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In arid regions where water may not be available for standard field compaction operations, compaction of soils at low moisture contents may be necessary. To determine whether these cohesive and cohesionless soils can be adequately compacted in a dry state, a laboratory vibratory soil compactor was built and used to conduct the investigation. After analyzing the effects if frequency of vibration, acceleration, static weight, and moisture content on



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# A LABORATORY INVESTIGATION OF VIBRATORY COMPACTION OF DRY SOILS

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A report submitted to Texas A&M University, College Station, Texas, in partial fulfillment of the requirements for the degree of Master of Science.

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OF DRY SOILS

A Thesis

by

CECIL RAY WEBSTER

Submitted to the Graduate College of
Texas A&M University
in partial fulfillment of the requirements for the degree of

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May 1984

Major Subject: Civil Engineering

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Approved as to style and content by:

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May 1984

# ABSTRACT

A Laboratory Investigation of Vibratory Compaction

of Dry Soils (May 1984)

Cecil Ray Webster, B.S., Prairie View A&M University

Co-Chairman of Advisory Committee: Dr. Louis J. Thompson
Dr. Wayne A. Dunlap

In arid regions where water may not be available for standard field compaction operations, compaction of soils at low moisture contents may be necessary. To determine whether these cohesive and cohesionless soils can be adequately compacted in a dry state, a laboratory vibratory soil compactor was built and used to conduct the investigation. After analyzing the effects of frequency of vibration, acceleration, static weight, and moisture content on compaction, a comparison of the unit weights obtained by Standard and vibratory methods was made. The test results indicate that cohesionless soils, if compacted dry, will yield dry densities greater than 100% Standard compaction. However, vibratory compaction of fine-grained and cohesive soils proved to be ineffective in obtaining high unit weights. It was also determined that the best frequency for compacting a soil was not a function of the soil alone, but of the soil and compactor together. In general the lighter compactor performed better than the heavier compactor at the lower frequencies.

# PREFACE

The Department of the Army, and the Corps of Engineers, Waterways Experiment Station, in particular, is keenly interested in the study of dry compaction. With increased tensions in North Africa and the Middle East, the possibility of an armed conflict in that region involving U.S. forces is forever increasing. The unavailability of an adequate water supply system, due to the arid nature of the region, could adversely affect combat and combat support operations.

As a result, normal combat support engineering construction operations (for example, the compaction of subgrades for roads and airfields) may have to be curtailed to accomodate this "new" environment. Alternatives to the conventional compaction process must be analyzed; drier compaction of these subgrades may be necessary.

As a potential "combat engineer" and as an engineer, the author, too, is keenly interested in dry compaction operations. As such, he has undertaken this research to determine the feasibility and applicability of this process to combat engineering operations.

This study is also being used to fulfill the thesis research requirements for a Master of Science degree in Civil Engineering.

Cecil R. Webster
Captain, U.S. Army
March, 1984

# DEDICATION

This research is dedicated to the thought that it will not be needed for the purposes for which it was originally investigated.

## ACKNOWLEDGEMENTS

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And to the United States Army for its officer professional development and management policies.

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# INTRODUCTION

Soil compaction is defined as the process of increasing the amount of solids per unit volume by mechanical means (4). The art of soil compaction has long been recognized as an integral part in obtaining increased support from the soil. It is one of the basic construction procedures used in building subgrades and bases for roads and airport pavements, embankments, earth-fill dams, and other similar structures.

Although prior to the 1920's no known engineering literature gave precise relationships between moisture content, unit weight, compactive effort, and soil type (16), man has always been aware of the problems (trafficability, support, settlement, etc) which exist in areas where there is too much or too little moisture in the soil.

Beginning in the late 1920's, numerous research projects were performed to analyze the effects of different types of compactors/ rollers in compacting various types of soil and to determine the effect of soil type, moisture content, and compactive effort on a soil's unit weight (14,16,17,29). That research has resulted in a system whereby the maximum dry density can be determined in the laboratory and adequately achieved in the field. This maximum dry density has a corresponding optimum moisture content. (Following the convention used in compaction literature, the terms density and unit weight will be used interchangeably throughout this report).

In many regions, especially in semi-arid and arid regions, water will need to be added to the soil to bring it to the optimum moisture

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content so the maximum dry density can be achieved. This will require large quantities of water and pose severe problems. Generally, shallow groundwater sources, such as wadi alluvia, are very poor in quality and the wells have unproven yields (15). As a result, the economic cost of constructing additional wells or of importing the water will be considerable.

An even greater burden will be placed on the already under-developed water supply system if combat operations are conducted in these desert regions. These combat operations will require an extensive network of roads, airfields, and staging areas. As such, the water demand for combat construction operations will be tremendous and it must compete with the water demands of other forces in the theater of operations (for example, troop consumption, support facilities, vehicular operation). A recent projection by the author of combat construction water requirements in an arid region indicates that up to 120,000 gallons (454,800 liters) of water would be required for the construction of a mile of Class A road. This quantity represents that which is needed only for compaction operations. For dust control, soil stabilization, and bituminous treatment of these same roads, as well as airfield construction and quarry operations, this quantity of required water can easily increase exponentially. As a result, road construction personnel must look at alternative means of performing their mission.

An alternative is to compact the soil dry or at moisture contents lower than the optimum. That details the scope of this research. Several cohesive and cohesionless soils will be compacted with a "new" laboratory vibratory compaction device. The effects of moisture content, soil type, frequency of vibration, and other variables on soil's unit weight will be analyzed. These test results will be compared to data obtained with standard laboratory compaction procedures (1,6) to determine whether vibratory compaction represents a means of obtaining high degrees of compaction at very low moisture contents.

## REVIEW OF LITERATURE

Soil compaction is the process of mechanically densifying the soil, rearranging the solid particles and bringing them into closer contact, thereby decreasing the amount of voids in the mass. In the laboratory, this procedure is usually accomplished by the impact of hammer blows, vibration, static loading, or any other method or combination of methods which does not alter the moisture content of the soil. Laboratory compaction is usually an attempt to duplicate, within acceptable margins, what can be done in the field.

Although the principles of compaction were not set forth in writing until 1933, there is evidence that compaction had been used extensively before then in numerous works (16). One of the earliest recorded reports on mechanical compaction was in England. John Shotbolt was granted a patent in 1619 for using various "strong and massy engines... in making and repairing highways and roads;" however, his invention was not widely accepted (26).

Further developments in road rollers did occur after that time, but it was not until the latter half of the 19th century that dramatic increases in the development and use of road rollers came into practice.

The first patent of a steam road roller was granted to M. Louis Lemoine of France in 1859 (26). Thomas Aveling of England is credited with the first successful road roller (16). The first steam road rollers used in the United States were built in England by Aveling and they were purchased by the cities of New York and Brooklyn in 1869 (26).

Long before this period, however, animals had been used as a compaction tool. It is difficult to date their first use. Even with the dramatic increases in the development and technology of road rollers in the 19th century, the use of animals as compactors was still an acceptable alternative. As late as 1893, goats were used in Sante Fe, New Mexico to compact part of a water supply dam (12,14). Not only have goats been used as compactors, but cattle and sheep have been used as well. It is said that the first sheepsfoot roller owes its origin to a flock of sheep (16).

Development of the Fundamentals of Compaction

Largely due to the work of R. R. Proctor, the principles of compaction were detailed in 1933 (23). He determined that there were several factors which influenced the degree of compaction. The factors of major significance are moisture content, compactive effort and soil type.

Proctor's work was based on laboratory compaction tests on more than 200 different soils (23). These soils were compacted in what is known today as the Proctor mold, a cylindrical mold four inches (101.6 mm) in internal diameter and 4.58 inches (116.33 cm) in height which has a volume of 1/30 cubic feet (1/1071 cubic meters).

Following the publication of Proctor's report, numerous other studies were conducted to further expand on these principles. These additional studies were performed on soils in different size molds and at different compactive efforts (16). Proctor's work was validated.

As a result of this work, a standardized test procedure was adopted by the Committee on Materials of the American Association of State Highway Officials (AASHO, now AASHTO) and by Committee D-18 on Soils for Engineering Purposes of the American Society for Testing and Materials (ASTM). The AASHTO procedure, designated as T-99, was adopted in 1938 (16) while the ASTM procedure, designated as D-698, was adopted in 1942 (25). These tests employed a compactive effort of approximately 12,300 foot-lbs per cubic foot (600,000 newton-meters per cubic meter) of soil. A 5.5 lb (2.49 kilograms) hammer with a drop height of 12 inches (304.8 mm) was employed as the tamping force, the soil was compacted in three equal layers in the Proctor mold, and the hammer was dropped a total of 25 times per soil layer.

During World War II and later, it was found that these tests provided inadequate compaction standards for airfield construction due to the increased wheel loads of the newer aircraft. For this reason the compactive efforts were increased. The 5.5 lb (2.49 kilograms) hammer was replaced by a 10-lb hammer (4.53 kilograms), the drop height was increased to 18 inches (457.2 mm), and the soil was compacted in five layers instead of three. This resulted in an approximate compactive effort of 56,000 foot-lbs per cubic foot ($27 \times 10^6$ newton-meters per cubic meter) of soil. The AASHTO T-99 test was modified and the newer test was designated as T-180 and the modified ASTM test was designated as D-1557 (2,6). These tests remain essentially unchanged today. However, the T-99 and the D-698 still remain as the standard tests and the others are called modified Proctor tests.

## Influential Factors on Unit Weight

As indicated earlier, a direct relationship was established between the moisture content, compactive effort, and the unit weight. Proctor's original findings are restated below.

Influence of Moisture Content. To determine the influence of moisture content on a soil, Proctor compacted numerous samples of the same soil at varying moisture contents, while maintaining a constant compactive effort. When compacted at low moisture contents, the soil was a "hard and firm fill having practically no plasticity (23)". By slightly increasing the moisture content of the soil and recompacting it, a greater density was obtained. As this process was further investigated by steadily increasing the moisture content and compacting the soil, he found that the density increased to a peak or "maximum density" value and it then began to decrease (See Figure 1).

The maximum density, usually expressed in terms of dry density, has a corresponding "optimum moisture content (OMC)"—that moisture content which yields the maximum dry density (MDD). A plot of moisture content versus dry density is usually referred to as the "Proctor curve" or the "lab compaction curve".

If it were possible to completely fill all the air voids in the soil with water, even higher densities could be obtained. This is represented by the theoretical "zero air voids curve" or the "line of saturation".

Influence of Compactive Effort. Compactive effort (CE) is the amount of energy utilized to compact the soil. It is expressed in foot-lbs per cubic foot or newton-meters per cubic meter of soil and is determined as

$$CE = W \times H \times D \times L / V \quad \ldots\ldots\ldots\ldots\ldots\ldots (1)$$

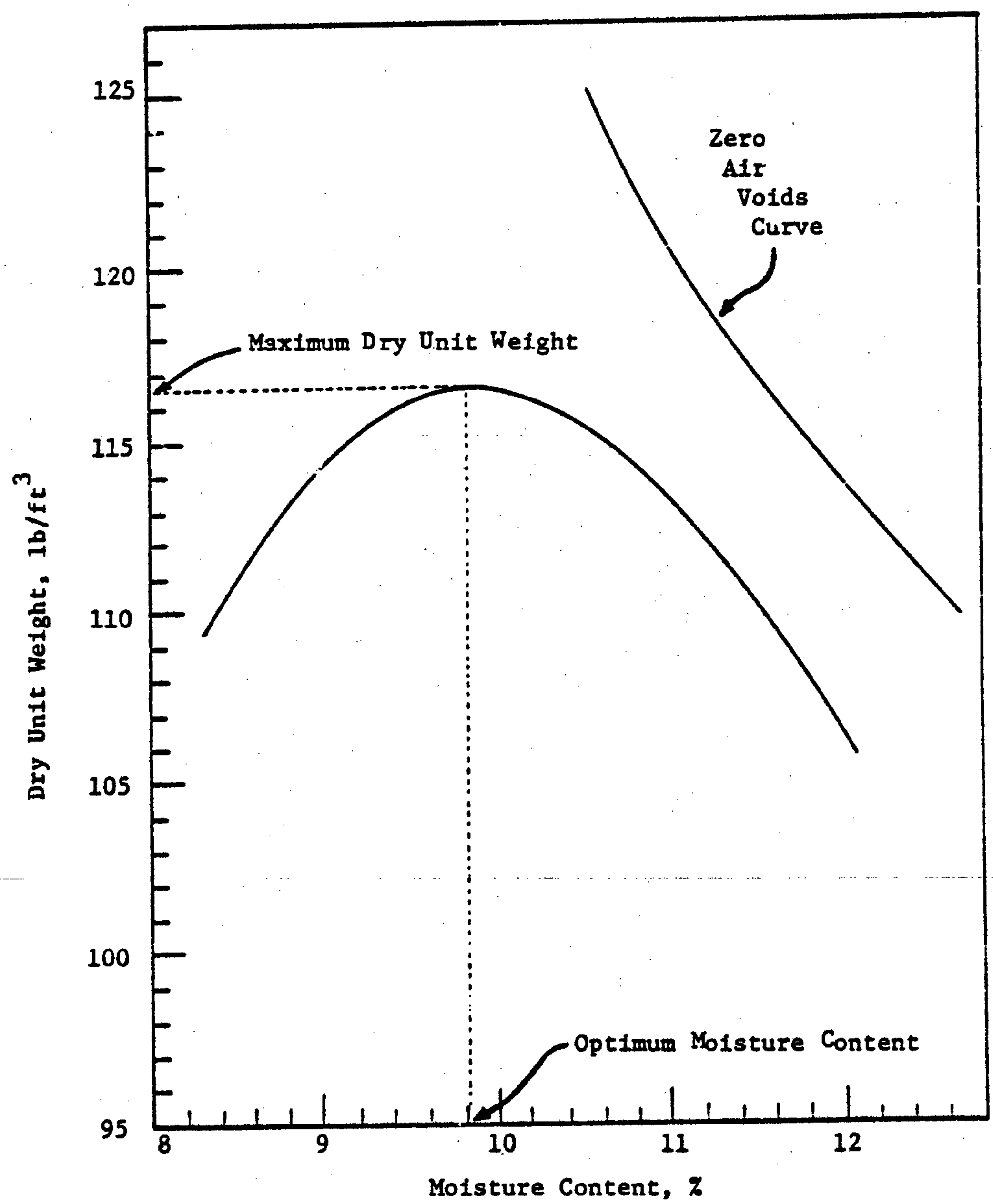



Figure 1. A Typical Laboratory Compaction Curve.
(1 lb/ft$^3$ = 0.159 kN/m$^3$)

where W = the weight of the rammer used, lbs (newtons)

H = the height of drop of the rammer, ft (meters)

D = the number of blows per layer of soil

L = the number of layers compacted

V = the volume of the mold, $ft^3$ ($m^3$) (27).

To determine the effect of compactive effort on a particular soil, Proctor, while maintaining all other variables constant, increased the compactive effort for each compaction test. He found that as the compactive effort was increased, higher maximum dry densities were obtained and the optimum moisture content decreased (See Figure 2). The line connecting the peaks of the curves is a straight line roughly parallel to the zero air voids curve.

Influence of Soil Type. A third important factor which greatly influences the degree of compaction is soil type. The values of maximum dry density and optimum moisture content, obtained as a result of the compaction of several different soils at a constant compactive effort, differ over a wide range. For example, when a clayey soil of volcanic origin is compacted under a standard compactive effort (AASHTO T-99), maximum unit weights as low as 60 pcf (9.54 $kN/m^3$) may be obtained (16). A "heavy textured" clay compacted under the same compactive effort may have a maximum dry density of 90 to 100 pcf (14.31 to 15.9 $kN/m^3$) (16). A sandy soil, Soil 1 of Figure 3, may have a maximum density in excess of 120 pcf (19.08 $kN/m^3$) (16). And of course, the optimum moisture contents may differ as well.

These varying maximum dry densities are dependent on the shape of the soil grains, their size distribution, specific gravity and

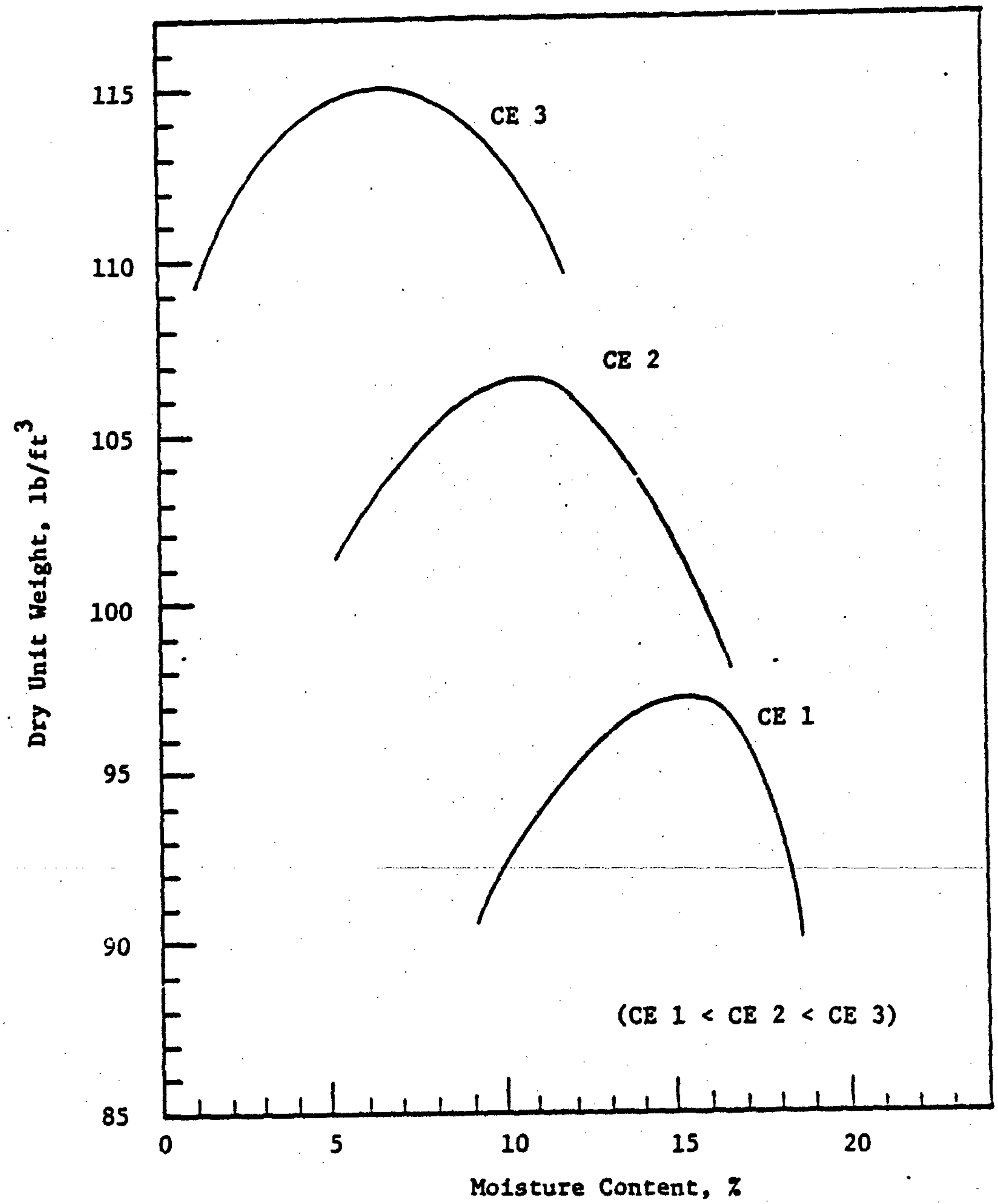



Figure 2. Influence of Compactive Effort on Maximum Dry Density and Optimum Moisture Content. (1 lb/ft$^3$ = 0.159 kN/m$^3$)

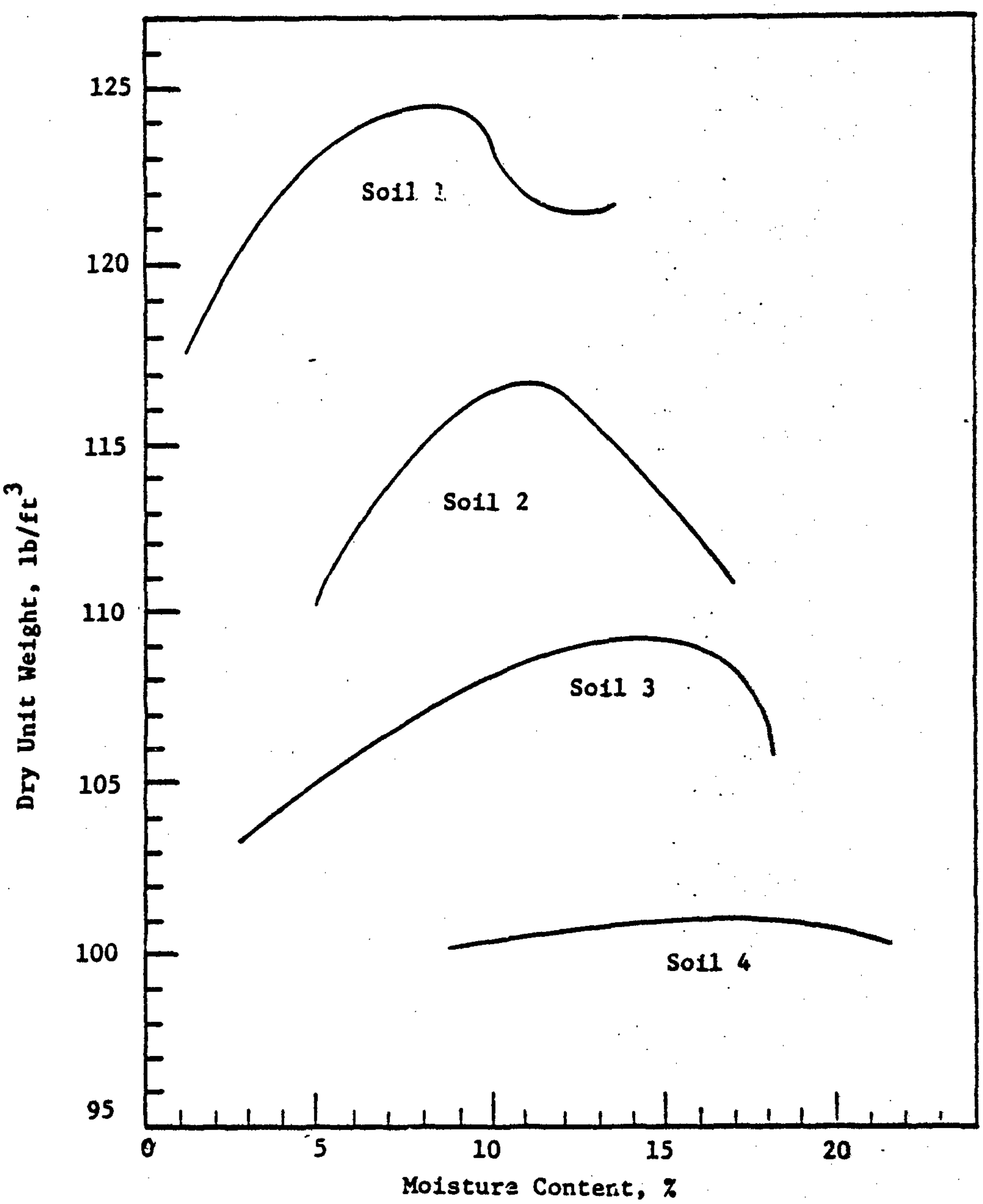



Figure 3. Influence of Soil Type on Maximum Dry Density and Optimum Moisture Content. (1 lb/ft$^3$ = 0.159 kN/m$^3$)

plasticity (16).

It is also evident from observing the curves of Figure 3 that the moisture content is less critical for some soils than it is for others. For example, Soil 4 (CH) may be compacted through a relatively wide range of moisture contents below optimum with comparatively small changes in dry density, while a slight change in moisture above optimum for a well-graded loam, Soil 3 (ML), would have a significant change in dry density. Soil 2 represents an SC.

Other Factors Which Influence Unit Weight. Other factors have been found to have an effect on a soil's unit weight (16). Temperature is one of those factors. Increasing the temperature of certain fine-grained soils from near freezing to 75°F (297°K) or more may increase the unit weight by three or more pounds per cubic foot (0.477 kN/m$^3$). The manner or degree of remolding clayey soils has also been found to affect the unit weight. The uniformity of moisture within the soil and the time period between wetting, mixing and compaction also influences unit weight. These and other factors, however, are usually of minor significance.

## Developments in Field Compaction

After the standardized laboratory compaction procedures were adopted in 1938 by the AASHTO, intensified efforts were directed towards obtaining the maximum dry density in the field to match that obtained in the laboratory.

Some of the earliest tests were conducted in Indiana and Ohio in 1938 (16) to determine the effectiveness of a smooth-wheel type roller in satisfying the "specification requirements of dry unit weight and moisture content based on the then newly standarized compaction test (16)". These tests were performed on a silty clay soil using a 10 ton (9070 kg) roller. In each case study the field moisture content varied from two percent below OMC to four percent above OMC. The maximum dry density based on the laboratory compaction test was obtained; however, the number of roller passes required to achieve this density varied with the thickness of the lift.

Most of the other tests were conducted during the late 1940's and 1950's (16,21).

Since it was not possible to obtain that single MDD and OMC economically, a range of moisture contents and dry densities was established as acceptable. The range of moisture content is usually OMC ± 2% and the range of dry density is usually based on the type of soil involved (3). For cohesive soils, the range is usually from 90% to 95% of the laboratory maximum dry density and for cohesionless soil, the range is usually from 95% to 100% of the laboratory maximum dry density. These ranges of moisture content and dry density establish what is commonly referred to as the "specification block" (See Figure 4). The specification block may be altered based on previous engineering experience with the soil.

It was determined that the same three factors which influenced laboratory compaction tests greatly influenced field compaction. Of those three factors, only the field compactive effort produces problems. This field compactive effort is primarily influenced by the number of roller passes involved, the contact pressure between the

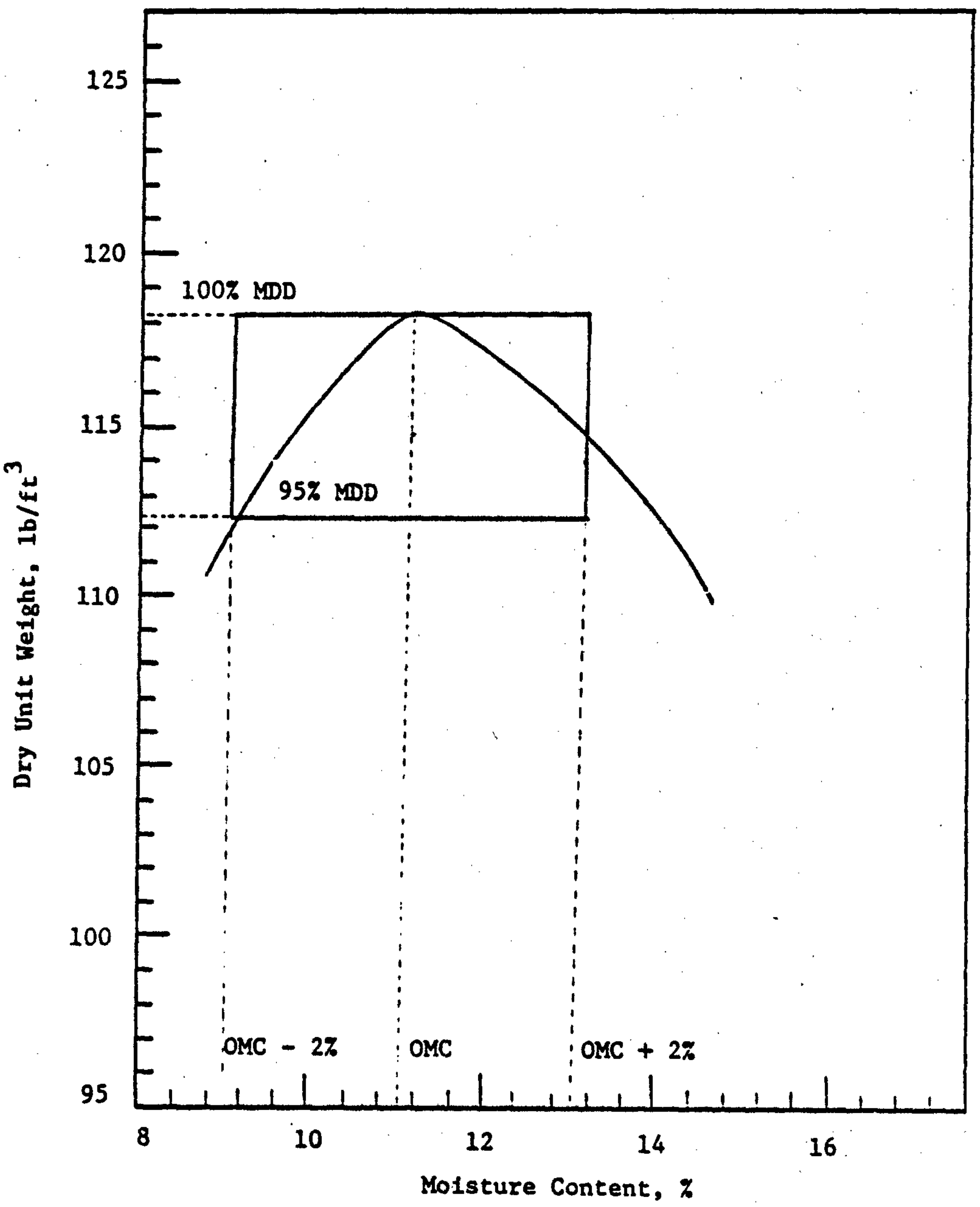



Figure 4. A Typical Specification Block for Field Compaction of a Cohesionless Soil. (1 lb/ft$^3$ = 0.159 kN/m$^3$)

roller and the soil, and the frequency of vibration, if any (16). Because of these many different variables, calculations of this compactive effort is difficult, although estimates may be made (27).

To analyze the effectiveness of various compactors in compacting a particular soil, relative compaction is often used; that is, as compared to the laboratory compaction test results, what percentage of compaction has been achieved. This relative compaction is usually based on a specific number of roller passes. For example, data extracted from a Corps of Engineers study (16) indicates that a silty clay compacted by a sheepsfoot-type roller at varying contact pressures, but after a specific number of roller passes, had its relative compaction decrease from 101.9% to 101.4% as the contact pressure went from 250 psi (1722.5 kPa) to 750 psi (5167.5 kPa) (See Table 1). The table also indicates that when this same soil was compacted with a pneumatic-tired roller under varying wheel loads and tire inflation pressures, the relative compaction increased from 99.6% to 108.5%.

Other noteworthy tests have been conducted by the British Road Research Laboratory (16). In one of their studies, four types of soil were compacted by various rollers (See Table 2).

From these and other similar tests, a suitable compactor can be selected based on a soil's properties and its classification (3,22). Table 3 represents a typical correlation which was developed by the Corps of Engineers (3). From Table 3 it can be observed that vibratory compactors are not recommended for soils with appreciable amounts of fines, that is, soils which contain more than 12% fines. However, more recent research indicates that vibratory compaction can be used for

TABLE 1

Compaction Data on a Lean Clay Using Sheepsfoot and Pneumatic-Tired Types of Rollers (Reference 16)

| Reference Number | | Number of Roller Passes | Maximum Dry Unit Weight: AASHTO T 99 (pcf) | Maximum Dry Unit Weight: Field Compactor (pcf) | Optimum Moisture Content: Lab (%) | Optimum Moisture Content: Field (%) |
|---|---|---|---|---|---|---|
| | **Sheepsfoot-Type Rollers** | | | | | |
| 46 | 250 psi max CP, 7 sq in CA, 5.5% TCA, silty clay | 6 | 105.3 | 107.3 | 17.9 | 19.1 |
| 46 | 500 psi max CP, 7 sq in CA, 5.5% TCA, silty clay | 6 | 105.3 | 106.8 | 17.9 | 18.5 |
| 46 | 750 psi max CP, 7 sq in CA, 5.5% TCA, silty clay | 6 | 105.3 | 106.8 | 17.9 | 19.1 |
| 87 | 125 psi max CP, 14 sq in CA, 10.9% TCA, lean clay | 12 | 107.5 | 109.0 | 17.8 | 17.0 |
| 87 | 375 psi max CP, 14 sq in CA, 10.9% TCA, lean clay | 12 | 107.5 | 109.0 | 17.8 | 17.0 |
| | **Pneumatic-Tired Rollers** | | | | | |
| 87 | 15,875-lb WL, 50 psi TIP, lean clay | 8 | 107.5 | 107.1 | 18.0 | 19.5 |
| 87 | 15,875-lb WL, 50 psi TIP, lean clay | 16 | 107.5 | 107.4 | 18.0 | 19.2 |
| 87 | 15,875-lb WL, 50 psi TIP, lean clay | 32 | 107.5 | 108.5 | 18.0 | 19.0 |
| 87 | 31,250-lb WL, 150 psi TIP, lean clay | 8 | 107.5 | 113.5 | 18.0 | 16.0 |
| 87 | 31,250-lb WL, 150 psi TIP, lean clay | 16 | 107.5 | 115.2 | 18.0 | 15.4 |
| 87 | 31,250-lb WL, 150 psi TIP, lean clay | 32 | 107.5 | 116.6 | 18.0 | 14.7 |

[a] Lean clay formerly classified as a silty clay.
[b] Percent of total contact area.
[c] Contact pressure
[d] Tire inflation pressure
[e] Wheel load

1 lb = 453.6g
1 psi = 6.89 kPa
1 $in^2$ = 6.4516 $cm^2$
1 pcf = 0.159 $kN/m^3$

TABLE 2

Compaction Data on Four British Soils Compacted by Five Different Types of Rollers
(Reference 16)

| Type and Rating of Roller | Maximum Dry Unit Weight (pcf) | | | | Optimum Moisture Content (%) | | | |
|---|---|---|---|---|---|---|---|---|
| | CH | CL | SW | GW | CH | CL | SW | GW |
| British Standard Compaction Test | 99.0 | 109.0 | 121.0 | 129.0 | 24.0 | 16.0 | 11.0 | 9.0 |
| Modified AASHTO Compaction Test | 116.0 | 126.0 | 130.0 | 138.0 | 16.0 | 12.0 | 9.0 | 7.0 |
| **3-Wheel Type Smooth-Wheel Rollers** | | | | | | | | |
| 9.5-ton roller | 104.0 | 116.0 | 132.0 | 138.0 | 20.0 | 15.0 | 9.0 | 7.0 |
| 3.09-ton roller | 95.0 | --- | 127.0 | 134.0 | 21.0 | -- | 10.0 | 8.0 |
| **Sheepsfoot Type Rollers** | | | | | | | | |
| 5.5-ton club-foot type roller | 107.0 | 118.0 | --- | 130.0 | 16.0 | 12.0 | -- | 6.0 |
| 5.04-ton taper-foot type roller | 107.0 | 118.0 | --- | 128.0 | 15.0 | 13.0 | -- | 5.0 |
| **Pneumatic-Tire Rollers** | | | | | | | | |
| British Standard Compaction Test | 99.8 | 109.4 | 124.4 | 129.5 | 22.8 | 16.5 | 10.2 | 9.2 |
| 2,985-lb wheel load, 36-psi tire pres. | 100.7 | 110.7 | 126.8 | 132.2 | 23.2 | 17.8 | 9.7 | 8.2 |
| 11,200-lb wheel load, 90-psi tire pres. | 107.1 | 117.1 | 129.8 | 134.0 | 20.7 | 14.7 | 9.0 | 7.1 |
| 22,400-lb wheel load, 140-psi tire pres. | 110.7 | 119.8 | 131.9 | 138.5 | 18.5 | 13.8 | 9.0 | 6.4 |
| **Vibrating Base-Plate Compactor** | | | | | | | | |
| 480-lb single unit, hand propelled | --- | --- | 128.0 | 127.0 | -- | -- | 10.0 | 9.0 |
| 1,570-lb single unit, self propelled | 87.0 | 114.0 | 130.0 | 137.0 | 20.0 | 16.0 | 9.0 | 7.0 |
| 4,480-lb single unit, self propelled | 98.0 | --- | 128.0 | 137.0 | 17.0 | -- | 9.0 | 7.0 |
| **Vibrating Rollers** | | | | | | | | |
| 5,400-lb tandem with vibr. front roll, 68-lb | 96.0 | --- | 133.0 | 139.0 | 21.0 | -- | 7.0 | 6.0 |
| 8,620-lb single drum-towed unit, 119-lb | 106.0 | 119.0 | 137.0 | 145.0 | 21.0 | 14.0 | 7.0 | 6.0 |

1 lb = 453.6g    1 psi = 6.89 kPa    1 ton = 907 kg    1 pcf = 0.159 kN/m$^3$

TABLE 3

Recommended Compactors for Various Soil Types
(Reference 3)

| Major Division | Symbol (USCS) | Name | Compaction Equipment | Dry Unit Weight (lb/ft$^3$) |
|---|---|---|---|---|
| GRAVEL AND GRAVELLY SOILS | GW | Well-grade gravels or gravel sand mixtures, little or no fines | Crawler-type tractor, Rubber-tired roller, Steel-wheel roller, Vibratory compactors | 125-140 |
| | GP | Poorly graded gravels or gravel-sand mixtures, little or no fines | Same as GW | 110-140 |
| | GM(d) | Silty gravels, gravel-sand-silt mixtures | Rubber-tired roller, Sheepsfoot roller (Close control of moisture) | 125-145 |
| | GM(u) | Silty gravels, gravel-sand-silt mixtures | Sheepsfoot roller, Rubber-tired roller | 115-135 |
| | GC | Clayey gravels, gravel-sand-clay mixtures | Rubber-tired roller, Sheepsfoot roller | 130-145 |
| SAND AND SANDY SOILS | SW | Well-graded sands or gravelly sands, little or no fines | Crawler-type tractor, Rubber-tired roller, Vibratory compactor | 110-130 |
| | SP | Poorly graded sands or gravelly sands, little or no fines | Crawler-type tractor, Rubber-tired roller, Vibratory compactor | 105-135 |
| | SM(d) | Silty sands, sand-silt mixture | Rubber-tired roller, Sheepsfoot roller, (Close control of moisture) | 120-135 |
| | SM(u) | Silty sands, sand-silt mixture | Rubber-tired roller, Sheepsfoot roller | 100-130 |

TABLE 3 (Continued)

Recommended Compactors for Various Soil Types
(Reference 3)

| Major Division | Symbol (USCS) | Name | Compaction Equipment | Dry Unit Weight ($lb/ft^3$) |
|---|---|---|---|---|
| SAND AND SANDY SOILS | SC | Clayey sands, sand-clay mixture | Rubber-tired rollers Sheepsfoot roller | 100-135 |
| SILTS AND CLAYS WITH LIQUID LIMIT LESS THAN 50 | ML | Inorganic silts and very fine sands, rock flour, silt or clayey fine sands or clayay silts with slight plasticity | Rubber-tired roller, Sheepsfoot roller (Close control of | 90-130 |
| | CL | Inorganic slays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays | Rubber-tired roller, Sheepsfoot roller | 90-130 |
| | OL | Organic silts and organic silt-clays of low plasticity | Rubber-tired rollers, Sheepsfoot roller | 90-105 |
| SILTS AND CLAYS WITH LIQUID LIMIT GREATER THAN 50 | MH | Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts | Sheepsfoot roller, Rubber-tired roller | 80-105 |
| | CH | Inorganic clays of high plasticity, fat clays | Sheepsfoot rollers, Rubber-tired rollers | 90-115 |
| | OH | Organic clays of medium to high plasticity, organic clays | Sheepsfoot rollers, Rubber-tired roller | 80-110 |

1 pcf = 0.159 $kN/m^3$.

these fine-grained soils, as well (8,18,20,29,33).

A test strip is usually employed to determine which of the available recommended compactors is best suited for the needs of the project (16).

Irregularly Shaped Compaction Curves

Proctor's research alludes that each soil has a single maximum dry density and optimum moisture content. According to his diagram (Figure 1, p. 8), on either side of this MDD and OMC, the dry density decreases as the moisture content is increased or decreased. This dry density decreases to a limiting value. Other research, however, has found that some soils have irregularly shaped compaction curves; that is, they may have more than one peak value of dry density or they may have no distinguishable peak at all (7,9,11,19).

A study by Suedkamp and Lee (19) on numerous soil samples found that four distinct types of compaction curves exist--a single-peak compaction curve (Figure 1, p. 8), a one and one-half peak compaction curve (Figure 5), a double-peak compaction curve (Figure 6), and a curve with no distinct peak or an oddly shaped compaction curve (Figure 7). They found that soils with liquid limits between 30 and 70 usually yield the typical single-peak compaction curve, while soils with liquid limits outside of this range usually yield the irregularly shaped compaction curves. In soils with liquid limits greater than 70, both double-peak and oddly shaped compaction curves were found, whereas both double-peak and one and one-half peak compaction curves were found for soils with liquid limits less than 30. Suedkamp and Lee also found

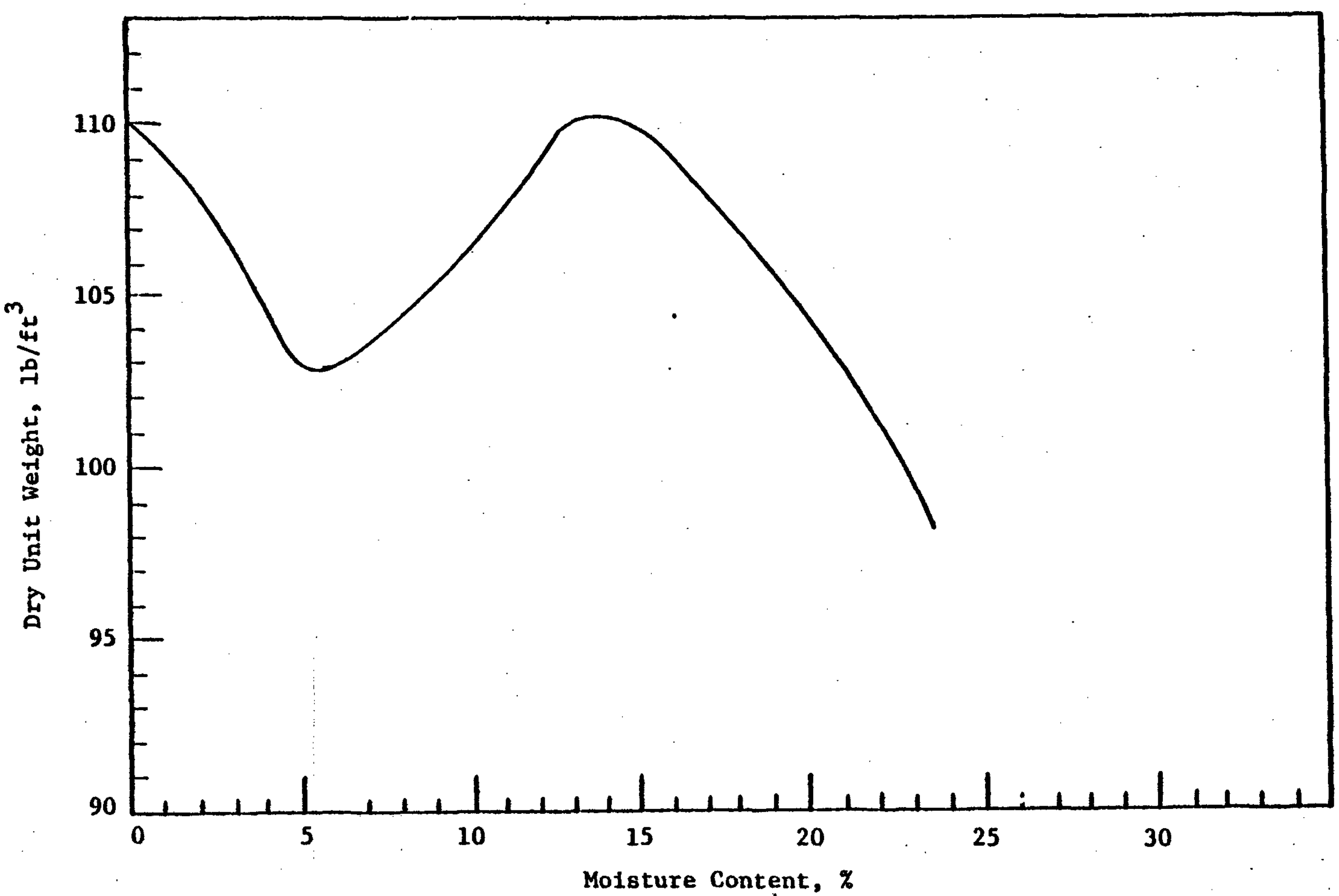



Figure 5. One and One-Half Peak Compaction Curve.
(1 lb/ft$^3$ = 0.159 kN/m$^3$)

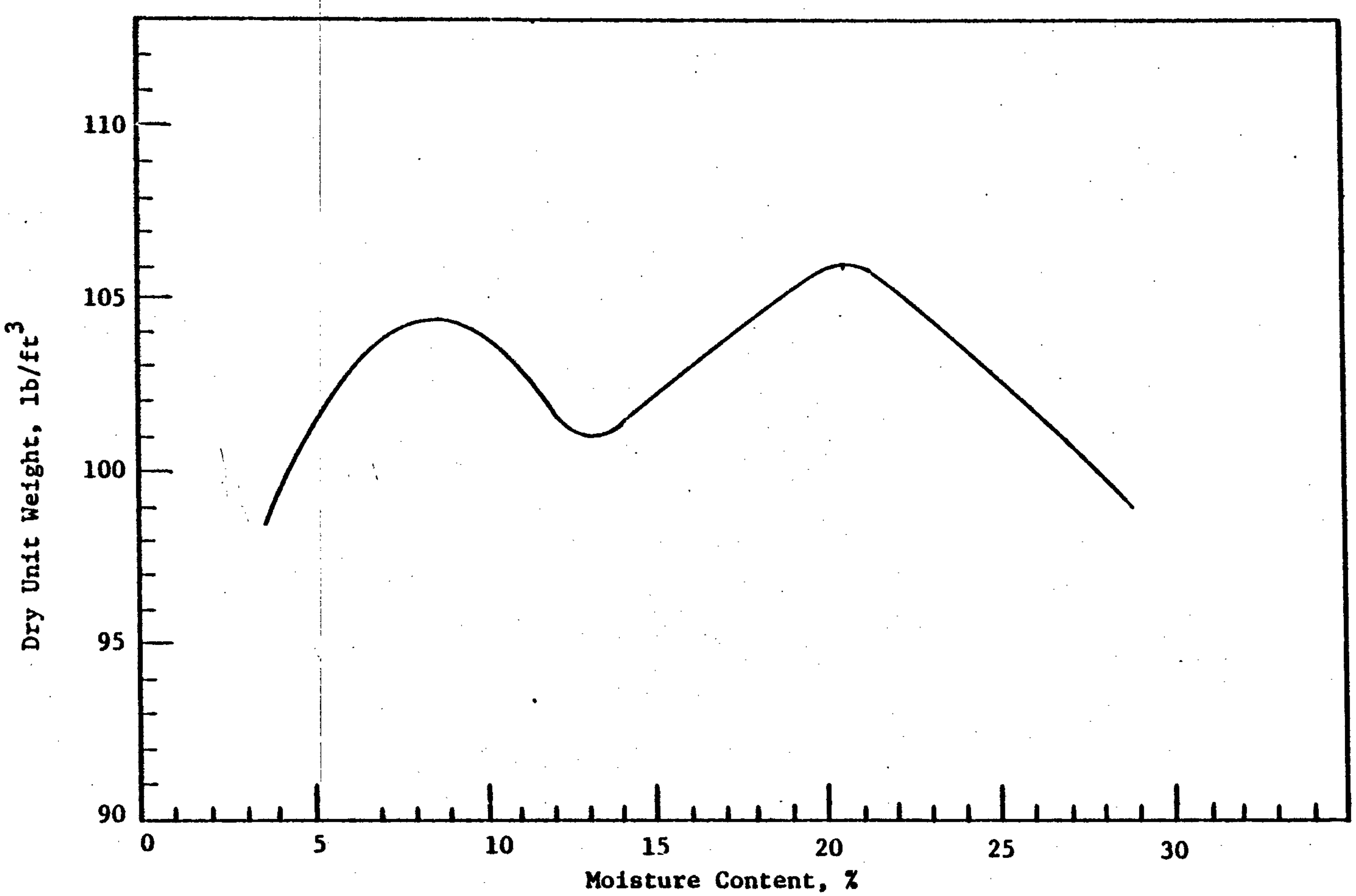



Figure 6. Double-Peak Compaction Curve.
(1 lb/ft$^3$ = 0.159 kN/m$^3$)

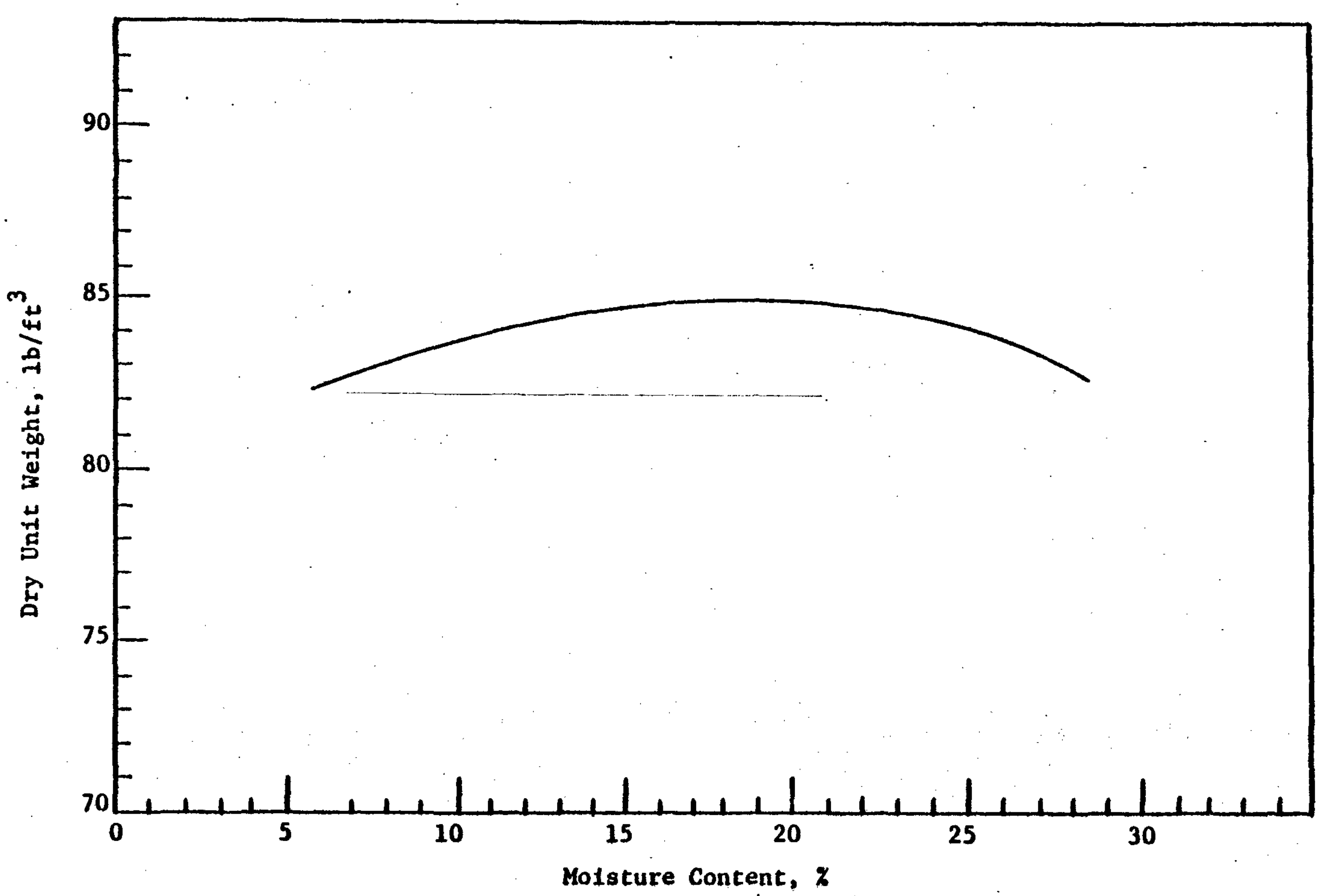



Figure 7. Oddly-Shaped Compaction Curve.
(1 lb/ft$^3$ = 0.159 kN/m$^3$)

that the quantity and type of clay minerals present in a soil had an important effect on the resulting compaction curve. Soils with the one and one-half peak compaction curve usually contained illite or montmorillonite along with large quantities of sand, and soils with double-peak curves contained a small percentage of kaolinite and a dominant percentage of sand. Additionally, they state that soils with more than 50% montmorillonite usually had oddly-shaped compaction curves. Their results were based on more than 700 compaction tests involving more than 30 different types of soil.

Field investigation and verification of the findings of Lee and Suedkamp have been conducted (7,9,11).

This research of irregularly shaped compaction curves indicates that a high dry density for a soil may be obtained at a moisture content other than the usual OMC. This can be very important in areas where adequate quantities of water for compaction are not available.

Compaction Methods in Arid Regions

As indicated earlier, vibratory compaction is most effective on cohesionless soils, although it has been found to be an adequate means of compacting cohesive soils. It has also been mentioned that adequate dry densities may be obtained at moisture contents dry of the optimum moisture content. Putting these two facts together, it is not surprising that quite a bit of research has been conducted on vibratory compaction in desert or arid regions. However, a discussion of arid regions, in general, is in order to dispel the concept of a desert being all dry and sandy before research into the compaction methods in arid regions is presented.

Terrain Composition in Arid Regions. An arid region or desert is defined as an area where evaporation exceeds all types of precipitation (including rain, snow, and dewfall). Approximately one-third of the world's land surface is characterized as arid (32). Large areas of Iraq, Iran, Egypt, and other areas of northern Africa and the Middle East consist of this type of terrain, as well as various portions of the North American and Asian continents. These areas generally average less than ten inches of rainfall per year and the evaporation may be in excess of 80 inches. The temperature frequently exceeds 100°F (310.8°K) (10).

After many years of studying these environments, Fookes developed a geomorphological division of desert terrain features (10), As shown in Figure 8, Fookes divided the region into four zones. Zone I consists of the mountain slopes; Zone II, the apron fan; Zone III, the alluvial plain; and Zone IV, the base plain. The engineering characteristics of each zone, as described by Fookes, are presented below:

> Zone I. The soil in this region generally consists of poorly sorted mediam angular gravel (GP soil classification by USCS) to very large boulders. Gravitation is the principal mechanism of soil deposition in this area.
>
> Zone II. This area consists primarily of mixtures of angular to sub-angular sands and gravels, with some inclusion of cobbles and boulders. This soil is principally deposited as a result of intermittent sheet and stream flow during flash flooding.

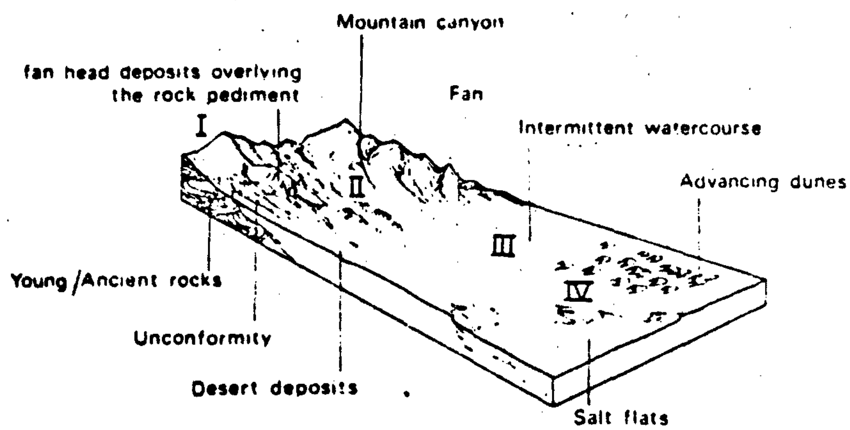



Figure 8. Block Diagram of Hot Desert Mountain and Plain Terrain Showing the Four Engineering Zones. (Reference 10)

Zone III. The soils in this zone are predominantly composed of silt, sand and gravel. Small amounts of clay and evaporite minerals may also be present. Additionally, the zone may contain local areas of stationary and/or mobile sand dunes and loess.

Zone IV. This is usually the largest area of the four zones. Soils consist of clays, silts, and sands which have been transported primarily by wind. The zone tends to be irregular in shape and its margins are constantly changing. Consequently, this zone presents the most engineering problems.

A typical set of geotechnical properties for a desert in Iran is shown in Table 4 (10).

From this and other data, it is obvious that a desert is not all sand. Nor is it all dry. Figure 9 is a soil moisture profile of a highly plastic clay (CH) soil typical of south Iraq and southwest Iran (13). Another soil moisture profile is contained in Figure 10 (9). This material is a "black silty clay" [which Ellis classifies as MH], found near Kosti, Sudan in northern Africa.

In comparison, Figure 11 represents a soil moisture profile "beneath two heavily trafficked desert roads in Libya (15)". This subgrade was composed of a cohesionless material with obviously much less water-holding capacity than the clays mentioned above.

Therefore, soil in a desert or arid region is not necessarily void of moisture. Depending upon the type of soil and the depth of interest, the moisture content can vary from practically zero percent to

## TABLE 4

### Granular Soils - Classification Test Results (Reference 10)

| Zone | Sample Type | Particle Size (percent passing) 20 mm | 2 mm | 0.06 mm | 0.002 mm | Atterberg Limits, % LL | PL | PI | Maximum Dry Weight, $Mg/m^3$ ($lb/ft^3$) | Optimum Moisture Content, % |
|---|---|---|---|---|---|---|---|---|---|---|
| II | Fan | 87 | 38 | - | - | - | - | - | 2.12 (132.3) | 8.4 |
| II | Fan | 63 | 27 | - | - | 22 | 27 | 6 | 2.24 (139.8) | 7.0 |
| III | Sandy desert | 93 | 54 | 21 | 8 | 18 | 36 | 18 | - | - |
| III | Sandy desert | 83 | 30 | - | - | - | - | - | 2.11 (131.7) | 9.5 |
| III | Silty desert | 97 | 77 | 31 | - | 58 | 112 | 50 | 1.60 (99.9) | 20.3 |
| III | Silty desert | - | 99 | 76 | 35 | 19 | 39 | 18 | 1.76 (109.2) | 18.2 |
| III | Silty desert | - | 96 | 63 | 20 | 15 | 29 | 17 | 1.94 (121.1) | 12.0 |
| IV | Silty desert | - | 100 | 57 | 15 | 26 | 39 | 23.5 | 1.93 (120.5) | 13.0 |
| IV | Loess | - | - | 83 | 21 | 26 | 64 | 38 | 1.57 (98.0 | 22.80 |
| IV | Loess | - | - | 89 | 18 | 17 | 33 | 6 | 1.81 (113.0) | 11.59 |
| IV | Loess | - | - | 90 | 20 | 19 | 36 | 17 | 1.57 (98.0) | 23.0 |
| IV | Sandy desert | - | 96 | 14 | - | - | - | - | 1.96 (122.4) | 12.00 |
| IV | Dune sand | - | 99 | 83 | 9 | 22 | 39 | 17 | 1.74 (108.6) | 18.3 |

$1\ Mg/m^3 = 1000\ kg/m^3$.

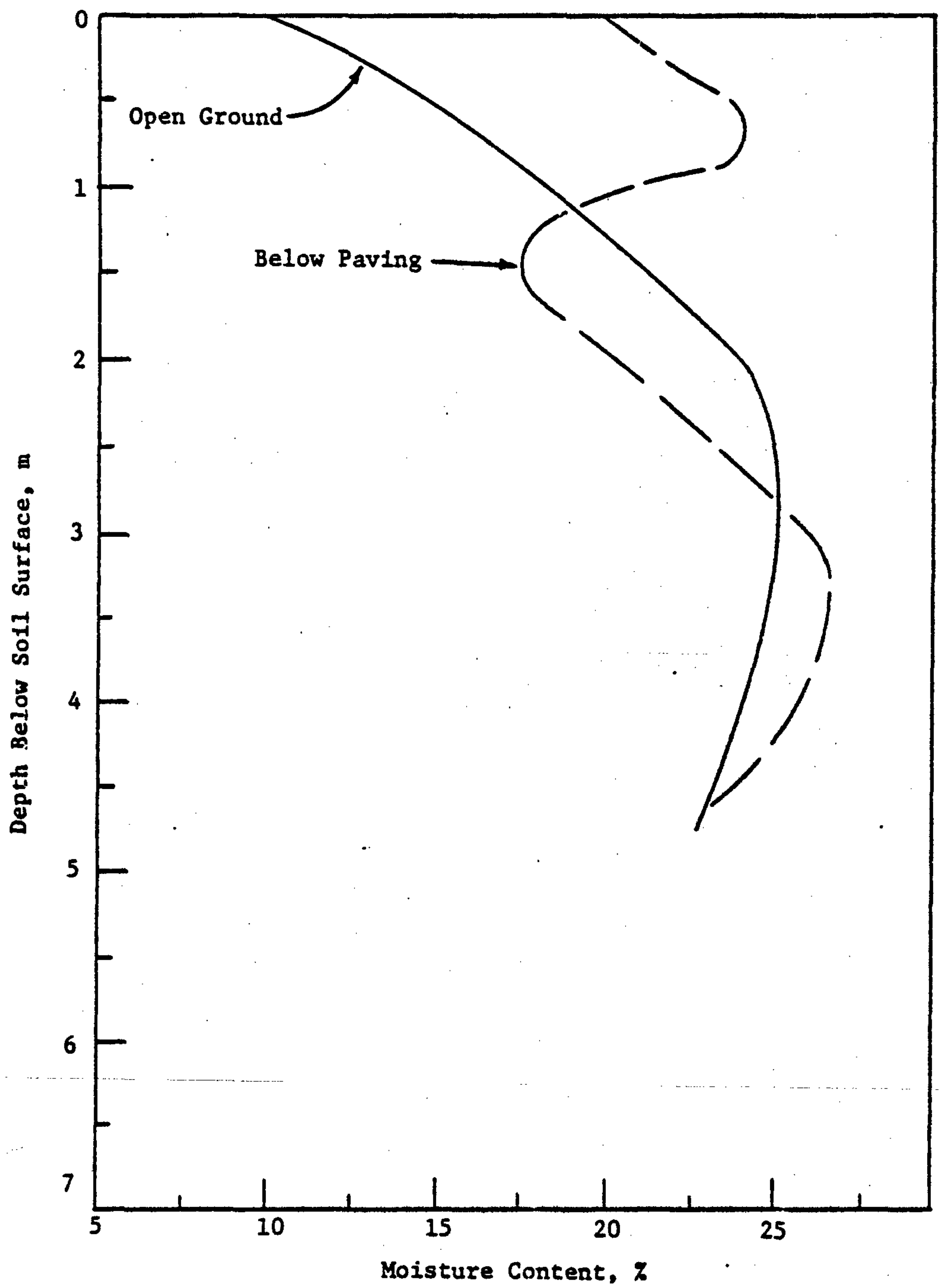



Figure 9. Variation in Moisture Content for Open Ground and Below Pavement. (Reference 13) (1 m = 3.28 ft)

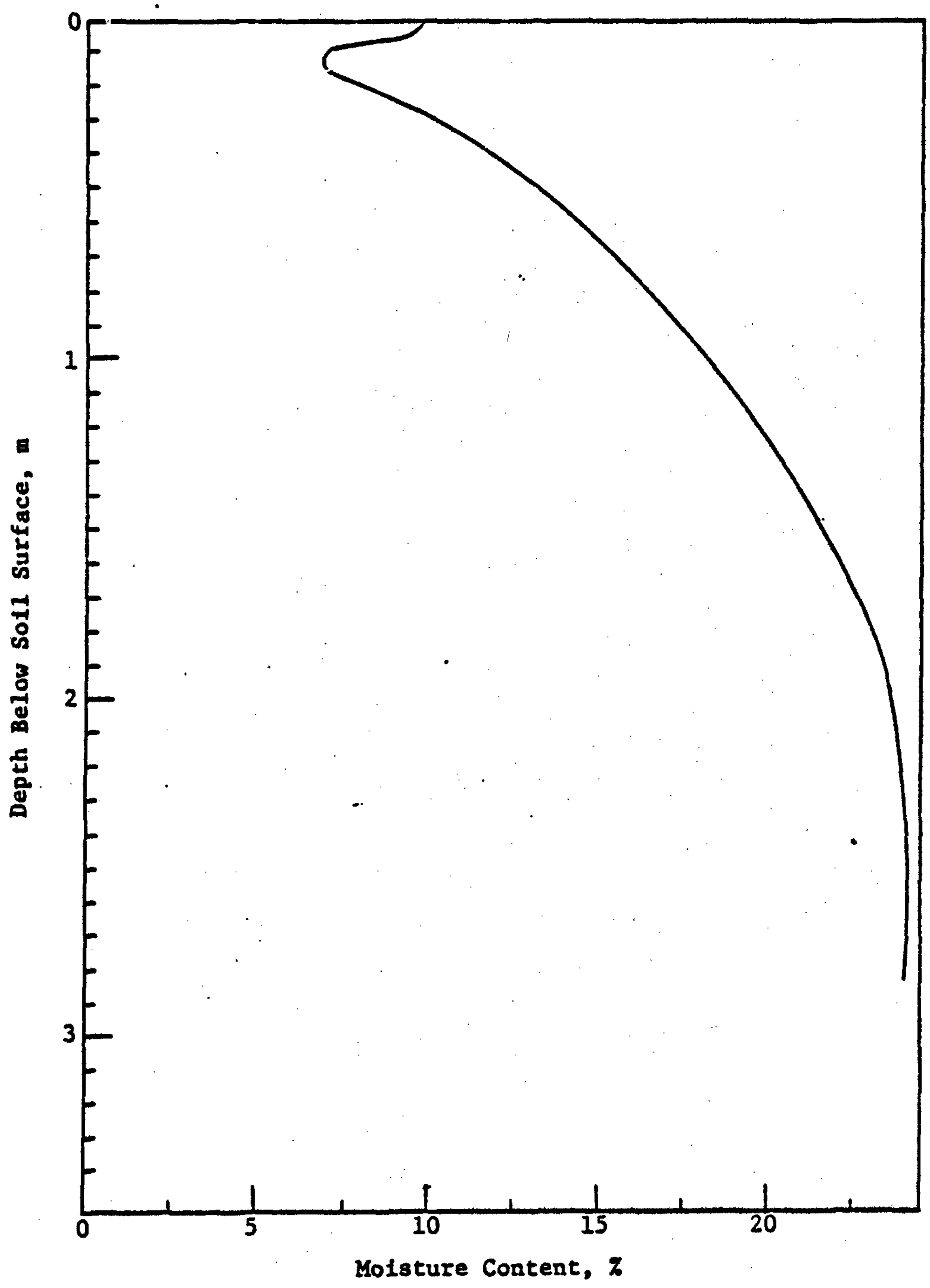



Figure 10. Moisture Content Profile in Natural Ground. (Reference 9) (1 m = 3.28 ft)

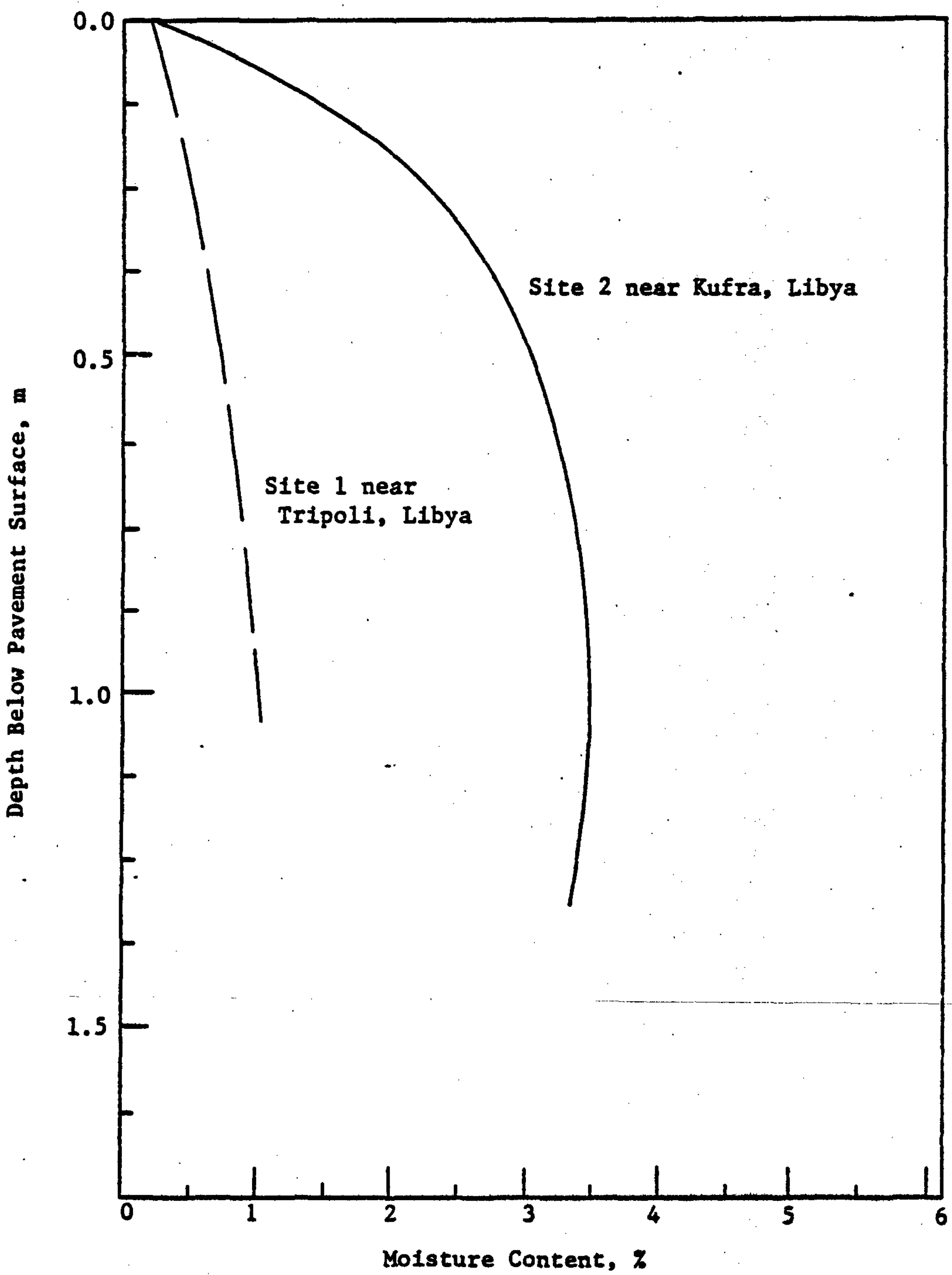



Figure 11. Natural Moisture Content Below Two Heavily Trafficked Roads, (Reference 15). (1 m = 3.28 ft)

over 20 percent. These natural moisture contents are most likely to be dry of the optimum moisture content, however.

Procedures for Compaction of Dry Soils. Since the natural moisture content of desert soils are usually dry of optimum, dry compaction has received increased emphasis in arid regions.

Ellis studied the compaction of a "black silty clay .... [which was] classified as MH" for use on a road embankment and subgrade (9). Six trial sections of 100 meters (328 ft) each were compacted in six equal layers of 200 mm (7.87 in.) compacted thickness. The only variables investigated were moisture content and the type of roller. Moisture content, which was controlled by selective excavation from the borrow area, varied from 7-11%, 11-14%, and greater than 14%. The optimum moisture content was 29.5%. The rollers used were a 10 ton (9070 kg) self-propelled vibratory roller and an 8 ton (7256 kg) pneumatic-tired roller, which when fully ballasted, operated at nearly 20 tons (18140 kg).

Ellis found that the difference in performance between the pneumatic and vibrating rollers was negligible. He found that the field dry density values ranged from 94% to 105% of the British Standards compaction test, which compares to the AASHTO or ASTM Standard compaction test. As for the road test section, Ellis made the following observations one and one-half years after completion of the test section:

> "Analysis of the cross-section levels suggests that there has been negligible differential settlement since completion of construction and there is no deterioration of the road shape which can be attributed to any effect of dry compaction procedures adopted during construction".

Furthermore, Ellis states that the "dry densities [obtained as a result of dry compaction] are likely to be lower than those to be expected at optimum conditions, but possibly higher than those often achieved in practice".

A laboratory study of dry compaction on a uniformly graded sand (SP) was conducted by Forsblad (11). He found that in comparison with the standard compaction procedures, dry compaction gave the highest density, both at the surface and at depth. A follow-up field study enabled him to further conclude that for a sandy soil, the most effective compaction was achieved when the moisture content of the soil was less than 1.5 percent.

Results similar to the two mentioned above have also been reported by others (7,9,11,18,30).

Vibratory Compaction. In a report on the compaction of dry soils, Thompson and Dunlap recommended a vibratory type compactor for use on both cohesive and cohesionless soils (30). Based on various results reported by others, they conclude that coarse material can best be compacted dry with a heavy smooth-wheel roller with a tuneable frequency. For dry loose sands and silts, a light vibrating roller is recommended initially; compaction should then be followed by a heavy vibrating roller to achieve deeper compaction. In the case of shales and clays at low natural moisture contents (10%-12%), they recommend a heavy low frequency vibrating sheepsfoot roller.

An experimental study by Converse indicates that cohesive material can be effectively compacted by low frequency vibrations (less than 25 Hertz) (8). He lists four basic principles involved in the compaction of cohesive soils:

1. The dead weight unit soil pressure should be adequate for the type of soil being compacted. For a sandy-loam or a clay-loam soil, he recommends a pressure of 6 psi (41.34 kPa) to 12 psi (82.68 kPa),

2. The frequency of the applied dynamic force should be such that the oscillator-soil mass is in resonance,

3. The dynamic force should be approximately equal to the dead weight of the oscillator, and

4. The moisture content should be on the wet side of the optimum obtained in the laboratory compaction tests.

Other research on vibratory compaction presents some interesting results. Lewis reports that the change in frequency of vibration was only of significance for granular soils (20). He says that "with cohesive soils, varying the frequency over the full range [of the roller tested, 1800-2950 cycles per minute for either a 3-3/4 ton 3401 kg) towed or tandem vibrating roller] .... affected the dry density by only about 1-2 pcf (0.159-0.318 kN/m$^3$)". No investigation was carried out at frequencies below 1800 cycles per minute and no explanation was offered as to why not. He indicates that the best results, in terms of dry density, were obtained at frequencies of 22002400 cycles per minute for the four soils analyzed (a heavy clay, a sandy clay, a well-graded sand, and a gravel-sand-clay).

Mechanism of Vibratory Compaction

Since vibratory compaction methods are often advised for dry compaction, any discussion of vibratory compaction would be incomplete if it failed to at least mention the fundamental principles underlying the mechanics of vibratory compaction. An excellent source of information on this topic is a paper by Selig and Yoo (28) which is briefly discussed below.

According to Selig and Yoo:

> "Compaction with vibratory rollers is probably the least understood of all methods. Uncertainty and contradictory opinions exist concerning what frequency should be used for a given material, whether light or heavy drums are better, the importance of roller travel speed, the significance of resonance, the relative contribution of the static machine weight and dynamic force, and in fact, even why vibration works".

They attribute this misunderstanding to research focusing "on either the machine or the soil, but not both, in spite of the fact that it is the combined characteristics of the machine and the soil which determine the amount of compaction".

Of the four often mentioned explanations as to why compaction works (particle vibration, impact, strength reduction, and cyclic straining), they discount all of them except cyclic straining. To demonstrate its effect, they conducted numerous laboratory and field tests.

Their results indicated that the superposition of oscillation to the static weight of a compactor significantly increased the amount of compaction as compared to that achieved by a comparable compactor without oscillations. They conclude that the total compaction achieved represented two modes of compaction: one component which was due to the static weight of the compactor, and another component which was due to the dynamic effects of the compactor. Figure 12 is an overview of those two components and their effects on compaction.

Further research by Selig and Yoo into the dynamic component effects led to a discussion of the roll vertical displacement of a compactor. They analyzed the parameters affecting the roll vertical displacement; those results are presented in Figure 13. The generated (dynamic) force indicated in Figure 13 is due to the frequency of vibration. A plot of vibration frequency versus roll vertical displacement (Figure 14) depicts the resonant frequency of the compactor-soil system. The resonant frequency is defined as that frequency which produces a maximum amplitude of motion. They determined that this frequency is affected by the properties of both the soil and the machine.

The advantage of operation of the compactor at the resonant frequency is increased efficiency of energy utilization and possibly increased productivity in terms of compacted unit weight. Figure 15 is a plot of vibration frequency versus dry density for a heavy clay which they compacted; as indicated by the figure, the best compaction was obtained with the heaviest roller at a frequency of 1500 rpm.

In their summary, Selig and Yoo indicated that an increase in frequency above the resonant frequency may produce a decrease in compaction. This is due to a decrease in the roll vertical displacement (Figure 14). However, this decrease in compaction may be partially

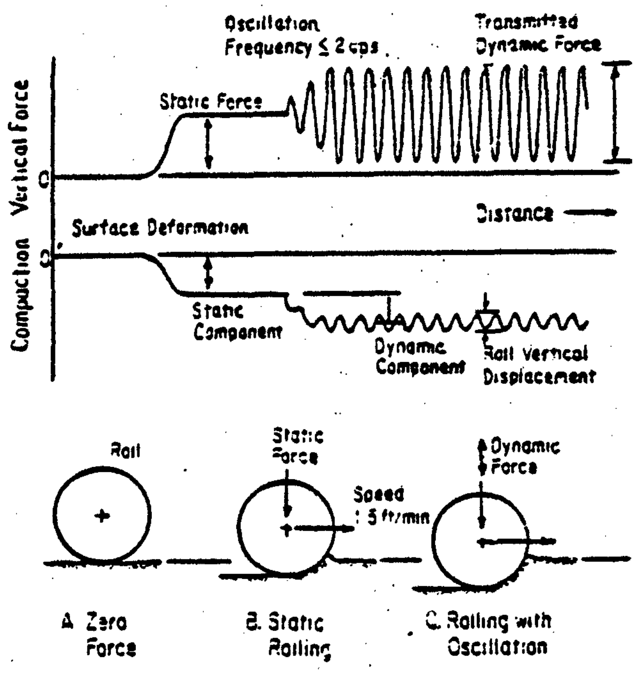



Figure 12. The Effect of Static Weight and Roll Oscillation on Compaction. (Reference 28).

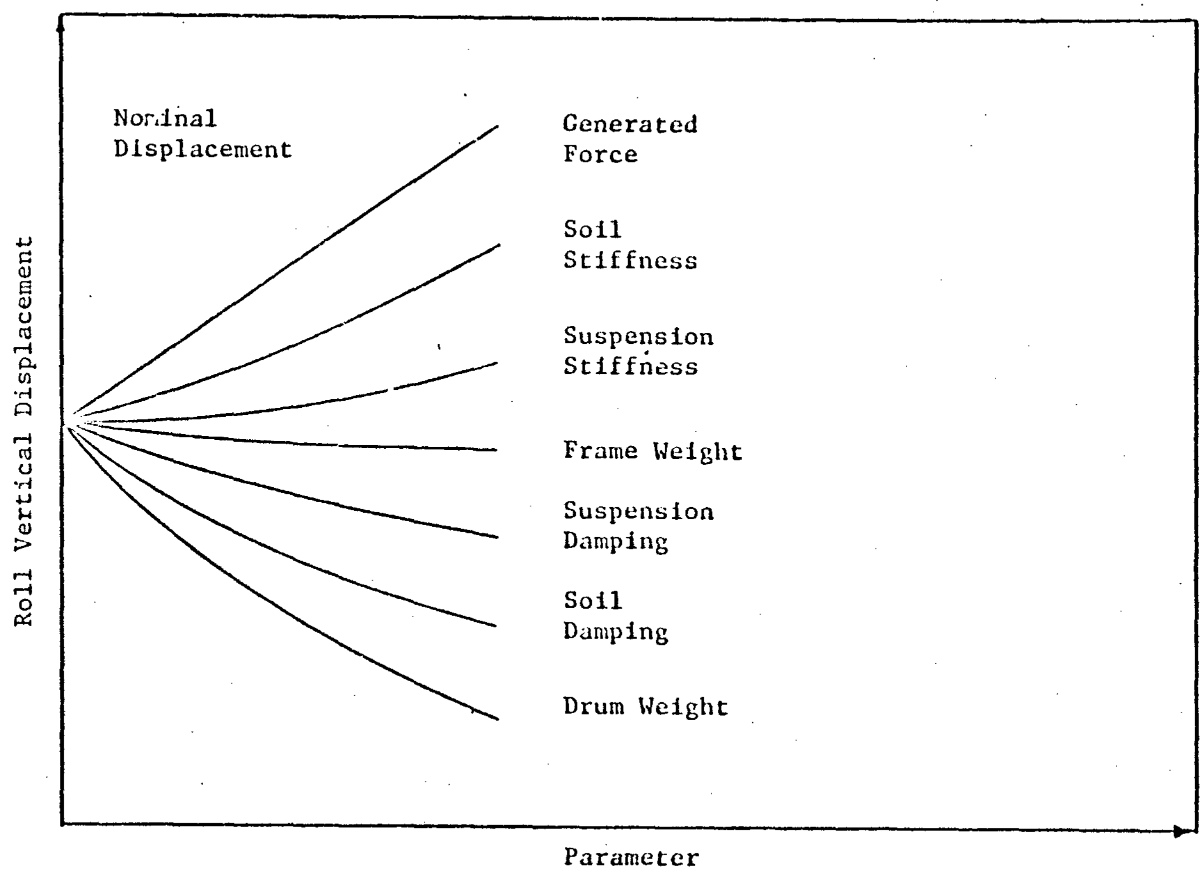



Figure 13. Representative Effect of Compactor and Soil Parameters on Roll Vertical Displacement. (Reference 28).

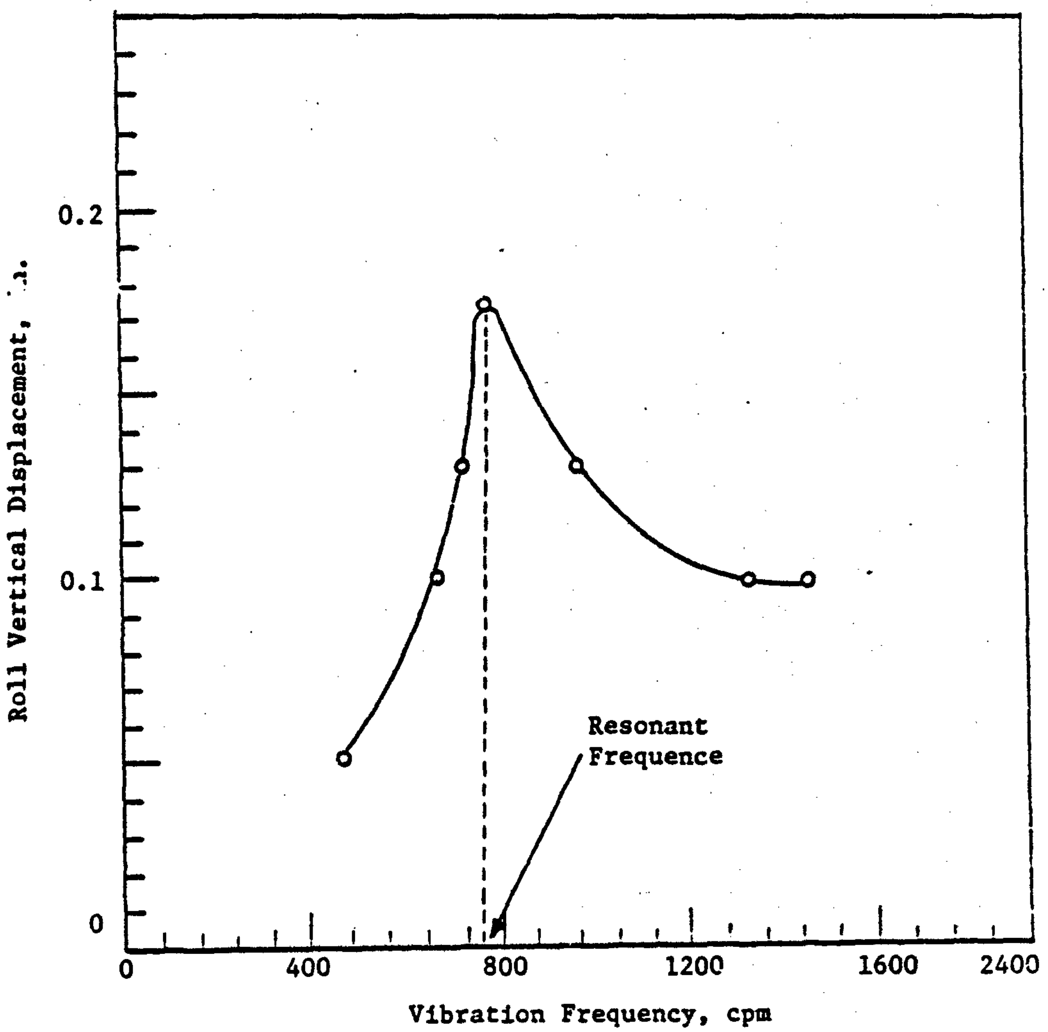



Figure 14. Variation of Displacement with Frequency for a 20,000 lb (9080 kg) Roller on 12 Inches (304.8 mm) of Gravel and Sand Material. (1 in. = 25.4 mm) (Reference 28).

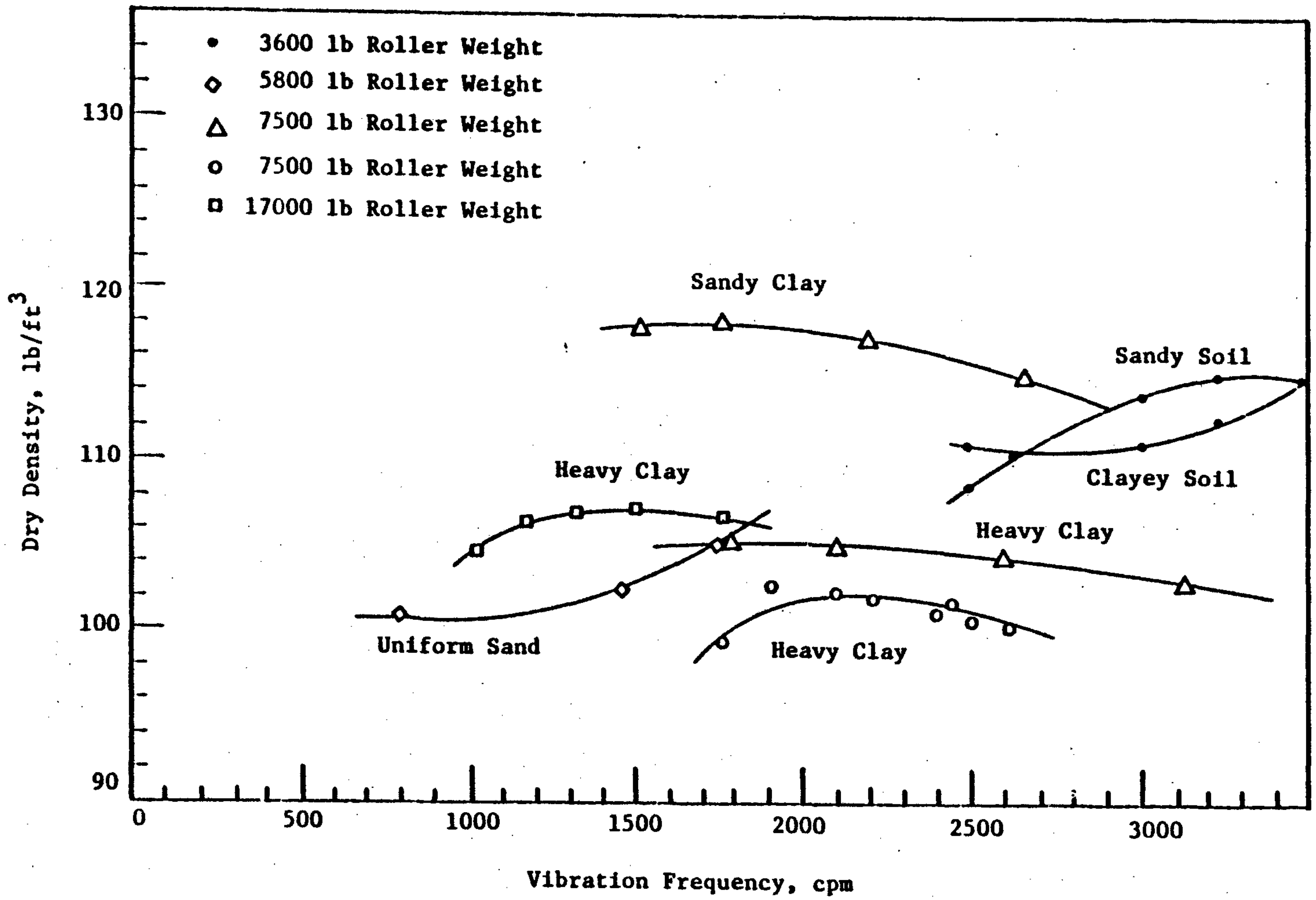



Figure 15. Variation of Dry Density with Frequency for Various Soils Compacted with Smooth-Drum Vibratory Rollers. (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lbm = 0.454 kg) (Reference 28).

compensated for by an increase in oscillation per unit of travel distance. Likewise, when compacting at frequencies below resonance, an increase in frequency will also increase compaction because both the roll vertical displacement and the oscillations per unit of travel will have been increased.

## Summary

Cumulatively, the results discussed above indicate that dry compaction of some soils will yield dry densities equivalent to or greater than the dry densities obtained as a result of the standard compaction method. This is a very important compaction alternative for engineers faced with compaction operations in arid regions where water is economically unavailable. Additionally, the literature review indicates that vibratory compaction works well for cohesionless soils and yields acceptable results for cohesive soils.

The above statements serve as the reason for conducting a laboratory investigation of vibratory compaction of dry soils. The results of this method of compaction should give an indication as to whether field compaction of dry soils will yield acceptable dry densities and it should also indicate under what conditions must the soil be compacted (frequency, moisture content, static weight). Such a method would have obvious financial and tactical advantages.

# DESCRIPTION OF VIBRATORY SOIL COMPACTOR

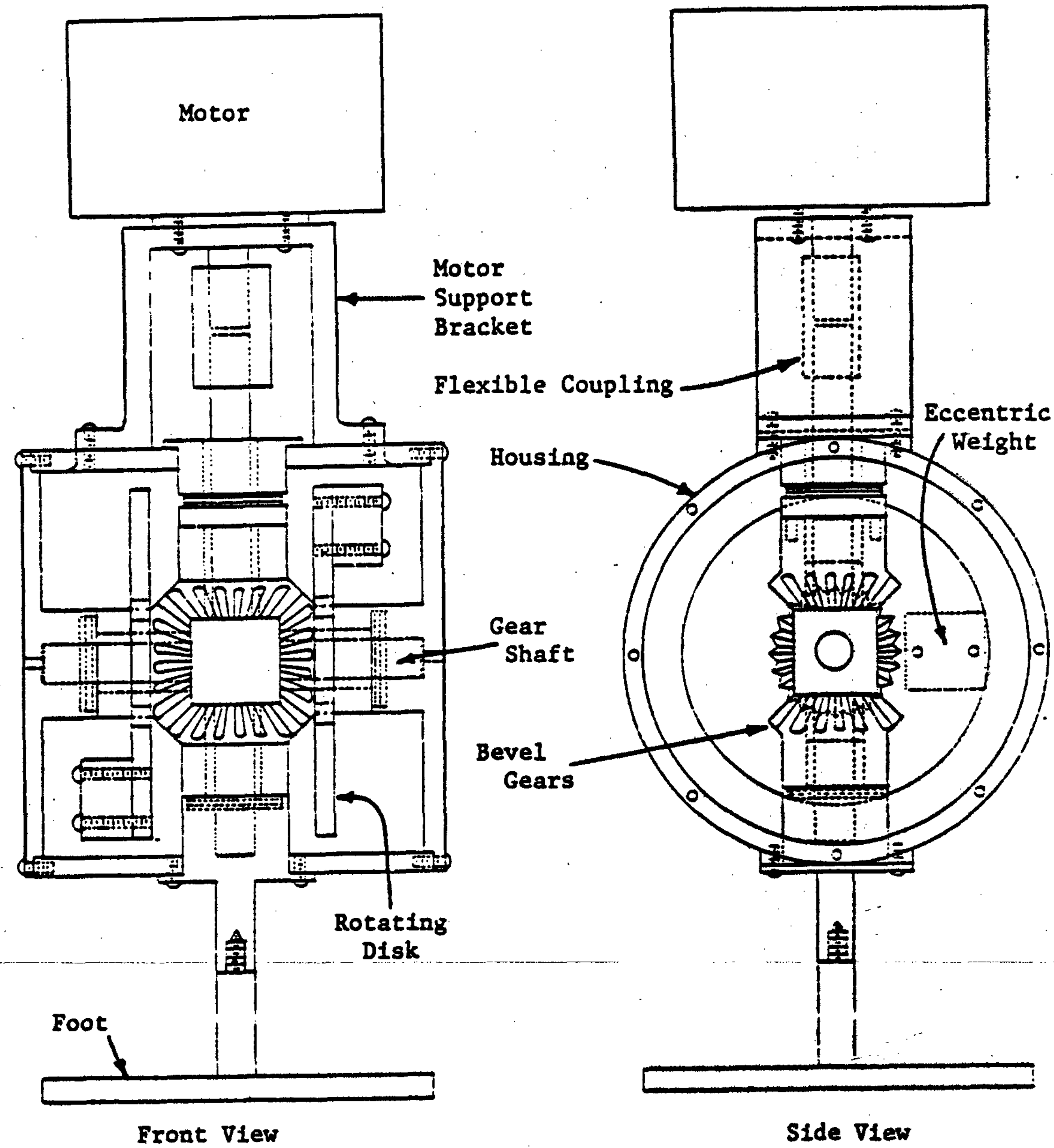
The only laboratory vibratory soil compactor which is standardized is used to obtain the relative density of sands according to ASTM Standard D 2049-69 (31). However, it cannot be used to determine the best frequency of compaction for a soil since it does not allow for frequency variation and it consists of a vibrating table, not a vibrating compactor. Thus a laboratory vibratory soil compactor was designed based on a model presented by Thompson and Dunlap (30).

This compactor consists of two counter-rotating synchronized disks mounted on bevel gears, all enclosed in an aluminum casing. The gears are driven by a variable speed fractional horsepower electric motor. A solid shaft extends from the bottom of the compactor so that interchangeable feet may be attached to it (Figure 16).

The compactor has been specially designed so that four variables may be controlled and thus analyzed. These variables are frequency of vibration, static weight, eccentric moment (dynamic weight), and foot size.

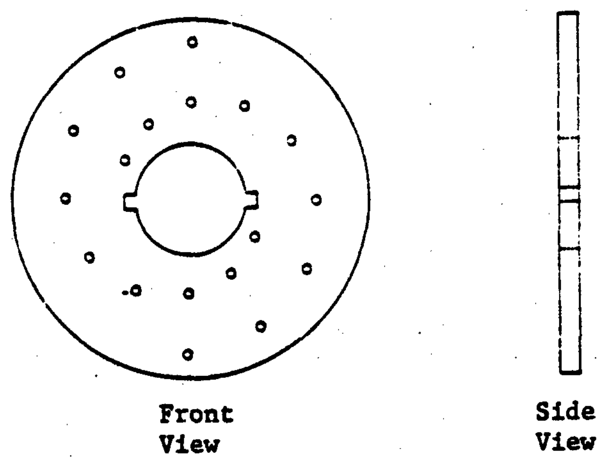
The motor is a one-half horsepower universal (AC-DC) electric motor with a maximum frequency of 10,000 rpm. It is operated with the aid of a variable speed controller which allows motor frequency ranges of 500 rpm to 7,000 rpm and at maximum frequency.

The counter-rotating disks are set with thread wells so that various combinations of eccentric weights and lever arm lengths may be analyzed. Two types of disks have been developed - a disk with spiral threads placed along its flat side and a disk with radial threads placed along the width of the disk (Figure 17).

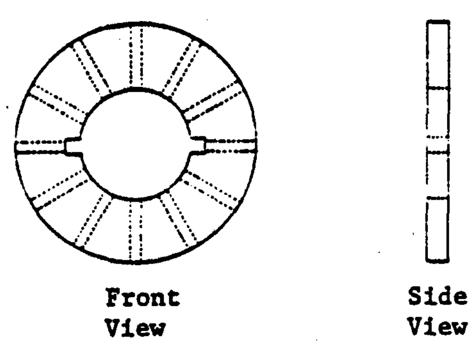



Scale: 1" = 2-1/4" (Approx) (with only one Rotating Disk)
(1" = 25.4 mm)

Figure 16. Details of the Laboratory Vibratory Compactor.




a. Spiral Disk




Scale: 1" = 2-1/4" (Approx)
(1" = 25.4 mm)

b. Radial Disk

Figure 17. Counter-Rotating Disks for Vibratory Compactor.

Three different attachable feet have also been fabricated - two flat circular feet of five and two inch (127 mm and 50.8 mm) diameters and a one inch (25.4 mm) semi-circular foot (Figure 18). A five inch (127 mm) extension has been constructed to extend the length of the shaft from the base of the compactor to the foot so that additional static weights can be added along that shaft.

The static weight of the compactor, excluding the attachable static weights and speed controller is 17.8 pounds (8.07 kg).

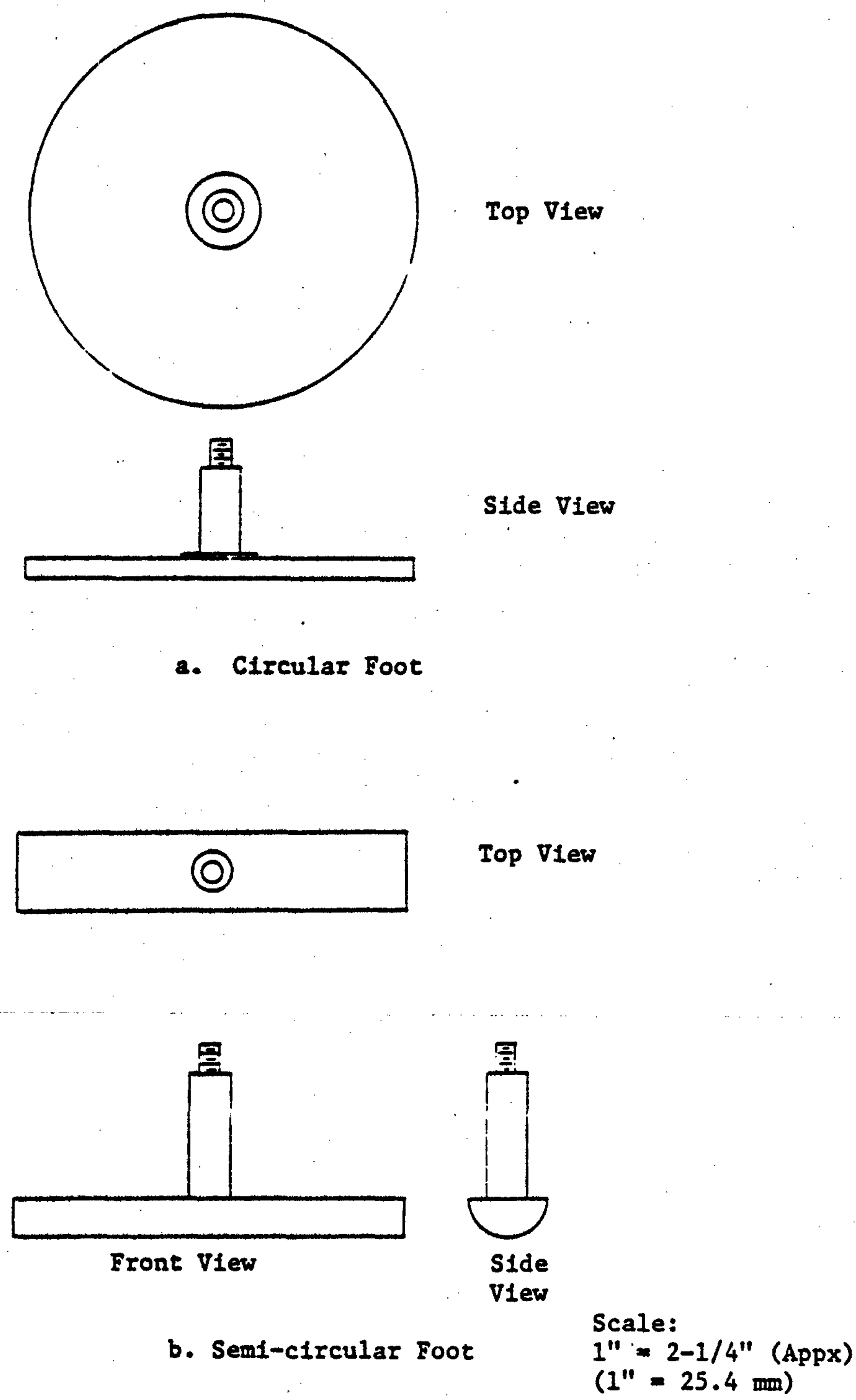



Figure 18. Attachable Feet for the Vibratory Compactor.

# EXPERIMENT DESIGN

The effectiveness of the vibratory soil compactor will be evaluated by comparing compaction data obtained from vibratory methods to results obtained using the standard Proctor compaction test.

## Description of the Soil

Three soil samples have been selected for evaluation - one sandy soil, one clayey soil and one silty soil. These soils were selected because of their similarity to desert soils.

Soil 1. Soil Classification - SP. This fine, uniformly graded beach sand is light brown colored with 80 percent of its grain sizes between 0.4 mm (#40 sieve) and 0.17 mm (#100 sieve) (Figure 19).

Soil 2. Soil Classification - ML. This brown, poorly graded soil, which was procured from WES, has a silt content of approximately 55 percent, based on a washed sieve analysis (Figure 20).

Soil 3. Soil Classification - CL. This whitish colored clay soil has a liquid limit of 45 percent and a plastic limit of 28 percent (Figure 21).

## Description of the Test Procedures

Soil Preparation. Soil preparation is to be performed in accordance with the procedures outlined in Reference 4.

Standard Compaction Method. The standard Proctor compaction method, as outlined in Reference 1, Method A, will be followed.

Vibratory Compaction Method. Each soil will be compacted in one layer, under controlled conditions, so that the four variables under

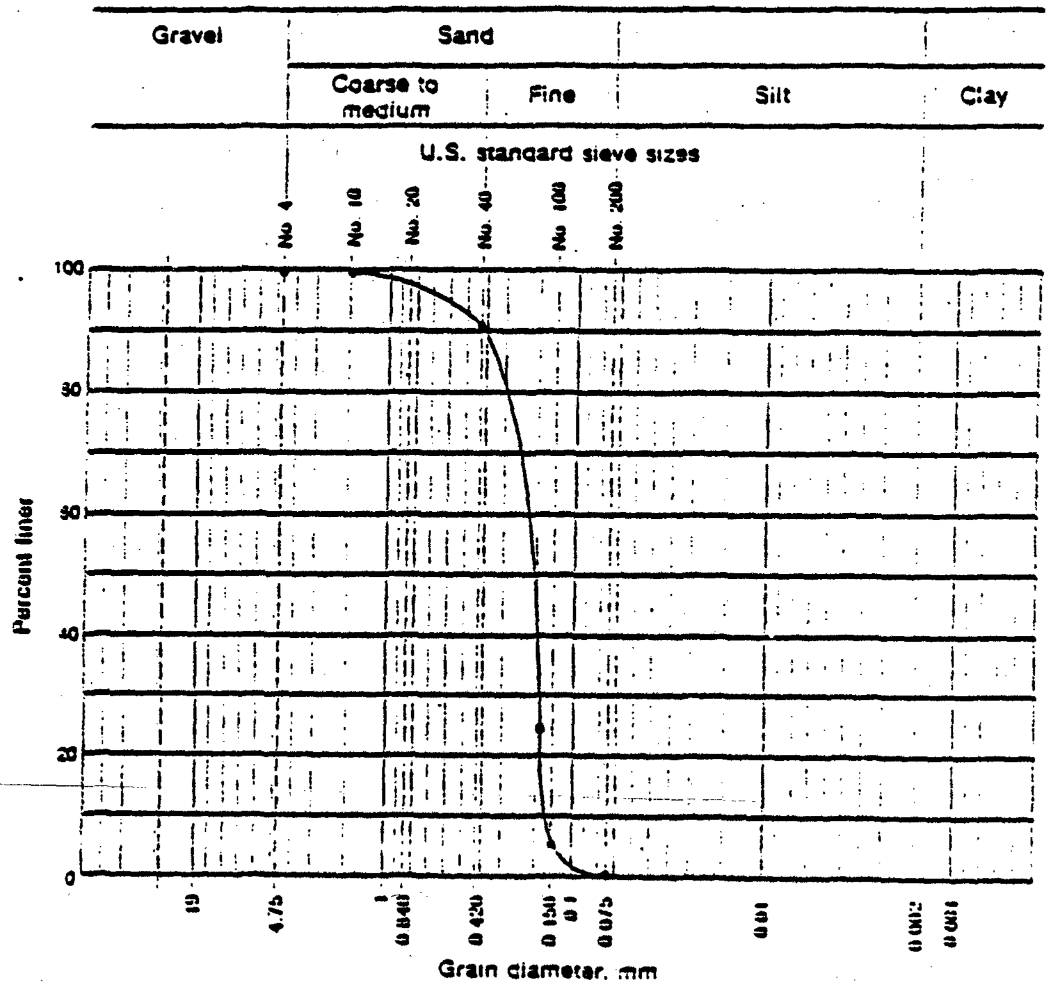



Figure 19. Mechanical Analysis Chart for Soil 1 (SP).

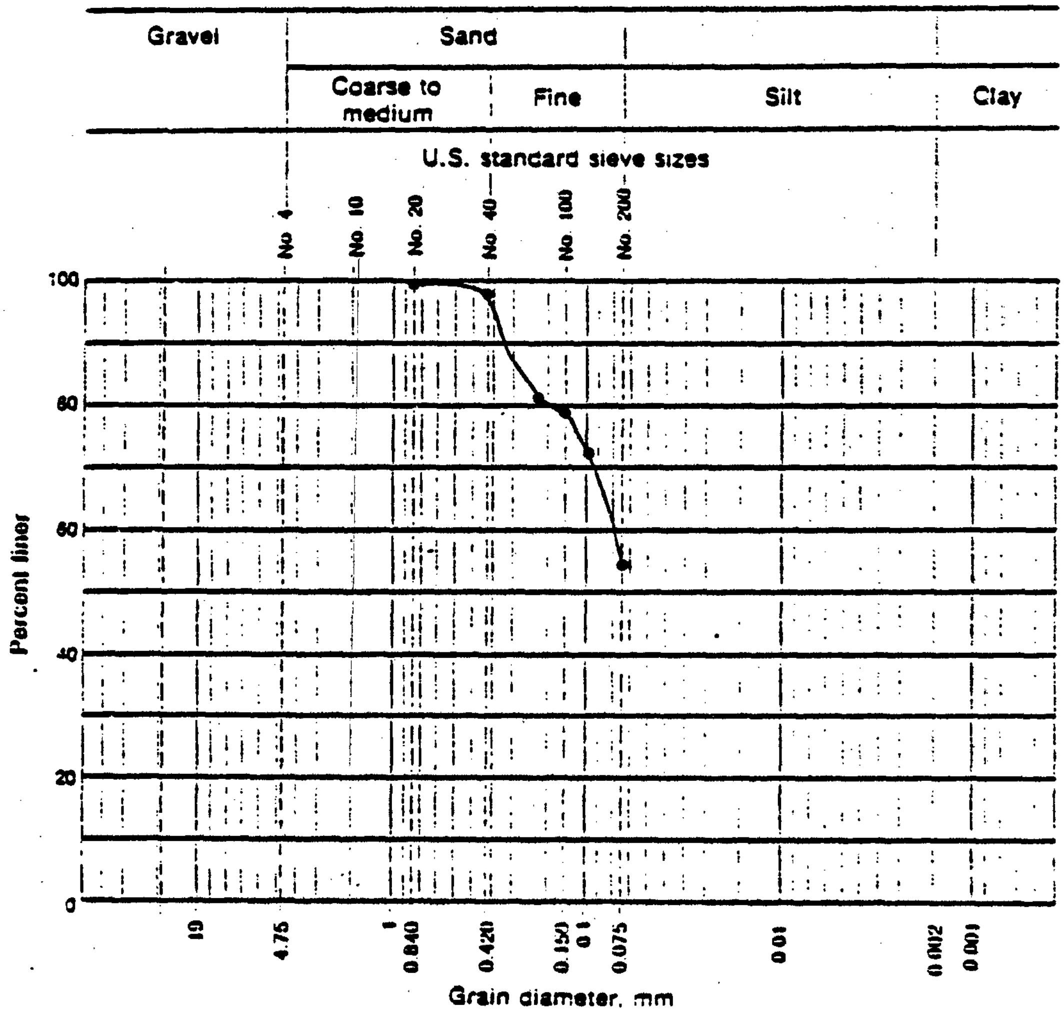



Figure 20. Mechanical Analysis Chart for Soil 2 (ML).

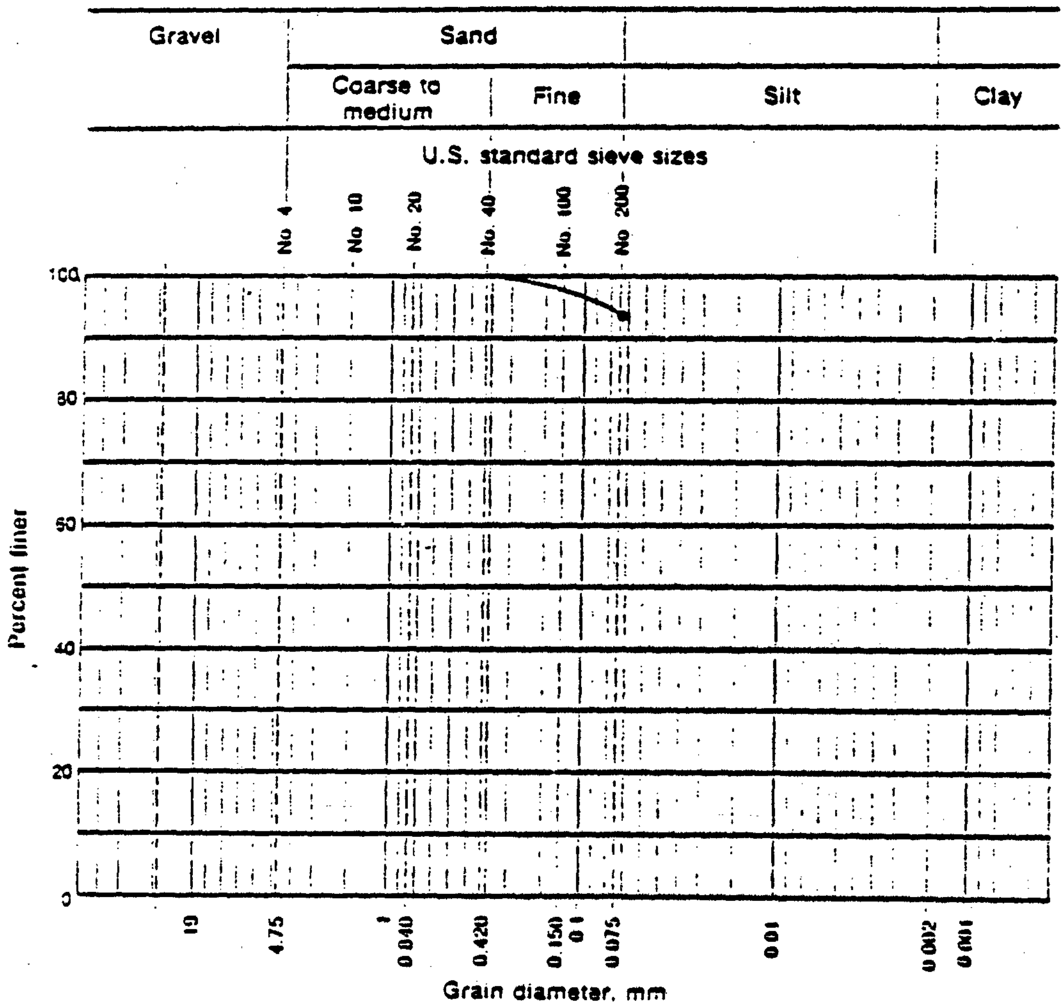



Figure 21. Mechanical Analysis Chart for Soil 3 (CL).

layer, under controlied conditions, so that the four variables under consideration may be analyzed. Each soil will be placed loose in a CBR mold by allowing it to flow freely from a scoop held at the top of the mold collar. The mold will have the two inch spacer inserted on top of the perforated base plate. An appropriate compaction time for each test will be determined and then maintained constant. The compactor will be moved inside the mold during the compaction process to ensure that the compactive effort is evenly distributed over the entire soil surface area. The compactor frequency will be set before the compactor is placed on the soil. The soil will be compacted with the mold sitting on a concrete floor. After compaction, the mold collar will be removed and the soil sample will be trimmed flush with the top of the mold for determination of total unit weight. The moisture content will also be taken so that the dry density can be calculated.

During the testing of each compactor parameter and its effect on compaction, only the parameter under investigation will be varied. For example, while testing for the effects of foot size on compaction, only the foot size will be allowed to vary, while the frequency, static weight, and soil moisture content will remain constant. Four combinations of foot size and shape will be investigated. Frequency ranges of 500 rpm to 3000 rpm and static weights of 18 lbs (8.17 kg) to 42 lbs (19.05 kg) will also be analyzed. Additionally, soil moisture contents dry of optimum will be analyzed.

# DISCUSSION OF RESULTS

Data obtained as a result of compacting each soil, using both Standard Proctor and Vibration methods are presented below.

## Standard Proctor Compaction Results.

Soil 1 (SP). The uniformly graded sand exhibits the one and one-half peak curve (Figure 22) discussed earlier. A maximum dry density of 107.5 pcf (17.09 kN/$m^3$) was obtained at a moisture content of approximately zero percent. The minimum dry density, 101.5 pcf (16.14 kN/$m^3$), was obtained at moisture contents of two to three percent. Beyond this minimum dry density as the moisture content was increased up to its limiting moisture content of 10% (the point at which water was forced from the soil due to the compaction process), the dry density increased to a maximum value of approximately 105 pcf (16.70 kN/$m^3$). At higher moisture contents dry densities were erratic. Therefore, impact compaction of this sand yields a maximum dry density near zero moisture content. These results were not unexpected for this type of material.

Soil 2 (ML). The optimum moisture content for this silty soil is 13.5 percent with a maximum dry density of 113.0 pcf (17.97 kN/$m^3$) (Figure 23). This soil also exhibits a one and one-half peak compaction curve. However, unlike the sand, its half-peak dry density of 103.0 pcf (16.38 kN/$m^3$) is much less than its maximum dry density at optimum moisture content. This nonplastic soil conforms to the compaction curve concepts presented by Lee and Suedkamp (19). As with the sand, the minimum dry density was obtained at moisture contents of

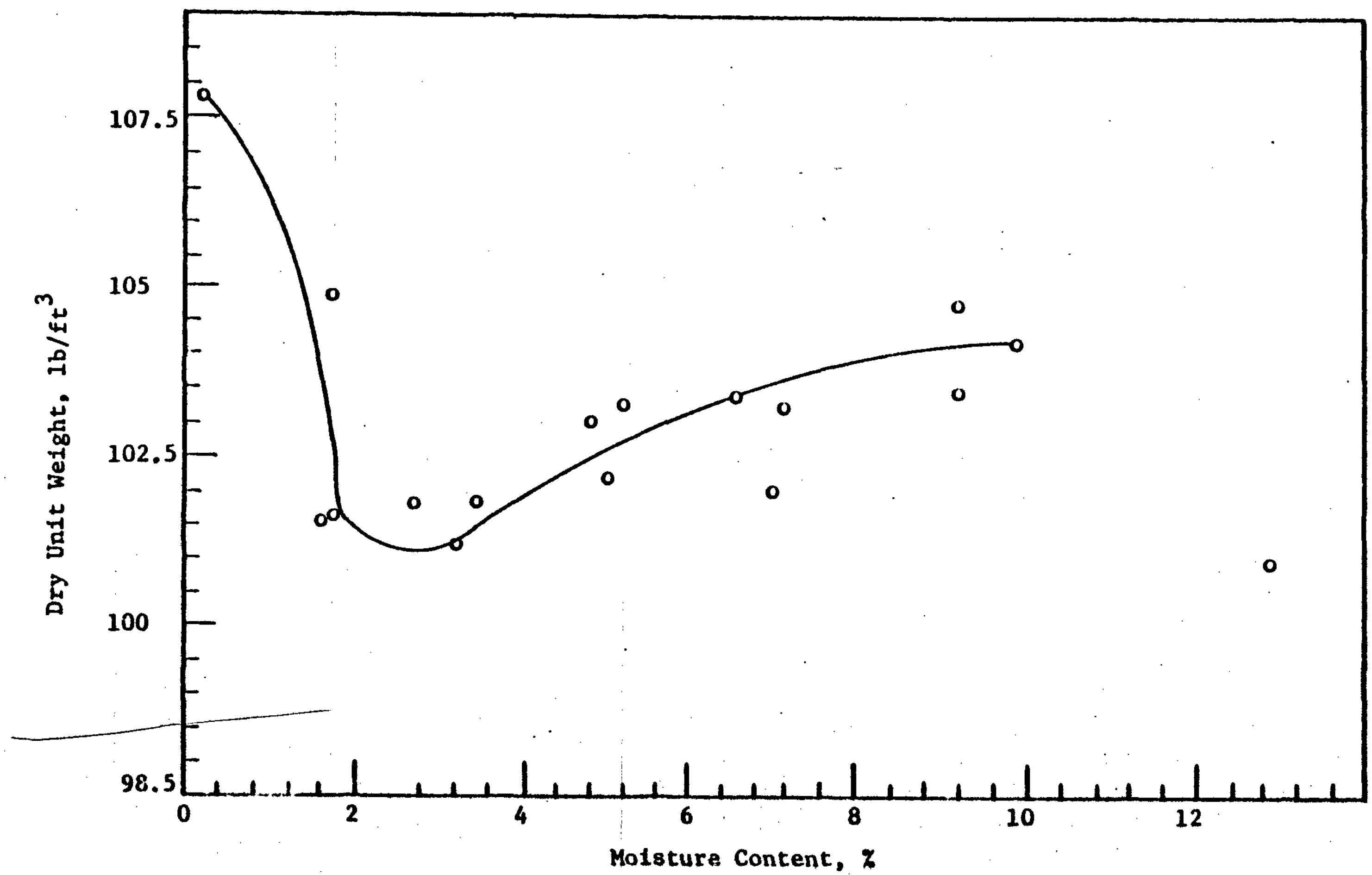



Figure 22. Standard Compaction Curve for Soil 1 (SP).
(1 lb/ft$^3$ = 0.159 kN/m$^3$)

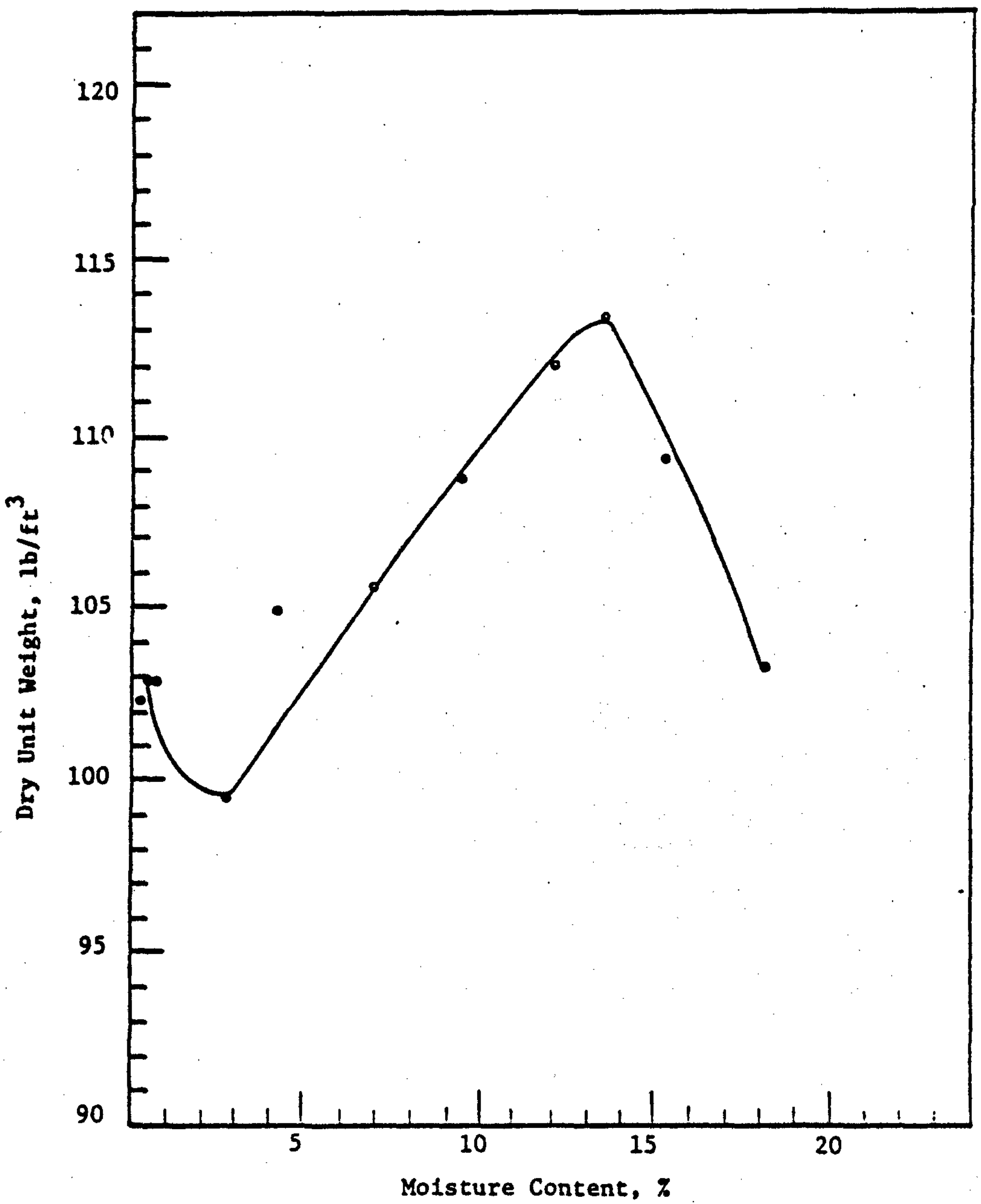



Figure 23. Standard Compaction Curve for Soil 2 (ML).
(1 lb/ft$^3$ = 0.159 kN/m$^3$)

two to three percent.

Soil 3 (CL). This clayey soil exhibits a double-peak compaction curve (Figure 24). It has a maximum dry density of 104.5 pcf (16.62 $kN/m^3$) at a moisture content of 19% and another high dry density of 103.0 pcf (16.38 $kN/m^3$) at 7% moisture content. With a liquid limit of 45%, this CL material does not conform to compaction curve concepts presented by Lee and Suedkamp (19).

During compaction of both the ML and CL at high moisture contents, the impact of the rammer left holes in the trimmed sample up to one-half inch in depth. These holes were refilled by hand before the unit weight was determined. Compaction of all samples at low moisture contents caused some soil to be ejected from the mold each time the rammer dropped. This soil was also replaced.

## Vibratory Compaction Results

Except for the moisture content variation tests, each soil was compacted in an air-dried state. This resulted in moisture contents of 0.2%, 1.2%, and 4.2% for the beach sand, silt, and clay soils, respectively.

Standardization of Compaction Time. To determine a constant time of compaction for each test, several soil samples were compacted and the amount of time required to achieve one-half inch of settlement for various frequencies was recorded.

The beach sand turned out to be the controlling soil since it took the longest time to yield the desired amount of settlement. The results of the test are presented in Figure 25. Most of the compaction

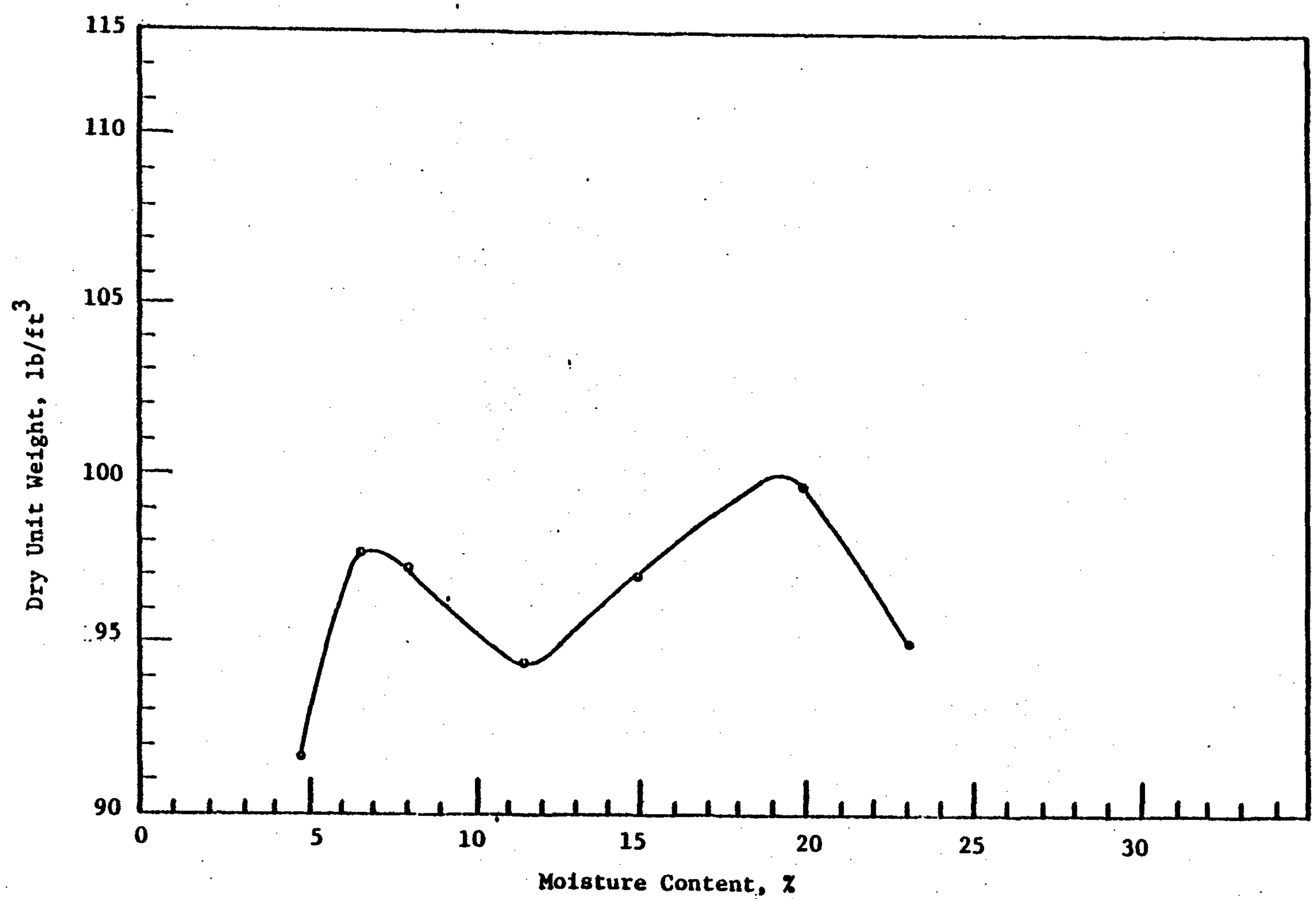



Figure 24. Standard Compaction Curve for Soil 3 (CL). (1 lb/ft$^3$ = 0.159 kN/m$^3$).

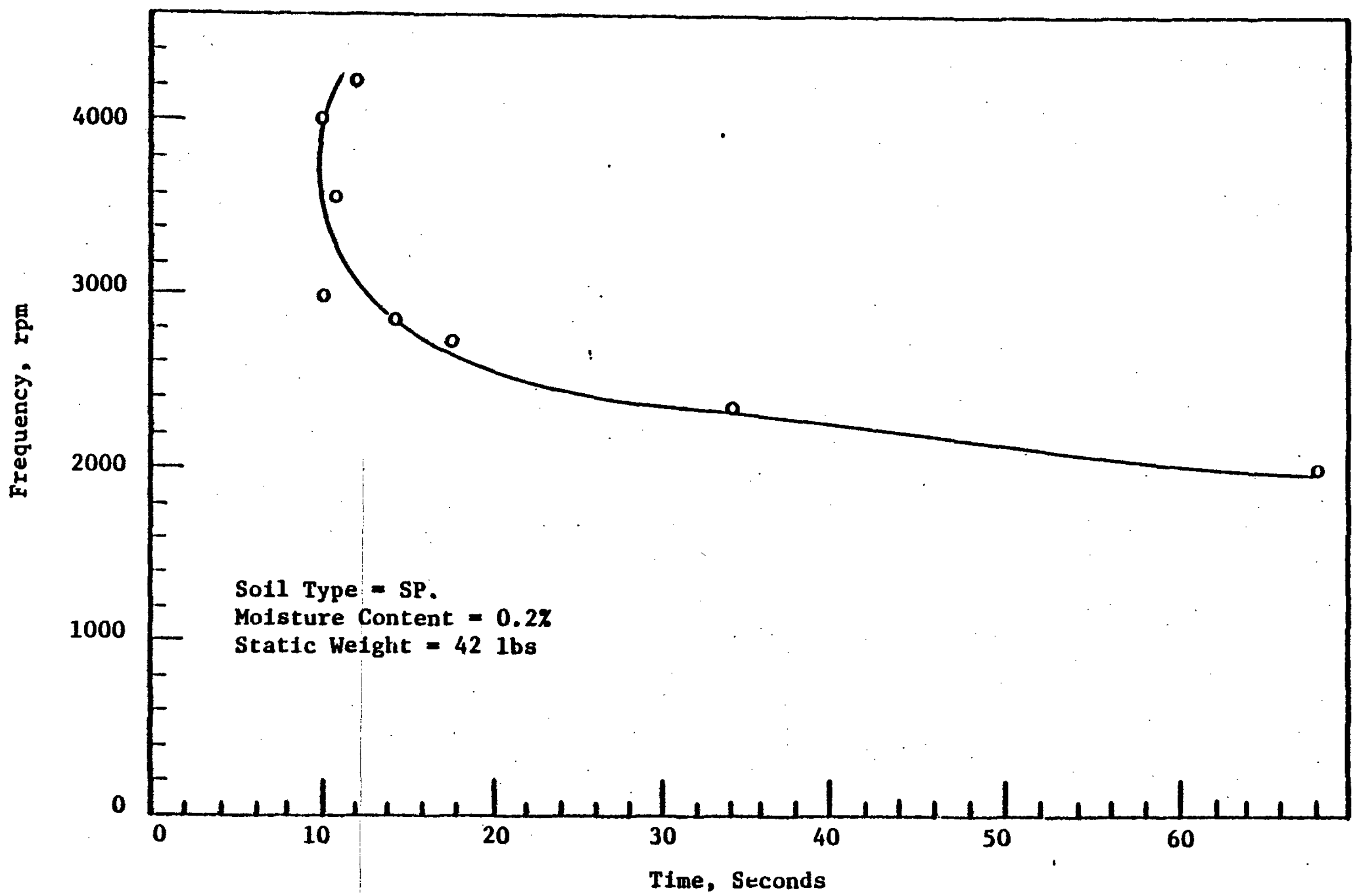


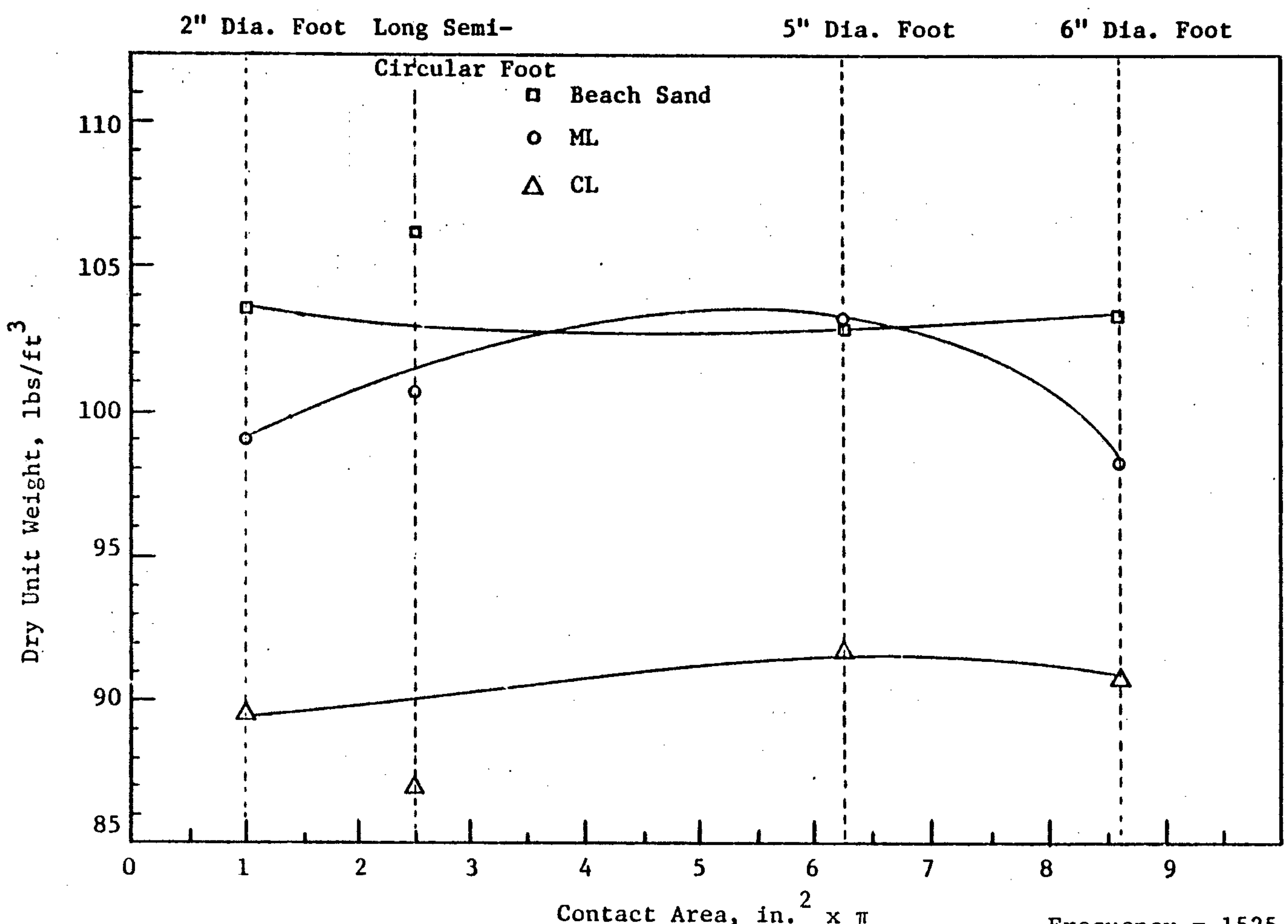

Figure 25. Effect of Frequency Variation on the Time Required to Achieve 1/2 inch (12.7 mm) of Settlement. (1 lb = 0.454 kg)

occurred within the first 20 seconds of application of the vibratory compactor for frequencies greater than 2000 revolutions per minute. For smaller frequencies, no compaction time would yield the desired amount of settlement. Based on the test results, a compaction time of 30 seconds would seem practical. However, ASTM recommends eigh minutest of vibration at 60 Hertz (3600 cycles per minute) for maximum density tests on granular soils and Mehdiratta and Triandafilidis recommend two minutes of vibration at various frequencies depending on the soil being compacted (31). Since most of the compaction tests were to be conducted with a large eccentric weight, 0.2 pounds (90.72 g), a compaction time of 60 seconds was selected as a reasonable compromise. This time also allows for maximum control of the distribution of the compactive effort throughout the soil, while minimizing the operation and wear on the compactor.

Analysis of Foot Size and Shape Effects

Selection of Variables. In addition to a compaction time of one minute and the use of large eccentric weights, the static weight of the compactor was arbitrarily set at 42 lbs (19.05 kg), the maximum possible weight. A frequency of 1525 rpm was selected since it yields a dynamic force of approximately 42 lbs (19.05 kg), thus balancing the static and dynamic forces as suggested by Converse (8).

Compaction Results. The data obtained from the analysis of foot size/shape effects on the compaction of each of the soil samples are contained in Figure 26. The results are portrayed in terms of the contact area of the compactor foot, but for the long semi-circular foot




Frequency = 1525 rpm
Static Weight = 42 lbs
Dynamic Force = 41 lbs

Figure 26. Foot Size Effects on Compaction of Various Soils. (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg; 1 in. = 25.4 mm)

the contact area is actually unknown since it depends on the depth of embedment of the foot. In Figure 26, the contact area for this foot is shown assuming complete embedment. Note that the curves are not drawn through the points for this foot since its location may be in error.

As indicated by the figure, changing the size of the circular foot had no significant effect on the degree of compaction of the beach sand or clay soil. For the variables tested the dry unit weights obtained for the beach sand were approximately 103.5 pcf (16.46 $kN/m^3$), and for the clay, 90.5 pcf (14.39 $kN/m^3$). The dry silty soil compacted best with a 5 inch (127 mm) diameter foot for a dry density of 103.0 pcf (16.38 $kN/m^3$). The low dry density for the silt, 98.5 pcf (15.66 $kN/m^3$), was obtained with both the 2 inch (50.8 mm) and the 6 inch (152.4 mm) diameter foot. The semi-circular foot produced the highest degree of compaction in the sand, the lowest compaction in the clay and had an intermediate effect in the silt.

As with all the tests on the silty and clayey soils, during the initial stages of compaction, the static compactor weight exceeded the soil's bearing capacity and the operator was required to gradually allow the compactor's weight to be transferred to the soil as the degree of soil compaction increased.

Discussion. In comparison to the maximum dry unit weights obtained using the Standard compaction test (Figure 22,23,24, pp. 53, 54,56), only the semi-circular foot yielded comparable unit weights for the dry beach sand. Compaction with any of the other feet tested yielded dry unit weights approximately equal to those of the Standard compacted soil at its limiting moisture content (p. 52). Therefore, it appears that compaction of the dry sand using vibratory methods will yield, a dry density equal to or greater than that obtained at the limiting moisture content using Standard compaction methods.

In contrast, for the silty and clayey soils, none of the feet tested yielded dry unit weights close to those obtained with the Standard compaction method.

Overall, especially for the beach sand and clay soils, the results tend to suggest that for the circular feet an increase in the contact area (and a decrease in the pressure exerted on the soil) has little effect on the compaction of the soil. However, this is not totally correct since the soil is more confined and less disturbed as the contact area increases. The data for this test yield inconclusive results as to which foot is best for compaction purposes. Since a foot must be selected in order to test the other variables, the 5 inch (127 mm) diameter foot was selected because it minimally disturbs the soil without totally confining it. The long semi-circular foot was also used for some of the tests on the beach sand since it yielded the highest dry density for that soil.

## Analysis of Frequency Effects

Selection of Variables. Initially, a compactor static weight of 42 lbs (19.07 kg) with an eccentric weight of 0.2 lbs (90.7 g) and an eccentricity of 1.5625 (39.68 mm) inches was selected. Both the long semi-circular foot and the 5 inch (127 mm) diameter foot were used to compact the sand, while only the latter was used to compact the silty and clayey soils. Subsequently, the compactor static weight was varied from 18 lbs (8.17 kg) to 42 lbs (19.07 kg) and the frequency effects at those static weights were evaluated as well.

Compaction Results. The results of the frequency tests on the sand are presented in Figure 27. As can be observed from the figure, for both feet tested, as the frequency increased, so did the dry unit weight. In contrast to the previous results, it appeared to make little difference which foot was used. Dry unit weights in excess of 110 pcf (17.49 kN/m$^3$) were obtained at frequencies greater than 2500 cycles per minute. The sandy soil was also compacted using the long semi-circular foot with a static weight of 18 lbs (8.17 kg). A comparison of the 18 lb (8.17 kg) and 42 lb (19.07 kg) static weight results are shown in Figure 28. In contrast to the results obtained with the 42 lb (19.07 kg) static weight, the dry density reached a maximum of approximately 107.0 pcf (17.01 kN/m$^3$) at 1000 rpm; any further increase in frequency beyond this point had no effect on compaction.

The beach sand was again compacted with the 5 inch (127 mm) diameter foot at additional vibrator static weights of 18 lb (8.17 kg), 20 lb (9.08 kg) and 29 lb (13.17 kg). The test results are shown in Figure 29. These results indicate that the dry densities obtained with an 18 lb (8.17 kg) and 20 lb (9.08 kg) vibrator reach a peak at frequencies of approximately 2300 rpm. For a static weight of 29 lb (13.17 kg), the dry unit weight versus frequency curve is nearly

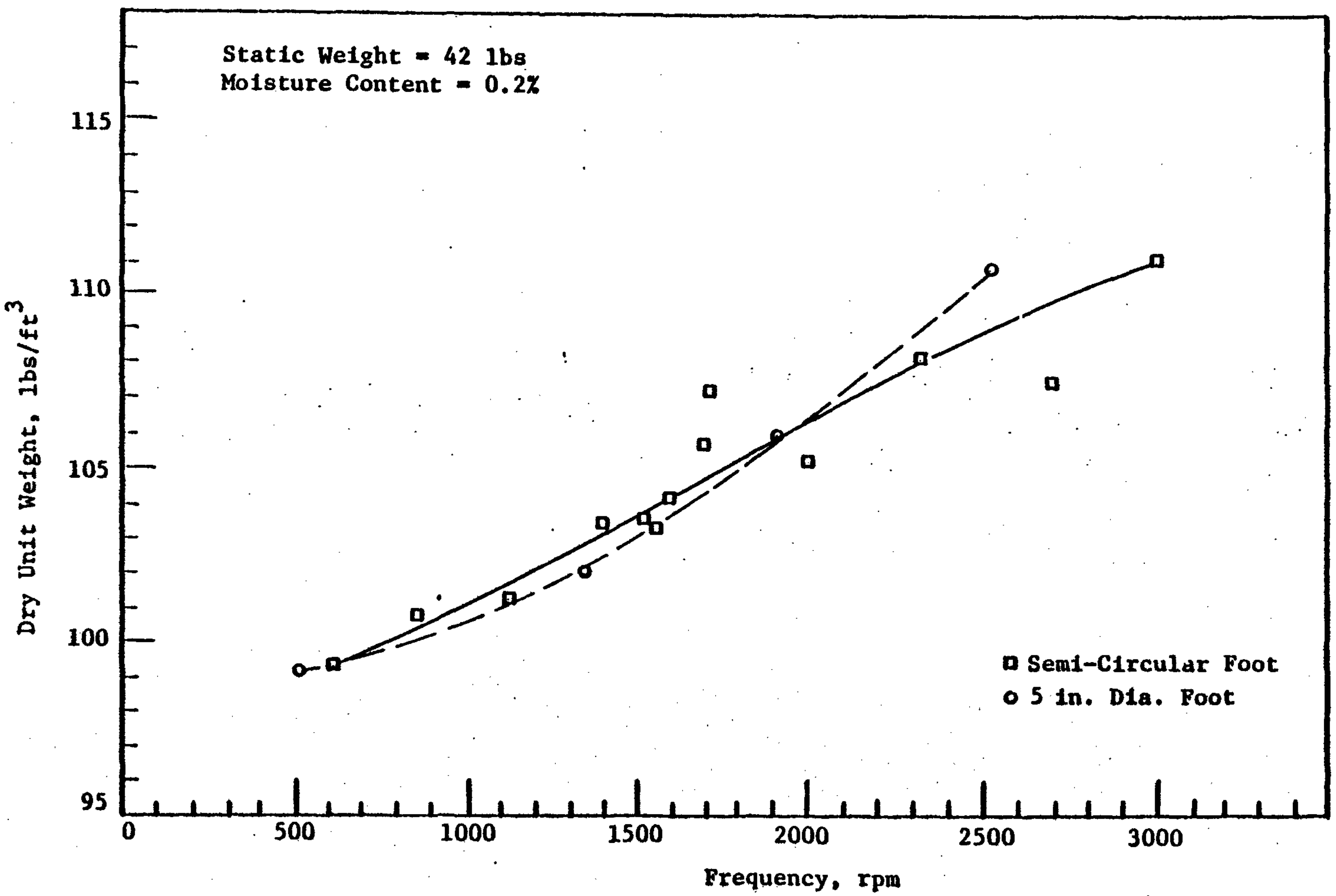



Figure 27. Effect of Frequency on the Compaction of Soil 1 (SP) Using Two Different Feet. (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg; 1 in. = 25.4 mm)

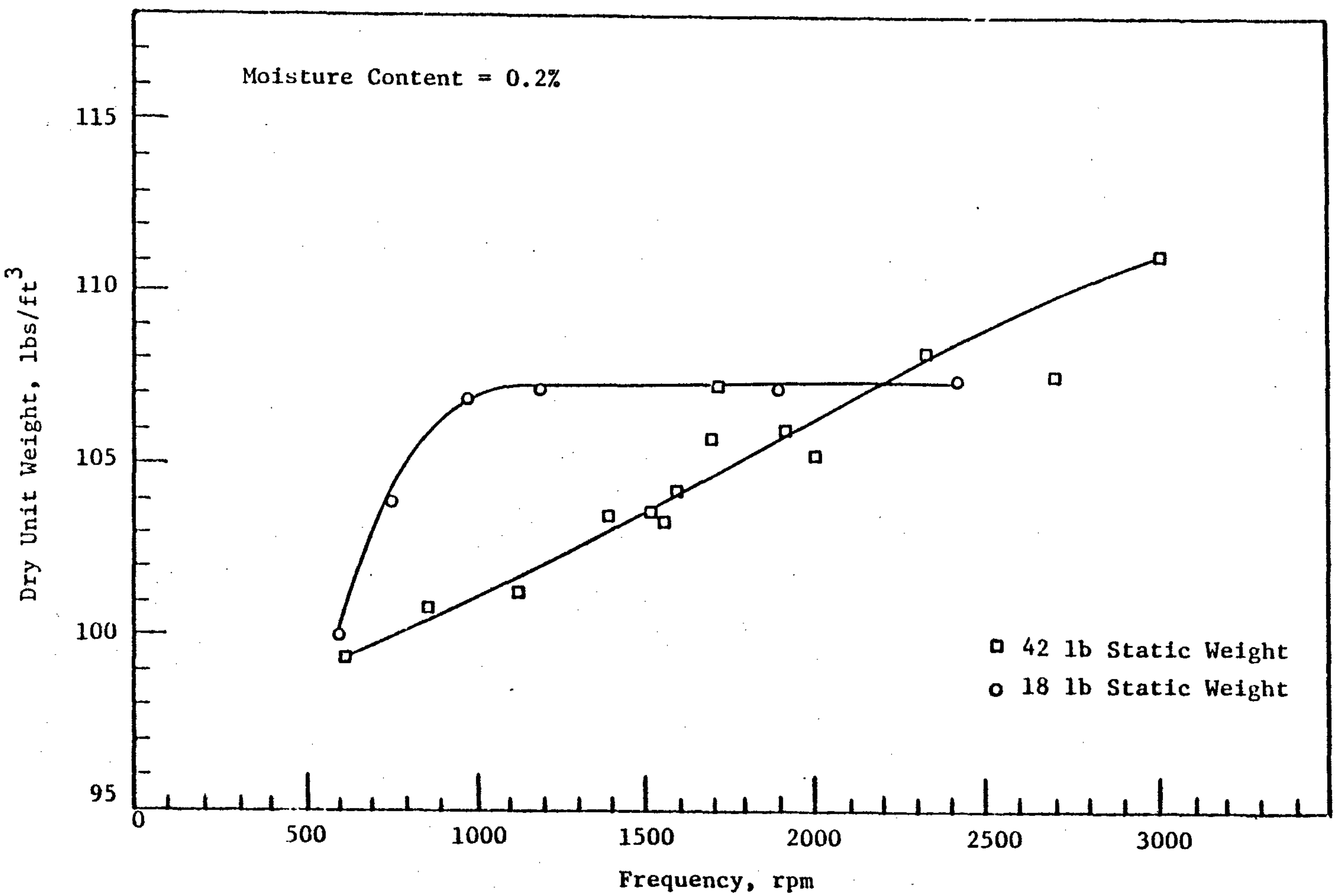



Figure 28. Effect of Frequency on the Compaction of Soil 1 (SP) Using the Semi-Circular Foot with Various Static Weights. (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg)

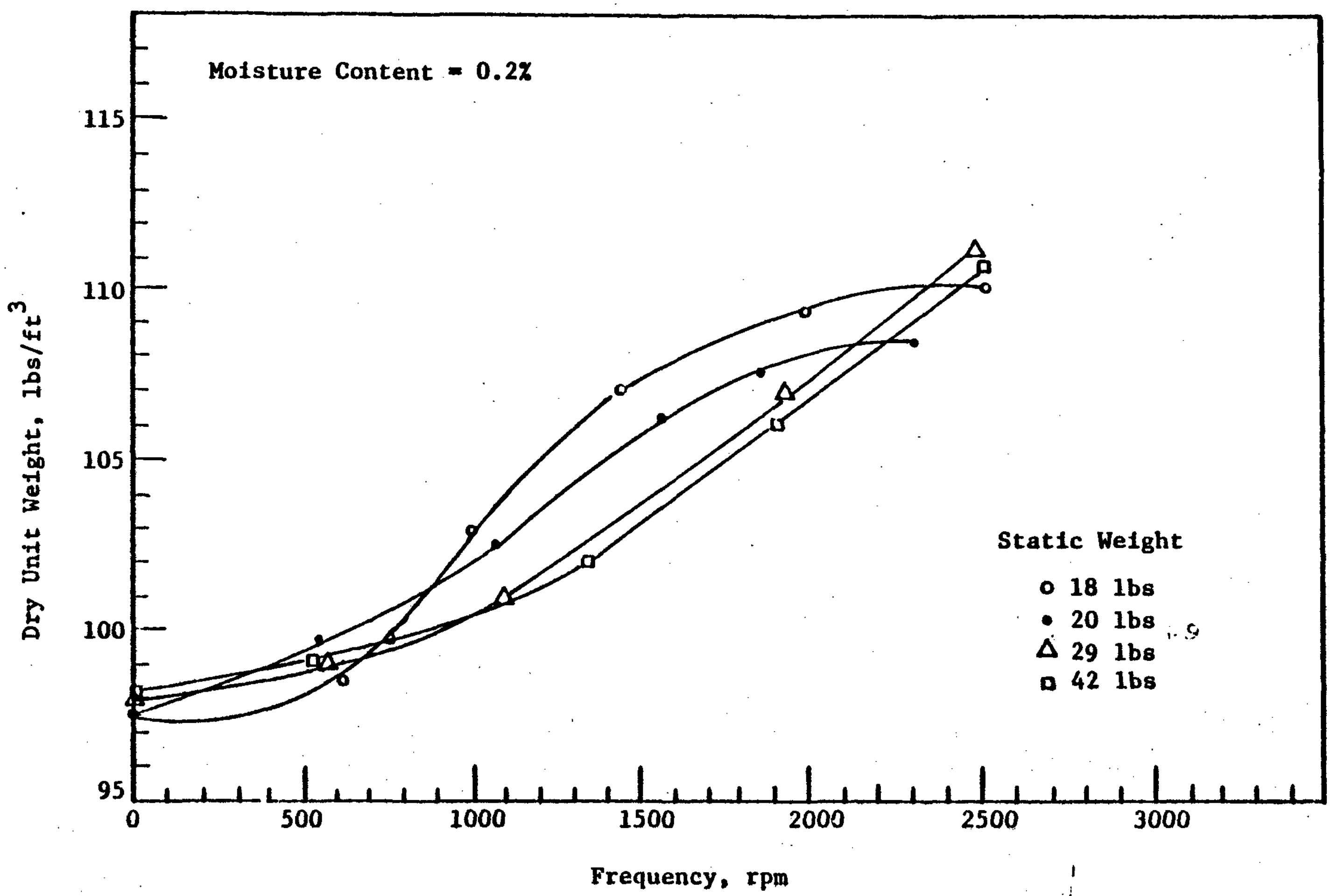



Figure 29. Effect of Frequency on the Compaction of Soil 1 (SP) Using the 5 Inch Diameter Foot at Various Static Weights. (1 lb/ft$^3$ = 0.159 kN/m$^3$ ; 1 lb = 0.454 kg; 1 in. = 25.4 mm)

identical to that obtained with the 42 lb (19.07 kg) vibrator static weight. In both cases the dry density increases with increasing frequency, but a peak or optimum frequency was not reached. These curves also indicate how much compaction is attributed to static weight alone. The loose dry unit weight fcr this soil waas 97.2 pct (15.45 kN/m$^3$). Static weight compaction produced 0.5 to 1.0 pcf (0.0795 to 0.159 kN/m$^3$) increases in unit weight.

The results of the frequency tests on the silty and clayey soils are presented in Figures 30 and 31, respectively. Each soil was compacted with vibratory compactor static weight of 18 lbs (8.17 kg) and 42 lbs (19.07 kg). In each of the four cases, a maximum dry density was obtained in the approximate range of 1500-2000 rpm. For the silty soil, maximum dry unit weights of 107.0 pcf (17.01 kN/m$^3$) and 102.0 pcf (16.22 kN/m$^3$) were obtained with vibrator static weights of 18 lbs (8.17 kg) and 42 lbs (19.07 kg), respectively; for the clayey soils, maximum dry unit weights of approximately 95.0 pcf (15.11 kN/m$^3$) and 93.0 pcf (14.79 kN/m$^3$) were obtained with vibrator static weights of 18 lbs (8.18 kg) and 42 lbs (19.07 kg), respectively. The loose dry unit weight of the silty soil was 87.1 pcf (13.85 kN/m$^3$) and for the clayey soil, 76.0 pcf (12.08 kN/m$^3$).

No frequency checks of greater than 3000 cycles per minute were conducted since the compactor became unbalanced and uncontrollable at approximately 3000 rpm.

Discussion. The results of Figure 27 suggest that good compaction can be obtained with either the long semi-circular foot or the 5 inch (127 mm) diameter foot. Using either foot and vibrator static weight

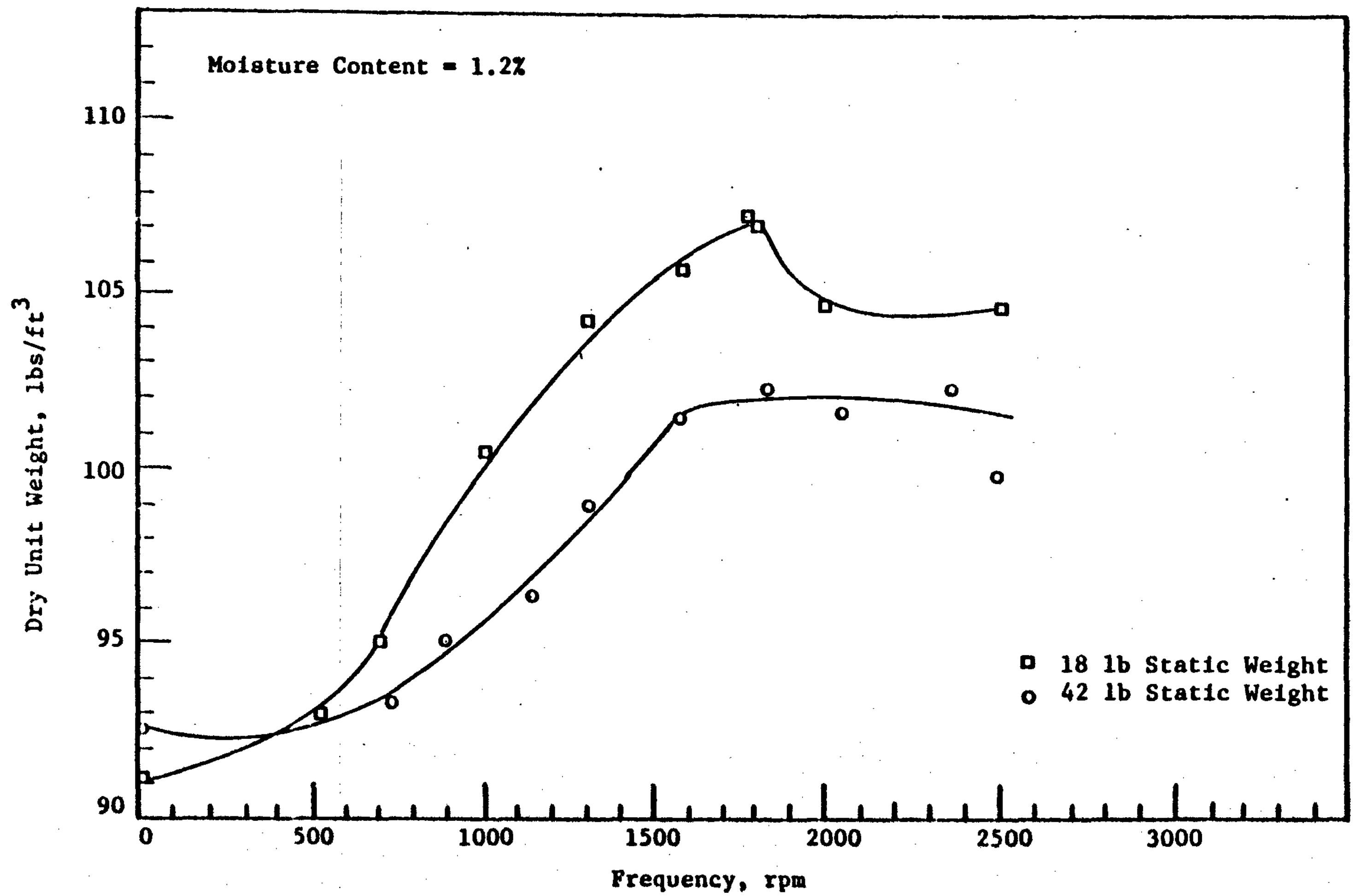



Figure 30. Effect of Frequency on the Compaction of Soil 2 (ML) at Various Static Weights. (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg)

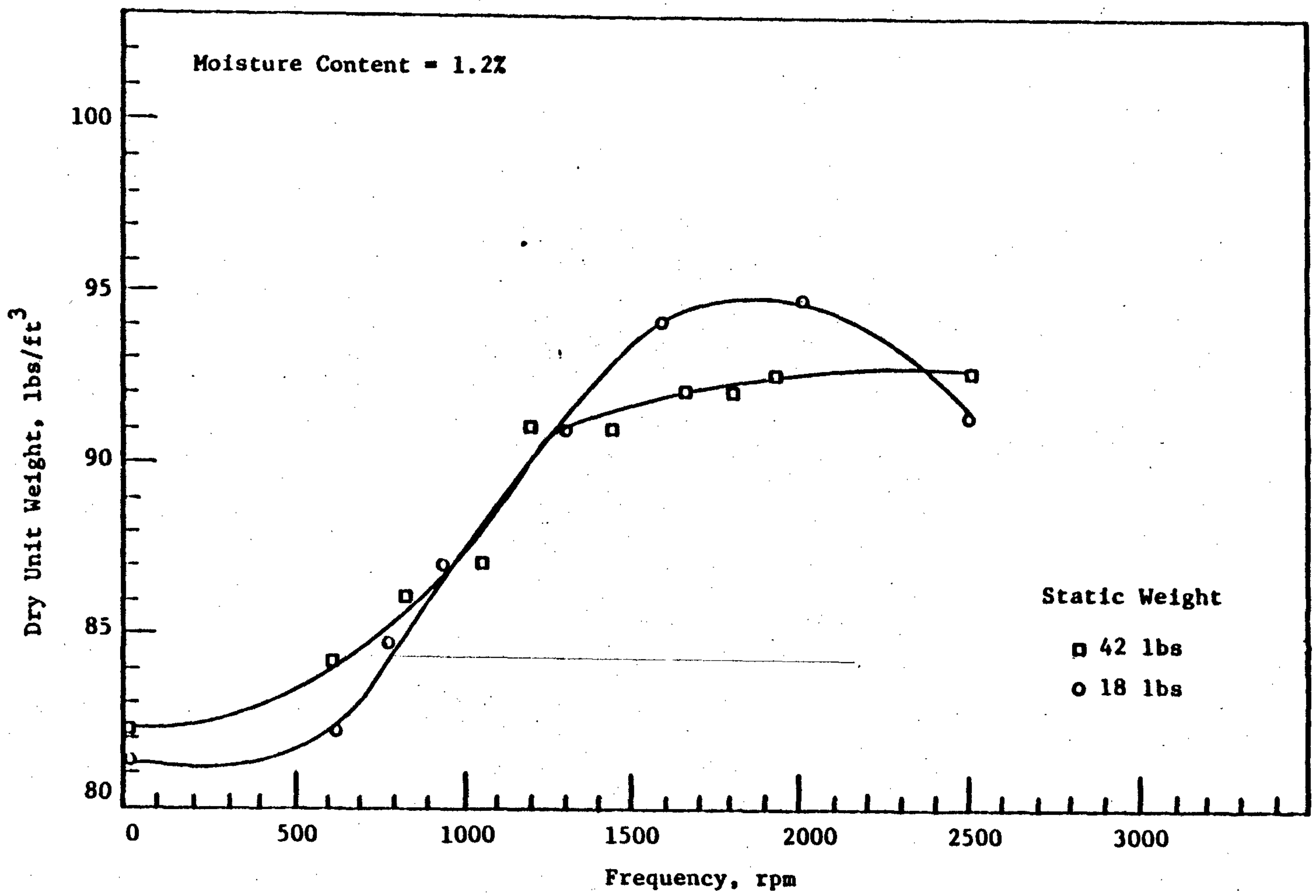



Figure 31. Effect of Frequency on the Compaction of Soil 3 (CL) at Various Static Weights. (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg)

of 42 lbs (19.07 kg), the dry unit weight of the sand increased as the frequency increased. However, Figure 28 indicates that if the long semi-circular foot is used in conjunction with a light vibrator weight of 18 lbs (8.17 kg), then a more rapid increase in dry unit weight results for frequencies up to 1000 rpm. Incidentally, 1000 rpm is the point at which the dynamic force is roughly equal to the vibrator static weight. This is also the point where the maximum dry density, 107.5 pcf (17.09 kN/m$^3$), is obtainable for this compactor configuration. In contrast, the heavier 42 lb (19.07 kg) vibrator with semi-circular foot doesn't yield this density until it operates at approximately 2300 rpm. Similarly, the circular foot vibrator with a lighter static weight also tends to yield higher dry densities at the lower freqencies.

A similar relationship was also observed for the silty soil (Figure 30), except that the maximum dry unit weight does not approximate that obtained using Standard compaction methods. Additionally, throughout the range of frequencies evaluated, the lighter 18 lb (8.17 kg) vibrator always gave dry unit weights significantly greater than the heavier 42 lb (19.07 kg) vibrator.

In the case of the clayey soil, the maximum dry density was also much lower than that obtained with Standard compaction methods (Figure 31). Unlike the earlier test results on sands and silts, the lighter and heavier vibrators yielded mixed results. At frequencies less than 900 rpm, the heavier vibrator tends to give higher dry densities and the opposite was true for frequencies of 1300-2400 rpm. Between 900 and 1300 rpm, each gave equal compaction results.

In general, the greater dry densities were achieved with the lighter weight compactor at the lower frequencies (less than 2500 rpm). This is due, in part, to a larger vertical foot displacement. Additionally, as the frequency was increased, the number of oscillations per unit of time was increased. As a result, the compactor was able to yield dry densities for sand greater than those obtained with Standard compaction methods. However, in the case of silty and clayey soils, vibratory compaction was deficient in matching the maximum dry unit weights obtained with the Standard method. The maximum dry densities of the silt and clay soil obtained with vibration, however, did approximate or exceed the Standard Compaction dry densities for that particular moisture content. For example, the dry density of the silty soil at one percent moisture was approximately 103.0 pcf (16.38 kN/m$^3$); the maximum dry density obtained with vibration was 107.0 pcf (17.01 kN/m$^3$). The Standard compaction dry density of the clay soil at 4% moisture was 96.5 pcf (15.34 kN/m$^3$); vibratory compaction yield a dry density of approximately 95.0 pcf(15.11 kN/m$^3$). The lower maximum dry densities for both the silty and clayey soils could be due to the low compactor weights and dynamic forces which were unable to overcome the effects of surface tension or cohesion in the soil.

## Analysis of Static Weight Effects

Selection of Variables. The eccentric weight and moment arm remain unchanged. Since vibrator static weights of 18 lbs (8.17 kg) to 42 lbs (19.07 kg) were to be evaluated, a dynamic force in the middle of this range, 29 lbs (13.17 kg), was selected so that data could be collected for static weights less than, equal to, and greater than the dynamic force. This dynamic force was obtained with a frequency of 1260 rpm.

Compaction Results. Figures 32, 33, and 34, are the results of the static weight tests on the sand, silt and clay soils. In the case of the sand and silt soils the highest dry unit weights were obtained with the lightest vibrator weight. At an 18 lb (8.17 kg) vibrator static weight, the beach sand had a dry density of 105.2 pcf (16.73 $kN/m^3$); the silt, 102.1 pcf (16.23 $kN/m^3$). The clay soil showed very little change in dry unit weight for the entire range of static weights evaluated, although a small increase did result at the higher static weights. Its dry density was approximately 92.0 (14.63 $kN/m^3$) pcf throughout the static weight range.

Discussion. It is obvious from the figures that the lighter compactor operating at a given frequency yields the best compaction results. As the compactor weight is increased, the dry density decreases or remains unchanged for both the silty and sandy soils. The clayey soil exhibits a slight increase in dry density with increasing vibrator weight. The higher densities at the lighter vibrator weights for the sand and silt may be attributed to an increased vertical foot displacement. The slight increase in density for the clay soil with increasing vibrator weight may be attributed to a larger vibrator force.

## Analysis of Moisture Content

Selection of Variables. A compactor static weight of 42 lbs

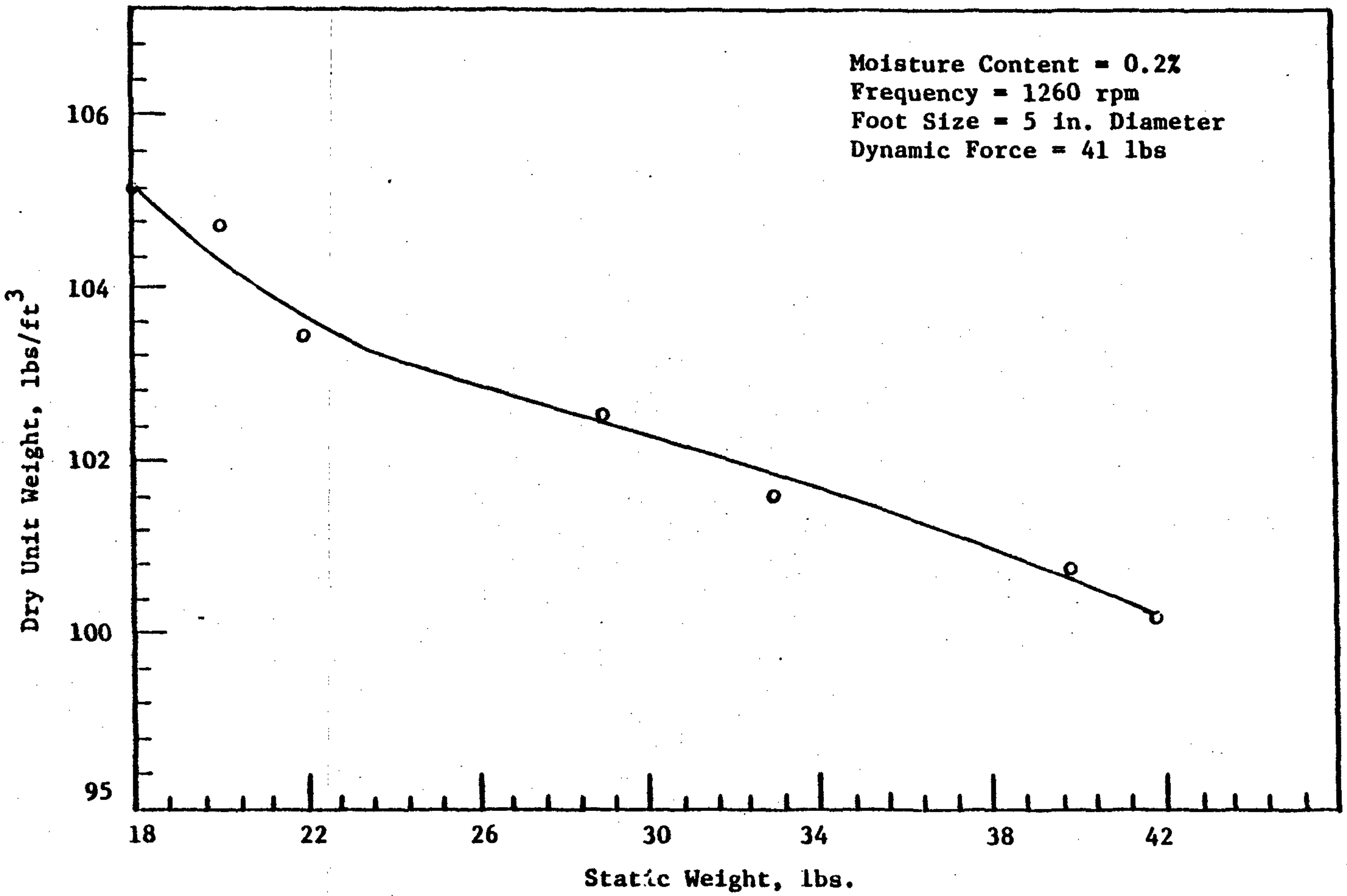



Figure 32. Effect of Static Weight on the Compaction of Soil 1 (SP). (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg; 1 in. = 25.4 mm)

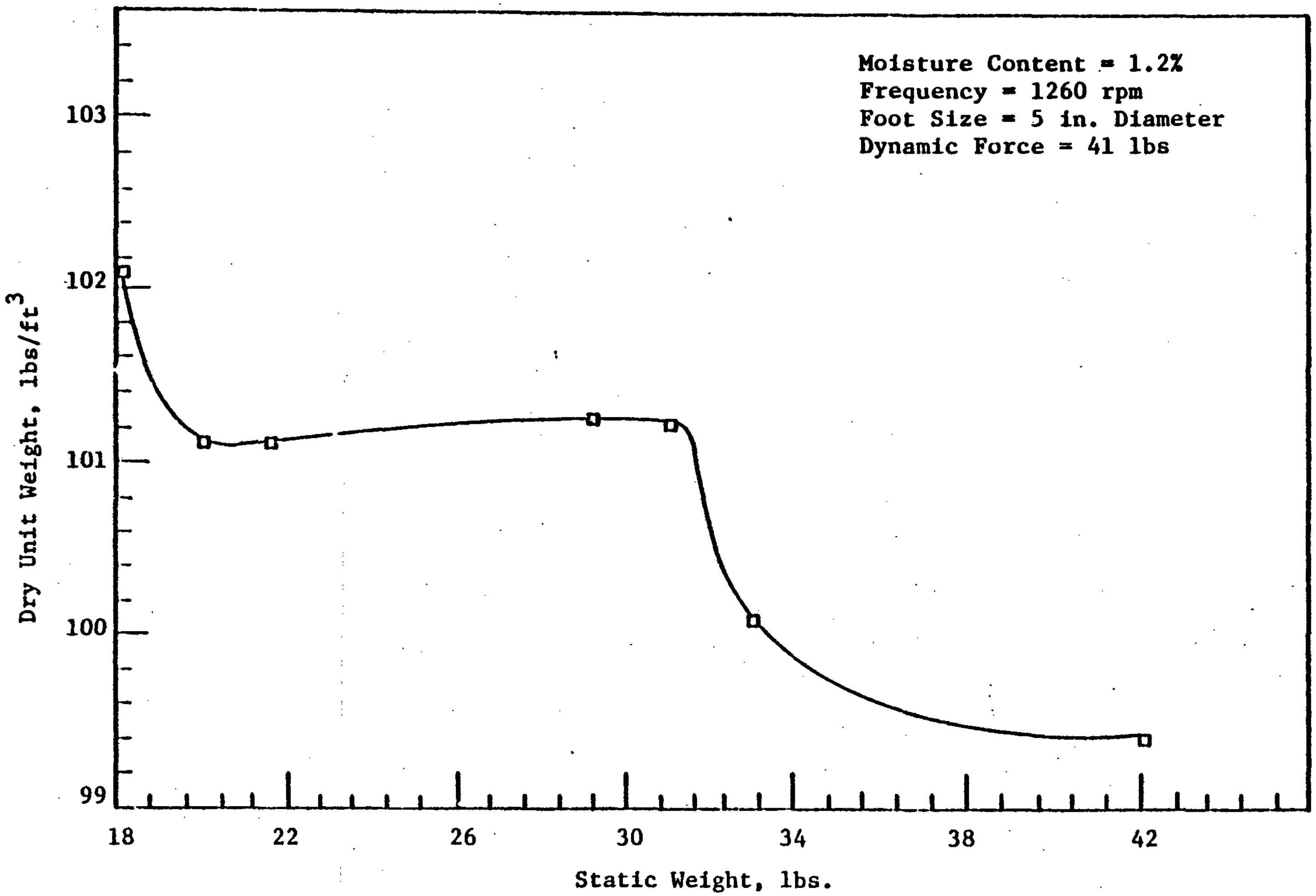



Figure 33. Effect of Static Weight on the Compaction of Soil 2 (ML) (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg; 1 in. = 25.4 mm)

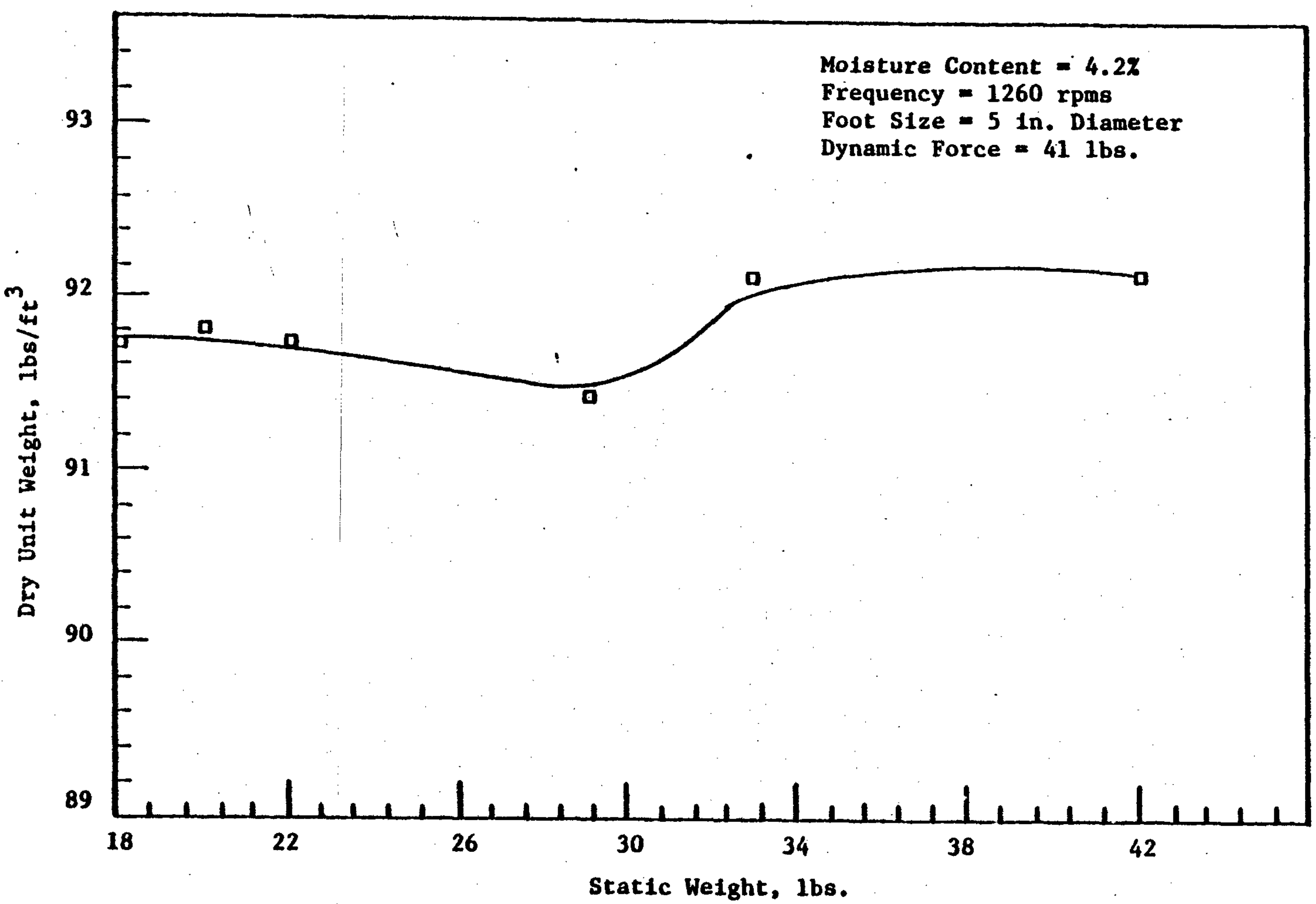



Figure 34. Effect of Static Weight on the Compaction of Soil 3 (CL)
($1\ lb/ft^3 = 0.159\ kN/m^3$; 1 lb = 0.454 kg; 1 in. = 25.4 mm)

(19.07 kg) with an eccentric moment of 0.2 lbs (90.8g) and an eccentricity of 1.5625 inches (39.688) was used for this test. A dynamic force of approximately 42 lbs (19.07 kg) was generated with a frequency of 1525 rpm. The 5 inch (127 mm) diameter foot was used for testing each soil. The moisture content was varied for each test.

Compaction Results. The results of this test are presented in Figures 35, 36, and 37. The dry density at the lower moisture content for each soil was extracted from previous tests. As can be seen from the figures, with slight increase in moisture content, each soil experienced a decrease in dry density. However, with the addition of more moisture the sandy soil's dry density remained constant at 98.5 pcf (15.66 $kN/m^3$), while the dry density for the silty and clayey soils decreased to a minimum and then increased, forming a generally U-shaped curve. Minimum densities for the silty and clayey soils were 87.5 pcf (13.91 $kN/m^3$) and 72 pcf (11.45 $kN/m^3$), respectively.

Discussion. None of the dry densities were approximately equal to those obtained with the Standard compaction method. This is due, in part, to low pressures being exerted on the soil by the vibrator. These pressures were not high enough to overcome the surface tension and cohesion in the soil. However, the general shape of the silt and clay compaction curves follow those obtained with the Standard compaction methods.

## Mathematical Modeling

In order to compare the effectiveness of impact versus vibratory compaction methods, a standard basis for comparison should be

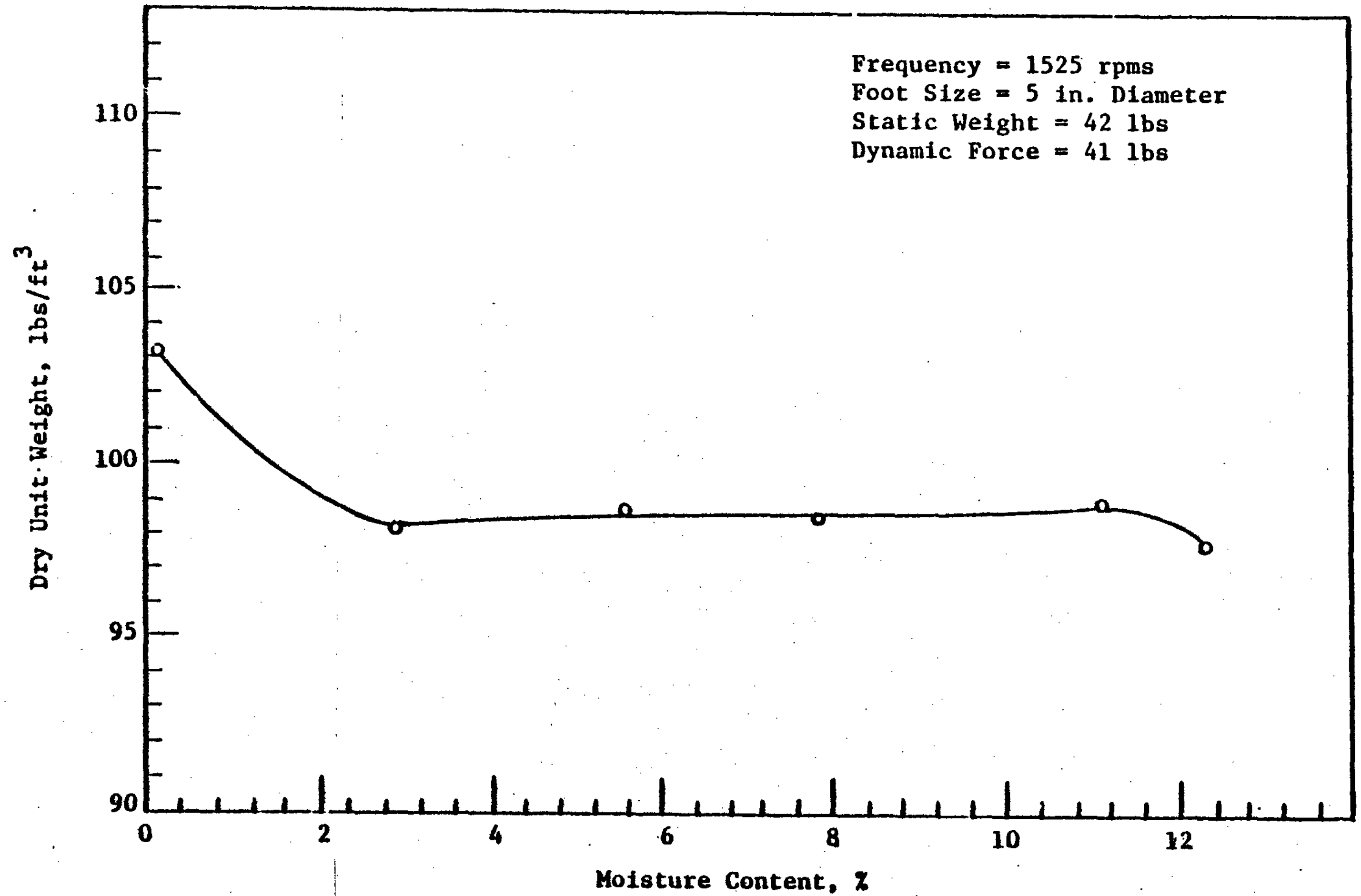



Figure 35. Effect of Moisture Content on the Compaction of Soil 1 (SP). (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg; 1 in. = 25.4 mm)

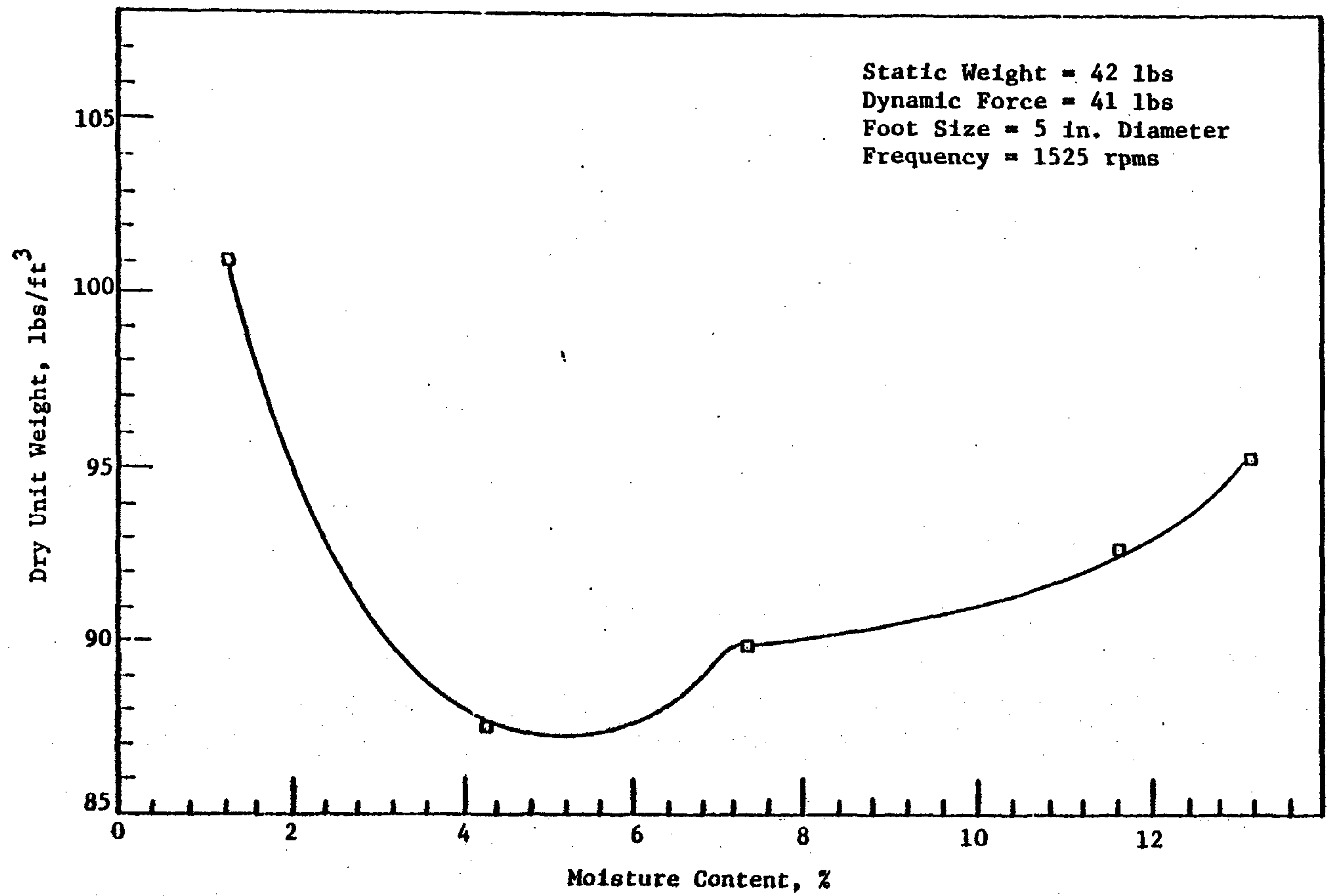



Figure 36. Effect of Moisture Content on the Compaction of Soil 2 (ML). (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg; 1 in. = 25.4 mm)

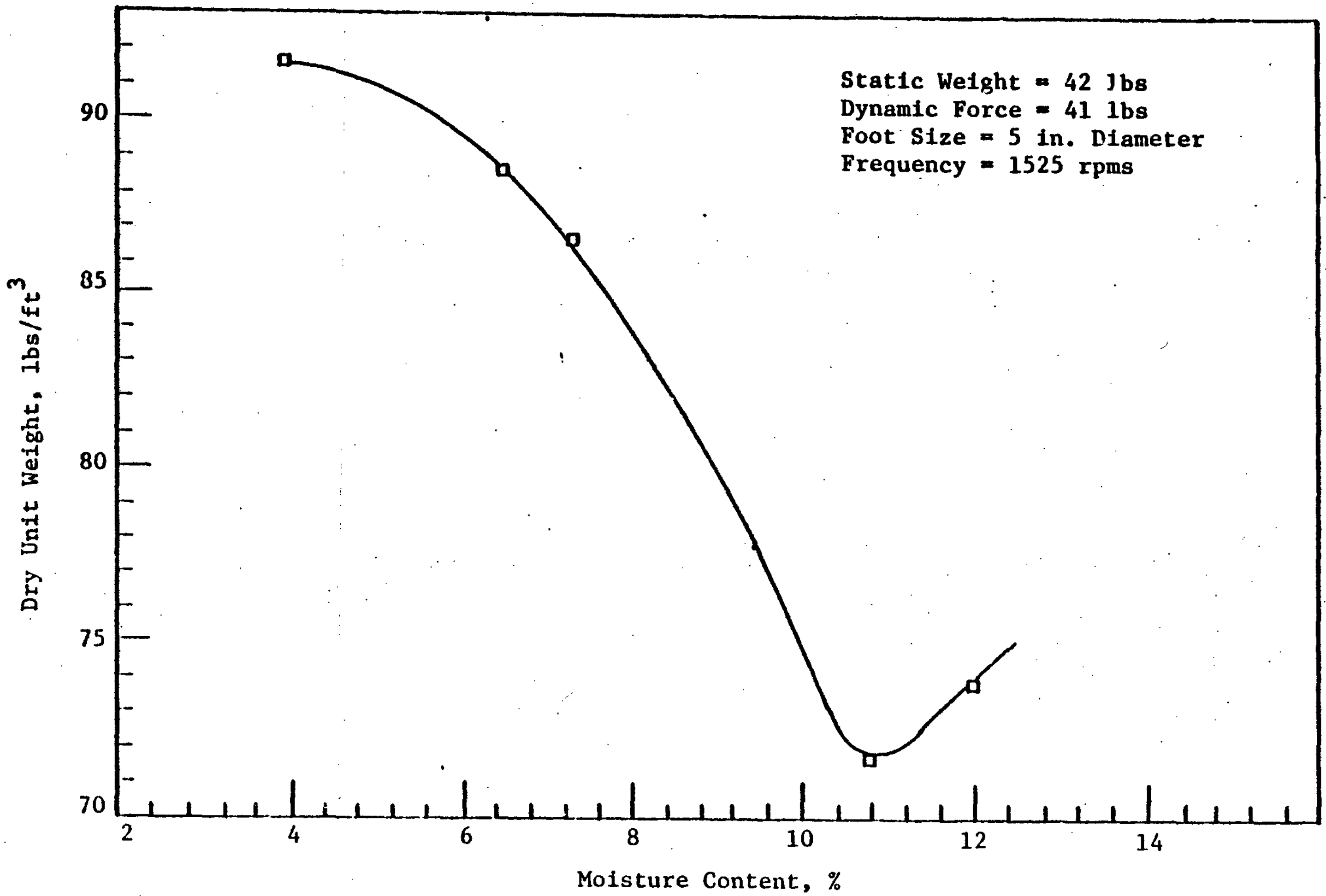



Figure 37. Effect of Moisture Content on the Compaction of Soil 3 (CL). (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 lb = 0.454 kg; 1 in. = 25.4 mm)

established between the two. A logical basis for comparison is to compact each soil by both methods with the same compactive effort and then compare the resulting unit weights. A method for determining the compactive effort utilized in the Standard Proctor test has already been presented (Equation 1, p. 7). For vibratory compaction, such a determination is much more complicated.

Mathematical modeling can be used to obtain an expression representing the vertical motion of the compactor. This expression, when combined with the forcing function, can be integrated to determine the work done by the compactor per unit of time. These results will represent the compactive effort used in compacting a given soil sample. By adjusting this compactive effort, realistic comparisons of Standard and vibratory compaction methods can be made.

Figure 38 represents an equivalent mechanical system for the vibratory compactor-soil system. A mathematical representation of this mechanical system is:

$$m\ddot{x} + c\dot{x} + kx = m_o\, w^2 e \sin wt \quad . . . . . . . . . . . . . . (2)$$

where $m$ = the total mass of the compactor,

$\ddot{x}$ = the velocity of the compactor,

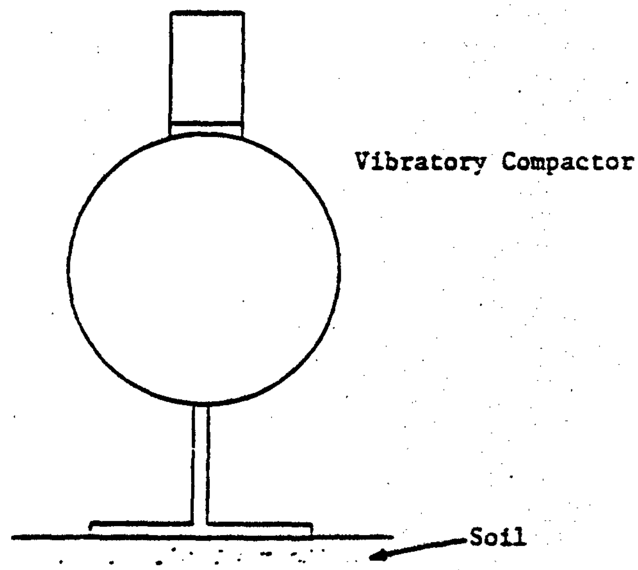
$m_o$ = the mass of the eccentric weights,

$k$ = the soil spring constant,

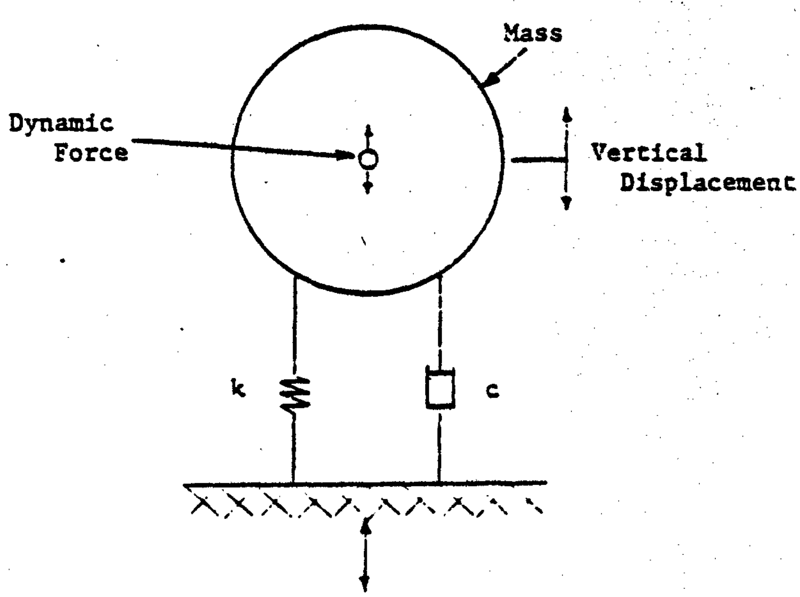
$c$ = soil damping constant,

$w$ = the frequency of vibration,

$e$ = the radial eccentricity of the rotating mass $m_o$,




a. Vibratory Compactor




b. Mechanical Model

Figure 38. Mathematical Modeling of Vibratory Compactor.

$t$ = the time of soil vibration,

$\ddot{x}$ = acceleration of the compactor in the vertical direction, and

$x$ = the displacement of the compactor in the vertical direction.

The solution to this second order linear differential equation (for a constant soil spring value) is

$$x = \exp\left[-\left(\frac{c}{2m}\right)t\right]\left[A \cos w_d t + B \sin w_d t\right] + \frac{m_o w^2 e}{k\sqrt{\left(1-\frac{w^2}{w_n^2}\right)^2 + \left(2\xi \frac{w}{w_n}\right)^2}} \sin(wt-\phi) \quad \cdots\cdots\cdots (3)$$

where $A, B$ = constants of integration to be determined from the boundary conditions,

$w_n$ = the natural frequency of the system

$w_d$ = the damped natural frequency of the system

$\phi$ = phase angle, and

$\xi$ = damping ratio.

However, the solution is complicated by the fact that the soil spring, k, will not be constant throughout the compaction test. As the time of compaction increases, the soil will become more compacted and the value of k will increase. Therefore, the soil spring is a function of time, as well as the material itself.

There are no concrete methods for determing a constant soil spring value, let alone a variable soil spring. For this reason, no attempt will be made at this time to determine a mathematical solution to this particular problem. Instead, an accelerometer and oscilloscope were used to measure the acceleration of the system. From this measurement, the actual displacement of the vibrator foot could be determined by integration. This information is then used to determine the work or compactive effort used in compacting the soil.

## Acceleration Measurements

To get some idea of how much compactive effort was utilized in compacting the beach sand, an accelerometer was mounted on the motor support bracket footing and acceleration measurements were recorded on an oscillographic recorder as the soil was being compacted. Measurements were made at various frequencies for two compactor static weights, and the dry unit weight of the soil was obtained for each frequency.

After the data had been collected, the accelerations were digitally integrated to obtain the compactor displacements. However, the displacements obtained were obviously incorrect (several inches for 5-6 cycles) and did not represent the actual displacements of the foot. Therefore, no comparison between the Standard and vibratory compaction efforts can be made with the data.

During the analysis of the data, it was discovered that two peaks or maximum acceleration values were generally obtained for each frequency (Figure 39). The frequency of the smaller peak represents

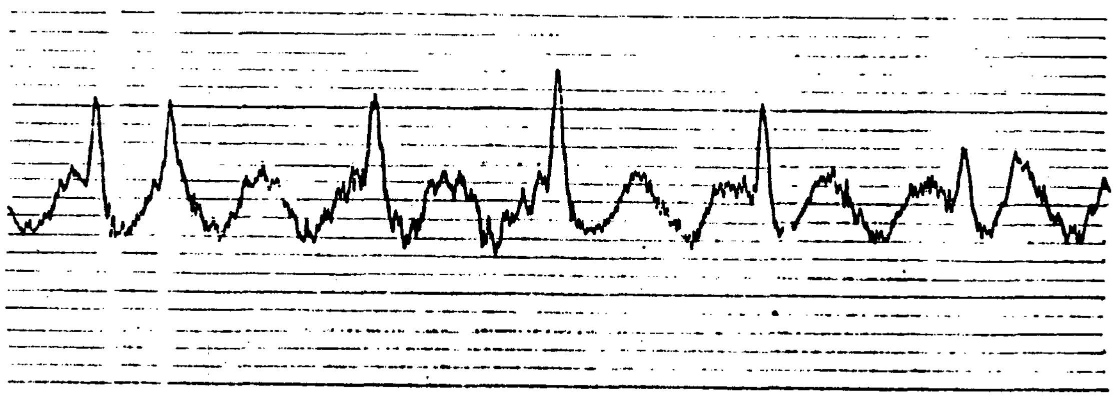


Figure 39. Oscillograph Recording of Compactor Acceleration.

the frequency of the compactor motor and the larger peak is from an unknown source. A plot of the ratio of the magnitude of large peak to small peak acceleration versus compactor frequency yields no discernible relationship with dry unit weight of the sandy soil (Figures 40, 41).

Figures 42 and 43 are plots of the average maximum accelerations versus compactor frequency for compactor static weights of 18 lbs (8.17 kg) and 42 lbs (19.07 kg). These data indicate that, in general, as the acceleration increases, so does the dry unit weight.

Also, a ratio of the peak frequencies was plotted versus compactor frequency and superimposed with dry unit weights (see Figures 44 and 45). In general, it is observed that as the ratio of larger to smaller peaks decreases, the dry unit weight increases, and vice versa. This indicates that higher dry unit weights can be obtained if the unknown source causing higher acceleration peaks can be eliminated.

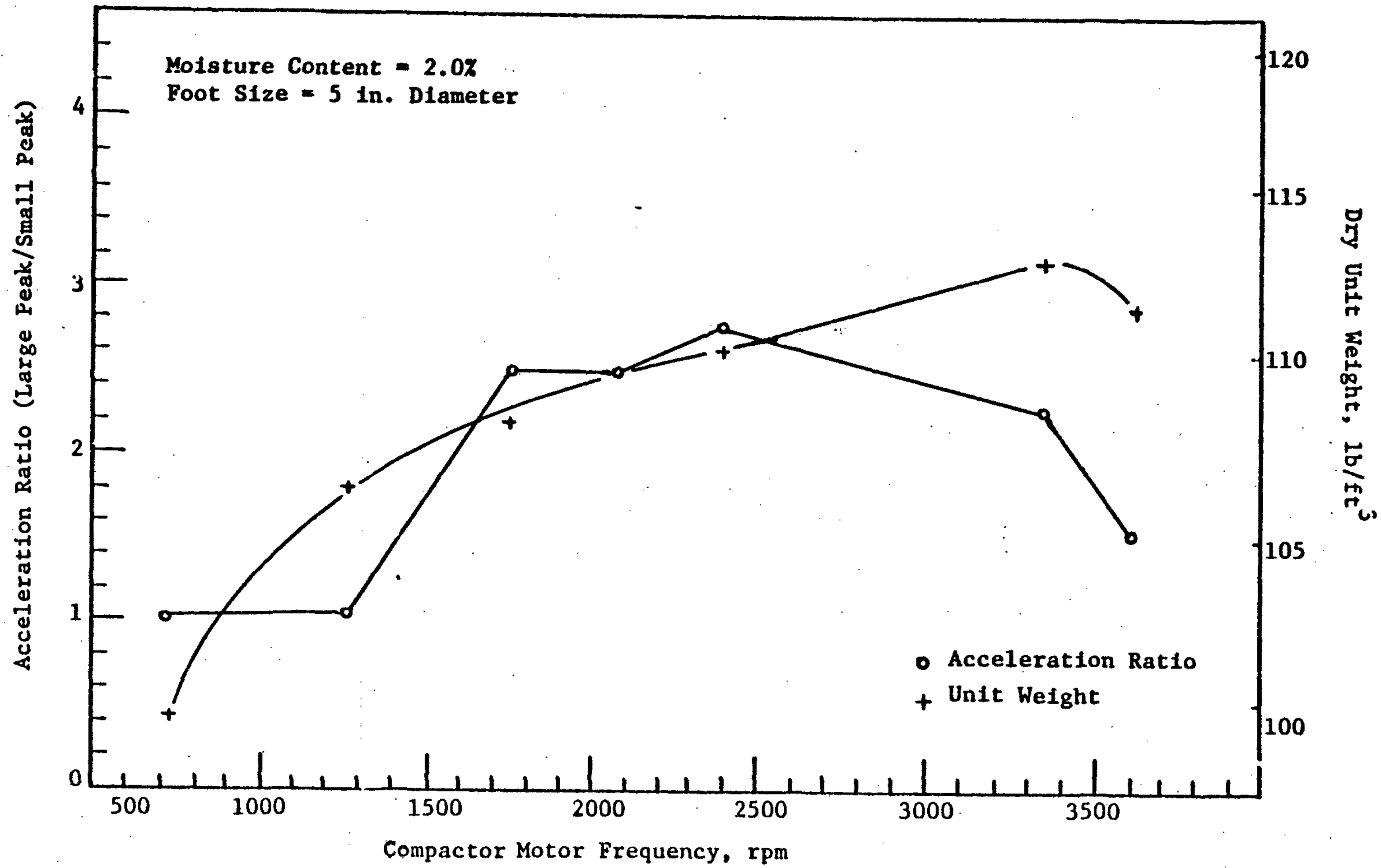



Figure 40. Variation of Dry Unit Weight with Acceleration Ratio for Soil 1 (SP) at a Static Weight of 18 lbs (8.17 kg). (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 in. = 25.4 mm)

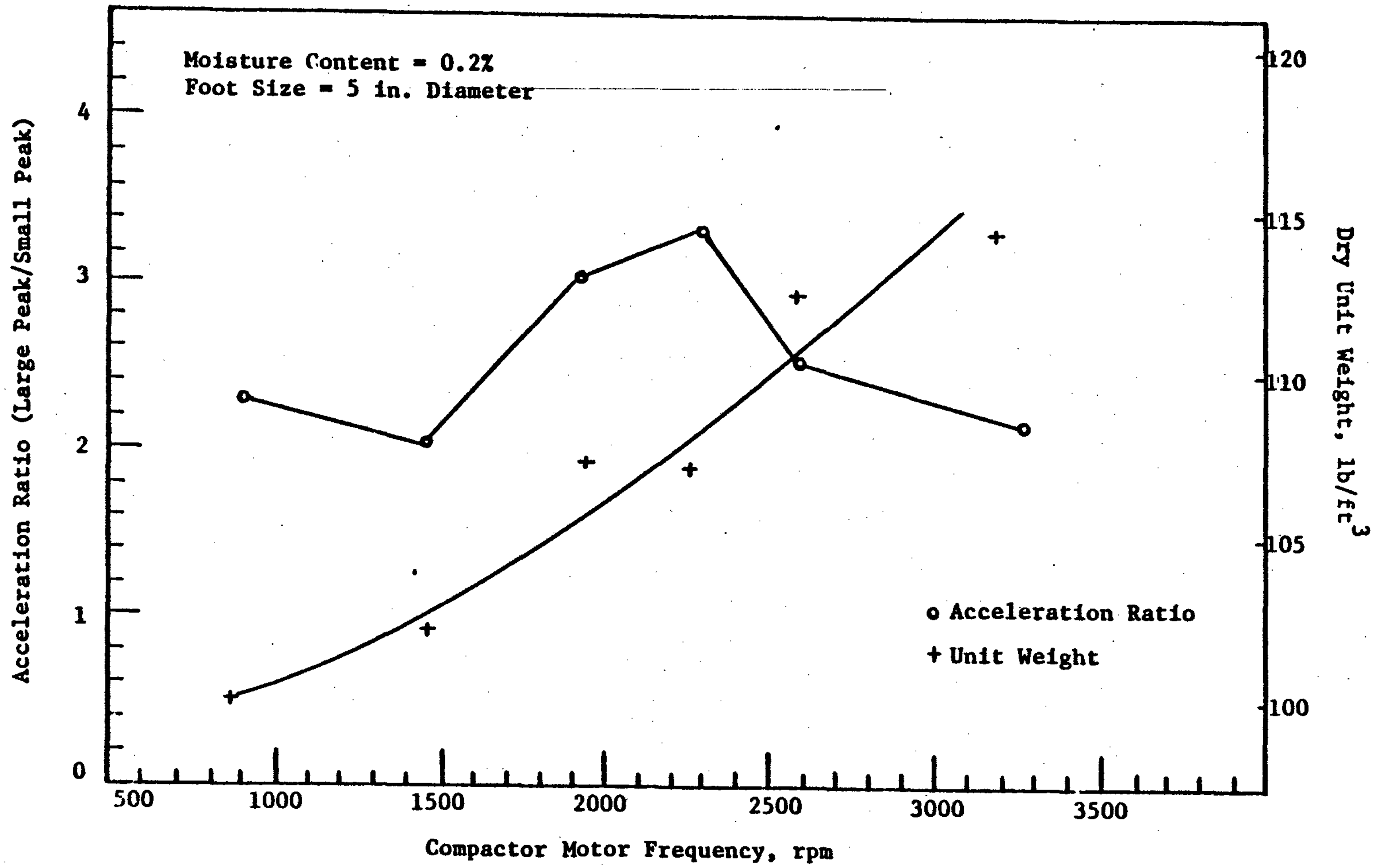



Figure 41. Variation of Dry Unit Weight with Acceleration Ratio for Soil 1 (SP) at a Static Weight of 42 lbs (19.07 kg). (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 in. = 25.4 mm)

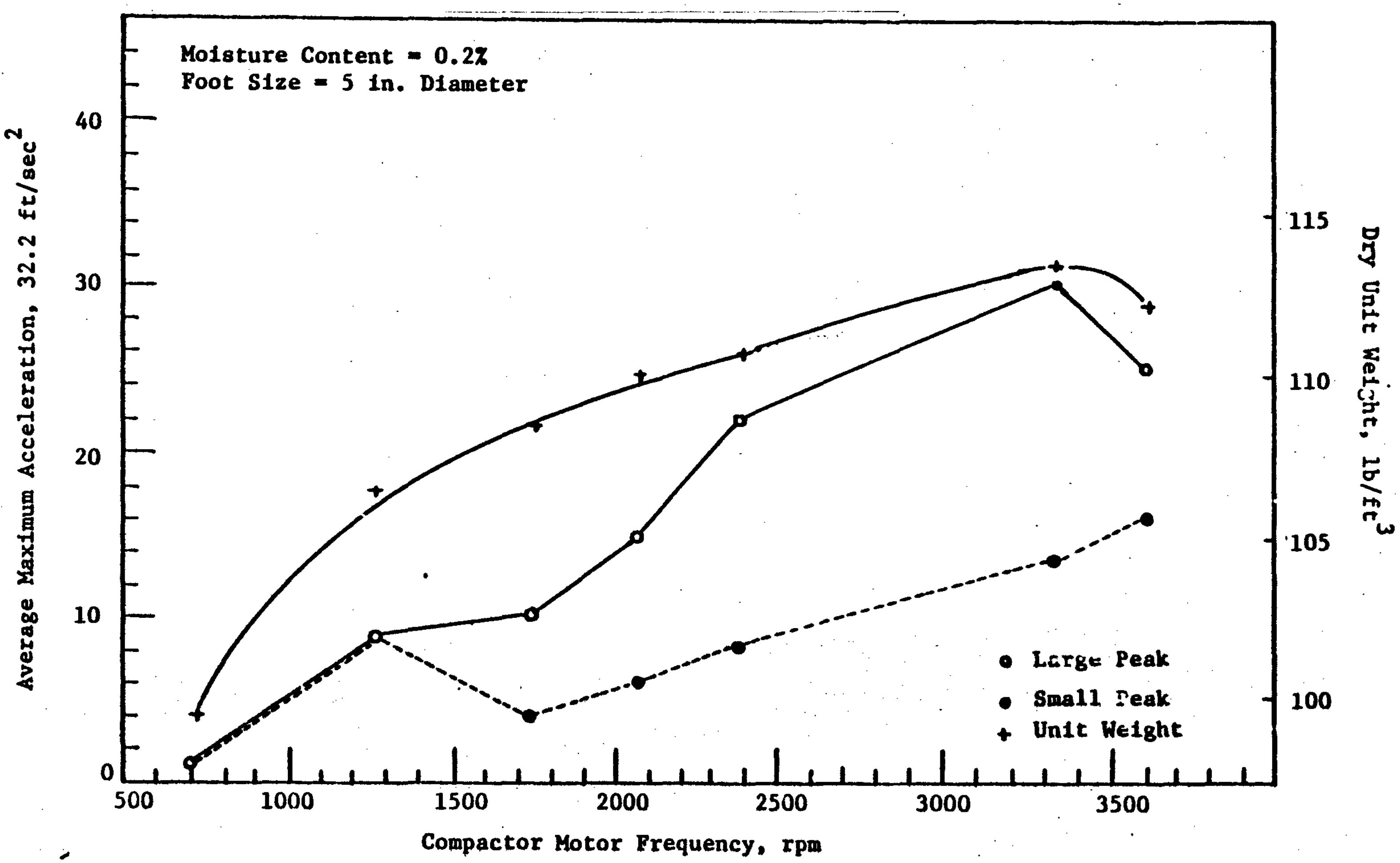



Figure 42. Variation of Dry Unit Weight with Peak Accelerations for Soil 1 (SP) for a Static Weight of 18 lbs (8.17 kg). (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 in. = 25.4 mm; 32.2 ft/sec$^2$ = 9.81 m/sec$^2$)

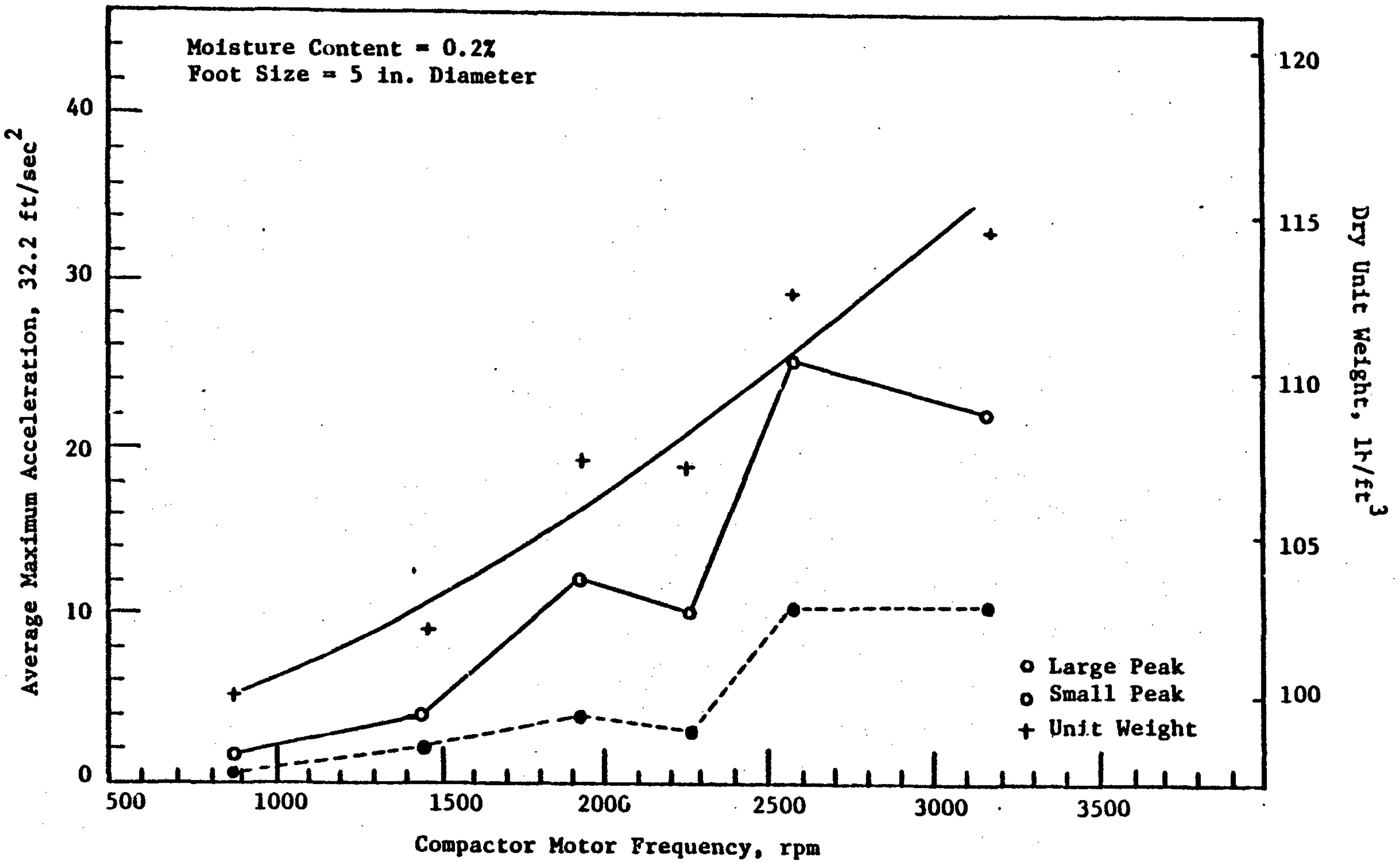



Figure 43. Variation of Dry Unit Weight with Peak Accelerations for Soil 1 (SP) at a Static Weight of 42 lbs (19.07 kg). (1 $lb/ft^3$ = 0.159 $kN/m^3$; 1 in. = 25.4 mm; 32.2 $ft/sec^2$ = 9.81 $m/sec^2$)

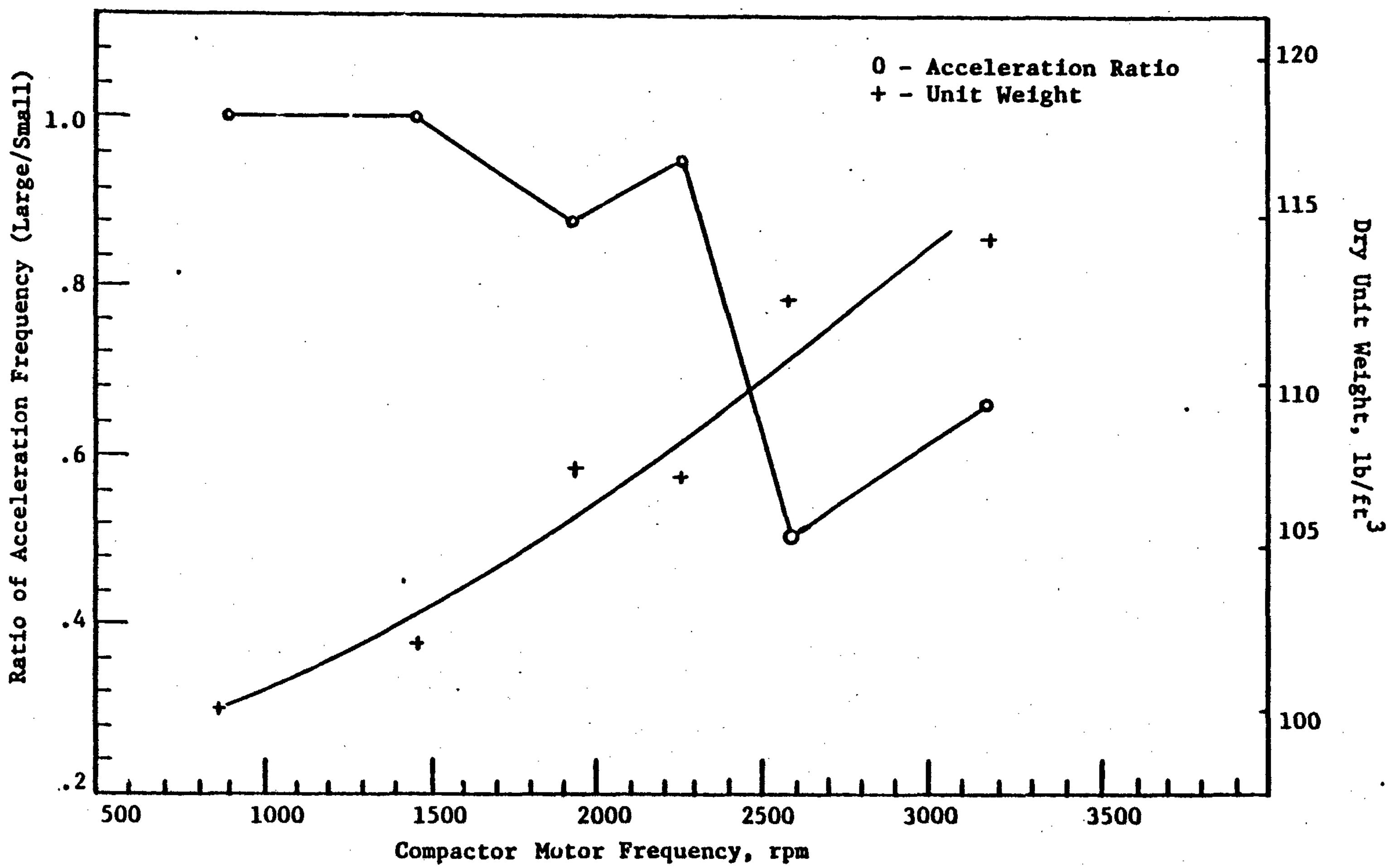



Figure 44. Variation of Unit Weight with Acceleration Frequencies for Soil 1 (SP) at a Static Weight of 42 lbs (19.07 kg). (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 in. = 25.4 mm)

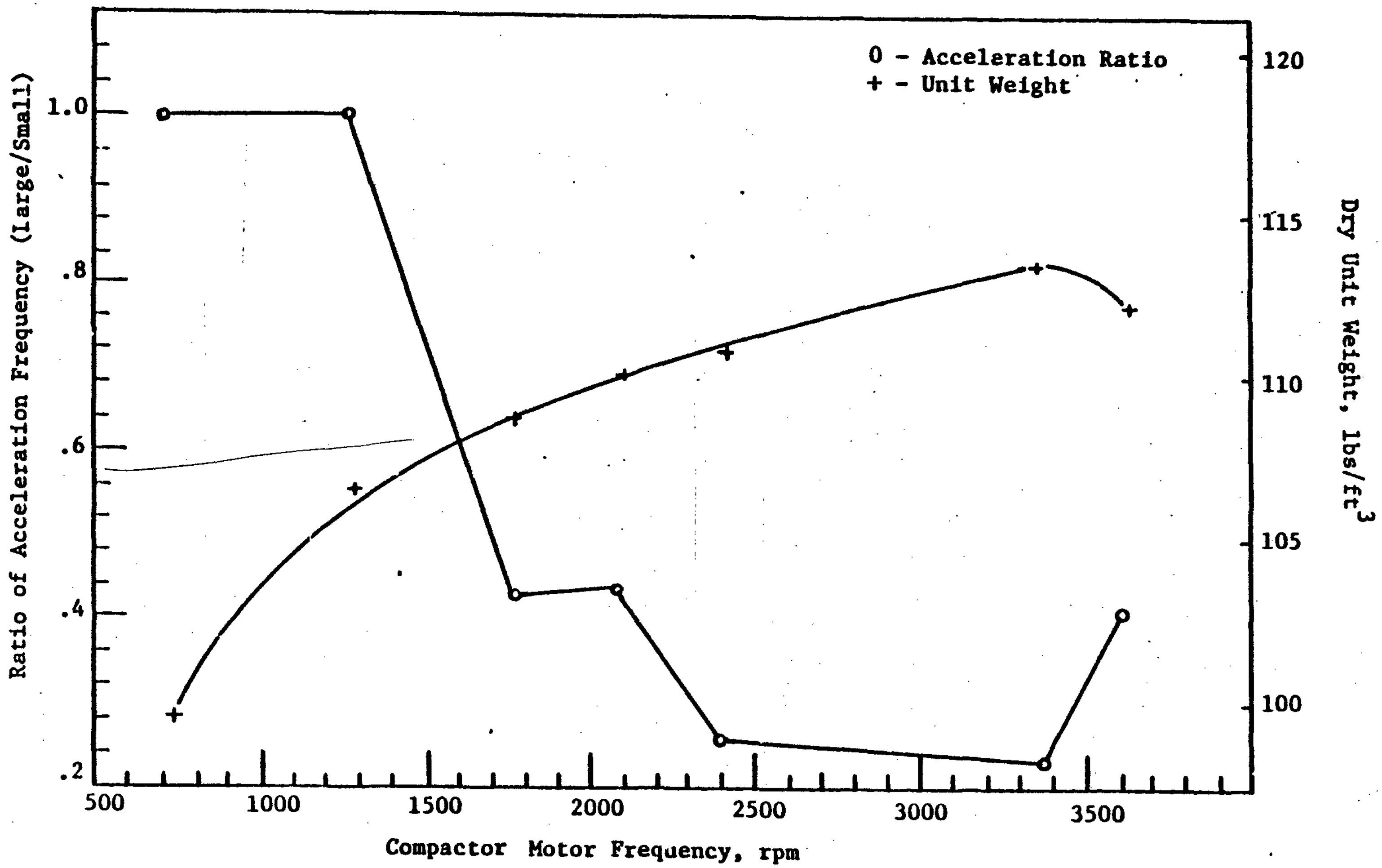



Figure 45. Variation of Unit Weight with Acceleration Frequencies for Soil 1 (SP) at a Static Weight of 18 lbs (8.17 kg) (1 lb/ft$^3$ = 0.159 kN/m$^3$; 1 in. = 25.4 mm)

## SUMMARY AND CONCLUSIONS

A comparative study of the data obtained from Standard and vibratory compaction, and an analysis of the variable effects on vibratory compaction permit the following conclusions to be made:

1. Vibratory compaction of cohesive and other fine-grained soils is ineffective in achieving dry unit weights equivalent to Standard compaction dry unit weights.

2. Vibratory compaction of a uniformly-graded sand may yield dry unit weights in excess of 100% Standard compaction.

3. There is no optimum frequency of compaction for a particular soil. The soil-compactor system as a whole ultimately governs the level of compaction.

4. The light-weight vibratory compactor tends to compact the soil better than the heavier vibratory compactor when both are compacting at low frequencies.

5. Vibratory compaction of dry soils appears to be more effective than vibratory compaction of moist or saturated soils.

6. For a constant frequency of compaction, merely increasing the vibrator static weight will not necessarily increase the dry unit weight.

7. The foot size effects on compaction yield inconclusive results.

## RECOMMENDATIONS FOR FURTHER RESEARCH

An analysis of the data indicates the need for further research into the following areas:

1. The foot size and shape effects on compaction of cohesionless soils in unconfined molds should be analyzed. Compaction should be performed with the five inch (127 mm) diameter foot in a larger mold to lessen confinement of the soil particles and to prevent soil disturbance.

2. An investigation of frequency effects on compaction for frequencies above 50 Hertz should be conducted

3. An investigation of static weight effects on compaction for static weights greater than 42 lbs (19.07 kg) should be performed.

4. The compactive effort employed in compacting a soil at various frequencies and static weights should be determined.

5. An investigation should be conducted to determine the maximum dry density and optimum moisture content of soils using vibratory methods.

6. These test results should be verified with a field investigation.

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# APPENDIX II. - NOTATION

The following symbols are used in this paper:

AASHTO = American Association of State Highway and Transportation Officials;

ASTM = American Society of Testing and Materials;

BS = British Standard Compaction Test;

CE = Compactive Effort;

$c$ = soil damping constant;

$D$ = number of blows per soil layer;

$e$ = moment arm, eccentricity of rotating weight;

$F$ = total force exerted on the soil;

$F_d$ = dynamic force;

$F_s$ = static force;

$H$ = height of drop;

$k$ = soil spring constant;

$L$ = number of soil layers compacted per mold;

MDD = maximu dry unit weight (density);

$m$ = mass of compactor;

$m_o$ = mass of eccentric weight;

OMC = optimum moisture content;

$t$ = time internal;

$V$ = volume of mold;

$W$ = rammer weight;

$x$ = vertical displacement;

$\dot{x}$ = velocity;

$\ddot{x}$ = acceleration;

# APPENDIX II. - NOTATION

The following symbols are used in this paper:

$\xi$ = damping ratio;

$\phi$ = phase angle;

$w$ = circular frequency;

$w_d$ = damped natural frequency; and

$w_n$ = natural frequency.

# APPENDIX III. - LETTERS OF RELEASE

5 February 1984

MEMORANDUM FOR RECORD

1. Figure 10 of this report was compiled from data presented by C.I. Ellis in a paper entitled "Soil Compaction at Low Moisture Content: Field Trials in Sudan". The paper was published in the Seventh Conference for Africa on Soil Mechanics and Foundation Engineering, ACCRA, June 1980.

2. Ellis's report is protected under Crown (British) Copyright 1979. However, he expressedly states that "Extracts from the text may be reproduced, except for commerical purposes, provided the source is acknowledged".

3. I have complied with those directives.

Cecil R. Webster

THE INSTITUTION OF HIGHWAYS AND TRANSPORTATION
3 Lygon Place Ebury Street London SW1W 0JS Telephone: 01 730 5245
Secretary: Miss P.A. Steel B.A.

REF: JEB

February 2nd, 1984

C.R. Webster,
1643-A Barak Lane,
Bryan,
Texas 77802, UNITED STATES OF AMERICA

Dear Mr Webster,

Thank you for your letter of January 26th requesting the Institution's permission to use data from the Paper "Road Geotechnics in Hot Deserts" published in October, 1976.

We have no objection to your using this material providing that the source reference is given and this you have agreed to do.

Every good wish for your thesis.

Yours sincerely,

John Barrett,
Assistant Editor.

NATIONAL RESEARCH COUNCIL
TRANSPORTATION RESEARCH BOARD
2101 Constitution Avenue Washington, D.C. 20418

January 31, 1984

Mr. Cecil R. Webster
1634-A Barak Lane
Bryan, Texas 77802

Dear Mr. Webster:

We are pleased to grant you permission to use Figures 41 and 42 from Highway Research Board Bulletin 272 for use in your thesis. Please be sure to give proper credit to the Transportation Research Board and include the title and authors of the publication.

Good luck with your studies.

Sincerely,

Nancy Ackerman
Publications Manager
Transportation Research Board

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20th February, 1984

C.R. Webster,
1634-A Barak Line,
Bryan,
Texas 77802,
USA.

Dear Mr. Webster,

Many thanks for your letter of January 26th, 1984.

I am pleased to give you permission to use data in your thesis from the Hunt & Hawkins' Papers you mention and note you will be acknowledging these

Please note the change in publishers and address for this journal. We moved out of 7b Ongar Road January, 1980 and have since moved again!.

Yours sincerely,

Derek R. Patey ACSM,
Editor.

# VITA

The author, Cecil Ray Webster, was born in Franklin, Texas on 29 March 1954. His permanent address is 507 East 20th Street, Bryan, Texas 77801. Webster graduated with honors from Bryan High School in May, 1972.

He graduated "magna cum laude" from Prairie View A&M University in May, 1976 with a Bachelor of Science in Civil Engineering and a Regular Army commission as a Second Lieutenant. While at Prairie View A&M University, Webster received the following awards and recognition: Outstanding Civil Engineering Student (1973-76); Outstanding Military Science Student (1974-76); Second Prize, Texas Section ASCE Student Paper Content (1975); Distinguished Military Graduate (1976); and Who's Who Among Students in American Colleges and Universities (1975-76). Webster was also active in numerous campus clubs and organizations: Tau Beta Pi Engineering Honor Society, American Society of Civil Engineers, and Army Reserve Officer Training Corp.

Webster, an Army Career Officer, has been stationed at Fort Campbell, Kentucky as an infantry officer and at Fort Blevior, Virginia as an instructor at the Army Engineer School. He has been awarded the Army Commendation Medal and the Army Service Ribbon.

In 1982 he was selected as an Outstanding Young Man of America by the Jaycees of America.

He is married to the former Marsha E. Burnett of Brenham, Texas. They have one child, Cecil Jr.