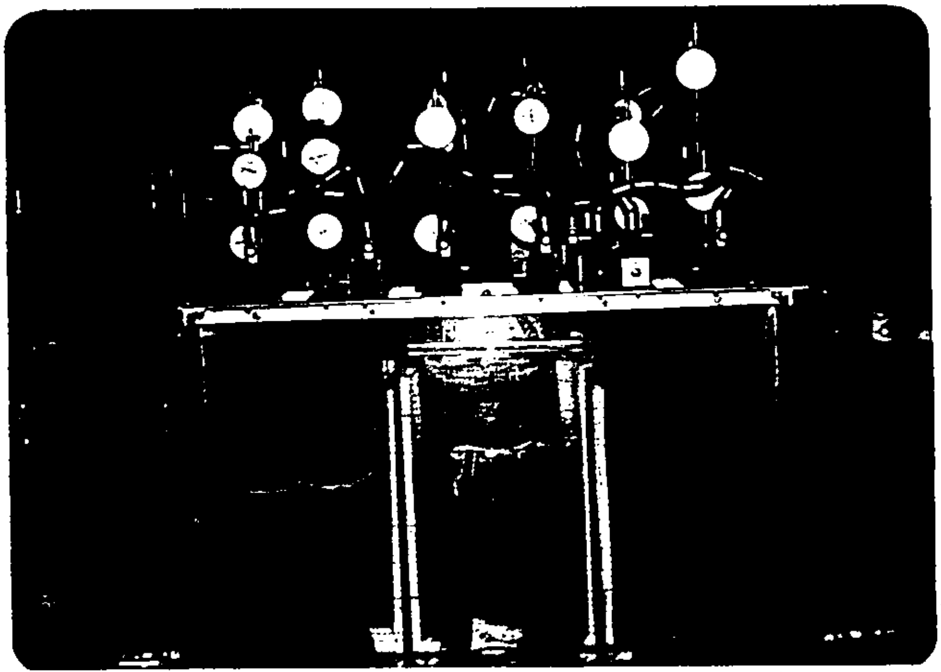


PHOTO 3.4 General View of the Apparatus Used with Three Soil Samples After Jetting and Dial Gauges Resting on the Top of the Steel Plates

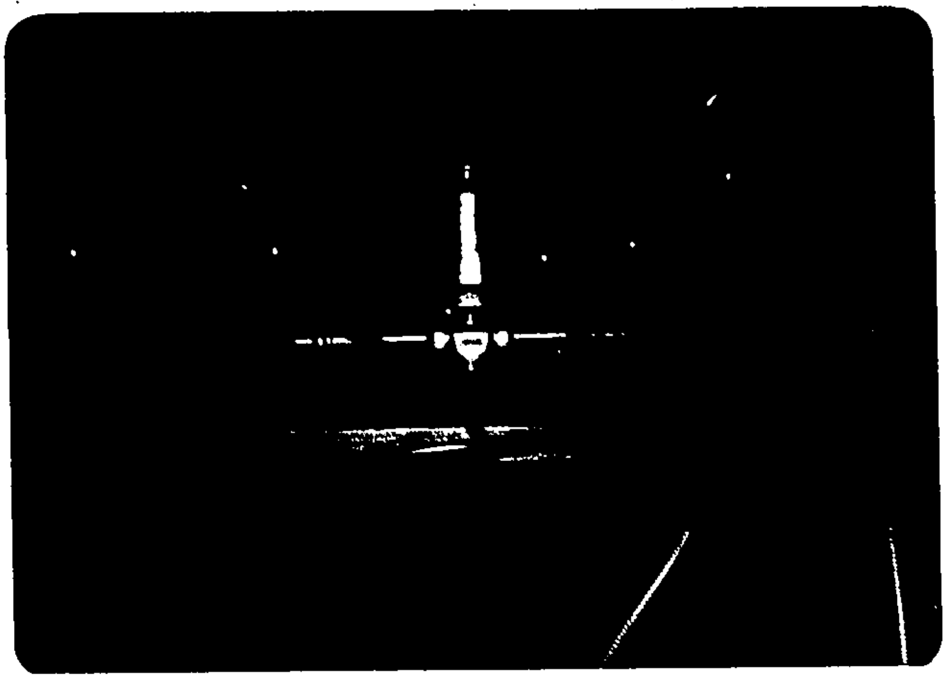


PHOTO 3.5 Jetting Pipe and Water Regulator

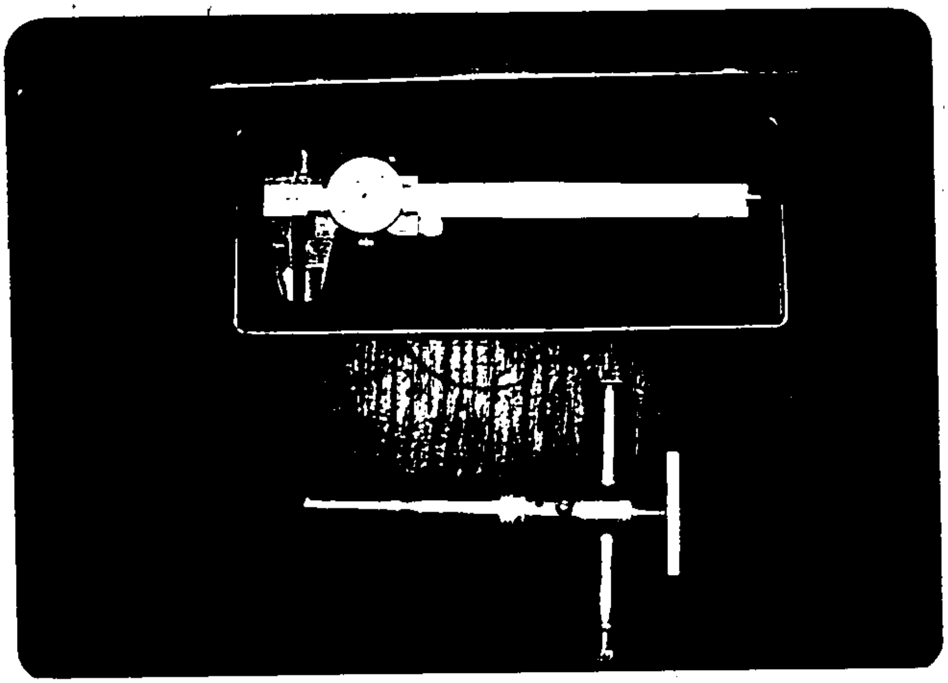


PHOTO 3.6 Sampler and Caliber Used for Density Determination

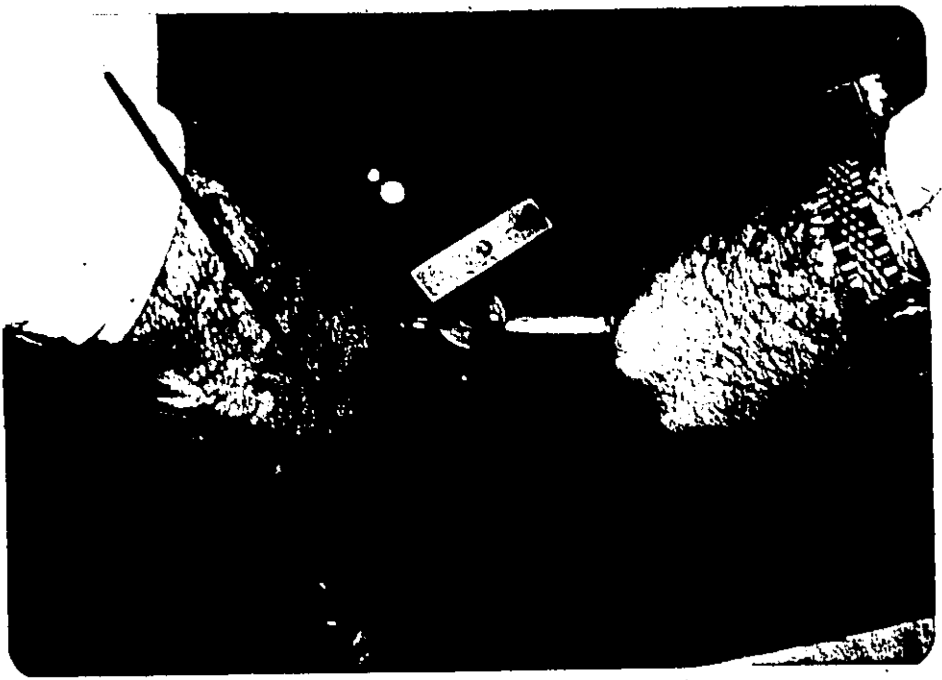


PHOTO 3.7 Soil Sampling for Density Determination

PHOTO 3.8 Measuring the Sampler Penetration in the Soil Mass (Actual Height of Sample)

APPENDIX B

FIGURES

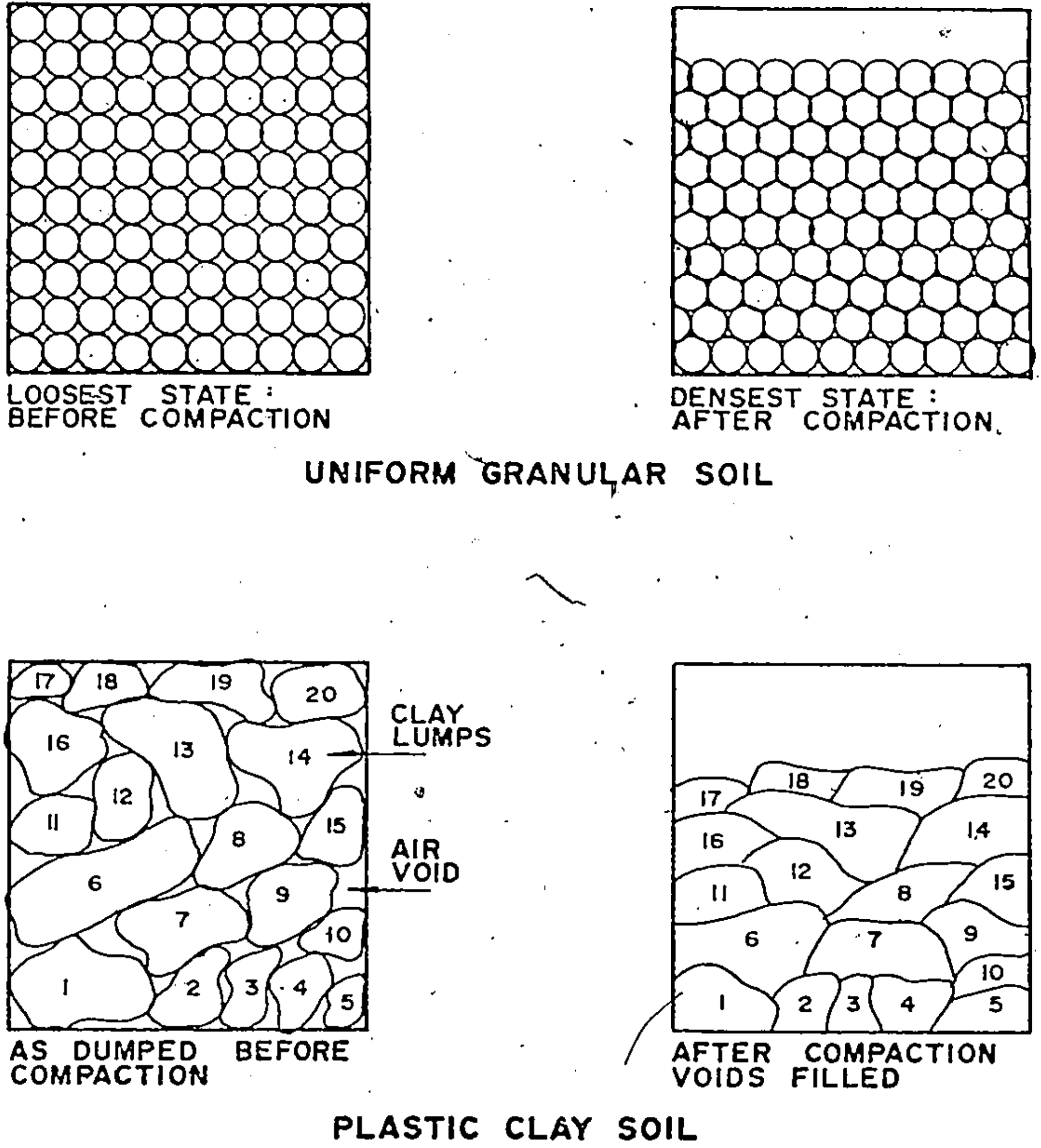
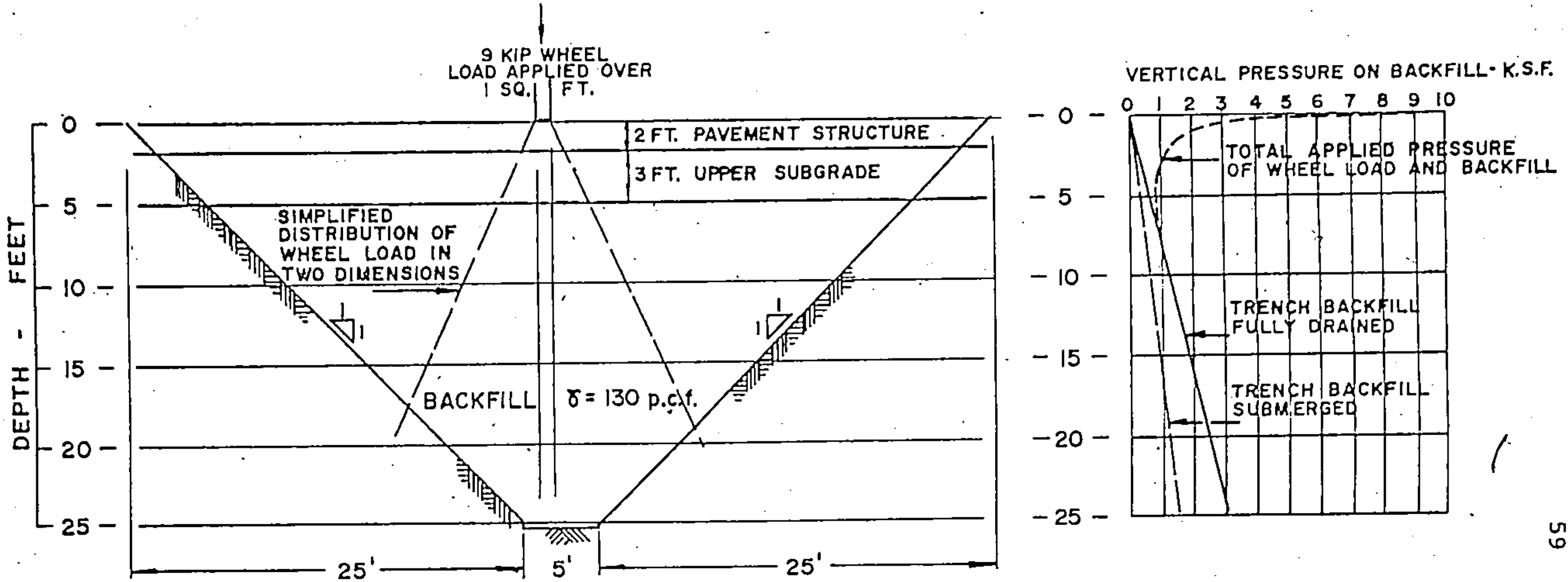


FIGURE 2.1 Schematic Representation of Effective Compaction (3)



DEPTH	VERTICAL PRESSURE K.S.F.		
	WEIGHT OF BACKFILL	DISTRIBUTED WHEEL LOAD *	TOTAL
0	0	9·0	9·0
1	0·13	2·25	2·38
2	0·26	1·00	1·26
3	0·39	0·56	0·95
4	0·52	0·36	0·88
5	0·65	0·25	0·90
6	0·78	0·18	0·96
7	0·91	0·14	1·05
8	1·04	0·11	1·15
9	1·17	0·09	1·26
10	1·30	0·07	1·37

* CALCULATED USING SIMPLIFIED DISTRIBUTION OF PRESSURE OF 1·HORIZONTAL FOR 2 VERTICAL

FIGURE 2.2 Approximate Distribution of Stress in Service Trench (3)

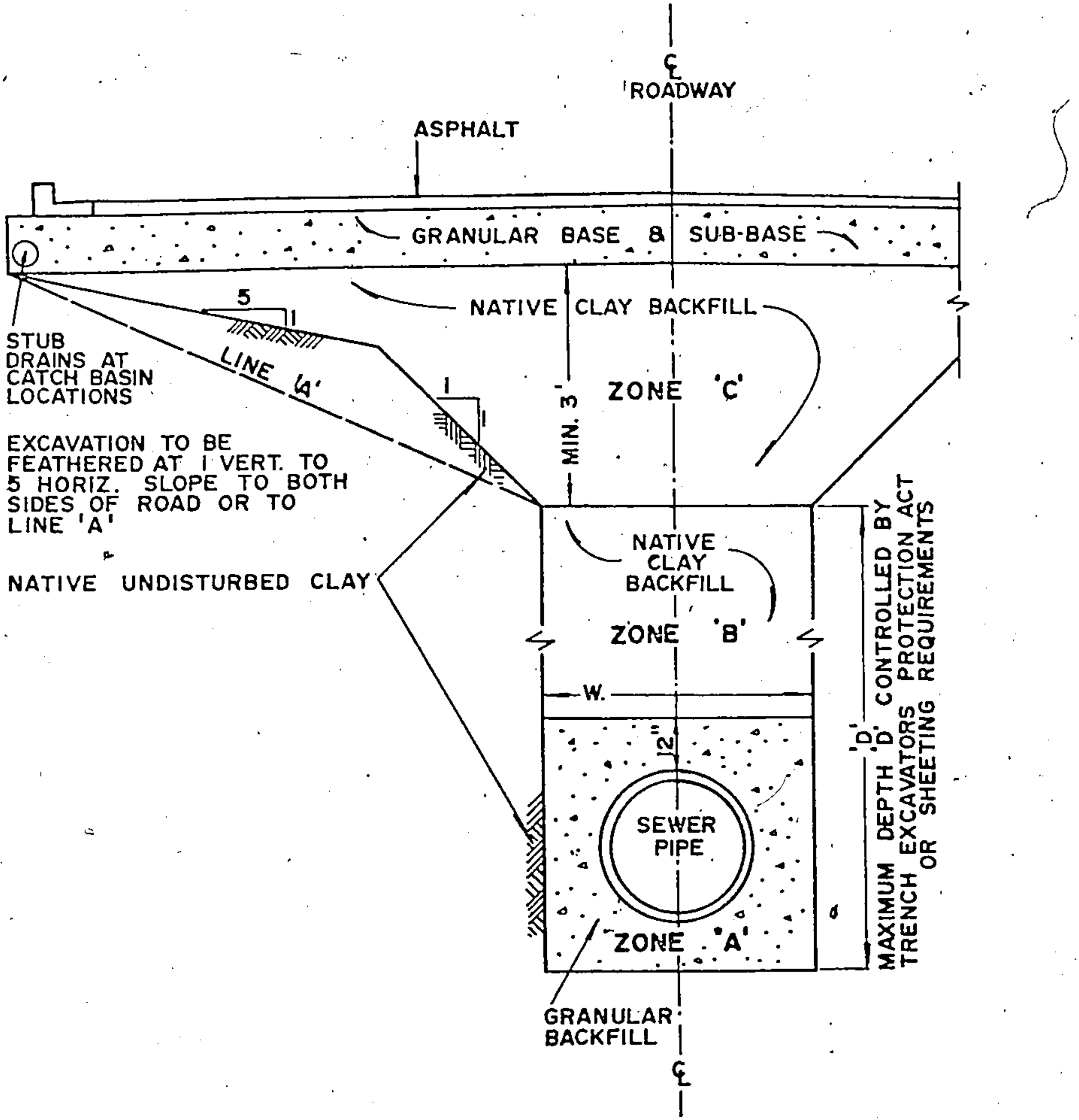


FIGURE 2.3 Service Trench Backfill Detail (Single Service) (3)

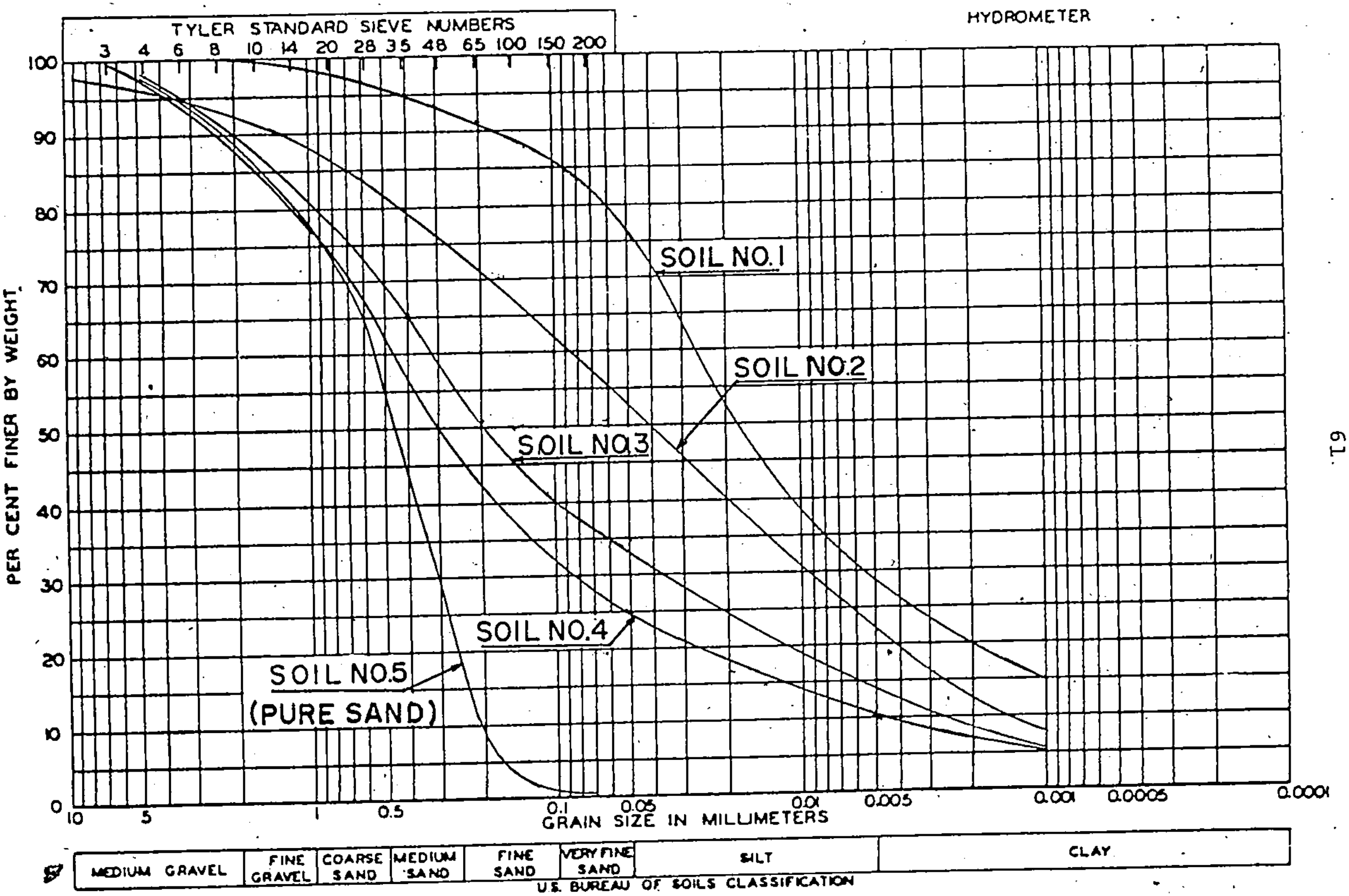


FIGURE 3.1 Grain Size Distribution Diagrams

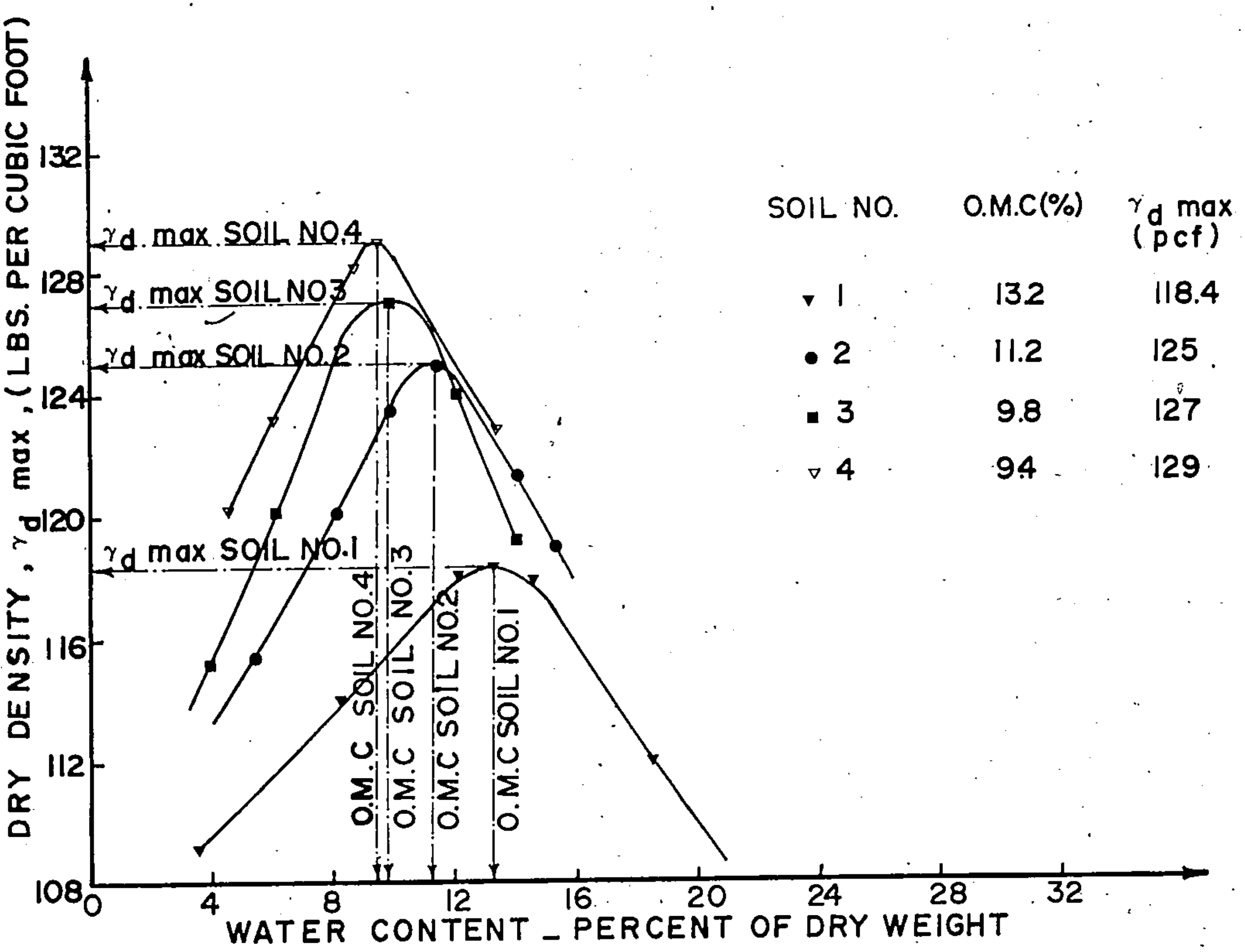


FIGURE 3.2 Proctor Test Results

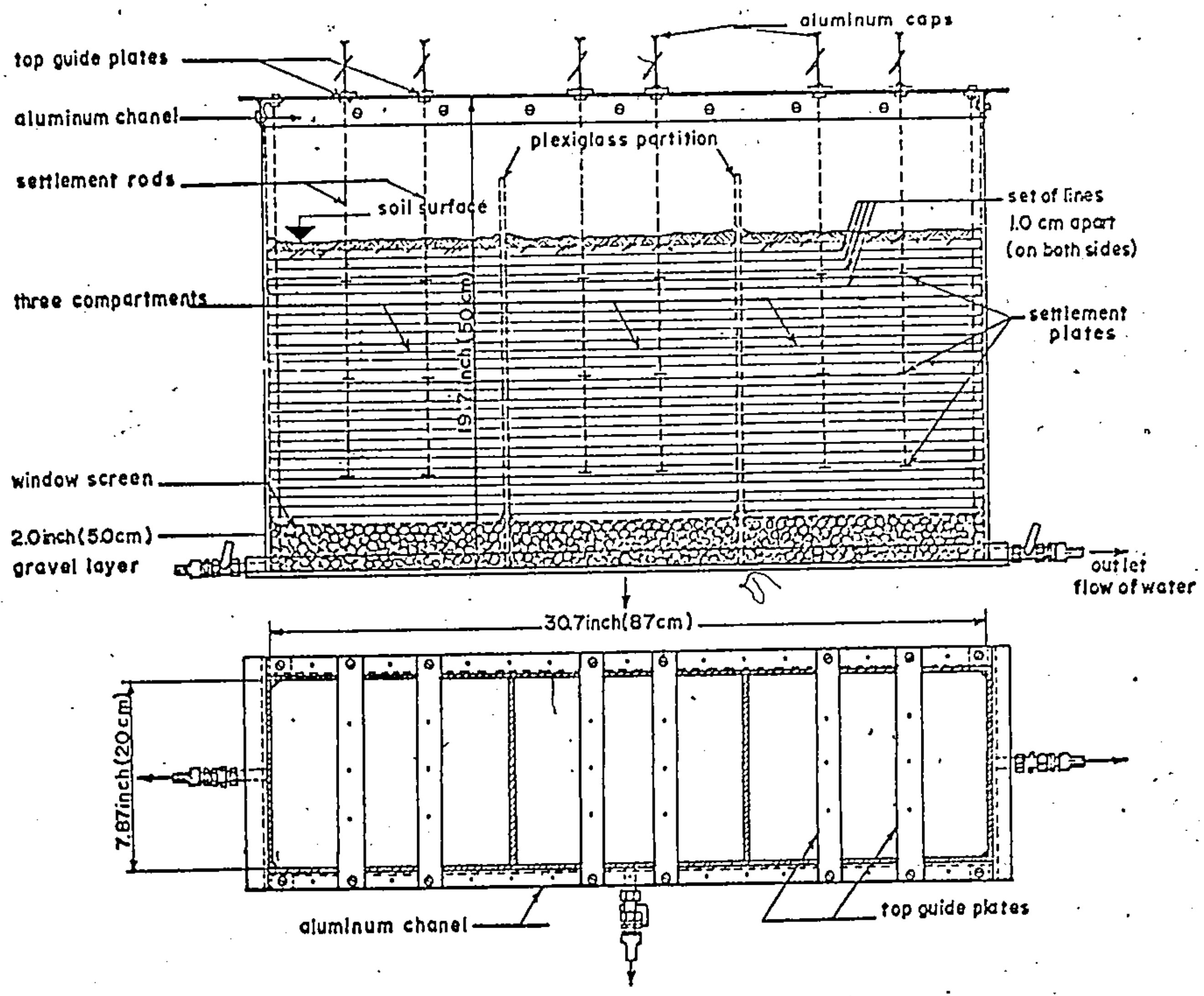
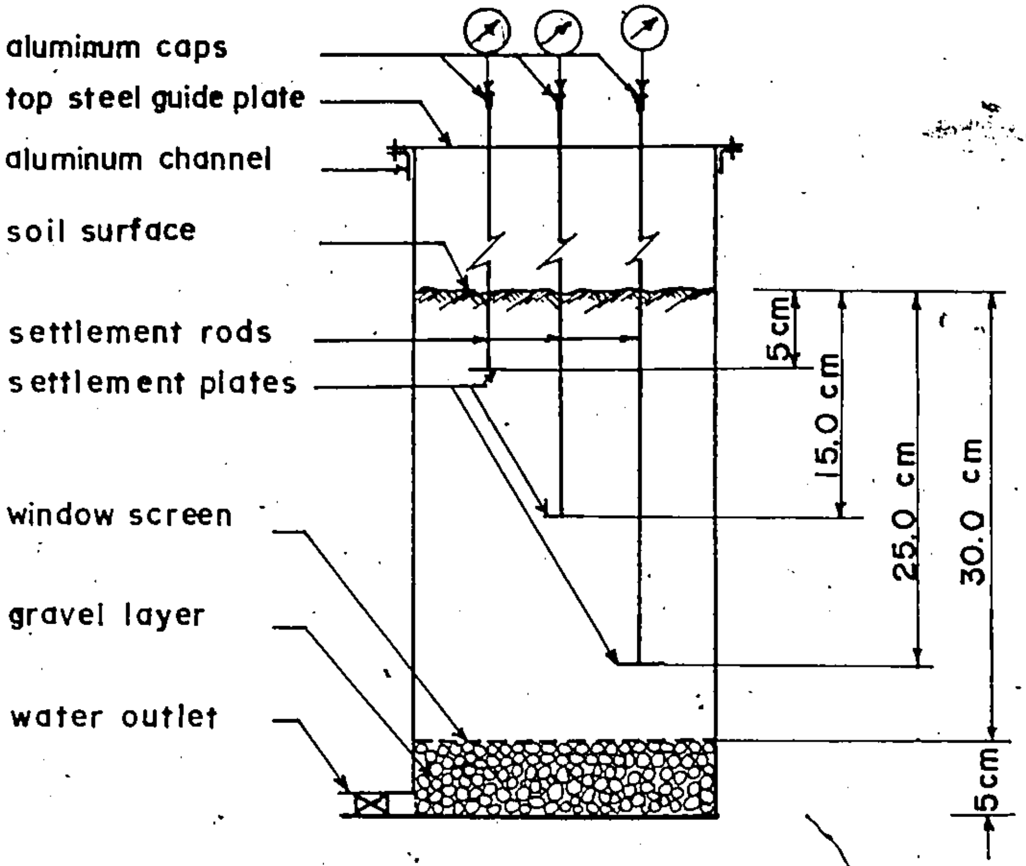


FIGURE 3.3 Side View and Plan View of the Test Apparatus



CROSS SECTIONAL VIEW SHOWING LOCATION OF SETTLEMENT PLATES

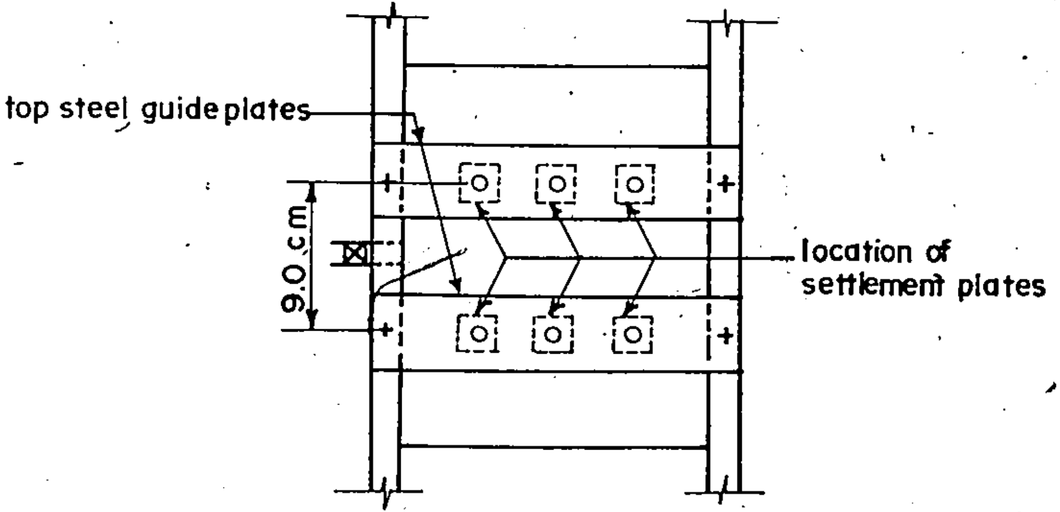


FIGURE 3.4 A Typical Layout of a Soil Sample

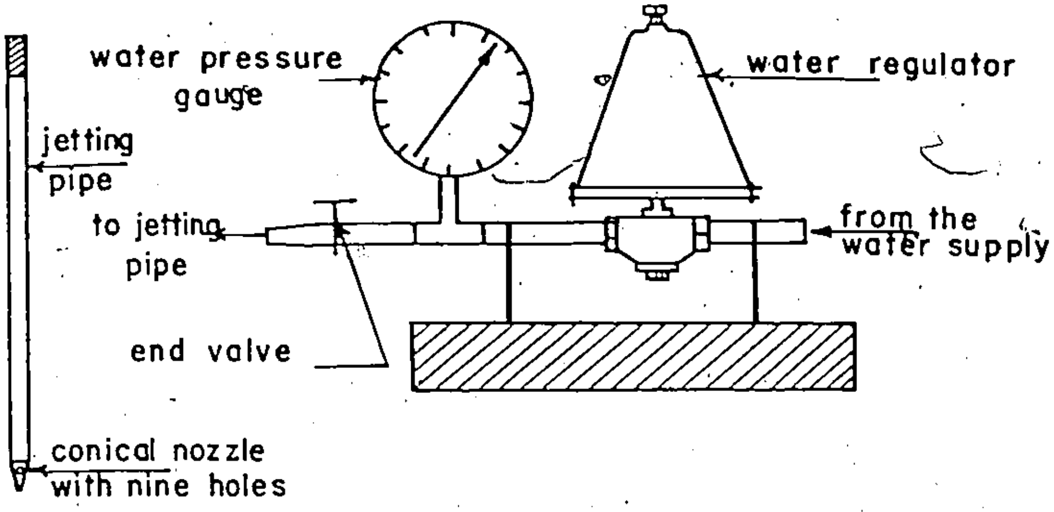


FIGURE 3.5 Water Regulator and Jetting Pipe

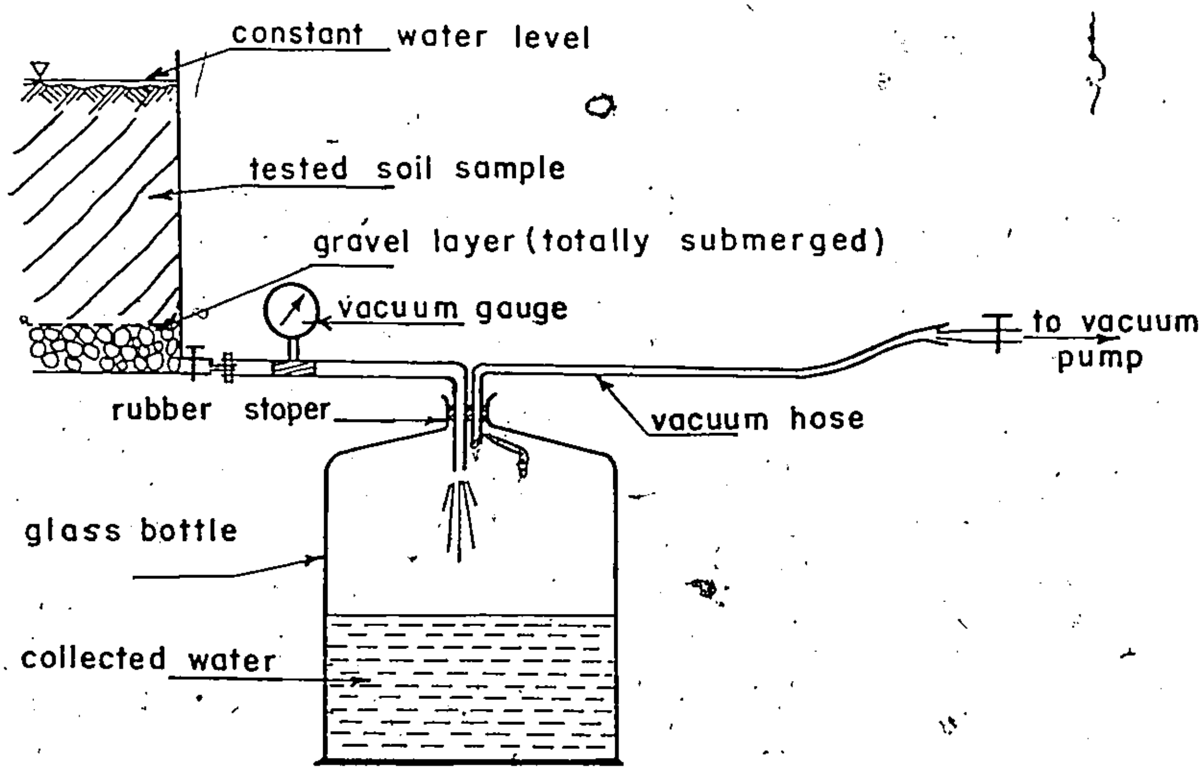


FIGURE 3.6 Vacuum System

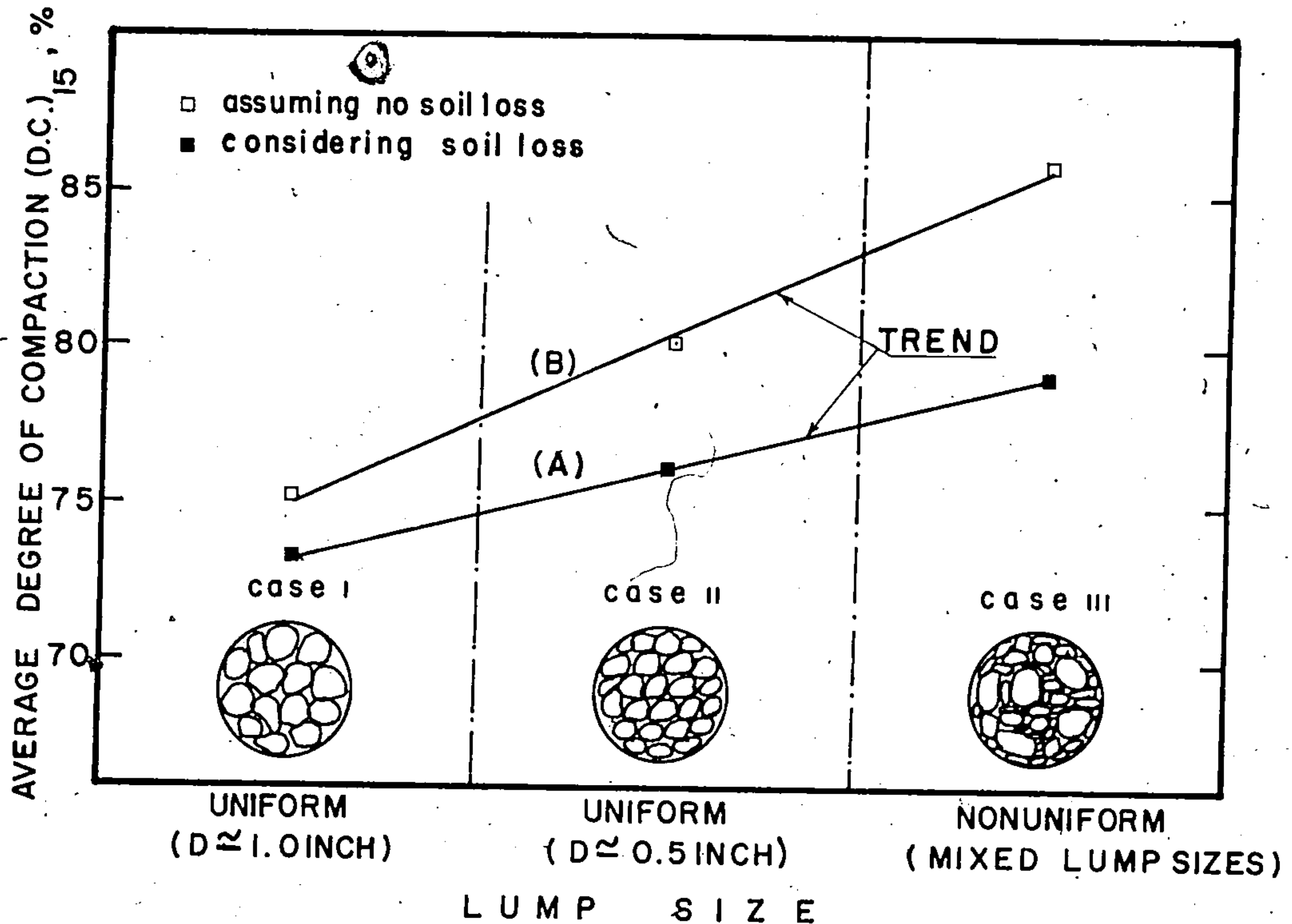


FIGURE 4.1 The Effect of Lump Size and Gradation on the Average Degree of Compaction, Fifteen Days After Jetting

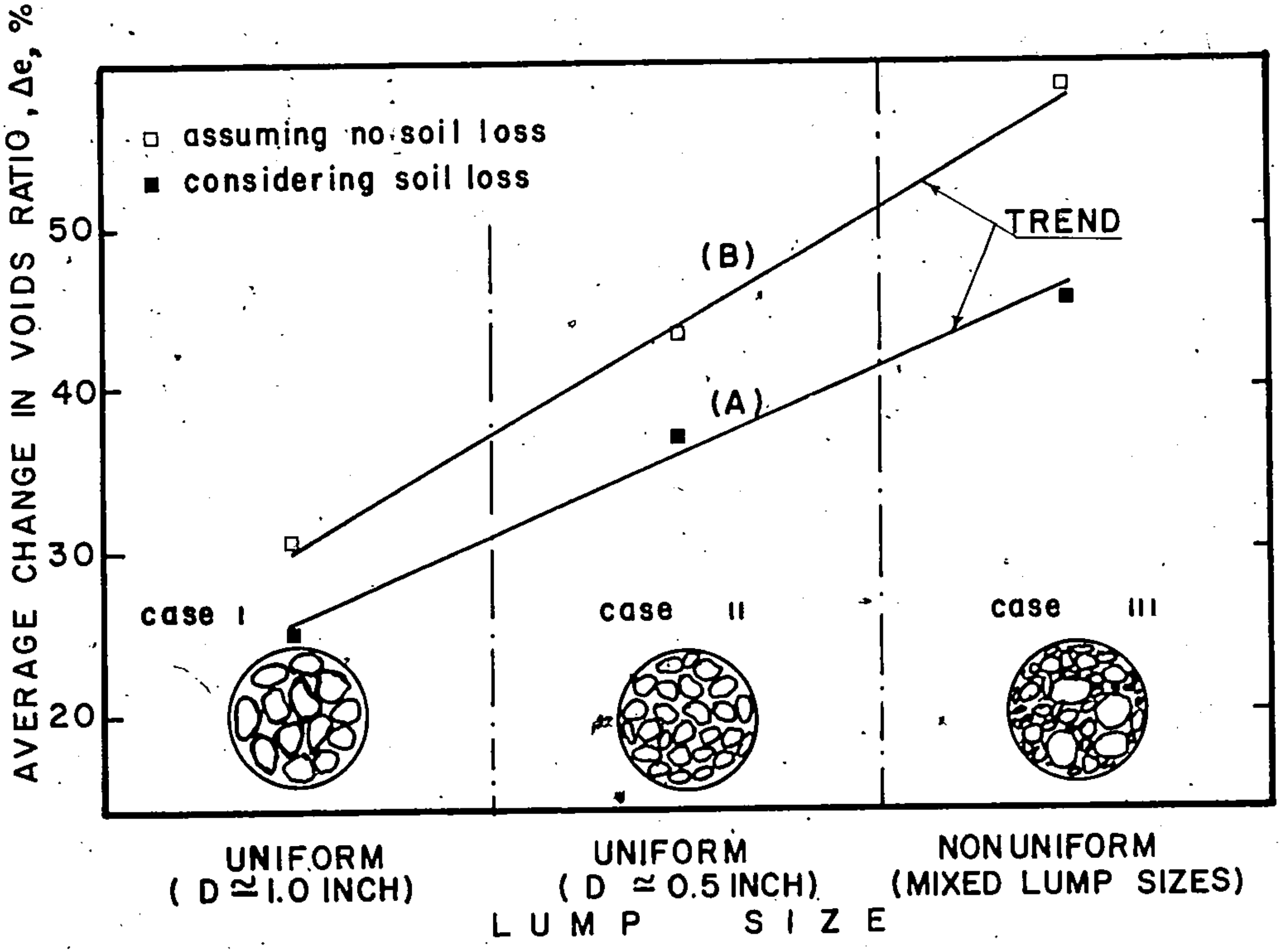


FIGURE 4.2 The Effect of Lump Size and Gradation on the Average Change in Voids Ratio

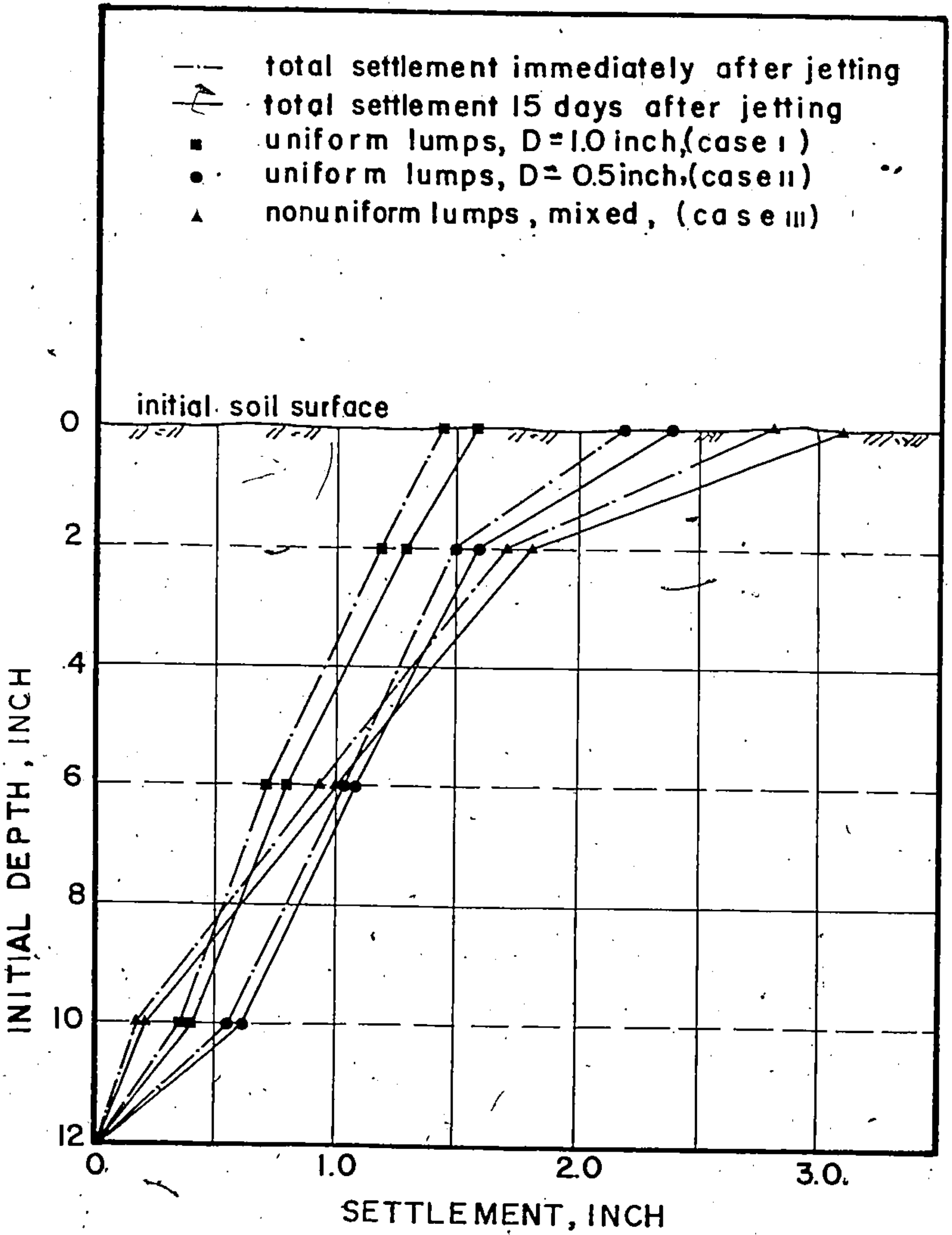


FIGURE 4.3 Settlement Profiles for Samples of Different Lump Size and Gradation

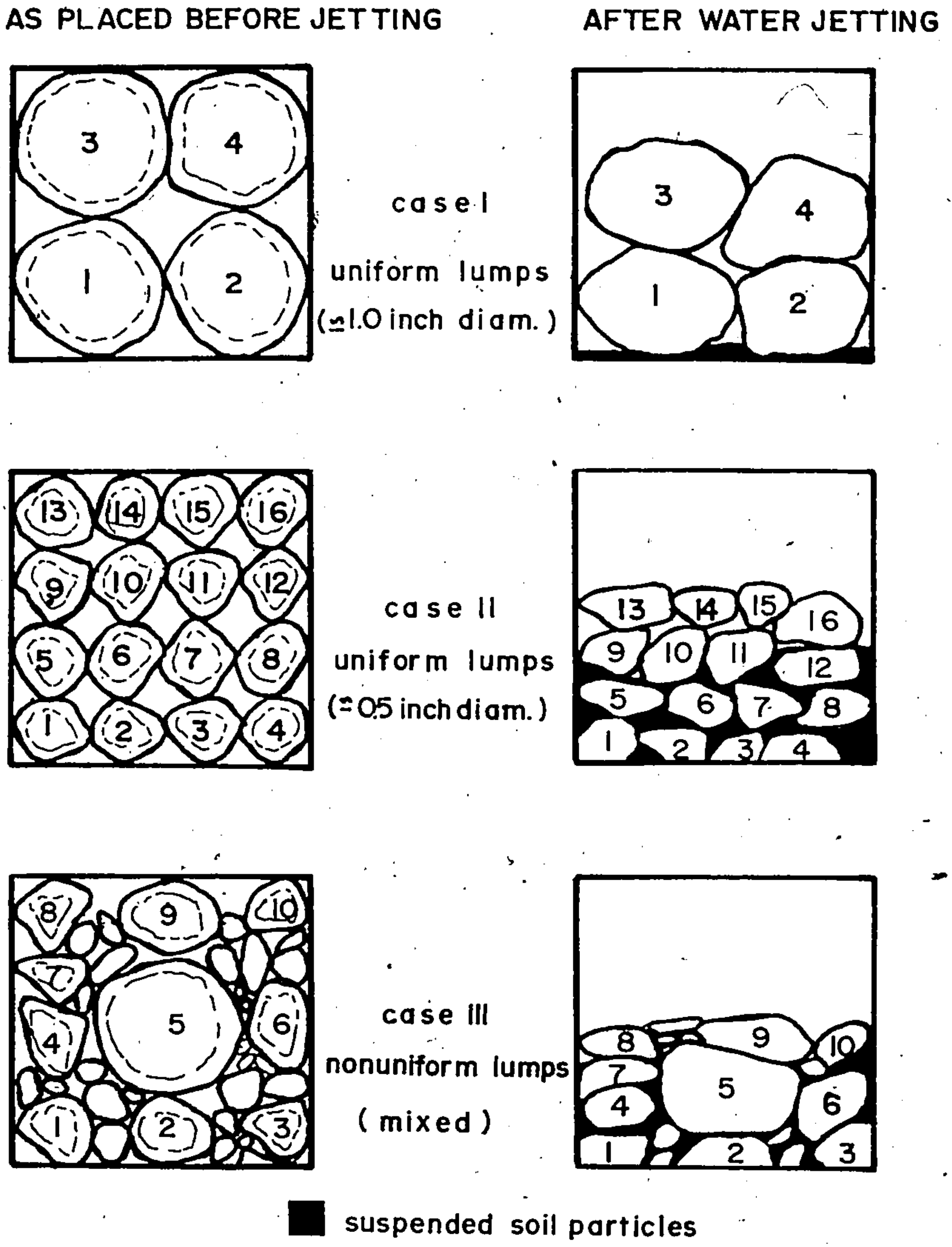


FIGURE 4.4 Schematic Representation of the Effect of Lump Sizes and Gradation

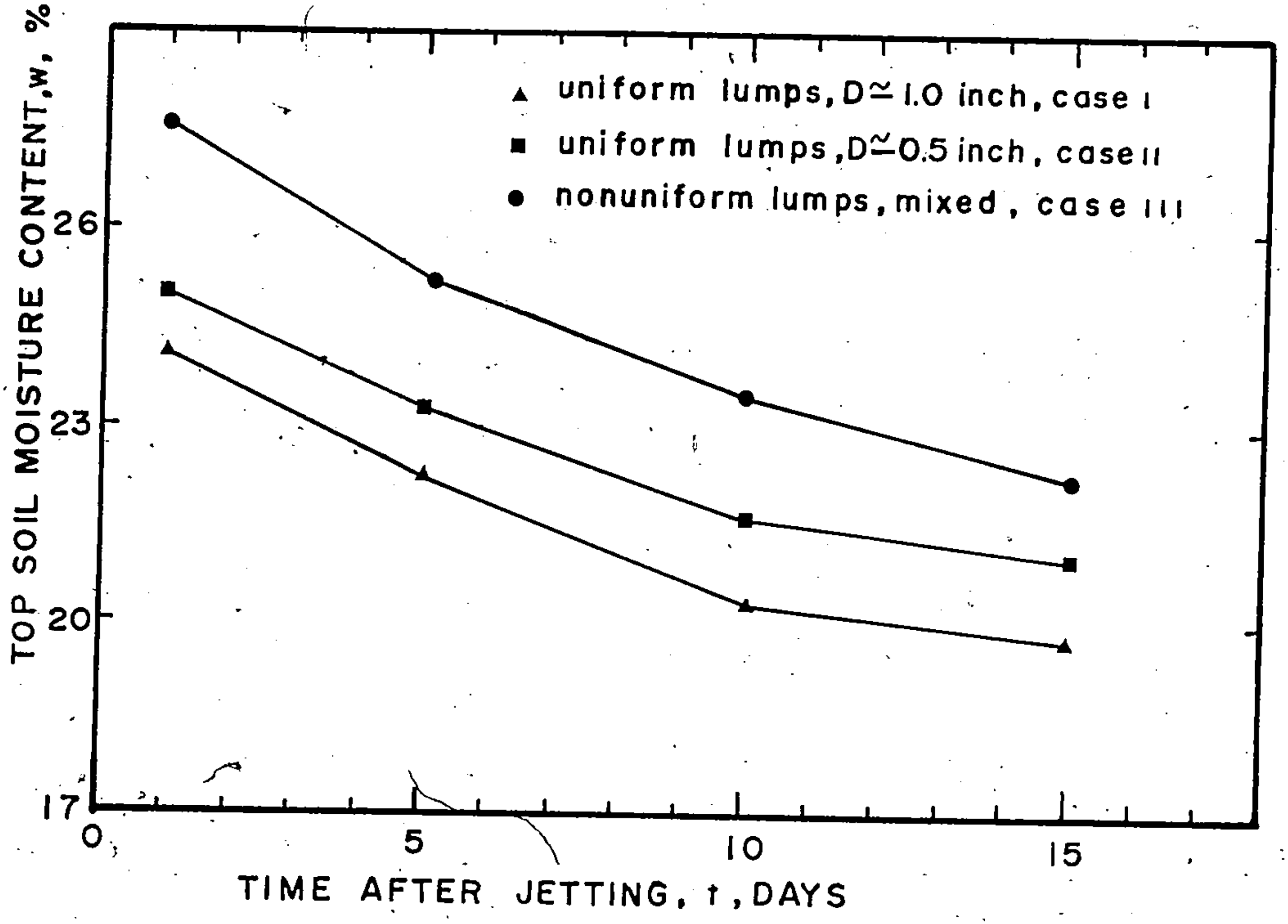


FIGURE 4.5 The Change in Top Soil Moisture Content with Time After Jetting for Samples of Different Lump Sizes

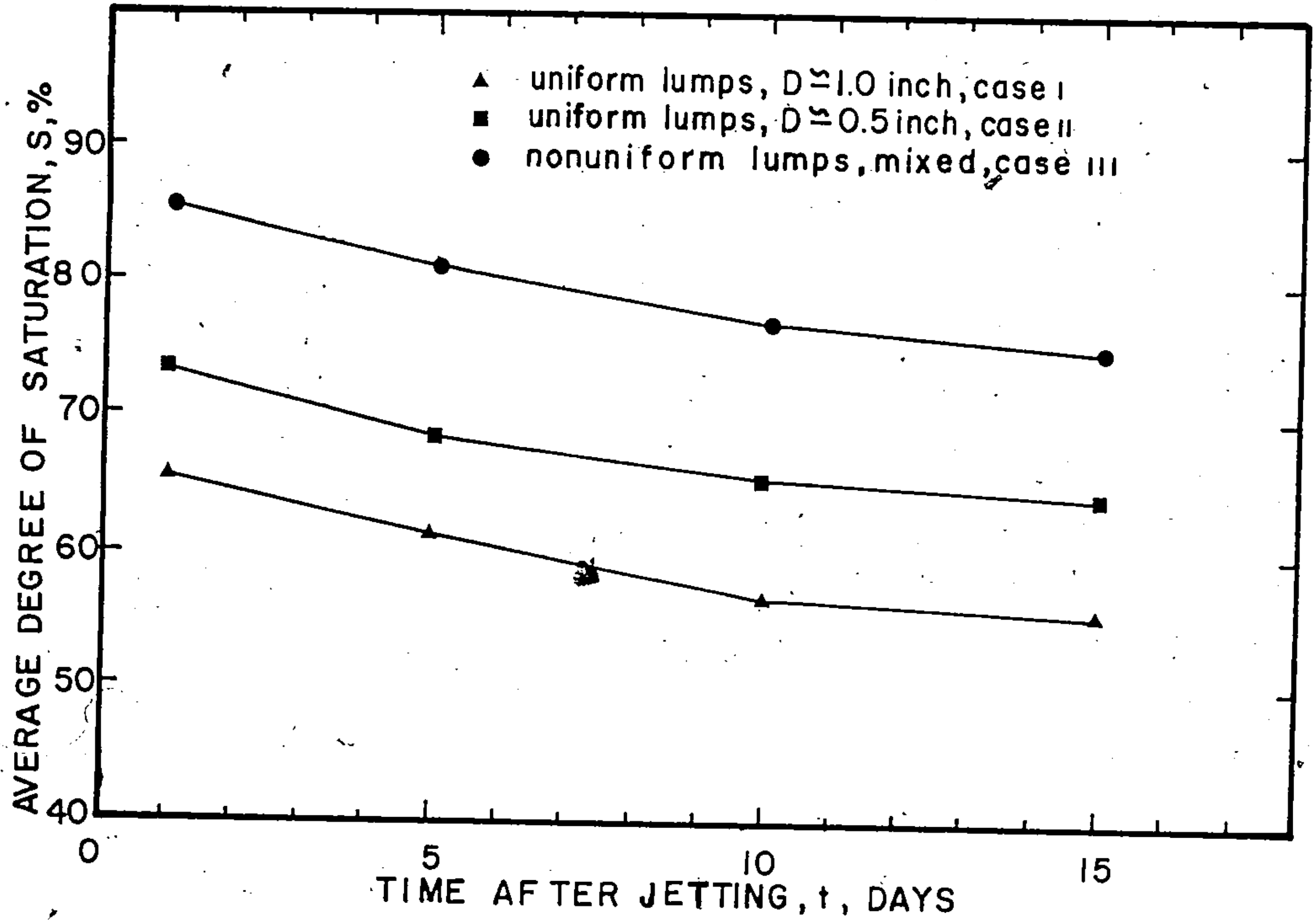


FIGURE 4.6 The Change in Average Degree of Saturation with Time After Jetting for Samples of Different Lump Sizes

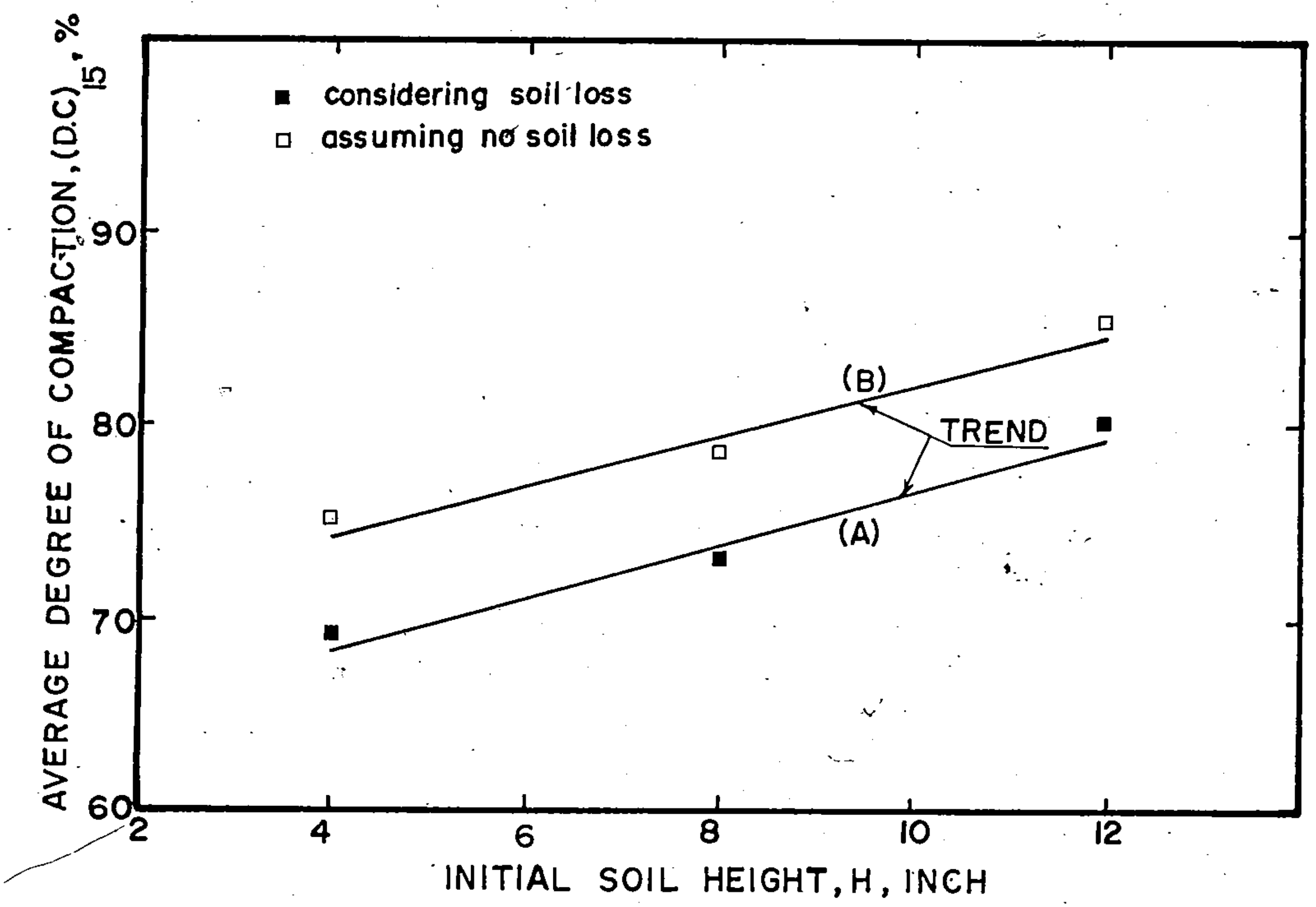


FIGURE 4.7 The Effect of Initial Soil Height on the Average Degree of Compaction Fifteen Days After Jetting

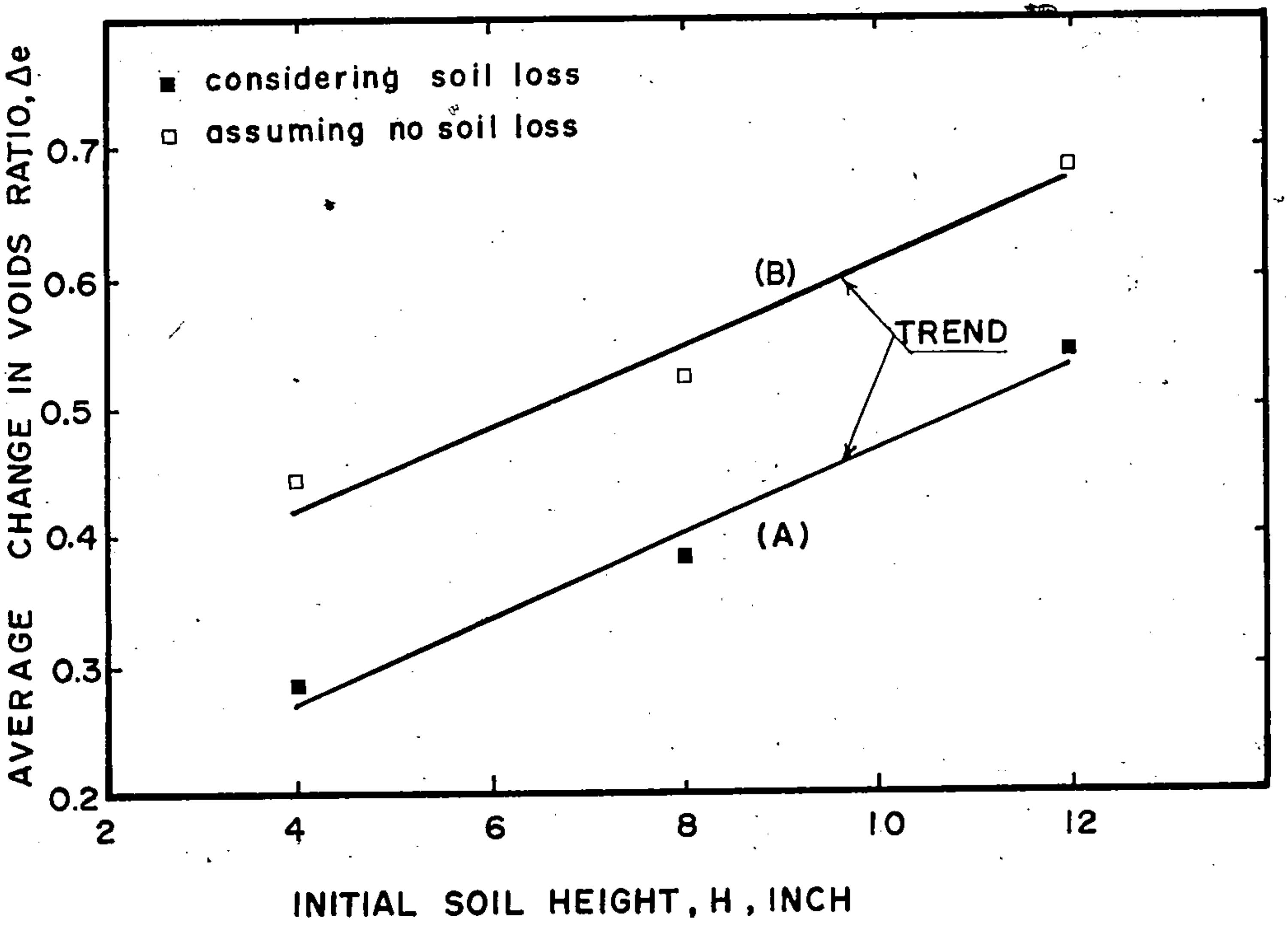


FIGURE 4.8 The Effect of Initial Soil Height on the Average Change in Voids Ratio

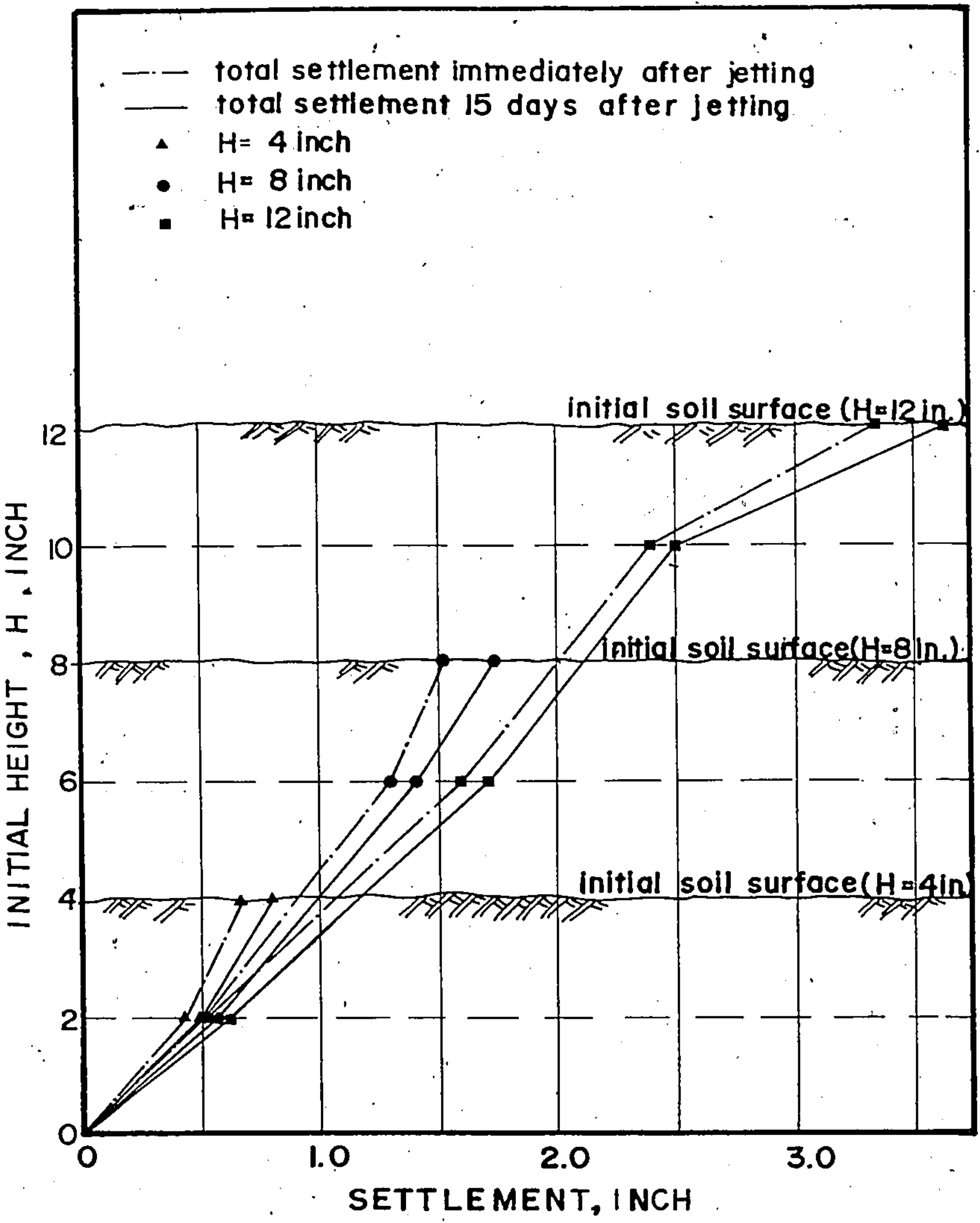


FIGURE 4.9 Settlement Profiles for Samples of Different Initial Soil Heights

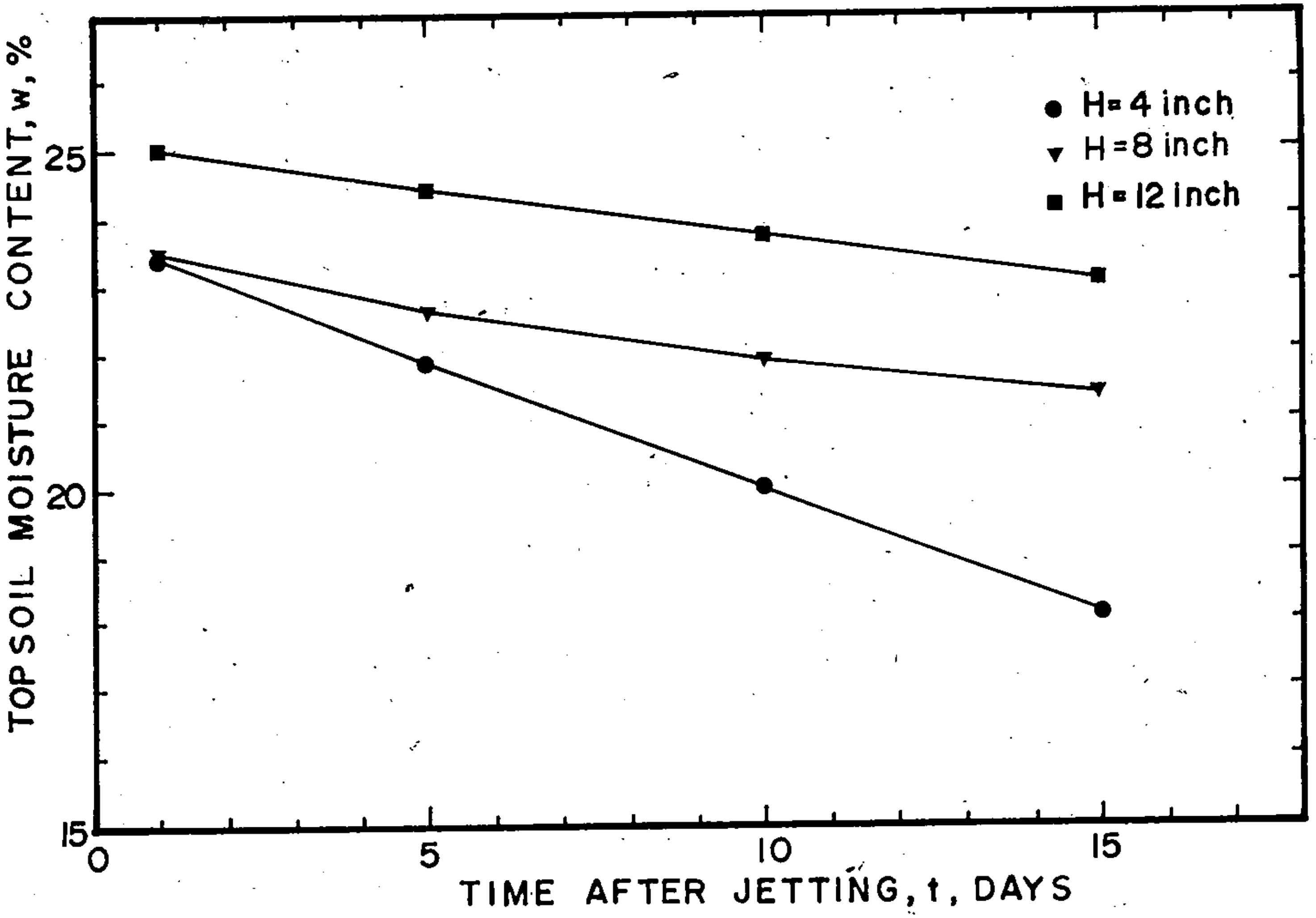


FIGURE 4.10 The Change in Top Soil Moisture Content with Time After Jetting for Samples of Different Initial Soil Heights

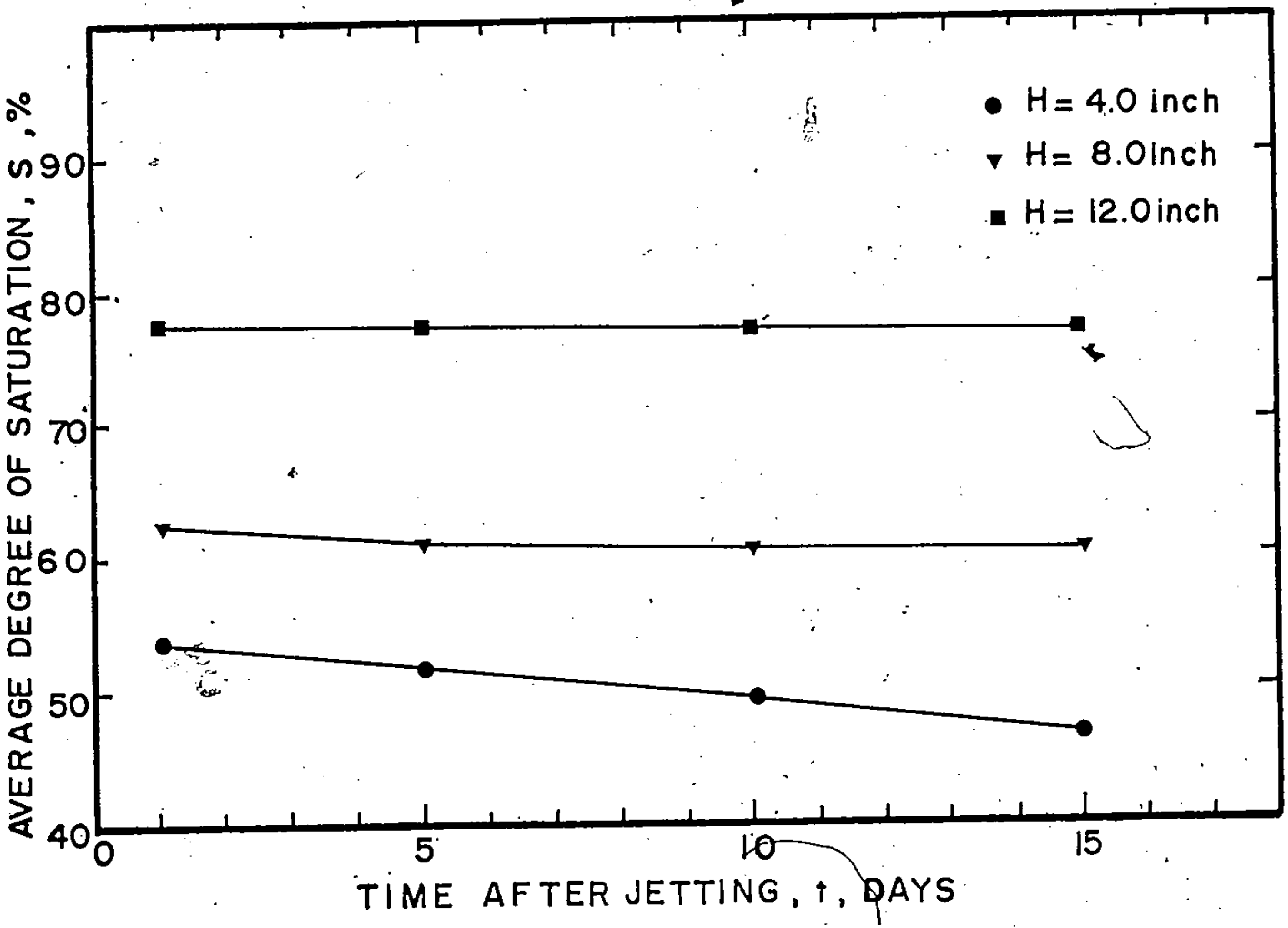


FIGURE 4.11 The Change in Average Degree of Saturation with Time after Jetting for Samples of Different Initial Soil Heights

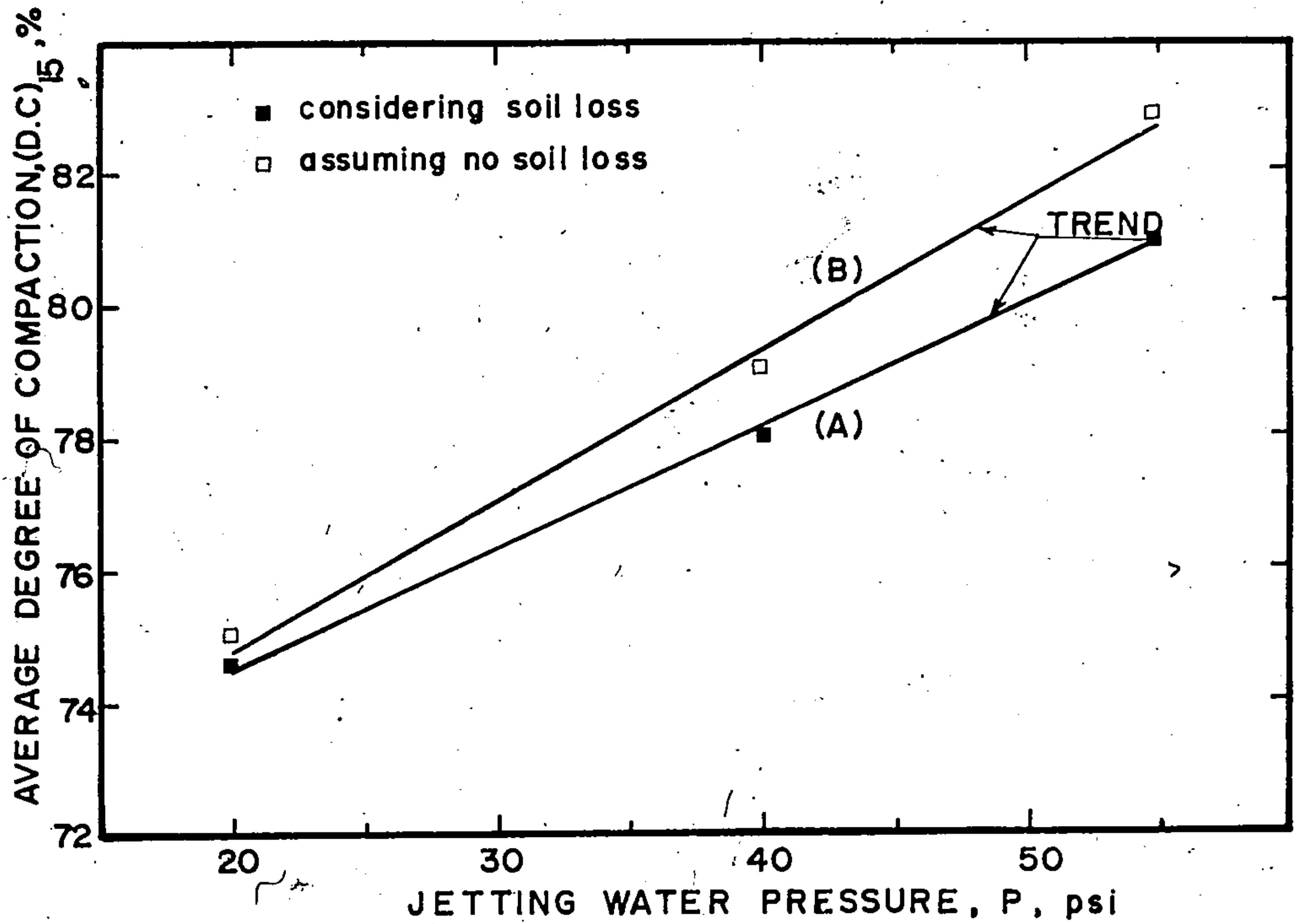


FIGURE 4.12 The Effect of Jetting Water Pressure on the Average Degree of Compaction, Fifteen Days After Jetting

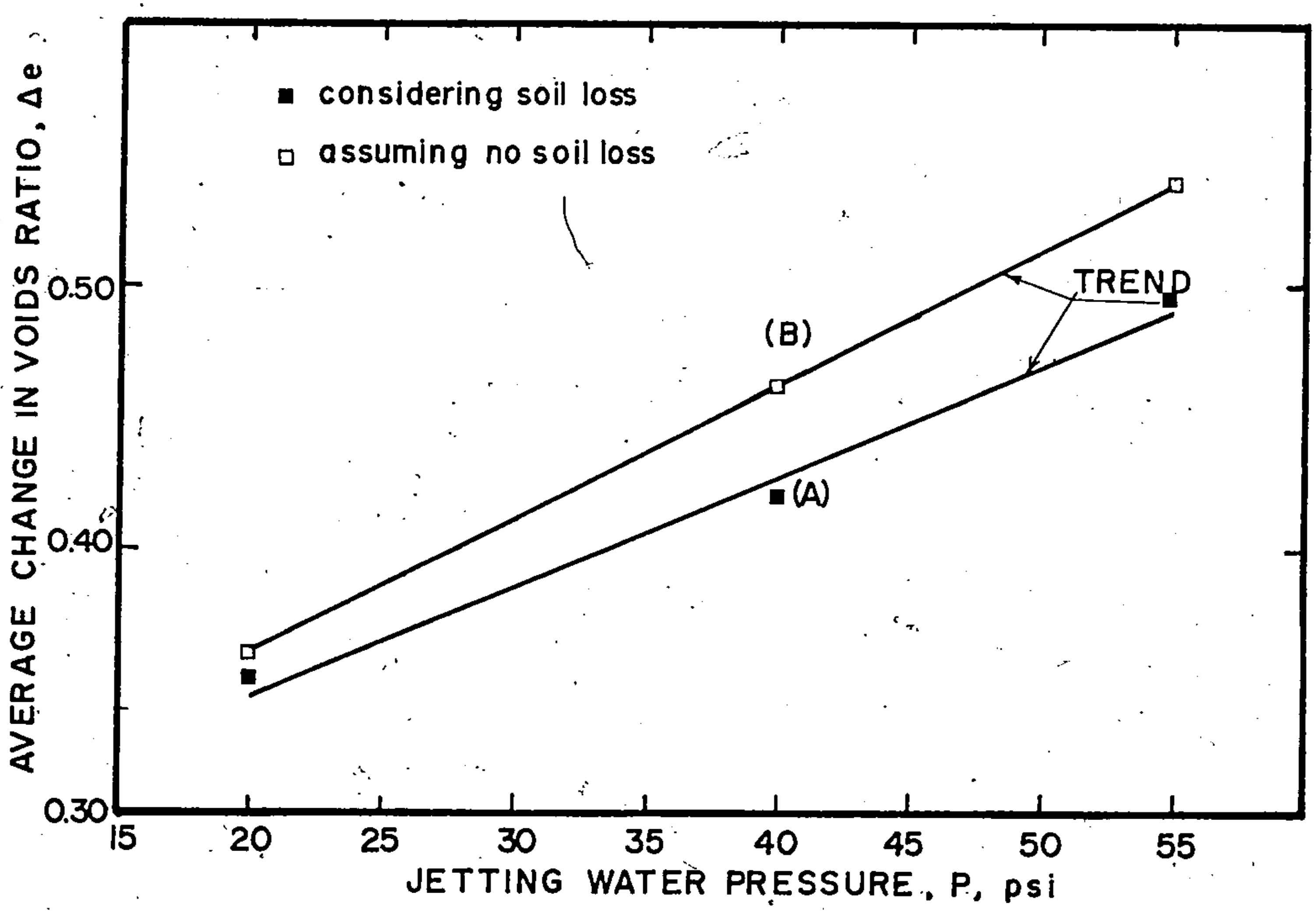


FIGURE 4.13 The Effect of Jetting Water Pressure on the Average Change in Voids Ratio

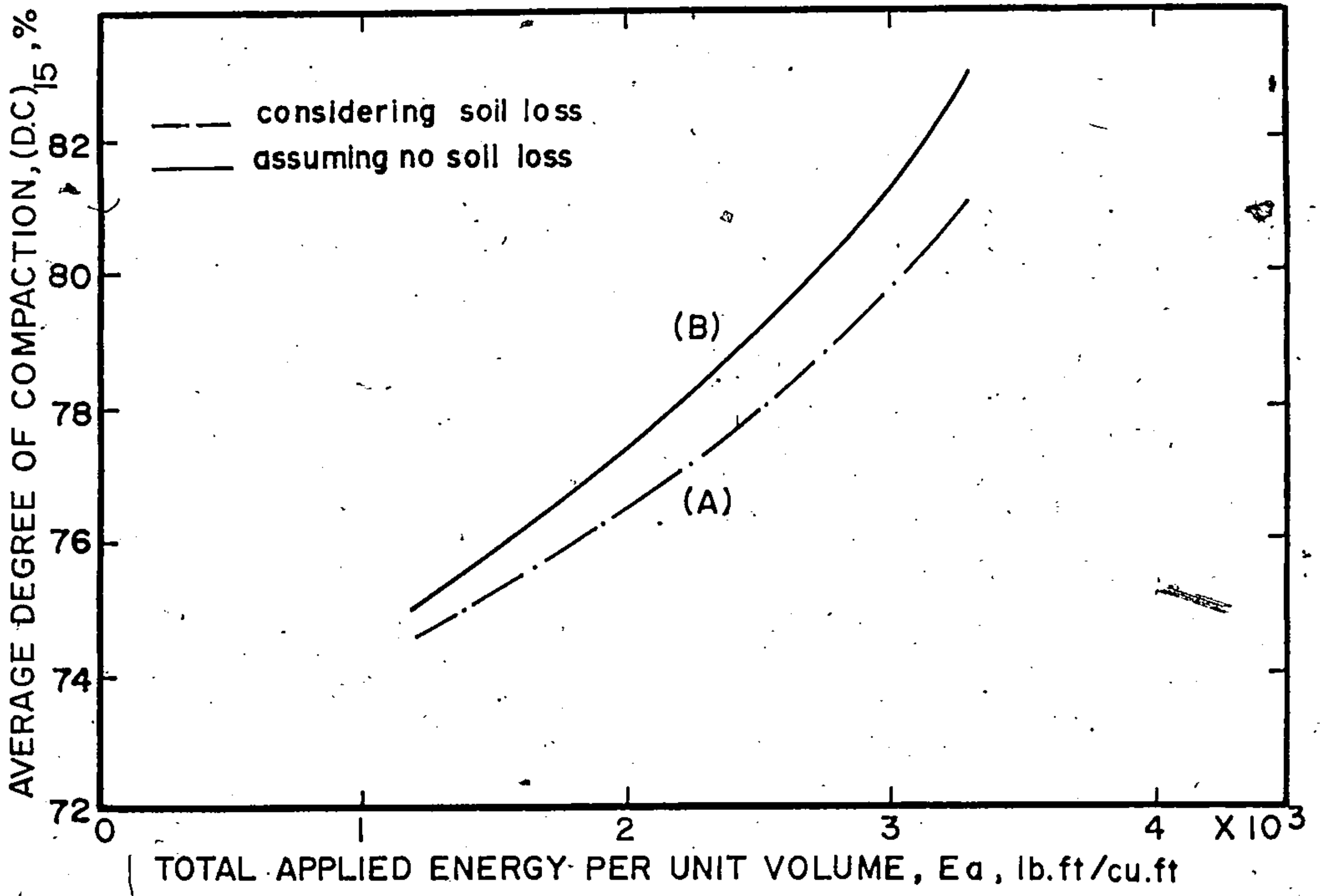


FIGURE 4.14 The Average Degree of Compaction, Fifteen Days After Jetting Versus the Total Applied Energy Per Unit Volume

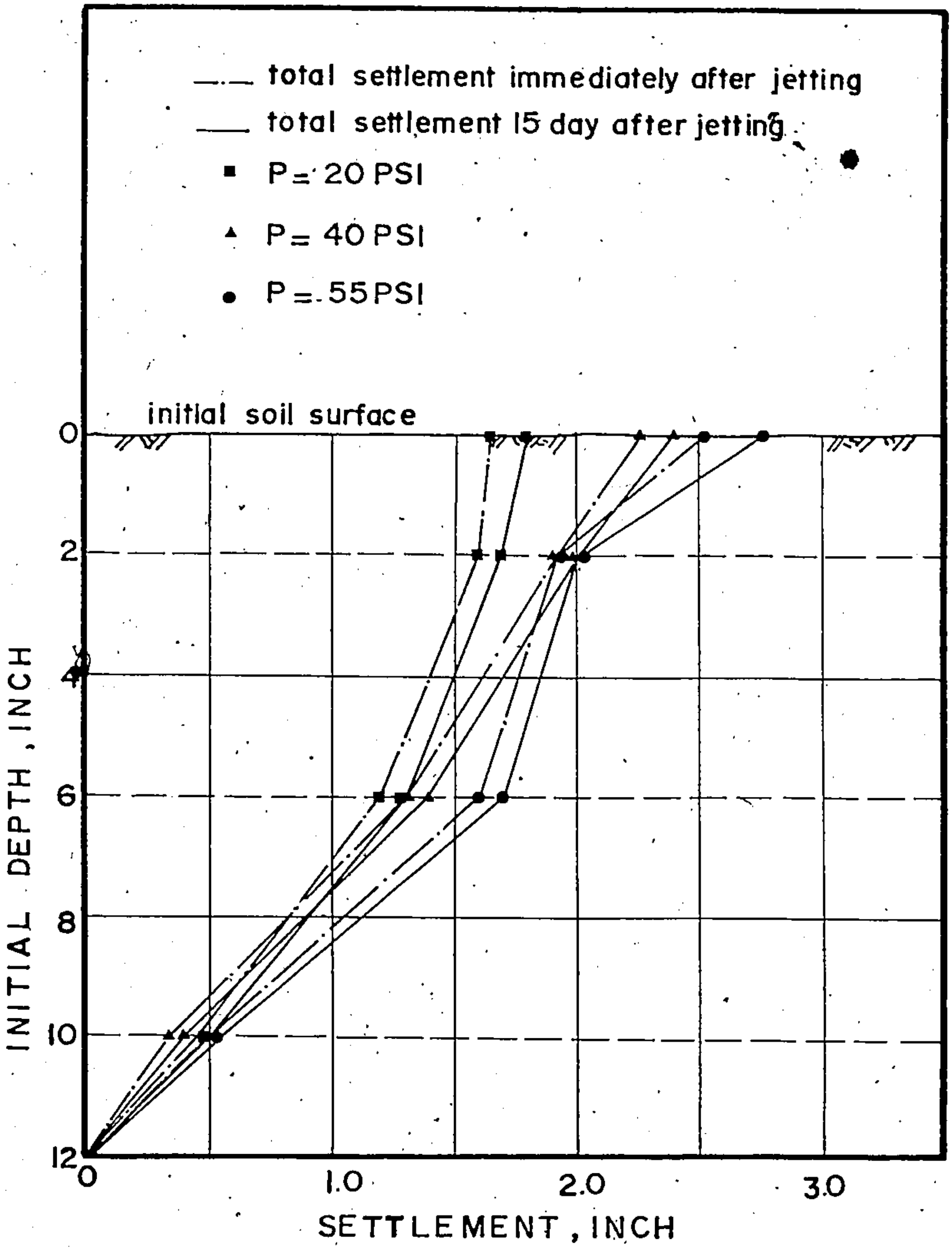


FIGURE 4.15 Settlement Profiles for Samples Jetted Under Different Jetting Water Pressures

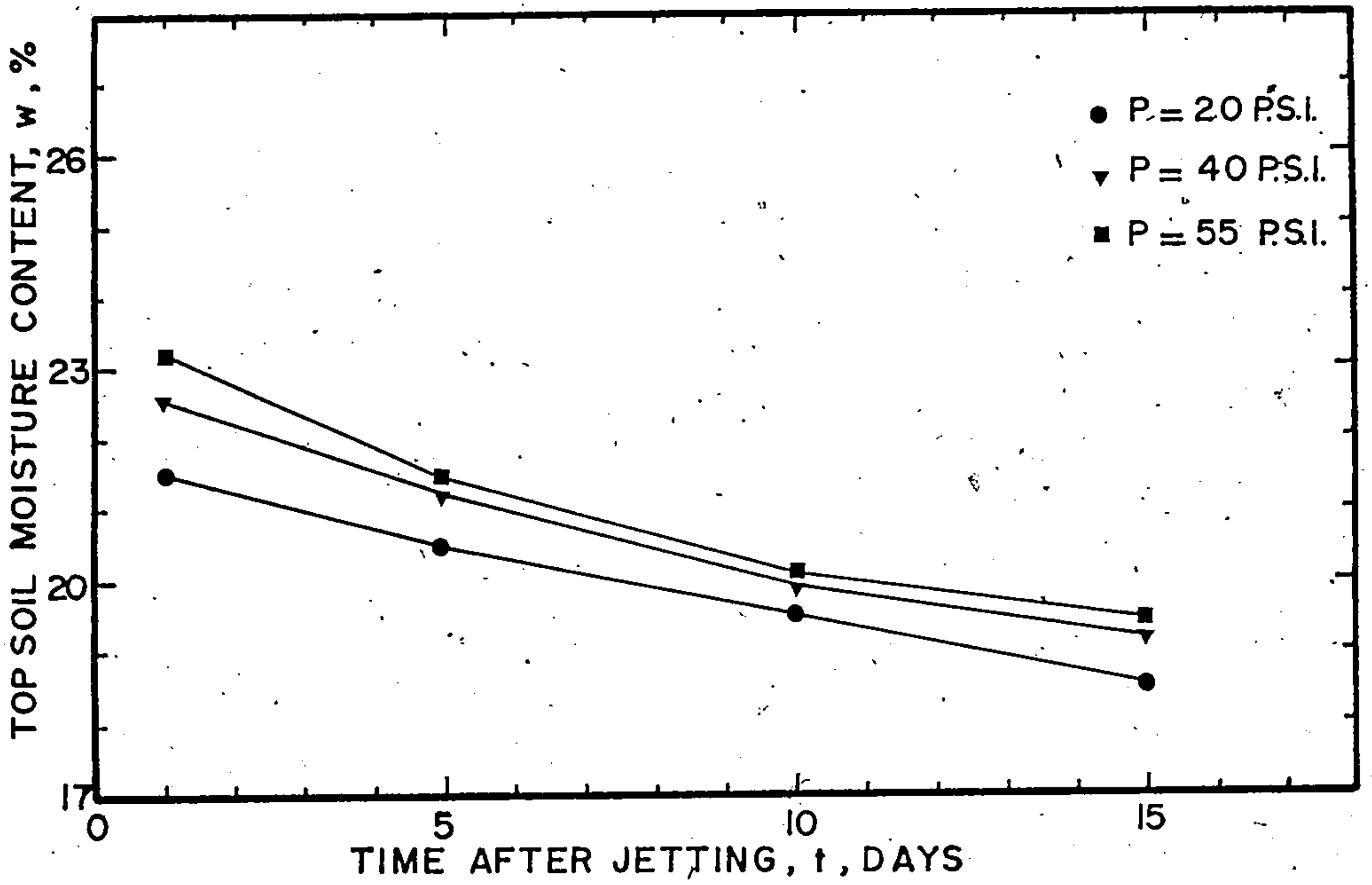


FIGURE 4.16 The Change in Top Soil Moisture Content with Time After Jetting for Samples of Different Jetting Water Pressures

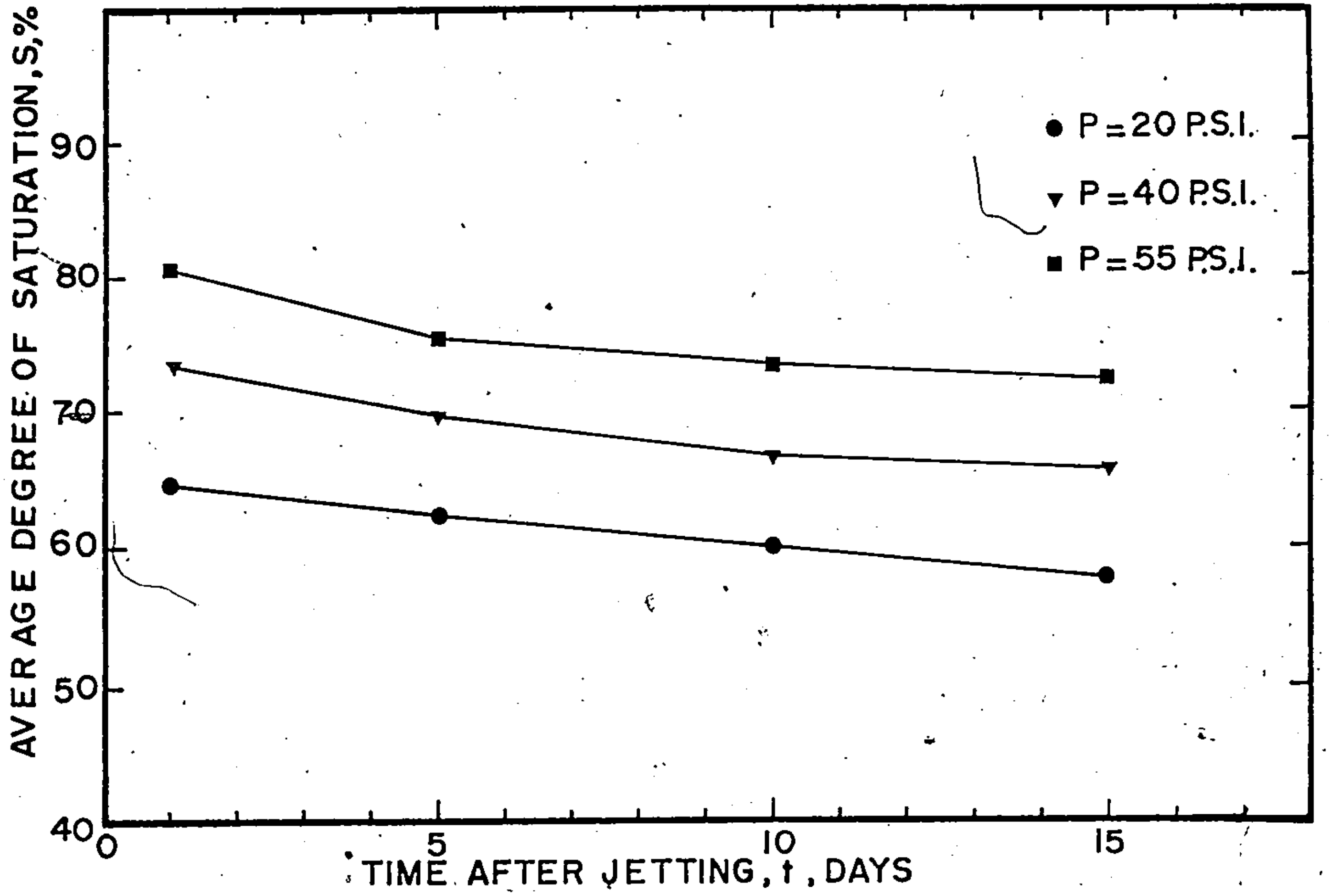


FIGURE 4.17 The Change in Average Degree of Saturation with Time After Jetting for Samples of Different Jetting Water Pressures

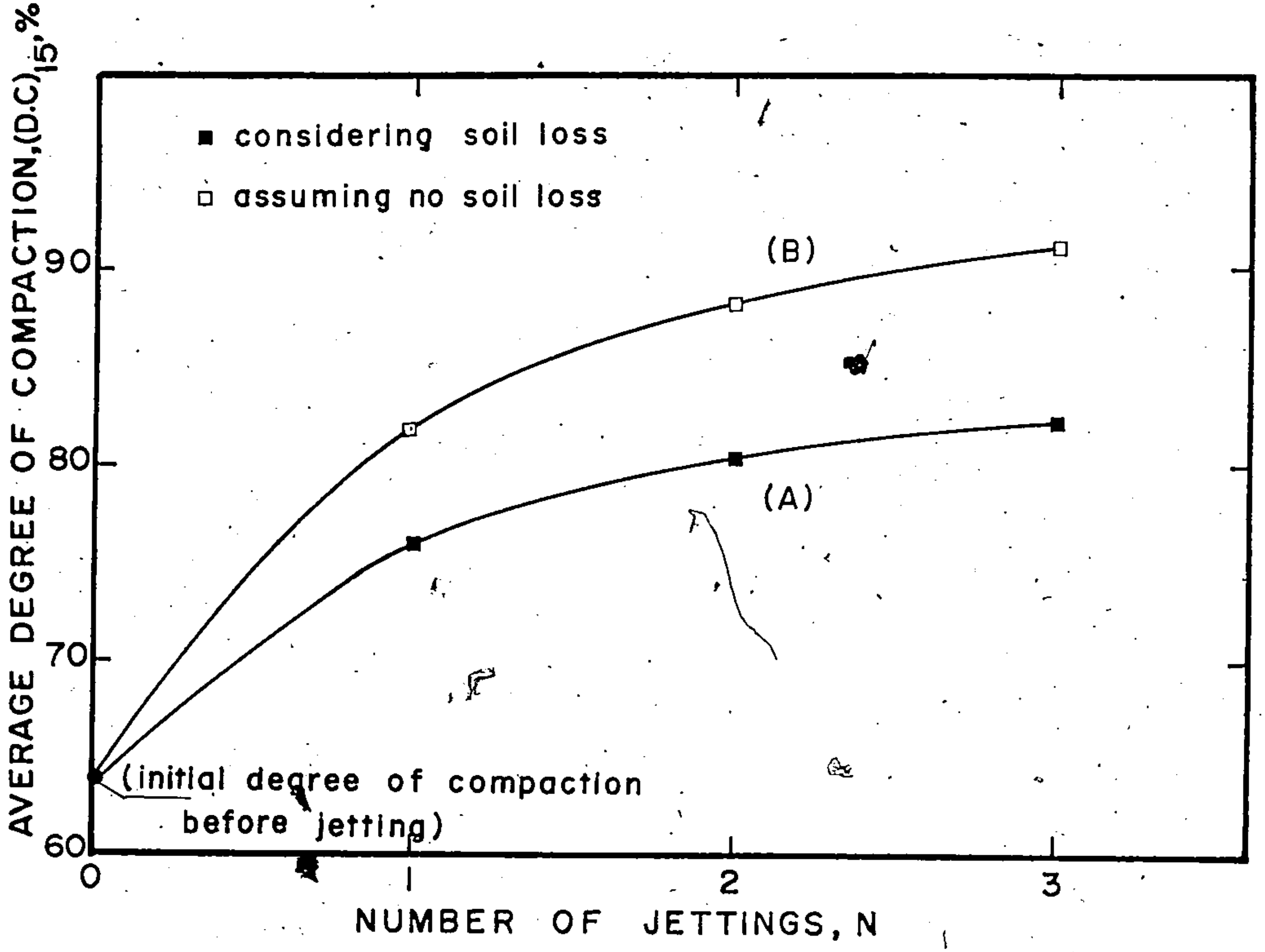


FIGURE 4.18 The Effect of Rejetting on the Average Degree of Compaction, Fifteen Days After Jetting

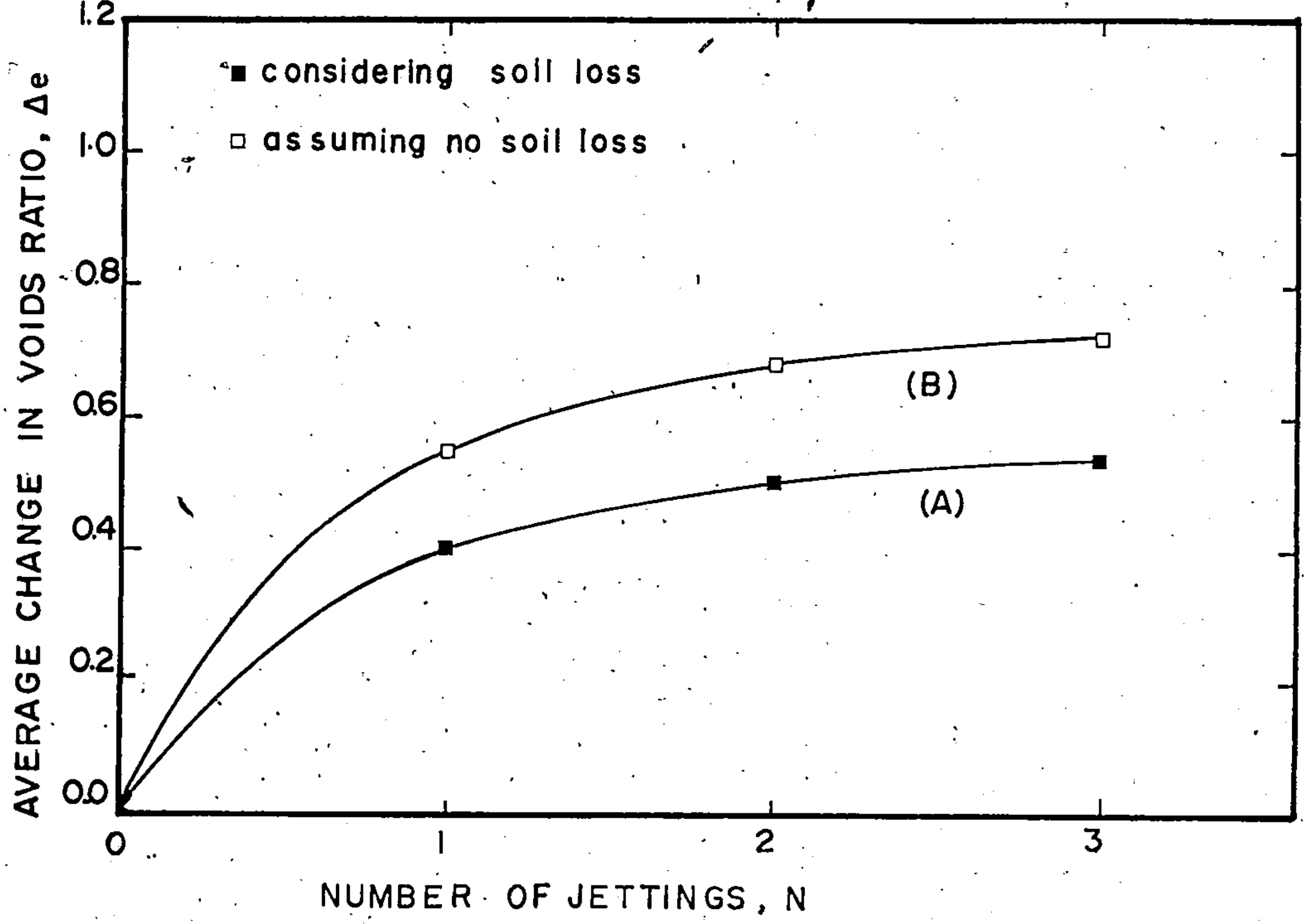


FIGURE 4.19 The Effect of Rejetting on the Average Change in Voids Ratio

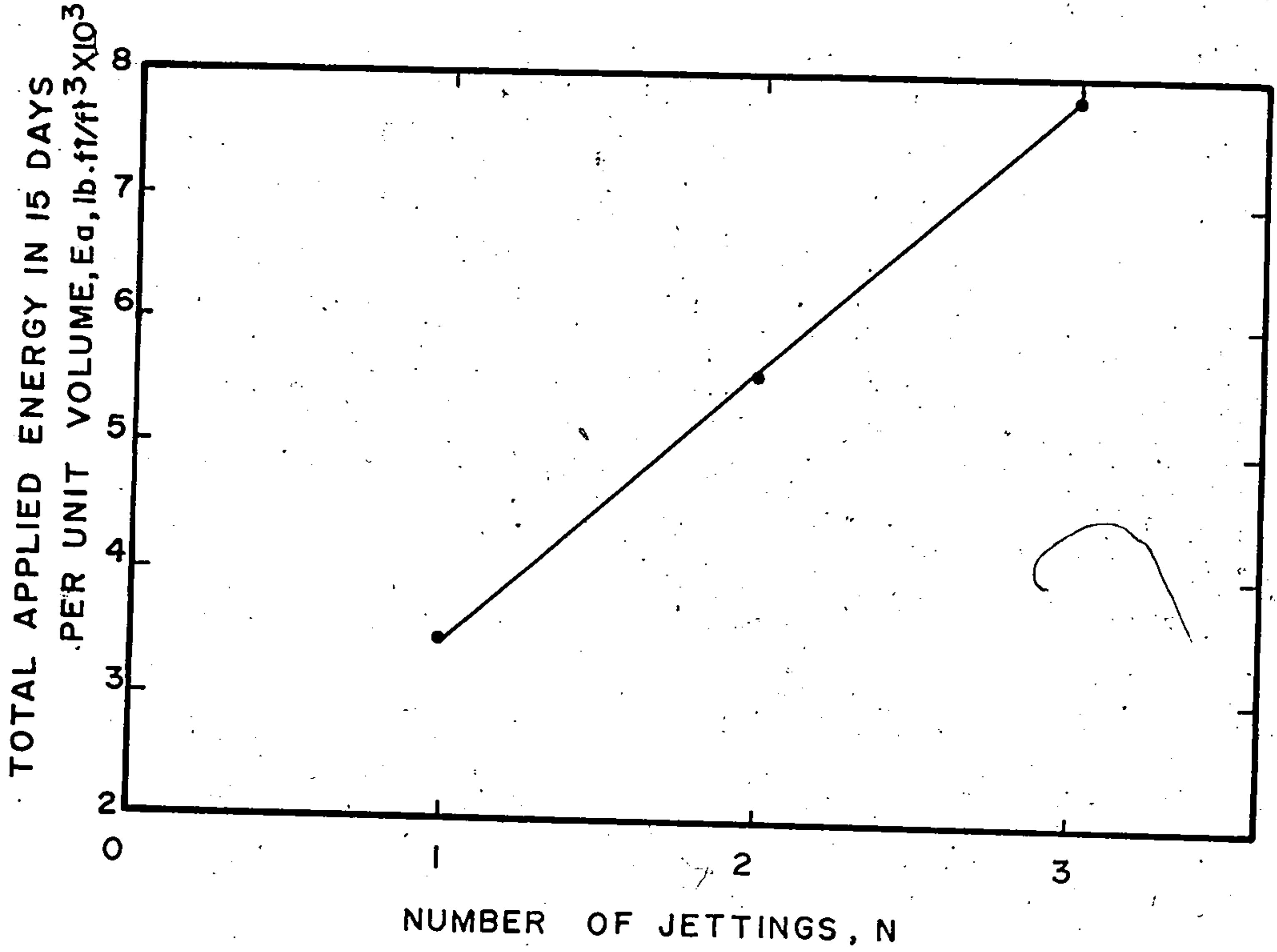


FIGURE 4.20 Total Applied Energy in Fifteen Days Per Unit Volume Versus Number of Jettings

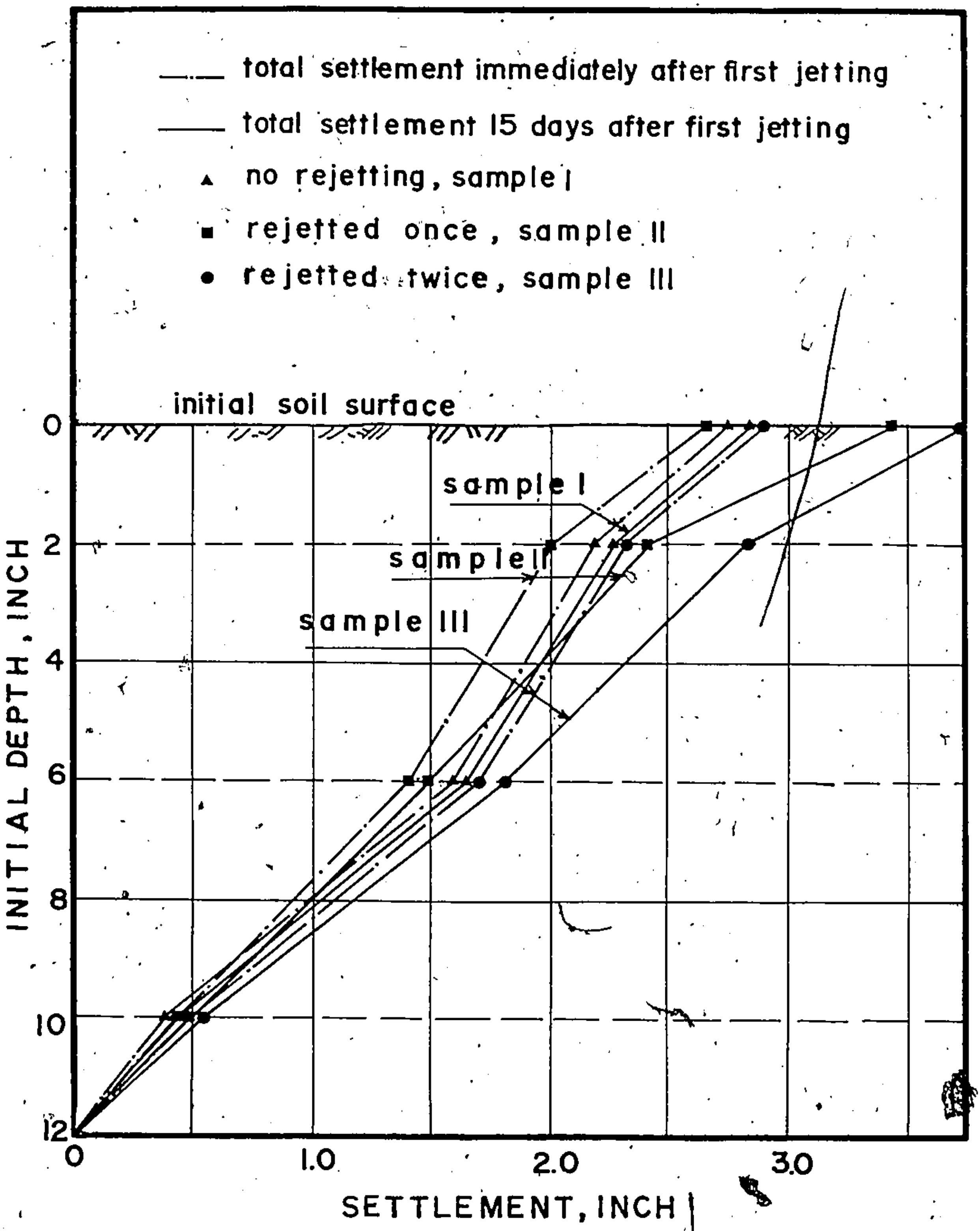


FIGURE 4.21 Settlement Profiles for Samples of Different Jetting Conditions

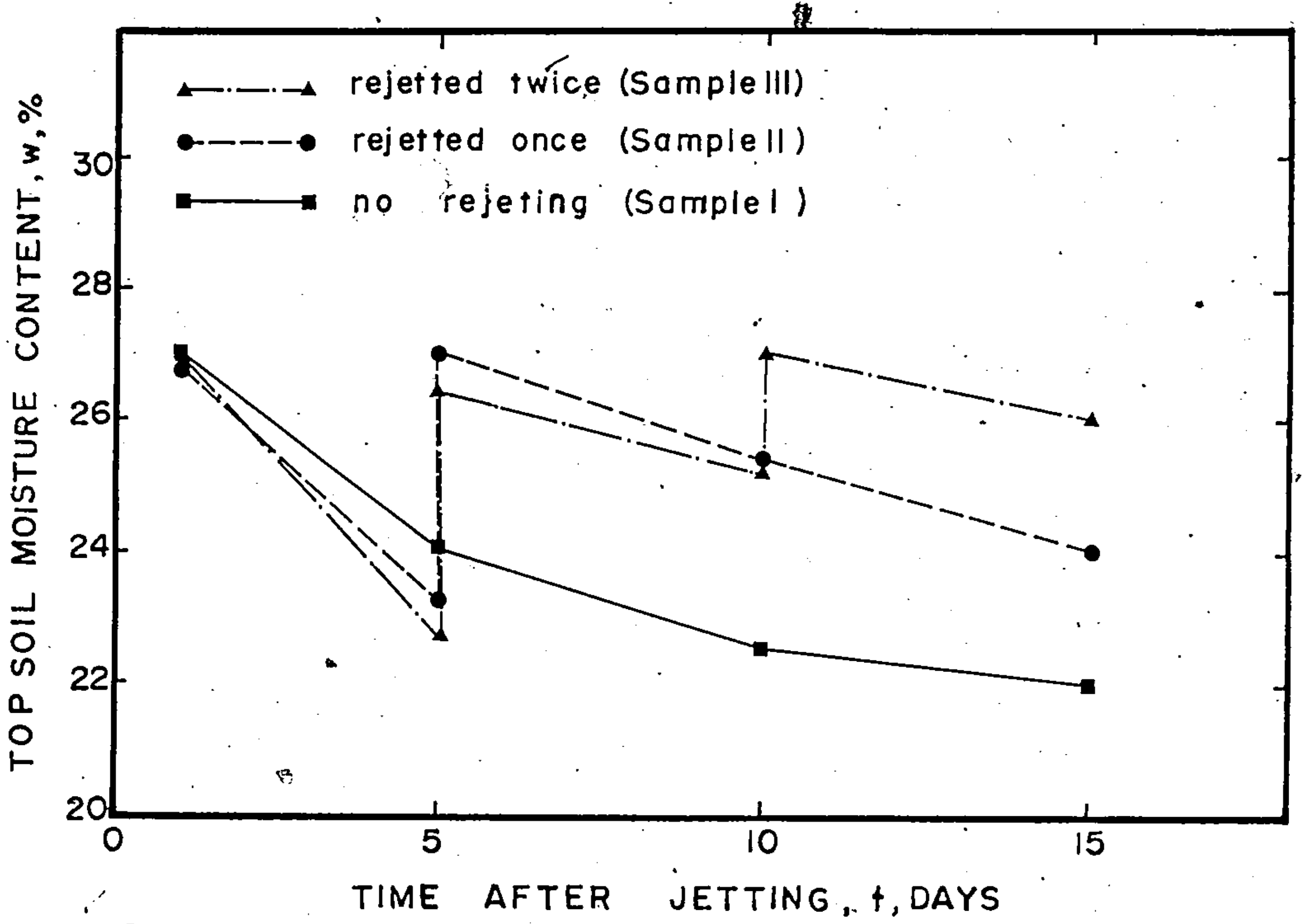


FIGURE 4.22 The Change in Top Soil Moisture Content with Time After Jetting for Samples of Different Jetting Conditions

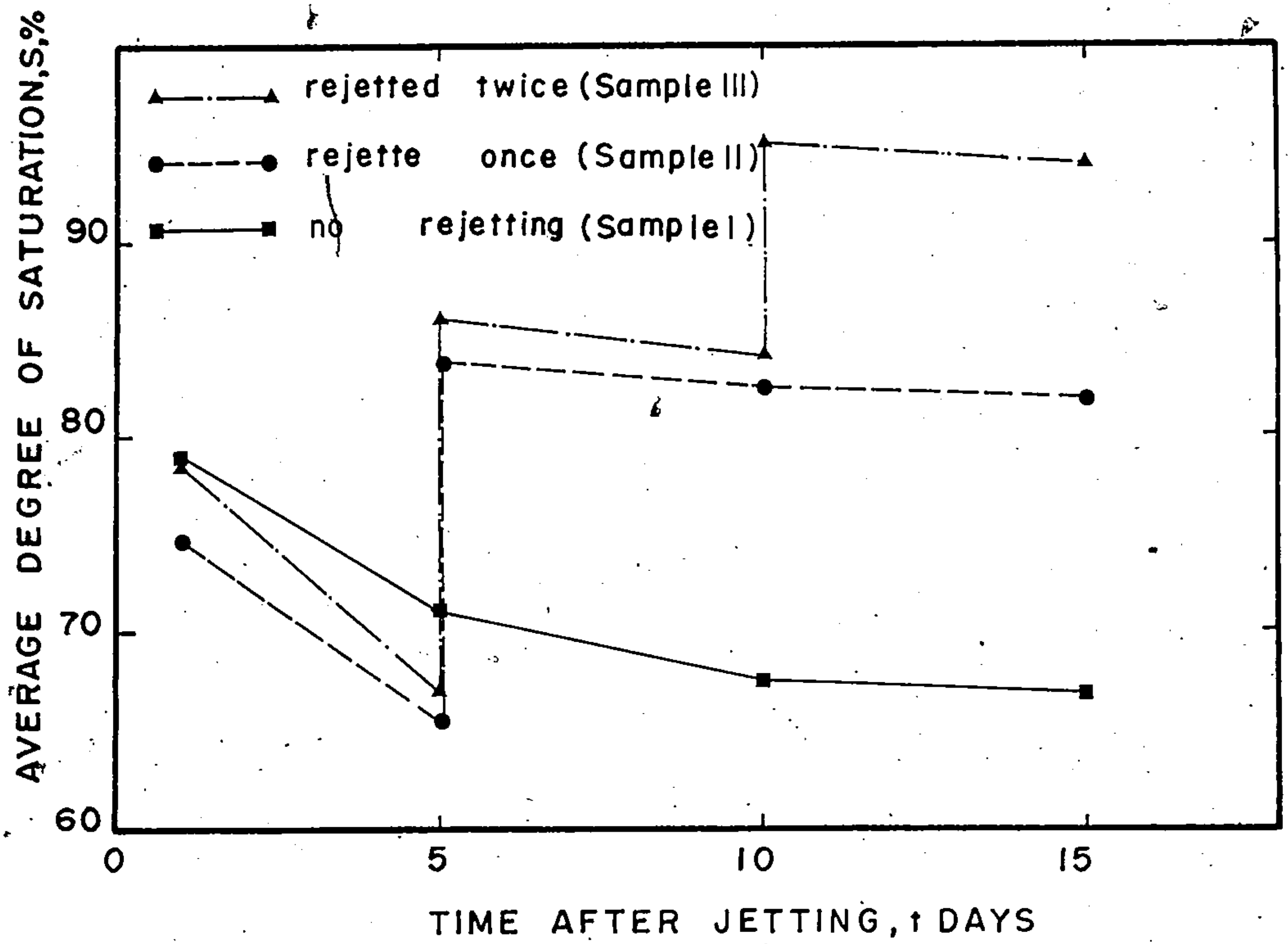


FIGURE 4.23 The Change in Average Degree of Saturation with Time After Jetting for Samples of Different Jetting Conditions

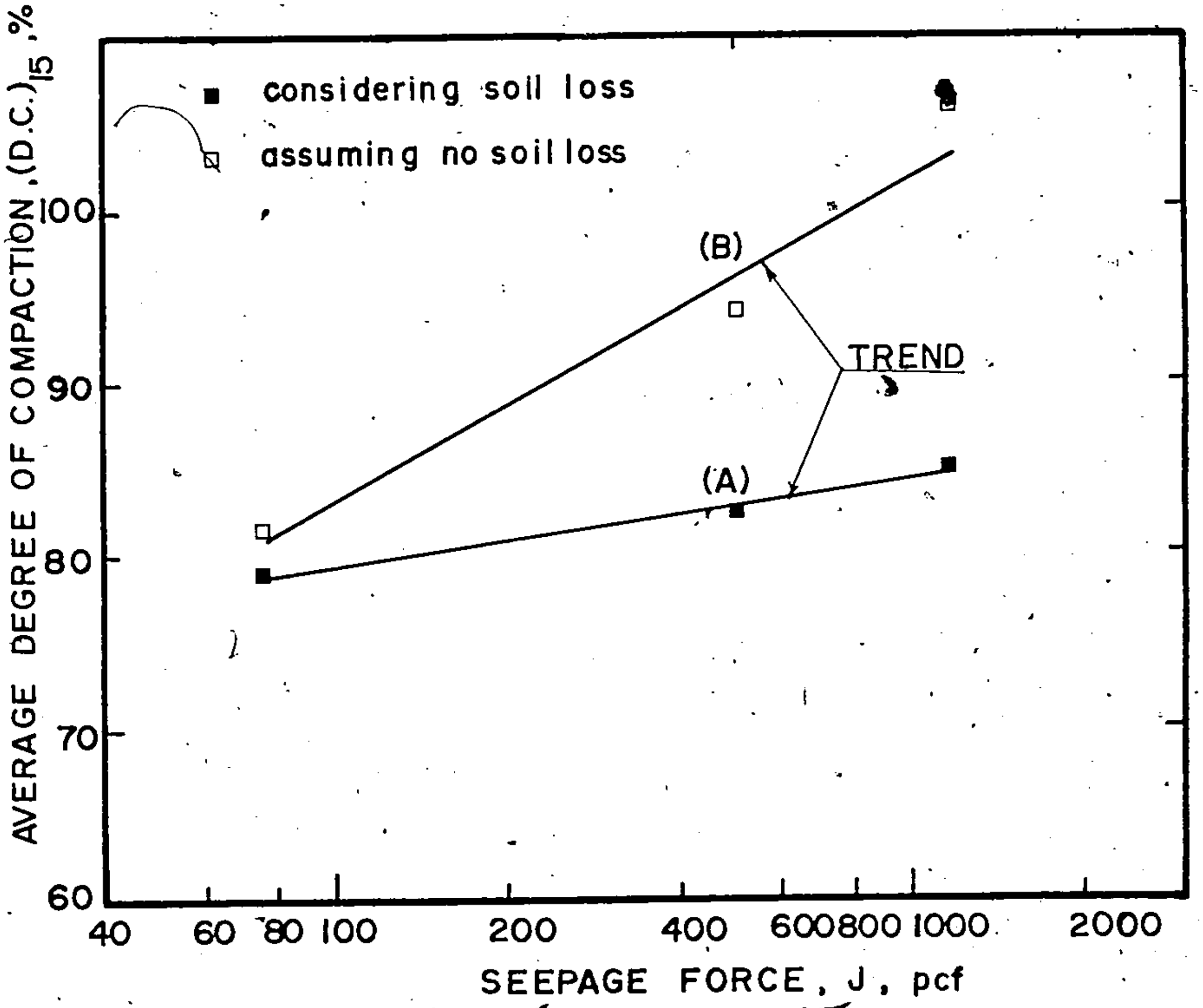


FIGURE 4.24 The Effect of Seepage Force on the Average Degree of Compaction Fifteen Days after Jetting

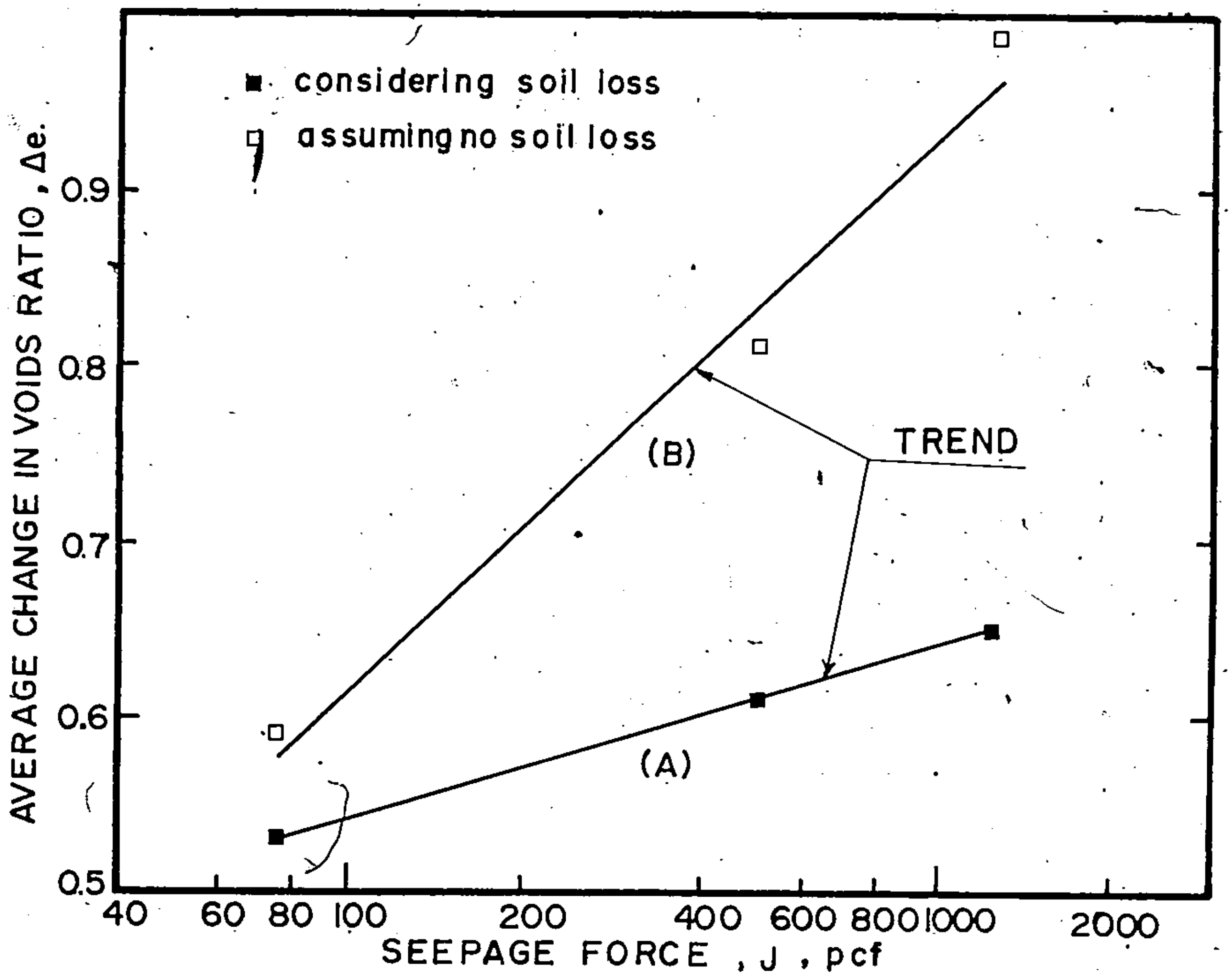


FIGURE 4.25 The Effect of Seepage Force on the Average Change in Voids Ratio

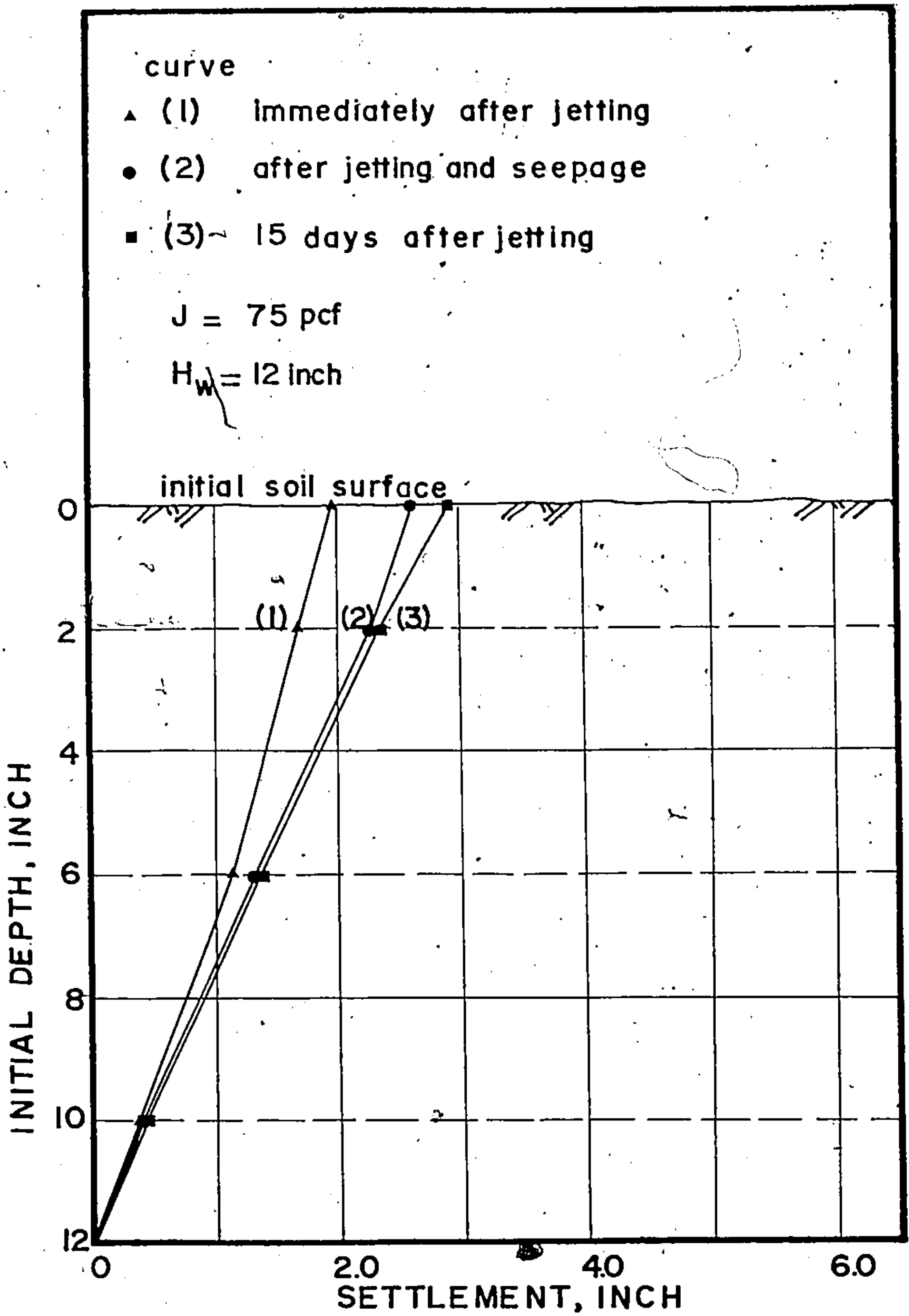


FIGURE 4.26 Settlement Profiles for a Sample Under Indicated Conditions

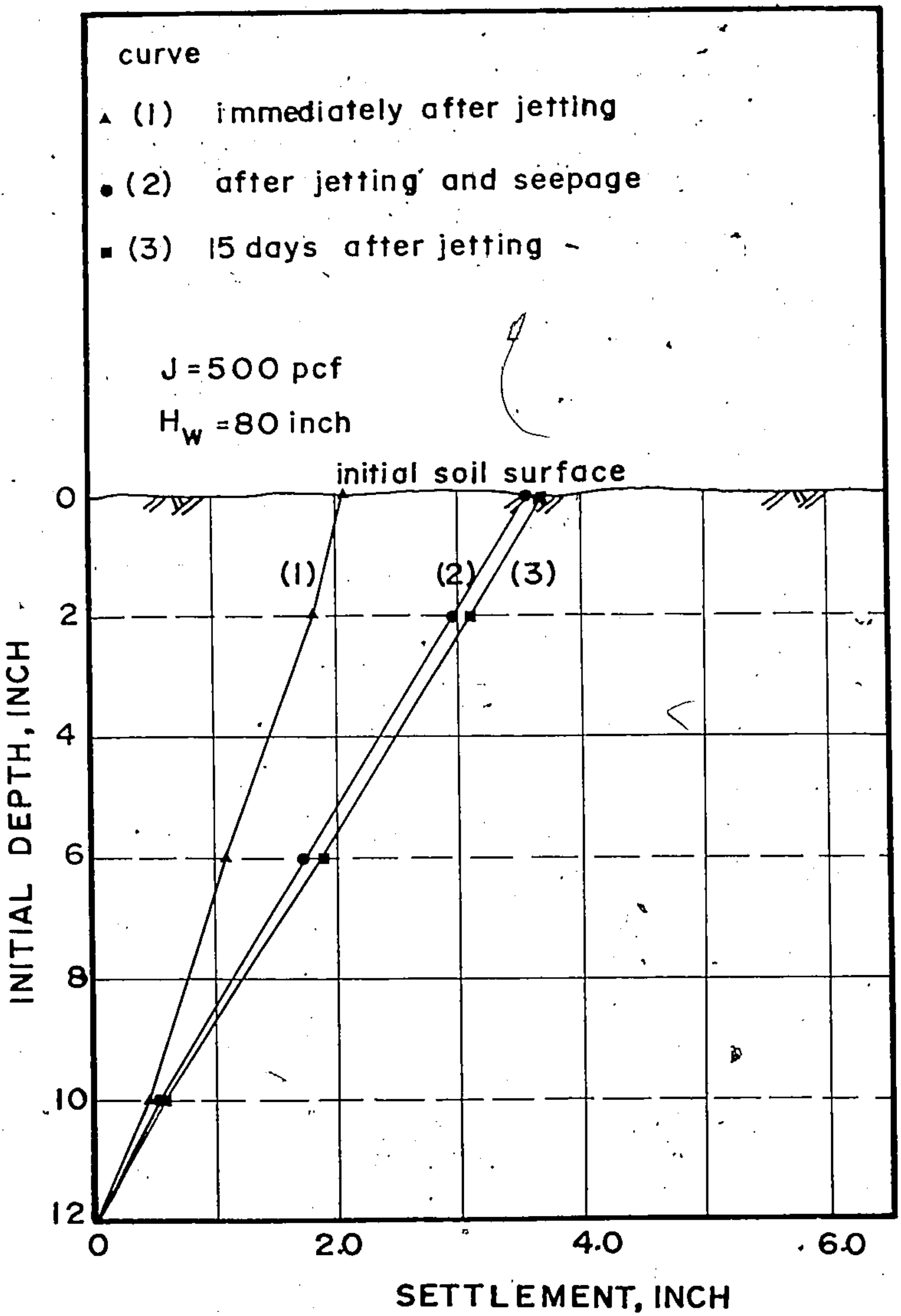


FIGURE 4.27 Settlement Profiles for a Sample Under Indicated Conditions

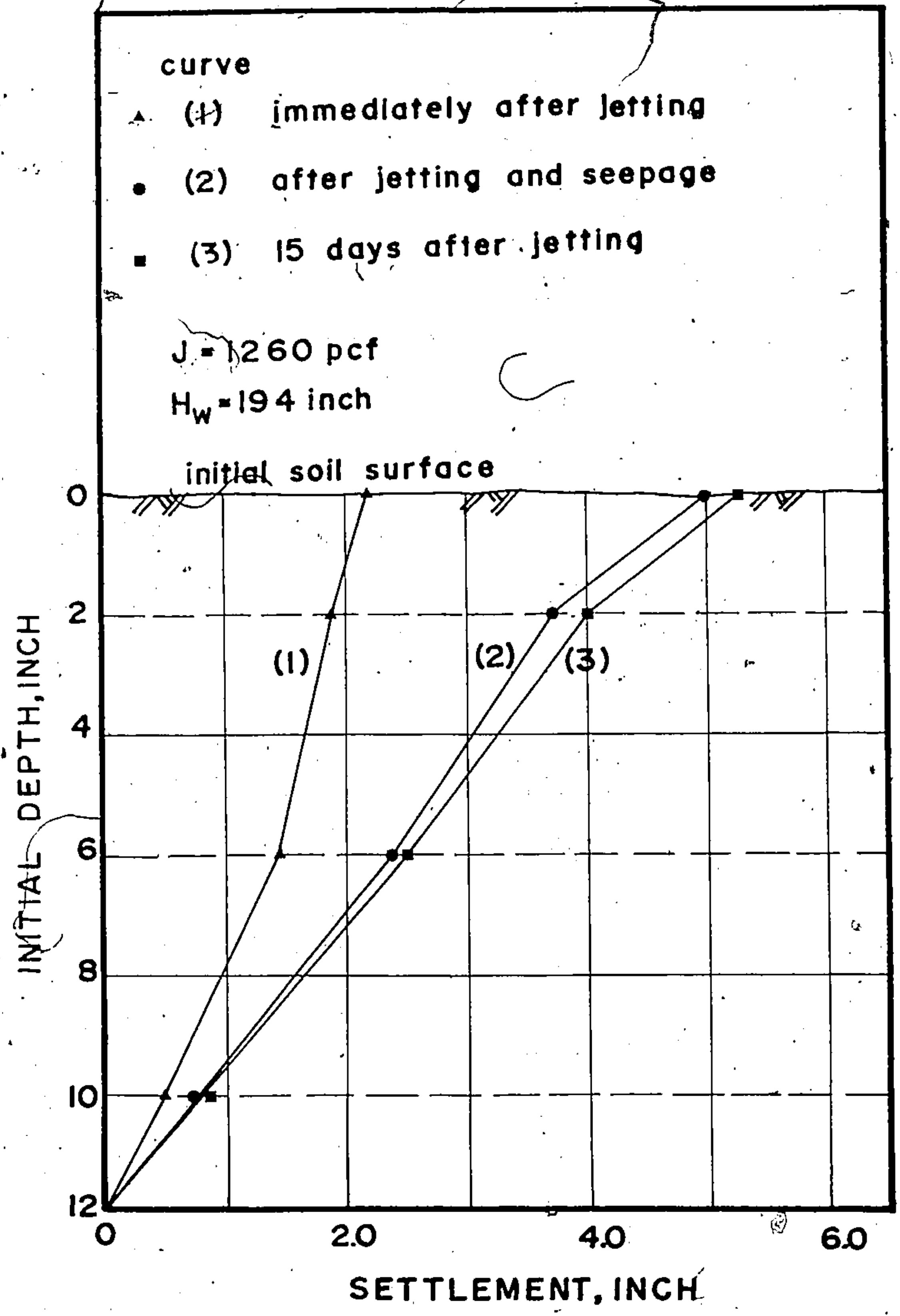


FIGURE 4.28 Settlement Profiles of a Sample Under Indicated Conditions

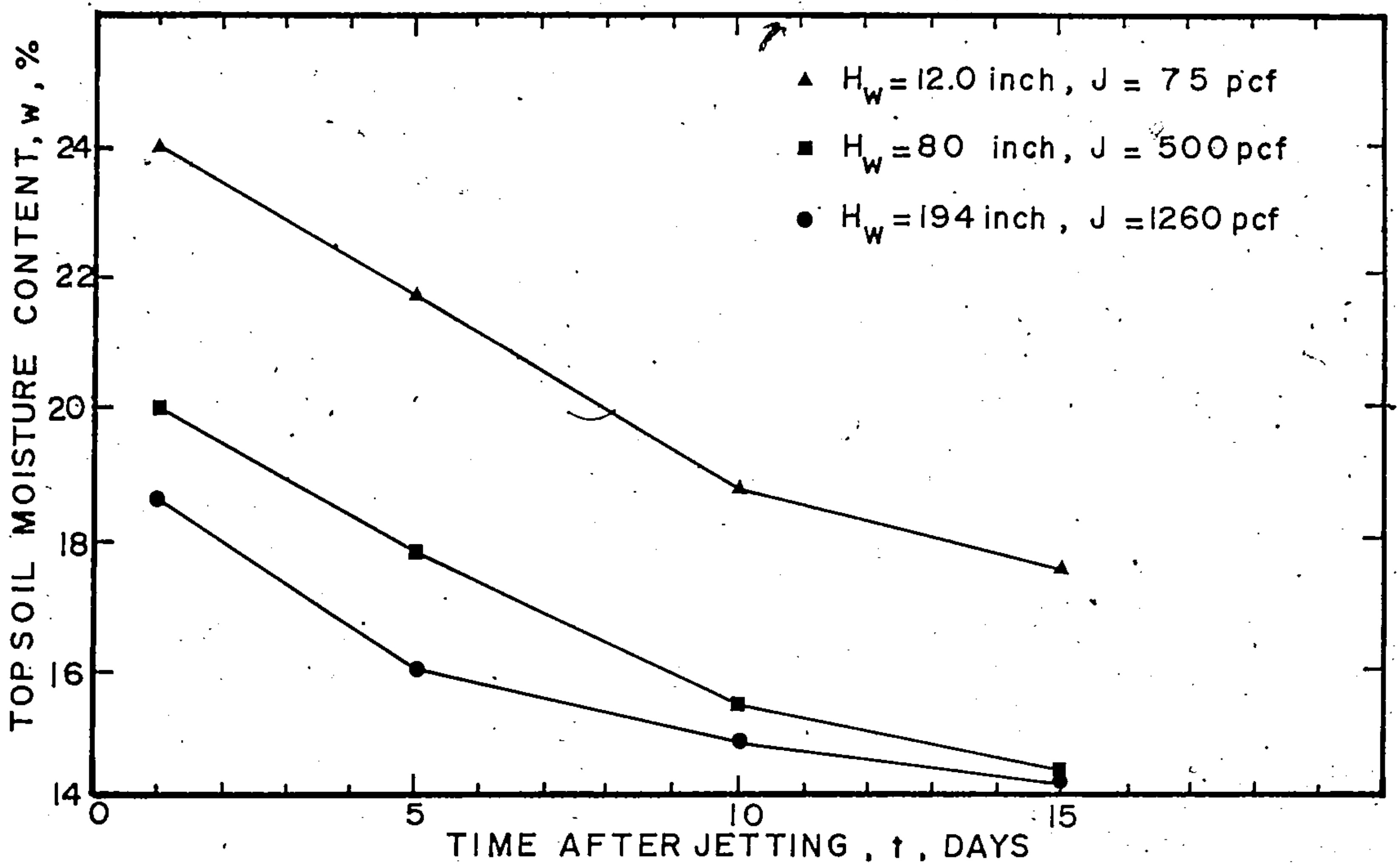


FIGURE 4.29 The Change in Top Soil Moisture Content with Time after Jetting for the Indicated Seepage Conditions

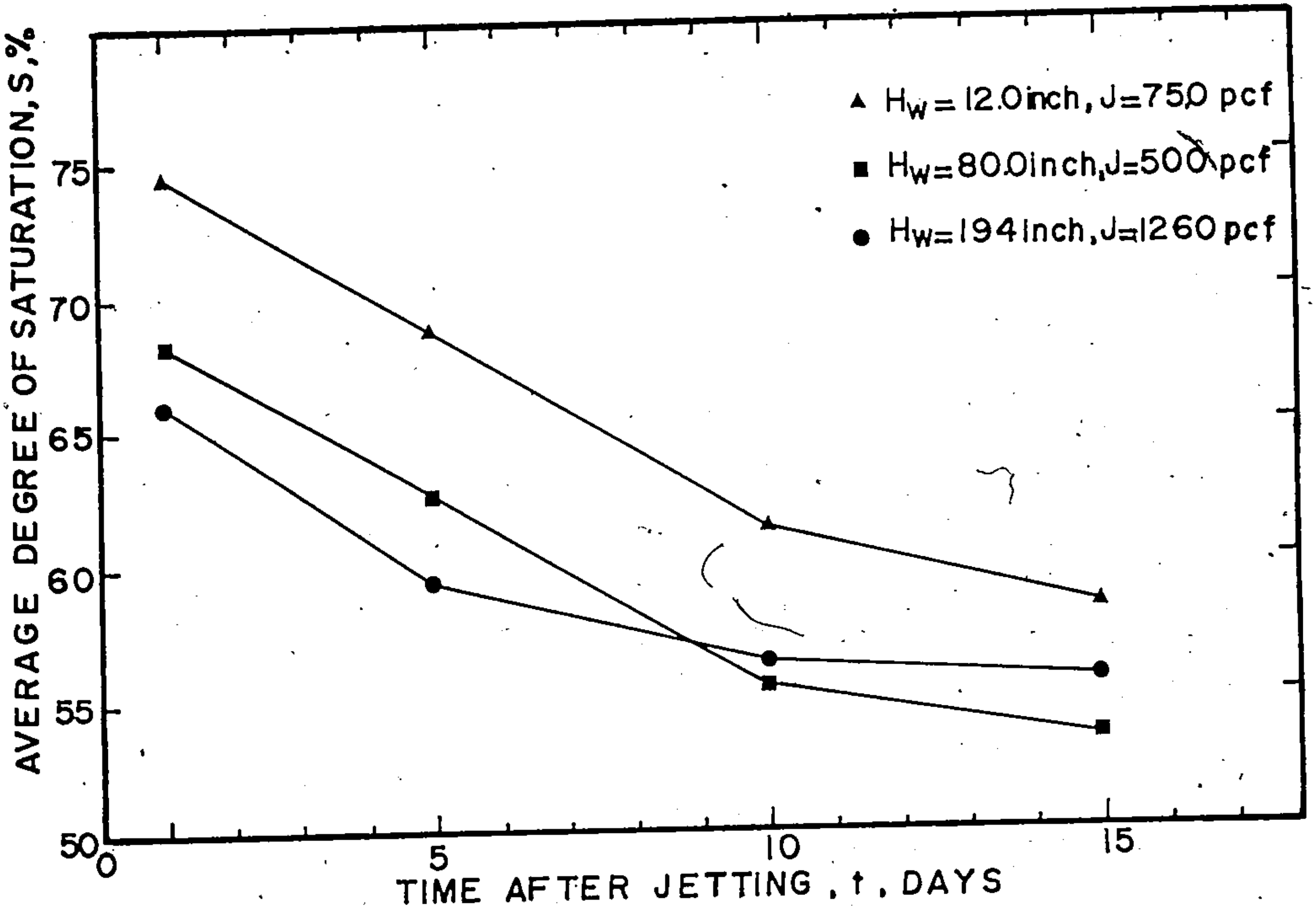


FIGURE 4.30 The Change in Average Degree of Saturation with Time after Jetting for the Indicated Seepage Conditions

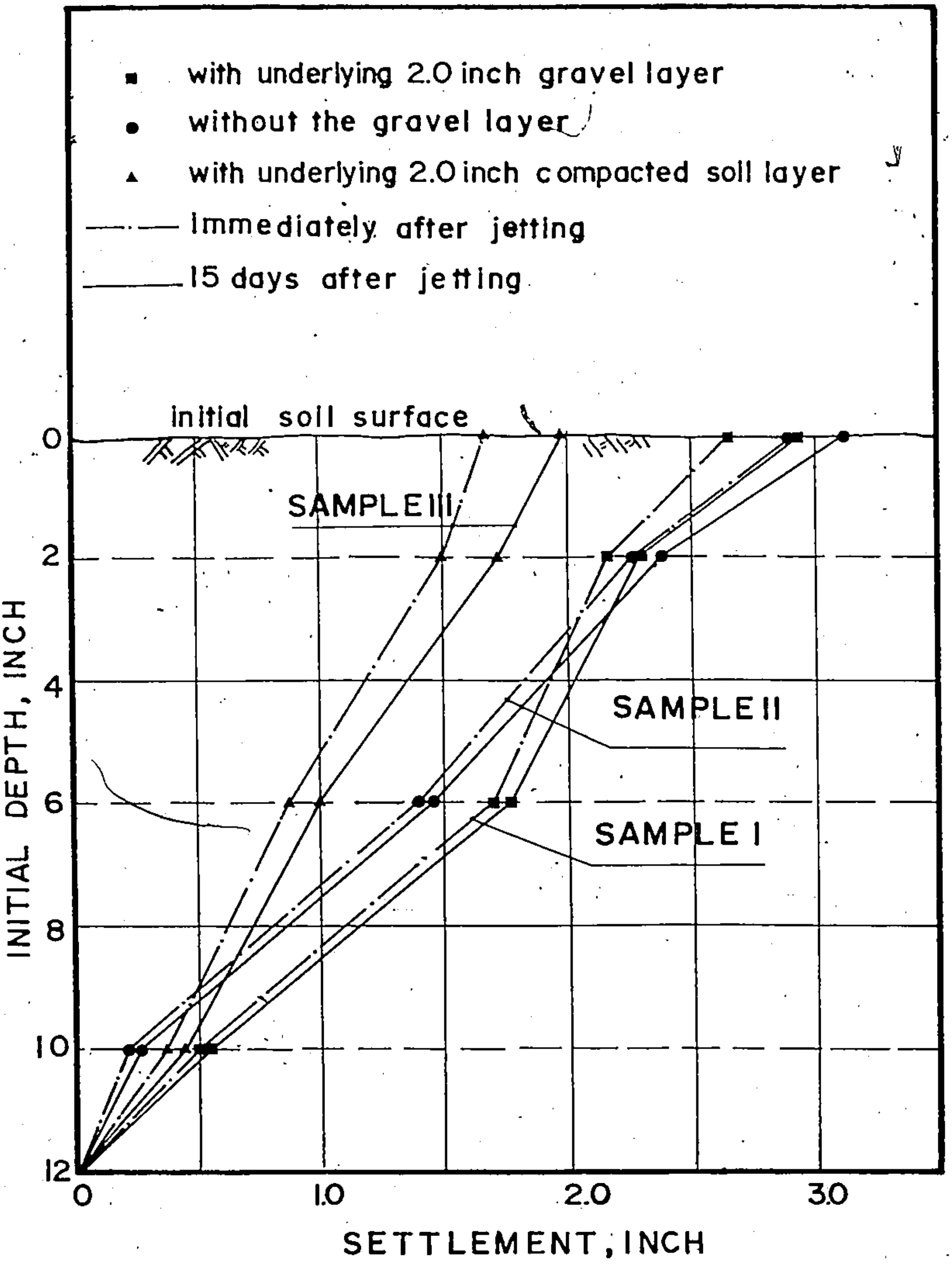


FIGURE 4.31 Settlement Profiles for Samples of Different Drainage Conditions

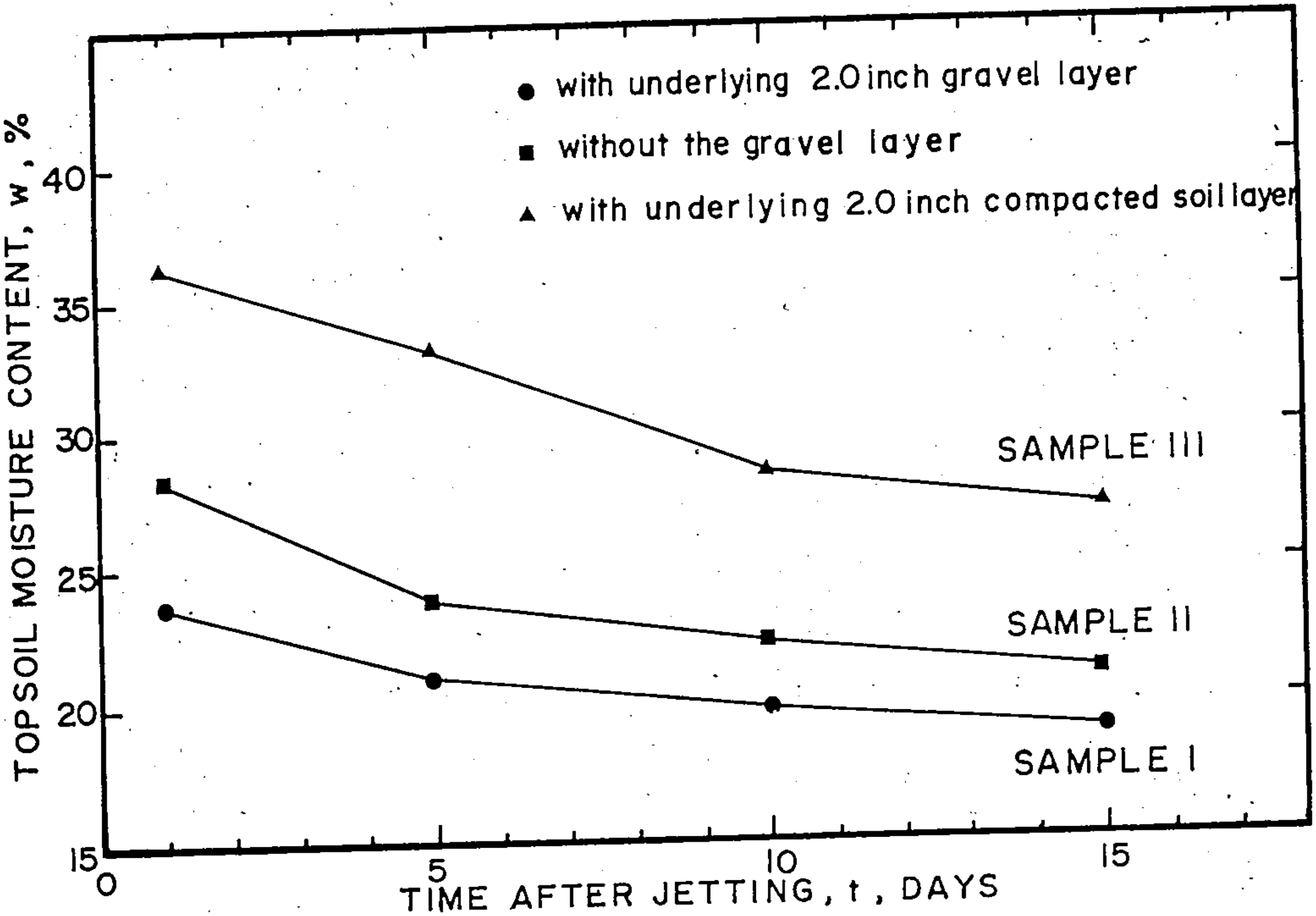


FIGURE 4.32 The Change in Top Soil Moisture Content with Time After Jetting for the Indicated Drainage Conditions

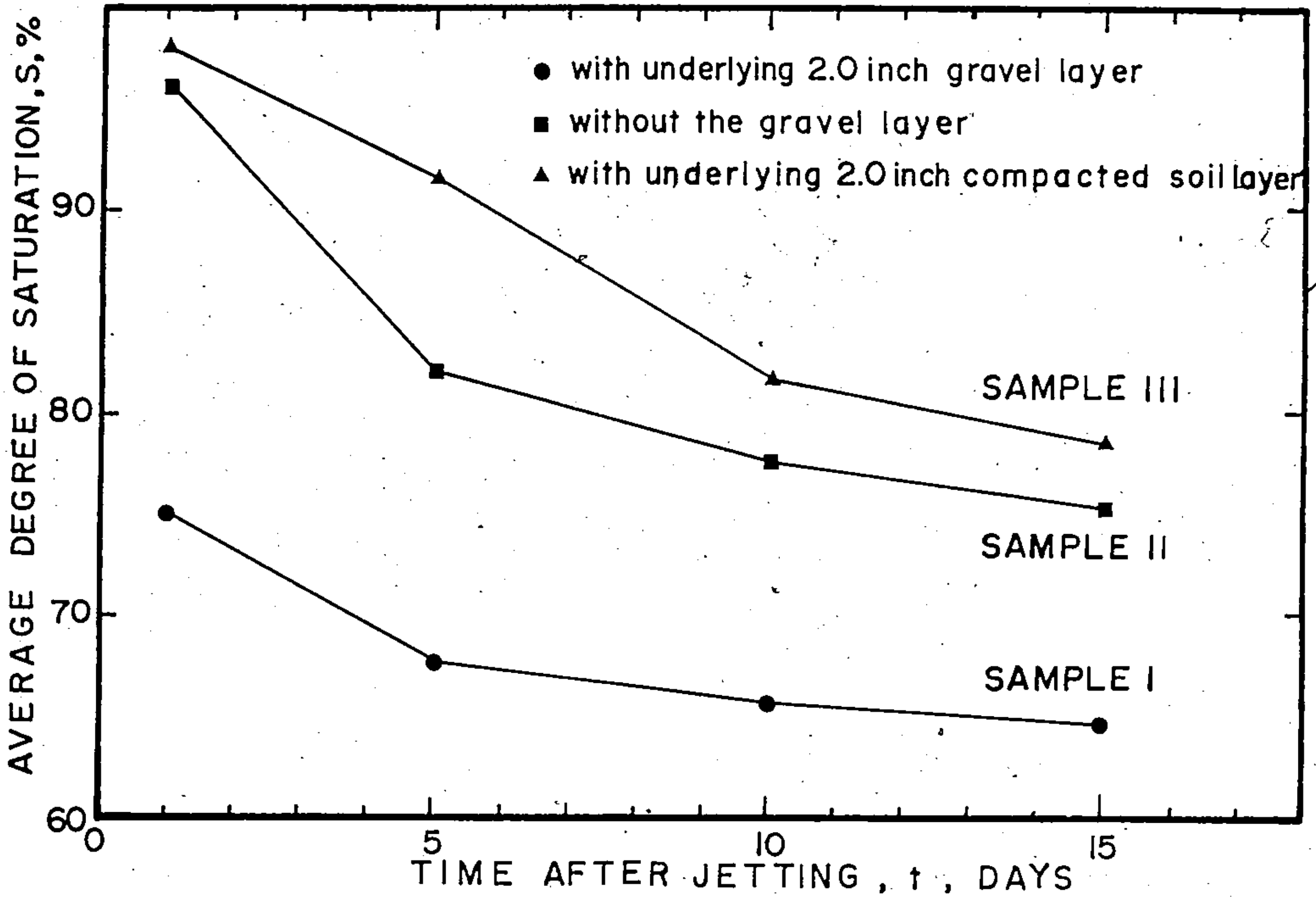


FIGURE 4.33 The Change in Average Degree of Saturation with Time After Jetting for the Indicated Drainage Conditions

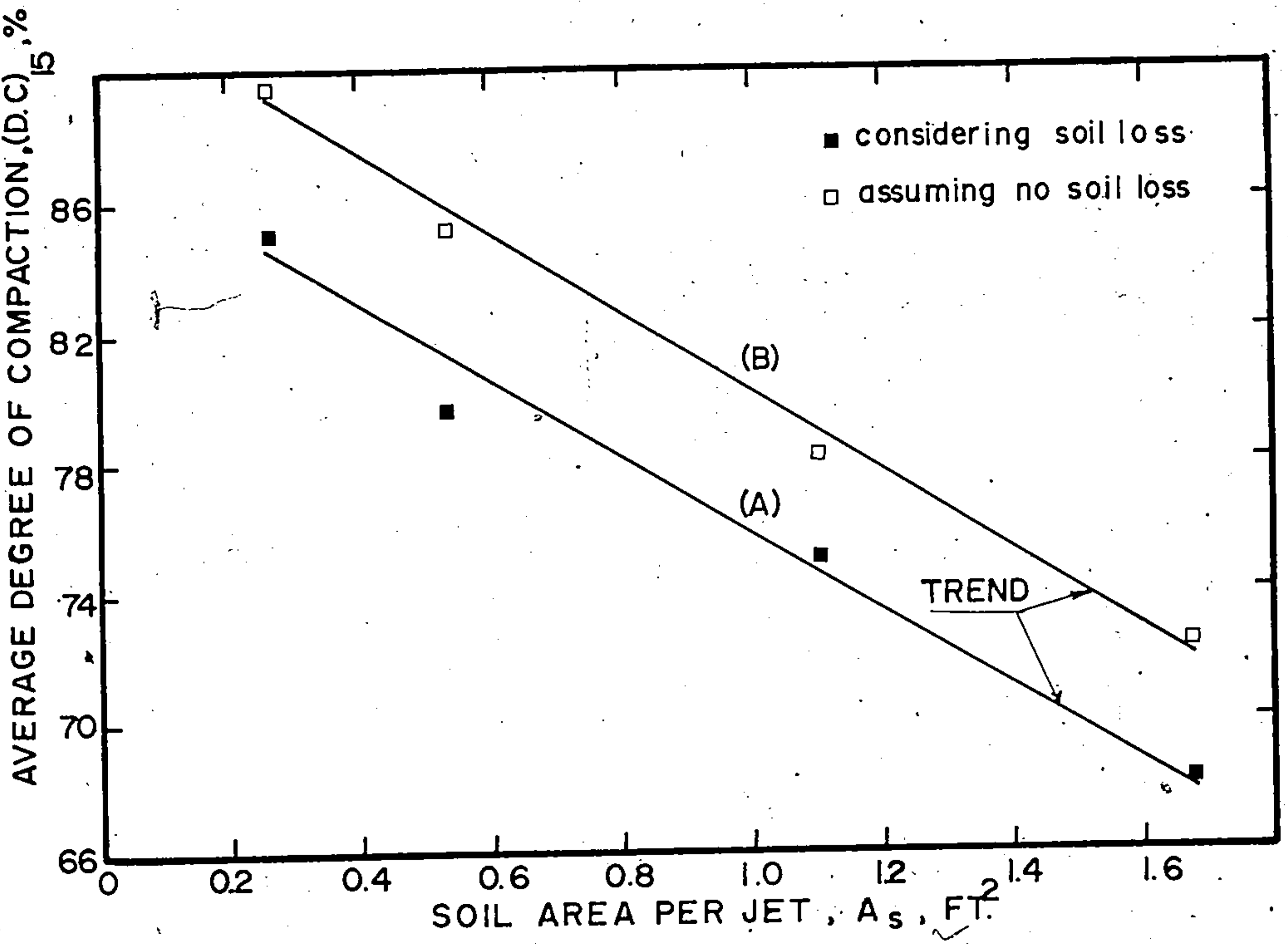


FIGURE 4.34 The Effect of Soil Area per Jet on the Average Degree of Compaction Fifteen Days after Jetting

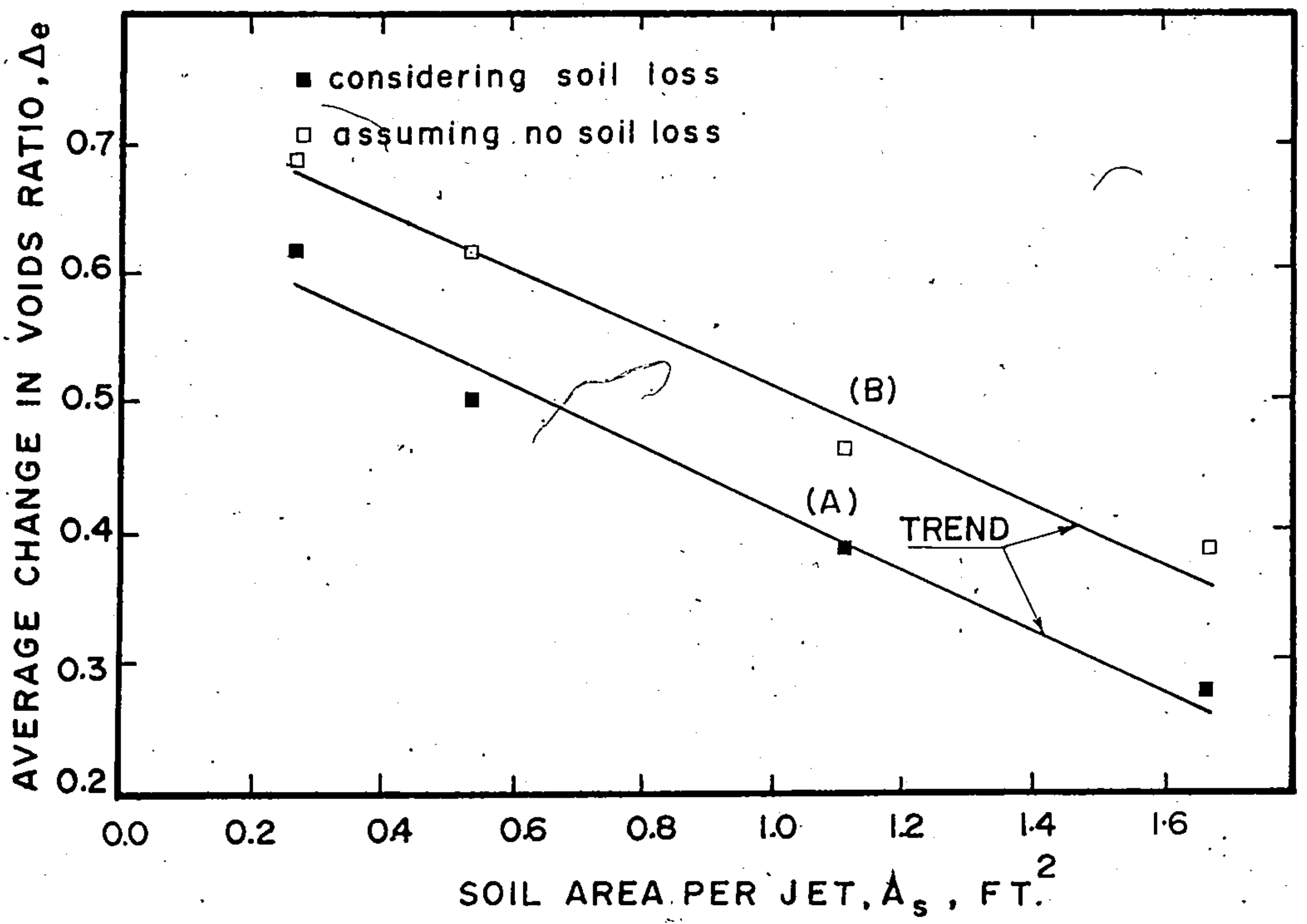


FIGURE 4.35 The Effect of Soil Area per Jet on the Average Change in Voids Ratio

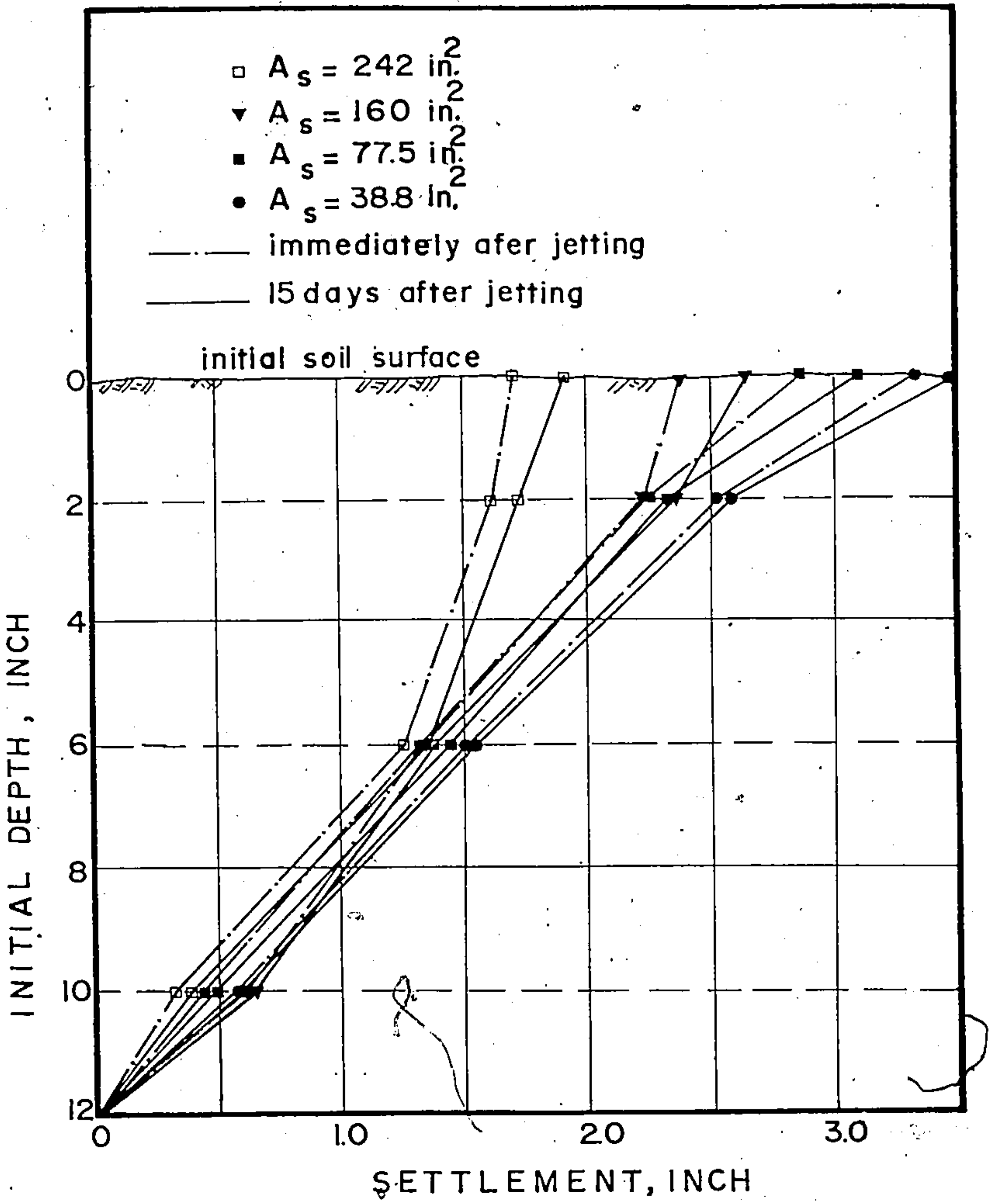


FIGURE 4.36 Settlement Profiles for Samples of Different Soil Areas per Jet

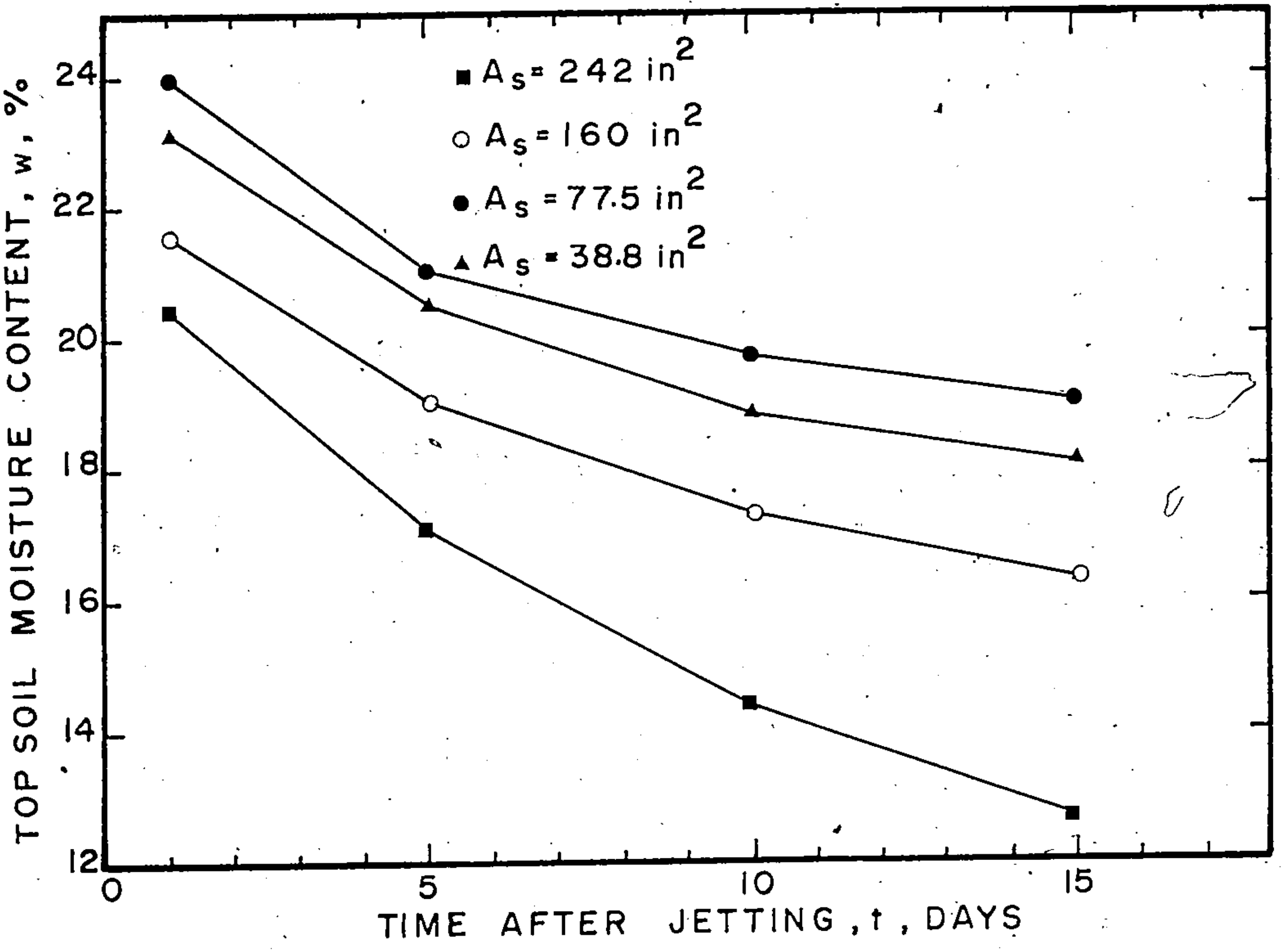


FIGURE 4.37 The Change in Top Soil Moisture Content with Time after Jetting for Samples of Different Soil Areas Per Jet

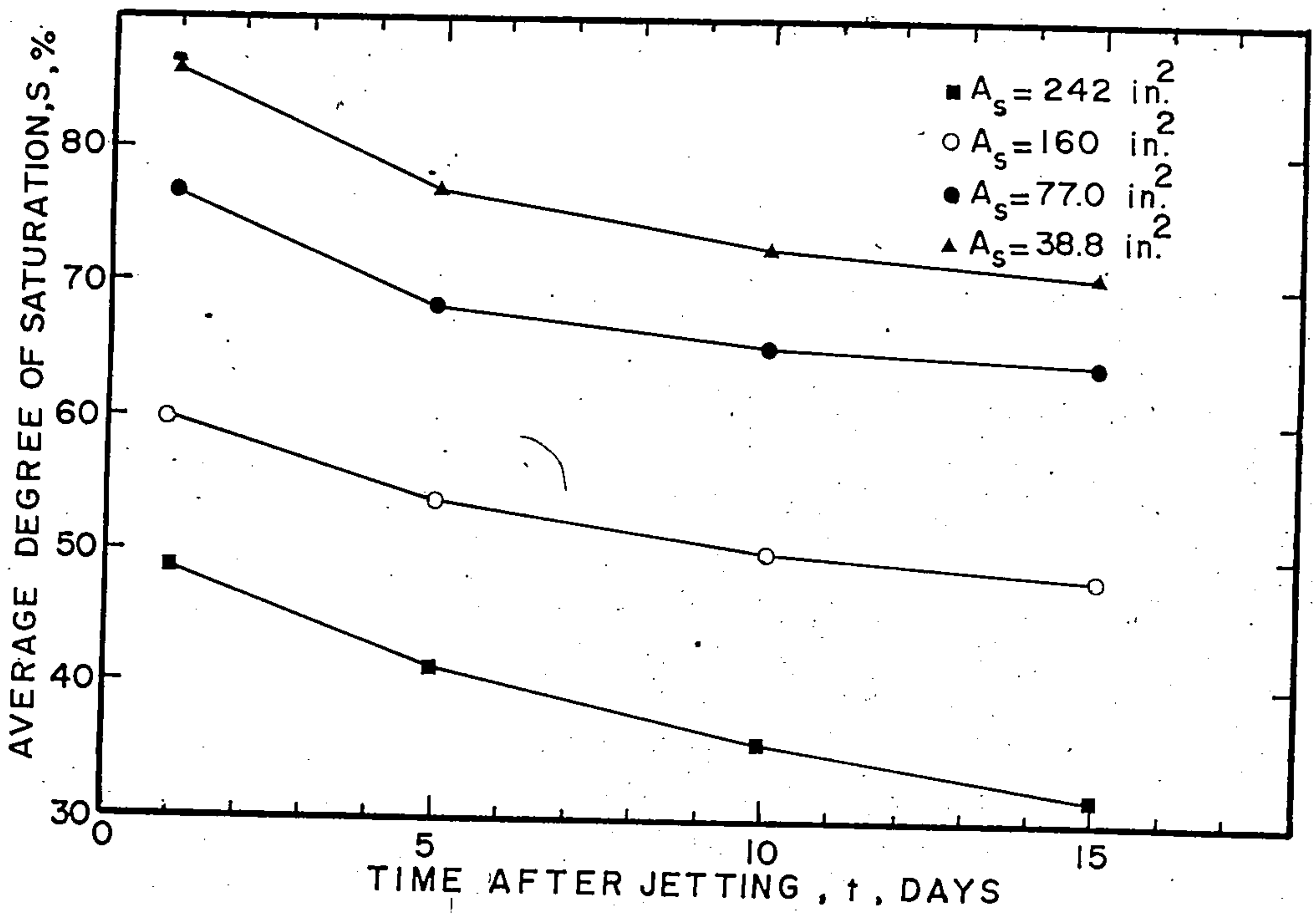


FIGURE 4.38 The Change in Average Degree of Saturation with Time after Jetting for Samples of Different Soil Areas per Jet

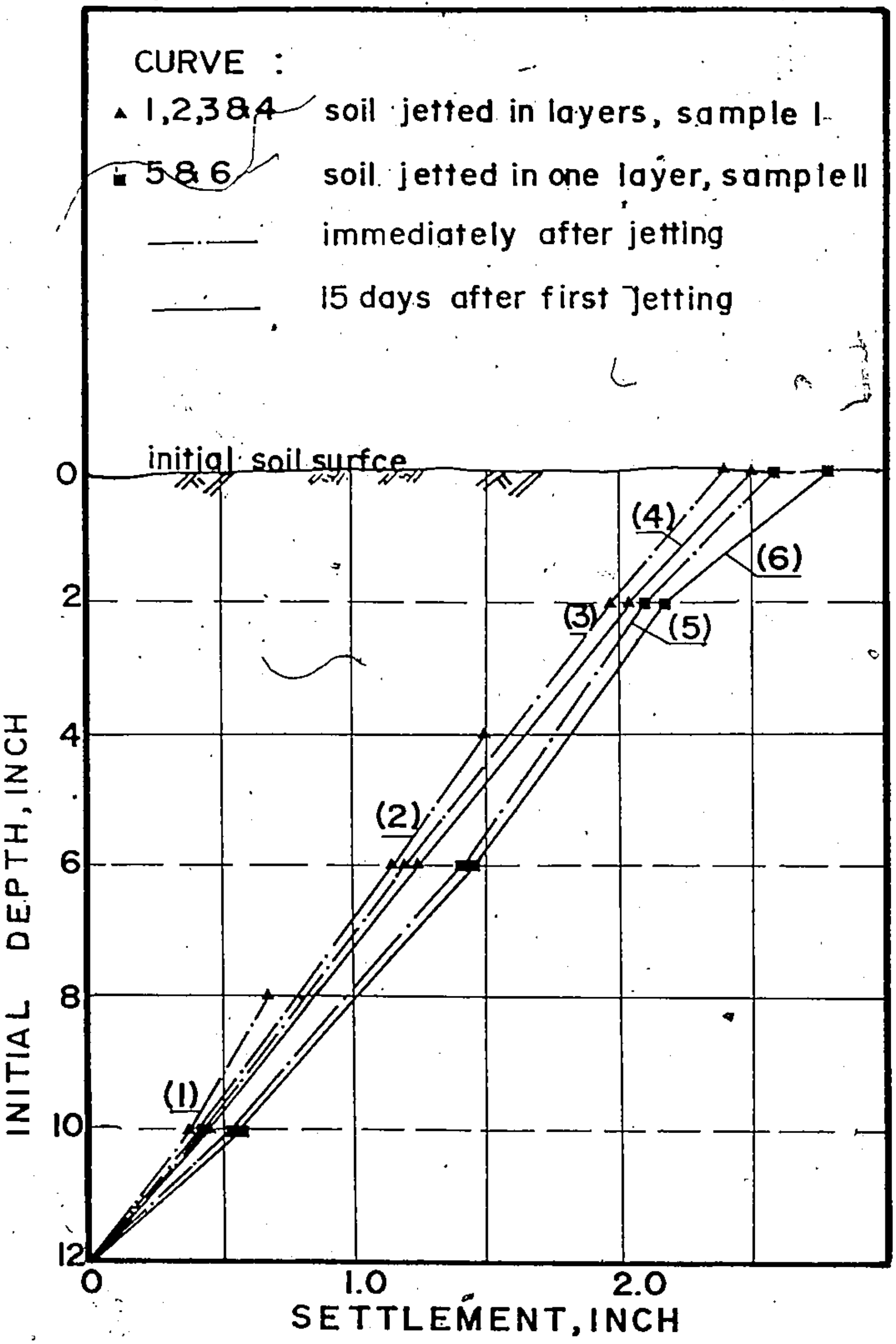


FIGURE 4.39 Settlement Profiles for Two Samples Showing the Effect of Jetting in Layers

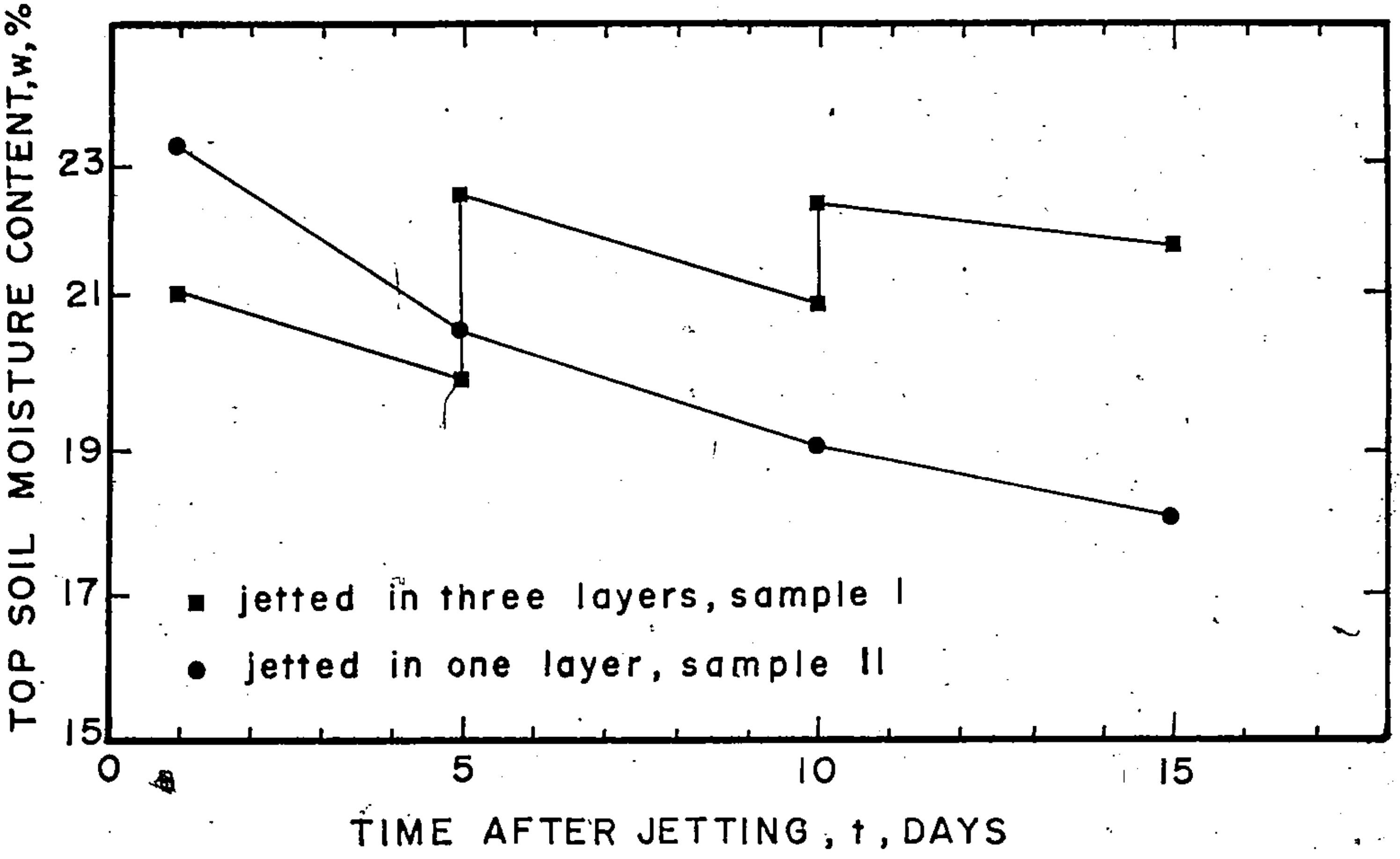


FIGURE 4.40 The Change in Top Soil Moisture Content with Time After Jetting for Indicated Conditions

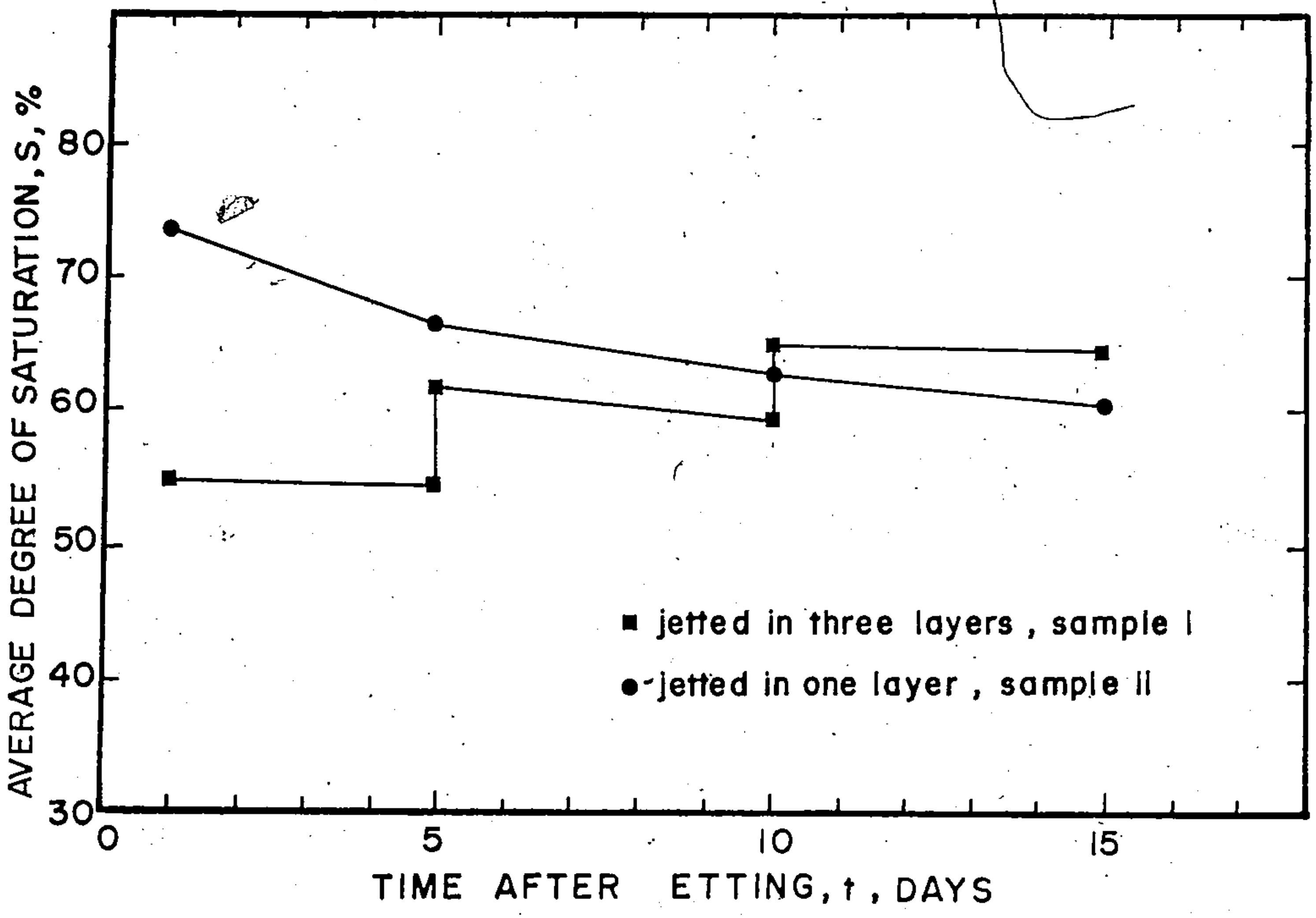


FIGURE 4.41 The Change in Average Degree of Saturation With Time After Jetting for Indicated Conditions

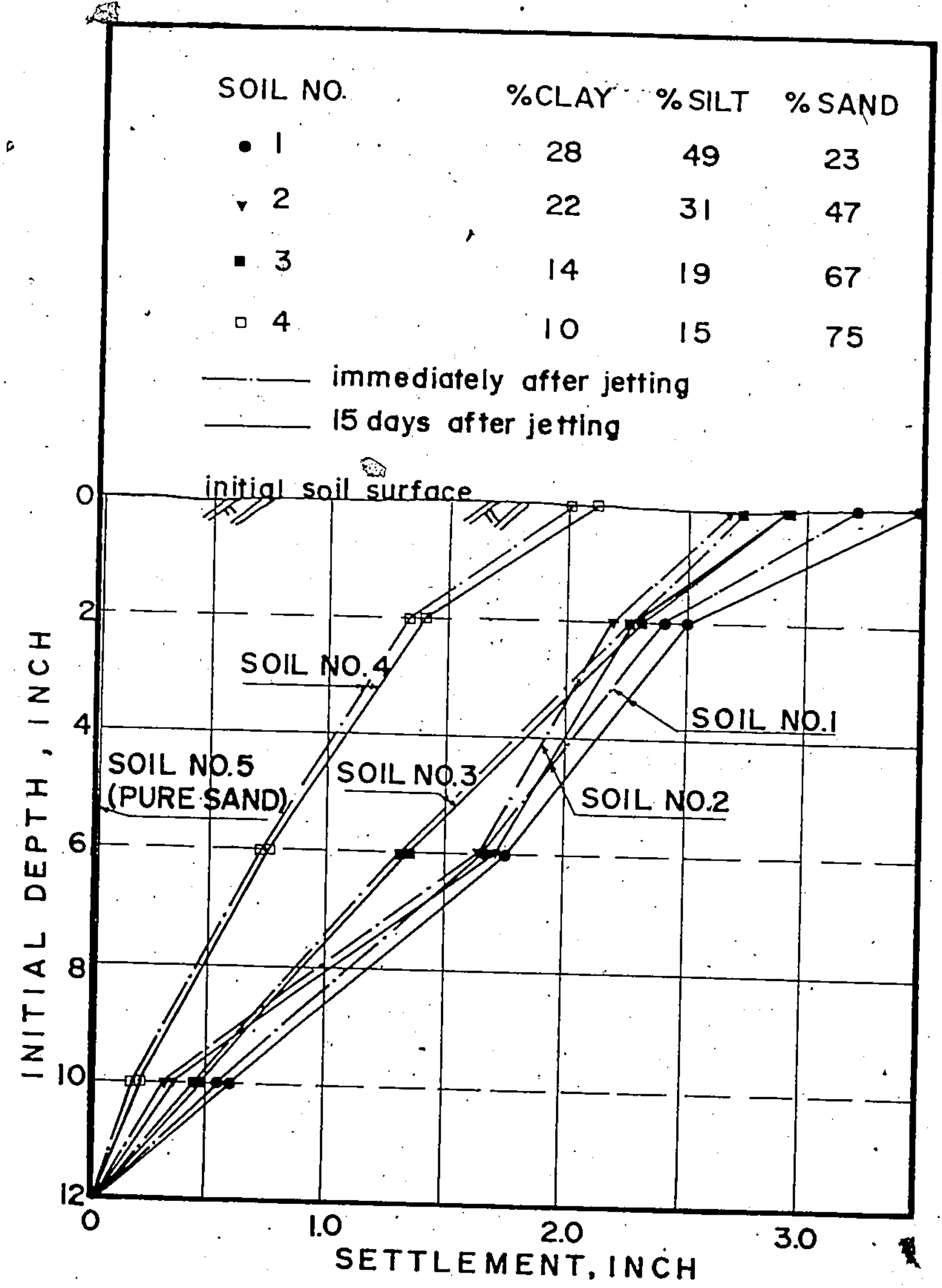


FIGURE 4.42 Settlement Profiles for Different Soil Types

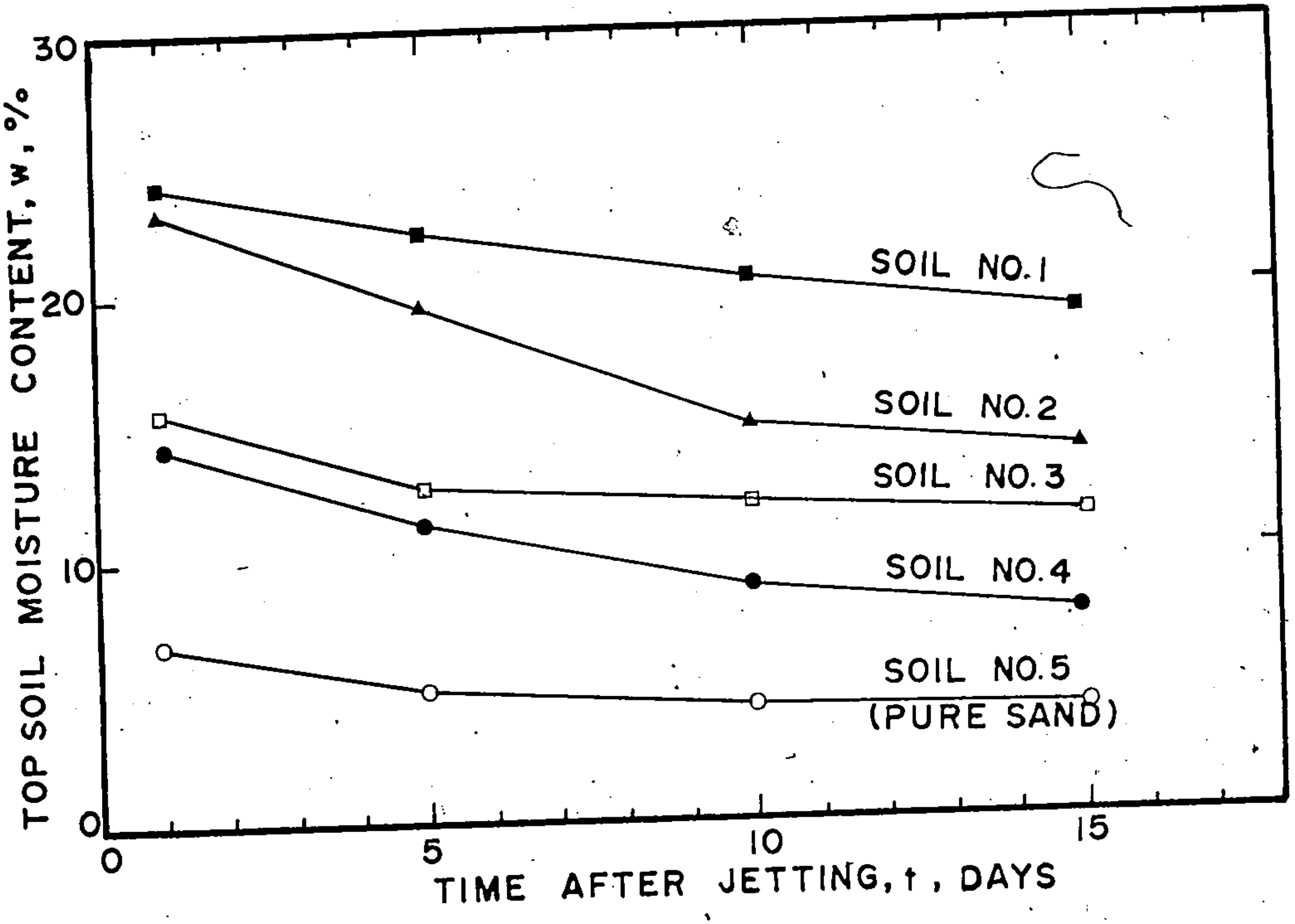


FIGURE 4.43 The Change in Top Soil Moisture Content with Time After Jetting for Different Soil Types

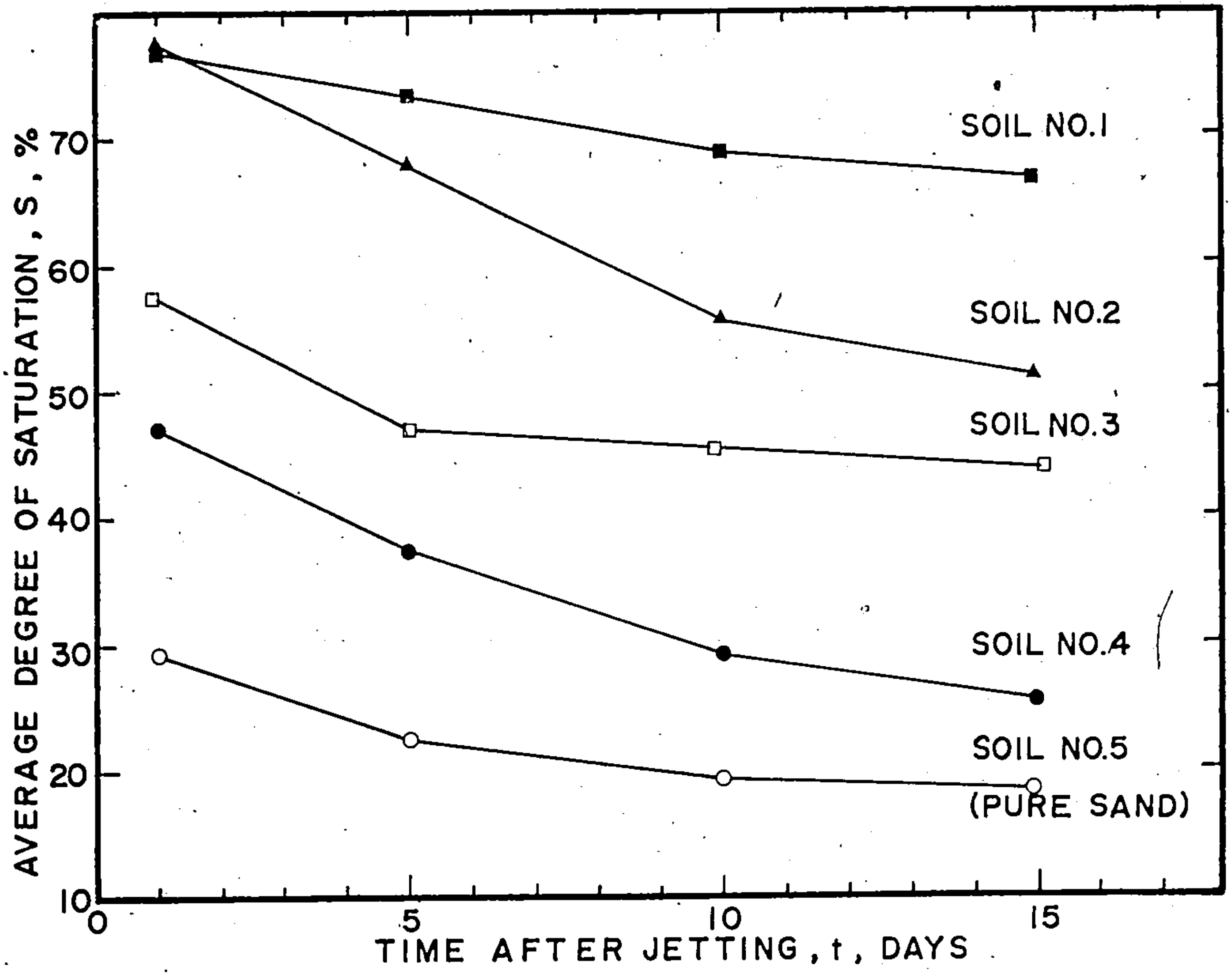


FIGURE 4.44 The Change in Average Degree of Saturation with Time After Jetting for Different Soil Types

APPENDIX C

TABLES

Soil No.		1	2	3	4	5
Composition	Clay %	28	22	14	10	0
	Silt %	49	31	19	15	0
	Sand %	23	47	67	75	100
Soil Classification (9)	Using triangular (Feret) Chart	Clay-Silt	Clay-Sand	Silty-Sand	Silty-Sand	Pure Sand
	Using Plasticity Chart *	CL	CL	SC-SM	SM	SP
Atterberg Limits	Liquid Limit (L.L.)	25.2%	24%	20%	18.8%	N/A
	Plasticity Index (P.I.)	11.2%	9.02%	5.45%	4.01%	N/A
Specific Gravity G_s		2.70	2.70	2.69	2.68	2.65

*C = Clay, M = Silt, S = Sand, and L = Low plasticity

TABLE 3.1 Soils Used in the Experimental Study

Lump Size and Gradation		Uniform D ≃ 1.0 inch	Uniform D ≃ 0.5 inch	Non-uniform Mixed
Soil No.		1	1	1
Sample Case		I	II	III
Initial Sample Height, H	inches (cm.)	12 (30)	12 (30)	12 (30)
Initial Soil Dry Density, γd_i	p.c.f. (gm/cm^3)	76.8 1.23	76.1 1.22	75.6 1.21
Initial Water Content, w_i	%	10	10	10
Water Jetting Pressure, P	p.s.i.	55	55	55
Time of Jetting, t_j	seconds	63	63	62
Applied Energy/Volume, Ea	$(lb.ft/ft^3) X 10^3$	3.53	3.53	3.47

TABLE 4.1 Initial Condition for Samples of Different Lump Size and Gradation

Depth (in.) \ Soil Case	Settlement Immediately After Jetting (inches)			Total Settlement 15 Days After Jetting (inches)			Net Settlement Occurred in 15 Days (inches)		
	I	II	III	I	II	III	I	II	III
0[a]	1.45	2.2	2.8	1.6	2.4	3.1	.15	.20	.30
2[b]	1.2	1.5	1.7	1.3	1.6	1.8	.10	.10	.10
4[c]	.96	1.27	1.32	1.05	1.35	1.4	.09	.085	.085
6[b]	.72	1.03	.93	.8	1.1	1.0	.08	.07	.07
8[c]	.54	.8	.54	.6	.85	.6	.065	.06	.06
10[b]	.35	.55	.15	.4	.6	.2	.05	.05	.05
12	0	0	0	0	0	0	0	0	0

[a] settlement at surface measured by lines inscribed on the plexiglass walls

[b] measured by settlement plates

[c] settlement obtained by interpolation

TABLE 4.2 Settlements for Samples of Different Lump Cases

Initial Conditions Initial Soil Height, H	inches (cm.)	4 (10)	8 (20)	12 (30)
Soil No.		1	1	1
Initial Dry Density, γd_i	p.c.f. (gm/cm^3)	72 1.15	72 1.15	72 1.15
Initial Voids Ratio, e_i		1.34	1.34	1.34
Initial Water Content, w_i	%	10.63	10.63	10.63
Jetting Water Pressure, P	p.s.i.	55	55	55
Time of Jetting, t_j	seconds	23	43	62
Applied Energy/Vol., Ea	(lb.ft/ft^3) X 10^3	3.86	3.6	3.47

TABLE 4.3 Initial Conditions for Samples of Different Soil Heights

Elev. (in.) \ Initial Height (inches)	Settlement Immediately After Jetting & Seepage (inches)			Total Settlement 15 Days After Jetting (inches)			Net Settlement Occurred in 15 Days (inches)		
	4	8	12	4	8	12	4	8	12
12			3.35[b]			3.65[b]			.35
10			2.4[a]			2.5[a]			.10
8		1.52[b]	2.0[c]		1.73[b]	2.1[c]		.21	.10
6		1.3[a]	1.6[a]		1.4[a]	1.7[a]		.10	.10
4	.67[b]	.9[c]	1.08[c]	.79[b]	.98[c]	1.15[c]	.12	.08	.07
2	.45[a]	.5[a]	.55[a]	.5[a]	.55[a]	.6[a]	.05	.05	.05
0	0	0	0	0	0	0	0	0	0

[a] measured using settlement plates

[b] surface settlements observed using the inscribed lines of the apparatus walls

[c] settlement obtained by interpolation

TABLE 4.4 Settlements For Samples of Different Heights

Initial Conditions / Jetting Water Pressure, P	p.s.i.	20	40	55
Soil No.		1	1	1
Initial Soil Height, H	inches (cm.)	12 (30)	12 (30)	12 (30)
Initial Dry Density, γd_i	p.c.f. (gm/cm^3)	75 (1.2)	75 (1.2)	75 (1.2)
Initial Voids Ratio, e_i		1.25	1.25	1.25
Initial Water Content, w_i	%	11.34	11.34	11.34
Time of Jetting, t_j	seconds	103	70	58
Applied Energy/Unit Vol., Ea	(lb.ft/ft^3) X 10^3	1.18	2.18	3.3

TABLE 4.5 Initial Conditions for Samples Jetted Under Different Water Pressures

Depth (in.) \ Water Pressure P (psi)	Settlement Immediately After Jetting (inches)			Total Settlement 15 Days After Jetting (inches)			Net Settlement Occurred in 15 Days (inches)		
	20	40	55	20	40	55	20	40	55
0[b]	1.65	2.25	2.50	1.80	2.4	2.75	.15	.15	.25
2[a]	1.60	1.90	1.90	1.70	2.0	2.0	.10	.10	.10
4[c]	1.40	1.60	1.77	1.50	1.70	1.85	.10	.10	.08
6[a]	1.20	1.30	1.60	1.30	1.40	1.70	.10	.10	.10
8[c]	.82	.82	1.04	.90	.90	1.10	.08	.08	.06
10[a]	.47	.47	.50	.50	.50	.55	.03	.03	.05
12	0	0	0	0	0	0	0	0	0

[a] measured using settlement plates

[b] surface settlements observed using the lines inscribed on the walls of the apparatus

[c] settlement obtained by interpolation

TABLE 4.6 Settlements for Samples Jetted Under Different Water Pressures

Initial Conditions / Number of Jettings, N		1	2	3
Soil No.		1	1	1
Sample No.		I	II	III
Initial Soil Height, H	inches (cm.)	12 (30)	12 (30)	12 (30)
Initial Dry Density, γd_i	p.c.f. (gm/cm^3)	75 1.2	75 1.2	75 1.2
Initial Voids Ratio, e_i		1.25	1.25	1.25
Initial Water Content, w_i	%	10.5	10.5	10.5
Jetting Water Pressure, P	p.s.i.	55	55	55
Time of Jetting, t_j	seconds	60	61,40	60,39,40
Total Applied Energy/Unit Vol., Ea	(lb.ft/ft^3) x 10^3	3.4	5.66	7.78

TABLE 4.7 Initial Conditions for the Study of Rejetting the Soil

Depth (in.) \ Sample No.	Settlement Immediately After Jetting (inches)			Total Settlement 15 Days After Jetting (inches)			Net Settlement Occurred in 15 Days (inches)		
	I	II	III	I	II	III	I	II	III
0[b]	2.75	2.65	2.9	2.85	3.44	3.74	.10	.79	.84
2[a]	2.2	2.00	2.3	2.25	2.4	2.81	.05	.40	.51
4[c]	1.9	1.72	2.00	1.93	1.95	2.31	.03	.22	.31
6[a]	1.6	1.43	1.70	1.65	1.50	1.80	.05	.07	.10
8[c]	1.00	0.94	1.10	1.05	1.00	1.18	.05	.06	.08
10[a]	.40	.45	.50	.45	.50	.55	.05	.05	.05
12	0	0	0	0	0	0	0	0	0

[a] measured using settlement plates

[b] observed using the lines on the apparatus walls

[c] settlement obtained by interpolation

TABLE 4.8 Settlements for Samples with Different Rejetting Conditions

Initial Conditions	Seepage Force, J	p.c.f. (N/cm^3)	75 (11.8)	500 (78.4)	1260 (198)
Initial Soil Height, H		inches (cm.)	12 (30)	12 (30)	12 (30)
Soil No.			1	1	1
Initial Dry Density, γd_i		p.c.f. (gm/cm^3)	72 1.15	72 1.15	72 1.15
Initial Voids Ratio, e_i			1.34	1.34	1.34
Initial Water Content, w_i		%	11.8	11.8	11.8
Jetting Water Pressure, P		p.s.i.	55	55	55
Time of Jetting, t_j		seconds	63	65	64
Applied Energy/unit Vol., Ea		(lb ft/ft^3) X 10^3	3.53	3.64	3.58

TABLE 4.9 Initial Conditions for the Study of the Effect of Seepage Force

Sample No.	I	II	III
Drainage Conditions	With Underlying 2 inch gravel layer	Without the gravel layer	With underlying 2 inch compacted soil layer
Initial Dry Density, γd_i p.c.f. (gm/cm^3)	75 (1.2)	75 (1.2)	75 (1.2)
Soil No.	[illegible]	1	1
Initial Soil Height, H inches (cm)	12 (30)	12 (30)	12 (30)
Initial Voids Ratio, e_i	1.25	1.25	1.25
Initial Water Content, w_i %	13.75	13.75	14
Time of Jetting, t_j seconds	66	61	63
Applied Energy/ Unit Vol., Ea (lb/ft/ft^3)x10^3	3.69	3.4	3.53

TABLE 4.10 Initial Conditions for Samples of Different Drainage Conditions

Sample		I	II	III
$(D.C)_{15}\%$	Case A	80	81.5	74
	Case B	85	86	76.2
Δe	Case A	.45	.50	.32
	Case B	.56	.59	.38

TABLE 4.11 $(D.C)_{15}$ and Δe Values for Samples of Different Drainage Conditions

Depth (in.) / Sample	Settlement Immediately After Jetting (inches)			Total Settlement 15 Days After Jetting (inches)			Net Settlement Occurred in 15 Days		
	I	II	III	I	II	III	I	II	III
0[a]	2.91	2.65	1.66	3.11	2.95	1.97	.20	.30	.31
2[b]	2.25	2.15	1.5	2.35	2.27	1.72	.10	.12	.22
4[c]	1.84	1.93	1.19	1.92	2.02	1.36	.08	.09	.17
6[b]	1.42	1.70	.87	1.48	1.76	1.0	.06	.06	.13
8[c]	.82	1.11	.62	.87	1.16	.73	.05	.05	.11
10[b]	.22	.52	.36	.25	.55	.45	.03	.03	.09
12	0	0	0	0	0	0	0	0	0

[a] observed using the lines on the apparatus walls

[b] measured using settlement plates

[c] settlement obtained by interpolation

TABLE 4.12 Settlements for Samples of Different Drainage Conditions

Soil Area per Jet, A_s	sq. feet (cm^2)	1.68 (1560)	1.11 (1030)	.54 (500)	.27 (250)
Initial Soil Height, H	inches (cm.)	12 (30)	12 (30)	12 (30)	12 (30)
Soil No.		1	1	1	1
Initial Dry Density, γd_i	p.c.f. gm/cm^3	73 1.17	73 1.17	73 1.17	73 1.17
Initial Voids Ratio, e_i		1.31	1.31	1.31	1.31
Initial Water Content, w_i	%	12	12.01	11.8	12.3
Jetting Water Pressure, P	p.s.i.	55	55	55	55
Time of Jetting, t_j	seconds	210	140	64	34
Applied Energy/Unit Vol., Ea	$(lb.ft/ft^3) \times 10^3$	3.78	3.82	3.6	3.88

TABLE 4.13 Initial Conditions for Samples of Different Soil Area Per Jet

Depth (in.) \ Soil Area (sq. feet)	Settlement Immediately After Jetting (inches)				Total Settlement 15 Days After Jetting (inches)				Net Settlement Occurred in 15 Days			
	1.68	1.11	.54	.27	1.68	1.11	.54	.27	1.68	1.11	.54	.27
0^b	1.71	2.38	2.90	3.35	1.92	2.67	3.15	3.54	.21	.29	.25	.19
2^a	1.62	2.25	2.25	2.56	1.75	2.38	2.35	2.60	.13	.13	.10	.04
4^c	1.44	1.80	1.82	2.05	1.56	1.89	1.90	2.09	.12	.09	.08	.04
6^a	1.25	1.34	1.38	1.54	1.37	1.40	1.45	1.57	.12	.06	.07	.03
8^c	0.78	0.99	0.91	1.07	0.88	1.03	0.98	1.09	.10	.04	.07	.02
10^a	0.34	0.65	0.45	.606	0.39	0.66	0.50	.612	.05	.01	.05	.006
12	0	0	0	0	0	0	0	0	0	0	0	0

[a] measured by settlement plates

[b] observed by lines on apparatus walls

[c] settlement obtained by interpolation

TABLE 4.14 Settlements for Samples of Different Soil Area Per Jet

Sample No.		I	II
Number of Layers		3	1
Initial Soil Height, H	inches (cm.)	4* (10)*	12 30
Soil No.		1	1
Initial Dry Density, γd_i	p.c.f. gm/cm^3	73* 1.17*	73
Initial Voids Ratio, e_i		1.31*	1.31
Initial Water Content, w_i	%	13*	13
Jetting Water Pressure, P	p.s.i.	55	55
Time of Jetting, t_j	seconds	29,38,48	59
Applied Energy/Unit Vol., Ea	lb/ft/ft^{3}x 10^3	4.8,3.2,2.7	3.3

*for each layer

TABLE 4.15 Initial Conditions for the Study of the Effect of Jetting the Soil in Layers

Sample		I	II
$D.C_{15}$	Case A	75%	79%
	Case B	79%	81.3%
Δe	Case A	.40	.50
	Case B	.50	.55

N.B. Case A considering soil loss
Case B assuming no soil loss

Sample I jetted in three layers
Sample II jetted in one layer

TABLE 4.16 $D.C_{15}$ and Δe Values for the Study of Jetting in Layers

Soil No.		1	2	3	4	5 (sand)
Composition:						
Clay %		28	22	14	10	0
Silt %		49	31	19	15	0
Sand %		23	47	67	75	100
Initial Soil Height, H	inches (cm.)	12 (30)	12 (30)	12 (30)	12 (30)	12 (30)
Initial Dry Density, γd_i	p.c.f. gm/cm^3	72 (1.15)	75 (1.2)	78.6 (1.26)	83.6 (1.34)	108 (1.73)
Specific Gravity, G_s		2.7	2.7	2.69	2.68	2.65
Initial Voids Ratio, e_i		1.35	1.23	1.13	1.0	.53
Initial Water Content, w_i	%	12.63	12.77	11.0	11.3	0.20
Jetting Water Pressure, P	p.s.i.	55	55	55	55	55
Time of Jetting, t_j	seconds	60	63	67	61	63
Applied Energy/Unit Vol., Ea	(lb.ft/ft^3) X 10^3	3.36	3.53	3.75	3.42	3.53

TABLE 4.17 Initial Conditions for the Study of the Effect of Soil Type

Soil No.		1	2	3	4	5 (pure sand)
Composition:						
Clay %		28	22	14	10	0
Silt %		49	31	19	15	0
Sand %		23	47	67	75	100
γd_{15}:						
Case (A) (considering soil loss)	gm/cm³	1.51	1.55	1.58	1.49	1.70
	p.c.f.	94	96.7	98.6	93	106.1
Case (B) (assuming no soil loss)	gm/cm³	1.64	1.61	1.68	1.64	1.73
	p.c.f.	102	100.5	104.8	102	108
$(D.C)_{15}$ (%)						
Based on $\gamma d_{max.}$						
Case A		80	78	77.8	72	88
Case B		86.8	80.7	82.8	79.2	90
Based on Proctor γ_d at identical w						
Case A		91	86.6	83	75	95
Case B		98.8	90.2	88.4	82.4	97
$\gamma d_{15}/\gamma d_{init.}$						
Case A		1.31	1.28	1.25	1.11	.98
Case B		1.43	1.33	1.33	1.22	1.00
Δe						
Case A		0.56	0.49	0.43	.20	≈0
Case B		0.70	0.56	0.53	0.37	=0

TABLE 4.18 Results Obtained from the Study of the Effect of Soil Type

APPENDIX D

SAMPLE CALCULATIONS

SAMPLE CALCULATIONS

I Degree of Compaction (Sample III, Section 4.2.1)

1. Case A

Wet weight of soil sample, fifteen days after jetting = 20.333 kg

Total height of soil sample (using the lines on the sides of the apparatus) = 22.0 cm.

Total volume of soil sample $= 20\text{x}25\text{x}22 = 11{,}000.0\ \text{cm}^3$

Bulk density, fifteen days after jetting $= \dfrac{20.333\text{x}10^3}{11{,}000} = 1.848\ \text{gm/cm}^3$

Average moisture content of soil sample, w = 23.5%

Dry density, γd_{15} $= \dfrac{\gamma\ \text{bulk}}{1 + w} = \dfrac{1.848}{1.235} = 1.496\ \text{gm/cm}^3$

Average voids ratio, $(e_{15})_A$ $= \dfrac{Gs}{\gamma d_{15}} - 1 = \dfrac{2.7}{1.496} - 1 = .80$

Degree of compaction, $(\text{D.C})_{15}$ $= \dfrac{\gamma d_{15}}{\gamma d_{max}} = \dfrac{1.496}{1.89} = 79\%$

2. Case B

Initial wet weight of soil = 19.767 Kgm

Initial moisture weight, w_i = 10%

Initial dry weight of soil $= \dfrac{19.767}{1+.10} = 17.97$ Kgm

γd_{15}, based on initial soil weight $= \dfrac{17.97\text{x}10^3}{11{,}000} = 1.63\ \text{gm/cm}^3$

Average voids ratio, $(e_{15})_B$ $= \dfrac{2.7}{1.63} - 1 = .66$

Degree of compaction $(D.C)_{15'}$
Case B $= \frac{1.63}{1.89} = 86\%$

II Average Change in Voids Ratio, Δe

Initial soil height $= 30$ cm.

Initial soil volume $= 20 \times 25 \times 30 = 15{,}000 \text{ cm}^3$

Initial bulk weight $= \frac{19.767}{15{,}000} = 1.318 \text{ gm/cm}^3$

Initial dry weight, $\gamma d_i = \frac{1.318}{1+.10} = 1.2 \text{ gm/cm}^3$

Initial voids ratio, $e_i = \frac{2.7}{1.2} - 1 = 1.25$

Δe, Case A $= e_i - (e_{15})_A = 1.25 - .80 = .45$

Δe, Case B $= e_i - (e_{15})_B = 1.25 - .66 = .59$

Check on γd_{15}, Case A by sampler method

Sampler diameter $= 1$ inch $= 2.54$ cm.

Area of sampler (samples) $= \frac{\Pi\ (2.54)^2}{4} = 5 \text{ cm}^2$

Weight of sampler empty $= 720$ gm.

Sample No.	1	2	3	4	5	6
Height of sample (cm)	5.0	6.2	7.3	4.8	5.1	6.2
Weight of samples and sampler	765.5	777.6	787.2	764.4	763.4	779
Weight of samples	45.5	57.6	67.2	44.4	43.4	59
γ bulk (gm/cm^3)	1.82	1.86	1.84	1.85	1.7	1.9

Average γ bulk $= 1.83 \text{ gm/cm}^3$

Average dry density $\gamma d_{15} = 1.48 \text{ gm/cm}^3$

III Applied Energy Per Unit Volume due to Jetting, Ea

Ea = applied energy per unit volume

HP = applied horse power

He = water head at exit

Q = water discharge at exit

γ_w = 62.4 lb/ft^3

P = jetting water pressure

V = jetting water velocity at exit

cv = velocity coefficient (.9 - .95)

V_t = total volume of soil

Applied energy = HP x 550 x t_j (lb.ft)

$$HP = \frac{\gamma w\ Q\ He}{550}$$

Q = 7.5 lit/min (experimentally) at P = 55 p.s.i.

$$= \frac{7.5 \times 1000}{(30.48)^2 \times 60} = .0044 \text{ cfs}$$

$$He = \frac{V^2}{2g}$$

$$V = c_v \sqrt{2g(P/\gamma)}$$

$\therefore$ He = $c_v{}^2$ P/γ (assuming no losses in the pipe, c_v = .925)

at P = 55 p.s.i. i.e. = 55 x (12)^2 = 7920 lb/ft^2

$$He = (.925)^2 \times \frac{7920}{62.4} = 108.6 \text{ ft.}$$

$$HP = \frac{\gamma Q He}{550} = \frac{62.4 \times .0044 \times 108.6}{550} = .054 \text{ HP}$$

Applied energy = .054 xt_j(sec) x 550= 29.7 t_j (lb.ft)

for Sample III, Sec. 4.2.1 t_j = 62 seconds

Applied energy = 29.7 x 62 = 1841.4 lb.ft

$$V_t = \frac{20x25x30}{(30.48)^2} = .53\ \text{ft}^3$$

Applied energy per unit vol, Ea $= \frac{1841.4}{.53} = 3.47 \times 10^3$ lb.ft/ft^3

IV Seepage force

J = Seepage force

i = Hydraulic gradient

L = Height (Length) of sample

H_w = Total head of water

h(-ve) = Negative head applied at water exit

For the third sample, section 4.2.5

h(-ve) = 13.25 inches of mercury

h1 = 34.4 cm. of water

L = 24.4 cm. (after jetting)

For the datum shown in Figure X

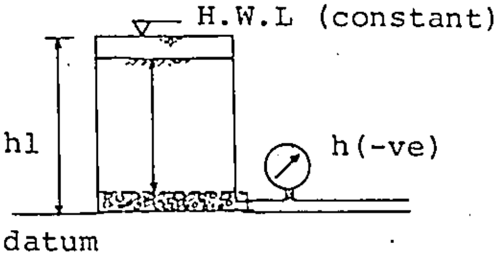


Fig. X

H_w = h1 + h(-ve)

= 34.4 + 13.25 x 2.54 x 13.6 = 492 cm. of water
= 193.7 inches of water

i $= \frac{492}{24.4} = 20.2$

J = γw.i

= 198 N/cm^3 or = 62.4 x 20.2 = 1260. lb/ft^3

APPENDIX E

NOMENCLATURE

NOMENCLATURE

A_s	Soil area per jet
C	Clay
CV	Velocity coefficient
D	Average diameter of lumps
$(D.C)_{15}$	Average degree of compaction, fifteen days after jetting
e	Average voids ratio
Ea	Total applied energy due to waterjetting per unit volume
e_i	Average initial voids ratio
e_{15}	Average voids ratio, fifteen days after jetting
g	Gravitational acceleration
G_s	Specific gravity of soil particles
H	Initial soil height
h (-ve)	Negative head applied at water exit
He	Water head at exit
HP	Applied horse power
H_w	Total water head
i	Hydraulic gradient
I.D	Internal diameter
J	Seepage force
L	Low plasticity
L.L	Liquid limit

M	Silt
N	Number of jettings
P	Jetting water pressure
P.I	Plasticity Index
Q	Water discharge at exit
S	Average degree of saturation
t	Time after jetting
t_j	Time of jetting
V	Jetting water velocity at exit
V_t	Total volume of soil
w	Moisture content
w_i	Initial water content
Δe	Average change in voids ratio
ΔH	Difference in total soil height, between time t and fifteen days after jetting
γbulk	Bulk density
γd_i	Initial dry density
γd_{max}	Standard Proctor maximum dry density
γd_{15}	Average dry density, fifteen days after jetting
γ_w	Specific weight of water

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