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THE EFFECT OF CHEMICAL WETTING AGENTS
ON THE COMPACTION OF CLAY AND SILT SOILS

A THESIS

Presented to

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by

Henry Garnett Shirley

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THE EFFECT OF CHEMICAL WETTING AGENTS
ON THE COMPACTION OF CLAY AND SILT SOILS

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SUMMARY

In this investigation a study was made of the effect of chemical wetting agents on the density of two soils when compacted at a constant moisture content and compactive effort with different percentages of wetting agent added to the water used for compaction.

The soils used in this investigation were a light brown, well graded micaceous silty sand from the Atlanta, Georgia area and a reddish brown finely graded clay from Giles County, Virginia.

The chemicals used were all commercially available surfactants donated by the manufacturers.

The method of evaluating the surfactants' effectiveness was to compact the soils to their Standard Proctor density at a 13 and 25 per cent moisture content, respectively, using percentages of surfactant admixture ranging from 0 to 3 per cent of the total soil moisture content. The test increments were 0.25, 0.50, 0.75, 1.0 and 3.0 per cent. The treated samples were then compared to a sample of the same soil compacted, without the admixture, at the same moisture content and compactive effort.

Test results for the four categories of admixtures tested (amphoteric, anionic, cationic and nonionic) showed that increases in percentage of admixture of all surfactants caused an increase in density of the clay soil. The most effective surfactants were the anionic and nonionic types and the least effective were the cationic and amphoteric types. The largest increase in density occurred at percentage admixtures

between 0.25 and 0.50 per cent. The average increase at these percentages was 9.0 per cent. Increased percentages of admixture above 0.50 per cent caused diminishing increases in density in all cases.

The silty soil was quite insensitive to the addition of the surfactants to the compaction moisture. Increases in the percentage of admixture caused the density to decrease when the cationic and amphoteric surfactants were used. The maximum decrease was 3 per cent and occurred at a 3 per cent concentration of surfactant. The anionic and nonionic surfactants caused an increase in density of 2 per cent at a percentage admixture of 3 per cent. The largest increase or decrease in density occurred at a percentage admixture between 0.25 and 0.50 per cent.

CHAPTER I

INTRODUCTION

General

The term "soil stabilization" in its broadest sense refers to any process, natural or artificial, in which any property of a soil is altered to improve its engineering performance.

Almost every building, dam, road, airport, etc., rests upon soil, and many of these structures employ soil as an integral part of their construction.

In the past decade the United States has been involved in one of the largest highway and airfield construction programs ever experienced by any country. Mountains have been leveled, swamps filled, and the sea held back in the construction of new airfields. The dream of a super-highway from coast to coast is now a reality. The completion of these feats would not have been possible without soil compaction.

During this period of phenomenal expansion, and in future expansions, the choice of building sites has been severely restricted, often with the poor site, from an engineering point of view, being the only one available. Thus, working with and using inferior material, more as a rule than as an exception, has focused more attention on means of soil stabilization as a method of obtaining the desired product with the available material.

Often it is desirable to treat a soil to make it more manageable

in addition to improving its engineering properties (e.g., treatment of certain clay soils with lime to aid compaction).

This research was undertaken to study two soils and to evaluate the effectiveness of commercially available surface active agents in altering the density of the soils. The admixtures used in this research were 25 organic wetting agents, a commercial laundry detergent, and hydroxyacetic acid.

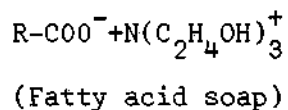
The use of surface active agents in soil stabilization has been limited to essentially laboratory studies. Most of these studies have been conducted using only a cationic surface active agent. Although laundry detergents are a relatively old surface active agent, they have not been used in soil stabilization. Hydroxyacetic acid is a relatively new chemical product and has enjoyed some success as a concrete admixture, but has not been used in soil stabilization.

The phrase "surface active agent" frequently is used interchangeably with "wetting agent." Wetting agents, however, are merely a group of compounds within the more general class of agents known as surface active. A surface active agent does not necessarily have good wetting power; it may be more effective as a dispersing and/or as a emulsifying agent.

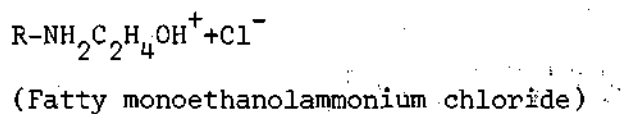
A wetting agent is a material that reduces the surface tension of water and also lowers the interfacial tension between water and another surface, by collecting or aggregating at the solid-liquid or liquid-liquid interfaces.

Chemicals displaying surface activity may be divided into four classes according to their electro-chemical behavior:

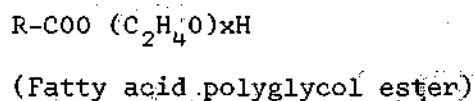
1. Anionic--those yielding, in solution, surface-active ions bearing a negative charge.



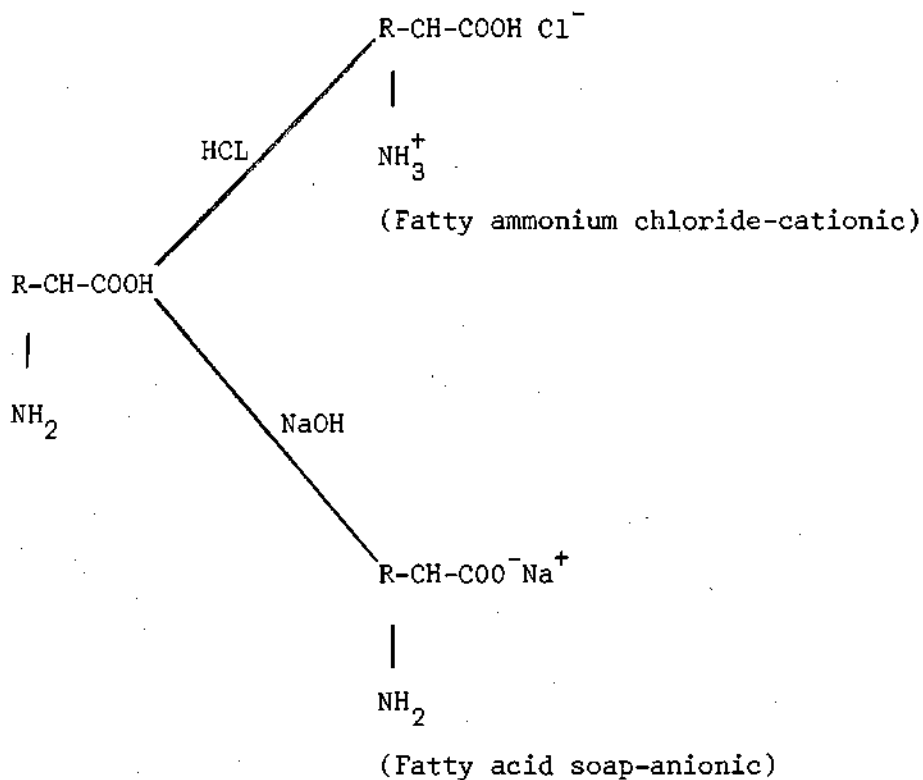
2. Cationic--those yielding positively charged surface-active ions in solution.



3. Nonionic--those which do not ionize in solution.



4. Ampholytic or Amphoteric--those which are cationic in acid media and anionic in basic media.



In general, anionic and cationic compounds cannot be used together because they tend to neutralize in the same system each other's effectiveness. Nonionic compounds can be used alone or in the presence of either anionic or cationic types.

The degree of surface activity of these agents depends primarily on the ratio of hydrophilic (water attracting) to hydrophobic (water repelling) constituents. This ratio or balance is affected markedly by the nature of the antagonistic groups and by their relative positions in the molecule as well as by the presence, concentration, and chemical nature of other ingredients in the system.

The effect of surface active agents on surface tension is influenced by the presence of water soluble salts, such as sodium chloride and sodium sulfate. The salts affect the hydrophilic nature of the water-soluble portion of the surface active agent making it less water soluble.

The criterion used to evaluate the admixtures was the Standard Proctor Density of the two soils.

Previous Studies

During the past 20 years the array of organic chemicals which involve the phenomenon of surface tension and its related manifestations has expanded tremendously. These chemicals have enjoyed wide use in industries ranging from textiles to cosmetics.

In 1949 Davidson and Glab (1)* conducted a laboratory investiga-

* Numbers in parentheses refer to corresponding numbers in the Bibliography.

tion of the effectiveness of certain cationic organic compounds to increase the all-weather stability of soils. This research on two soil-aggregate mixtures having plasticity indices higher than considered desirable for highway subgrade material produced the following conclusions:

1. Plasticity was decreased.
2. Shrinkage was decreased.
3. Maximum modified AASHO density and optimum moisture content were decreased.
4. Unsoaked California Bearing Ratio was decreased.
5. Swelling was reduced.
6. Soaked California Bearing Ratio was increased.
7. All percentages of the chemical reduced the plasticity but the rate of reduction decreased as the per cent of admixture increased.

Michaels (2) in 1952 described four treatments of soil with surface active chemicals that involved solely modification of the surface characteristics of soil particles and that affect mainly the solvation water in a soil system.

Maclean (3) discussed a method for stabilizing cohesive soils by incorporating small percentages of surface active chemicals. The object was to prevent a serious loss of bearing strength under wetting conditions by reducing the rate of water adsorption in the soil.

Research by Whitesell (4) showed that organic cations tend to decrease the maximum dry density of clay soils.

With this and other research as background, this study was under-

taken to determine the effects of the four types of surface active agents on the dry density of the two different soils.

CHAPTER II

MATERIALS AND TEST EQUIPMENT

Soils

The soils selected for this study are typical of those encountered in roadbuilding and airfield construction in the general area from which they were obtained. The two soils were a Georgia silt and a Virginia clay and throughout the remainder of this report will be referred to as Soil I and Soil II, respectively. Soil I is a light brown, well graded micaceous silty sand. Soil II is a reddish brown finely graded clay. Soil II was obtained from a side hill cut in Giles County, Virginia. It is typical of soils in this Appalachian Region of Southwest Virginia. Soil I was obtained from within the state of Georgia and is typical of soils encountered in the Atlanta area. A description of each soil is given in Table 1 with the grain size distribution shown in Figure 1. Figures 2 and 3 are x-ray analyses of Soils I and II, respectively.

Admixtures

The chemicals used were donated by the manufacturers and are all commercially available. The product name, ionic type, chemical type, manufacturer and pertinent data on the chemicals used are shown in Table 3.

The water used in the compaction of the test samples was tap water from the soils laboratory. Results of a water analysis are contained in Table 2.

Test Equipment

The moisture-density tests and the density samples were all prepared using the Standard Proctor compaction equipment consisting of a mold 1/30 cubic foot volume and a 5.5 pound compacting hammer falling 12 inches with the soil compacted in three layers with 25 blows on each layer. (Reference ASTM Standard D-698-58T.)

Table 1. Description of Soils

| Soil Number | I. | II. |
|-------------------------------------|-------------------|-------------------|
| Location by County and State | Fulton Georgia | Giles Virginia |
| Textural Analysis % Finer by Weight | | |
| Sieve No. 6 | 98 | 99 |
| Sieve No. 20 | 86 | 95 |
| Sieve No. 40 | 75 | 88 |
| Sieve No. 60 | 64 | 75 |
| Sieve No. 120 | 46 | 56 |
| Sieve No. 200 | 32 | 48 |
| Total Silt % | 13 | 26 |
| Total Clay % | 5 | 22 |
| Specific Gravity | 2.66 | 2.70 |
| Liquid Limit | 36 | 49 |
| Plastic Limit | NP | 29 |
| Plastic Index | -- | 20 |
| BPR Classification | A-4 | A-7-5(7) |
| Unified Soil Classification | ML | CL |

Table 2. Mineral Analysis of Tap Water

| Constituent | P.P.M. |
|----------------------------------|--------|
| Silica (SiO_2) | 9.5 |
| Chlorine Residual | 1.2 |
| Carbon Dioxide (CO_2) | 0.00 |
| Dissolved Solids (Conductivity) | 30.00 |
| Hardness (CaCO_3) | 22.0 |
| Iron (Fe) | 0.02 |
| Sulphates (SO_4) | 4.00 |
| Alumina (Al) | 0.05 |
| Chloride (Cl) | 4.00 |
| Calcium (Ca) | 7.1 |
| Magnesium (Mg) | 1.0 |
| Manganese (Mn) | 0.02 |
| Carbonate (CO_3) | 3.6 |
| Bicarbonate (HCO_3) | 12.2 |
| Dissolved Oxygen (Per Cent) | 97.00 |
| pH (Colorimetric) | 6.8 |

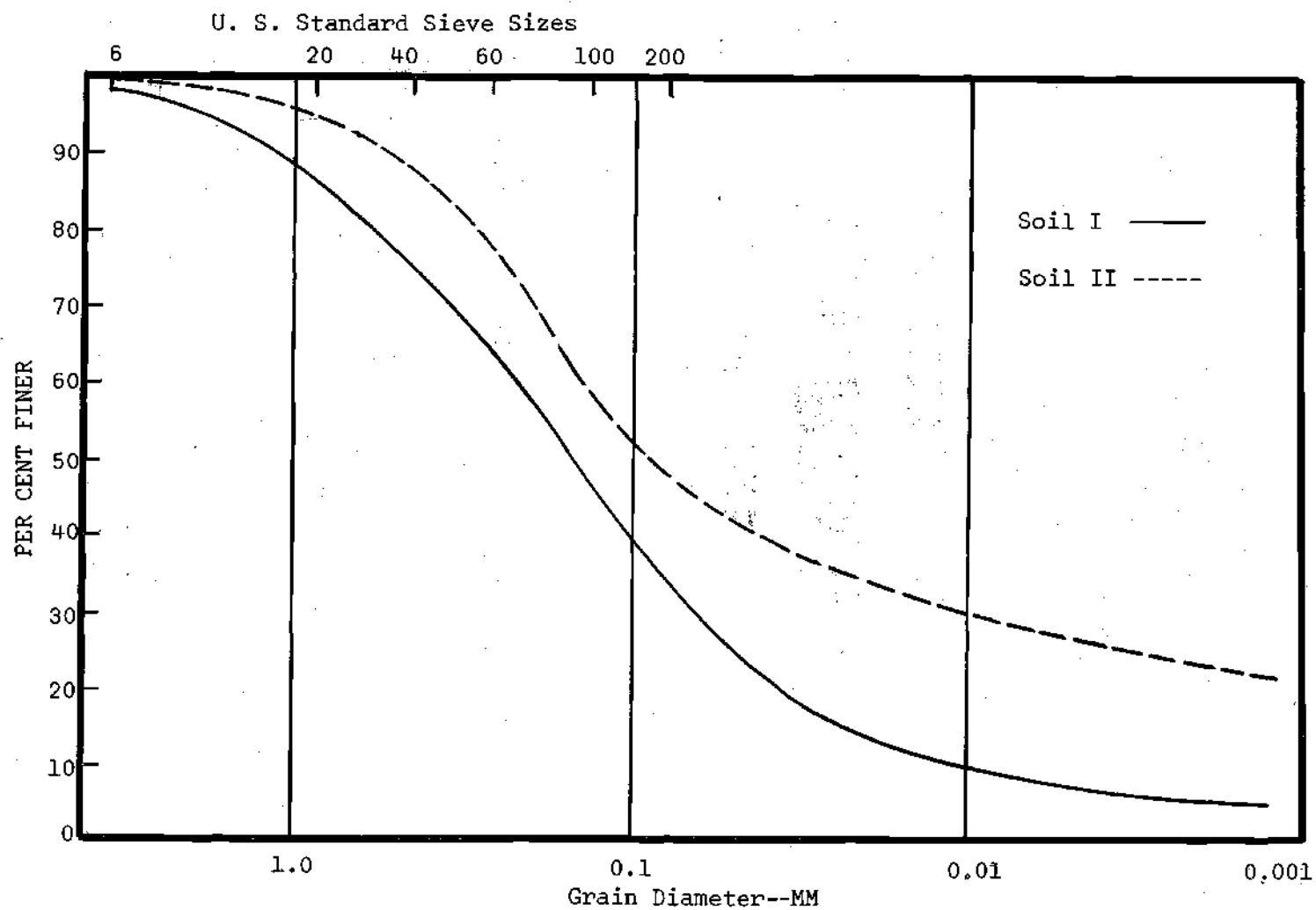


Figure 1. Grain Size Distribution

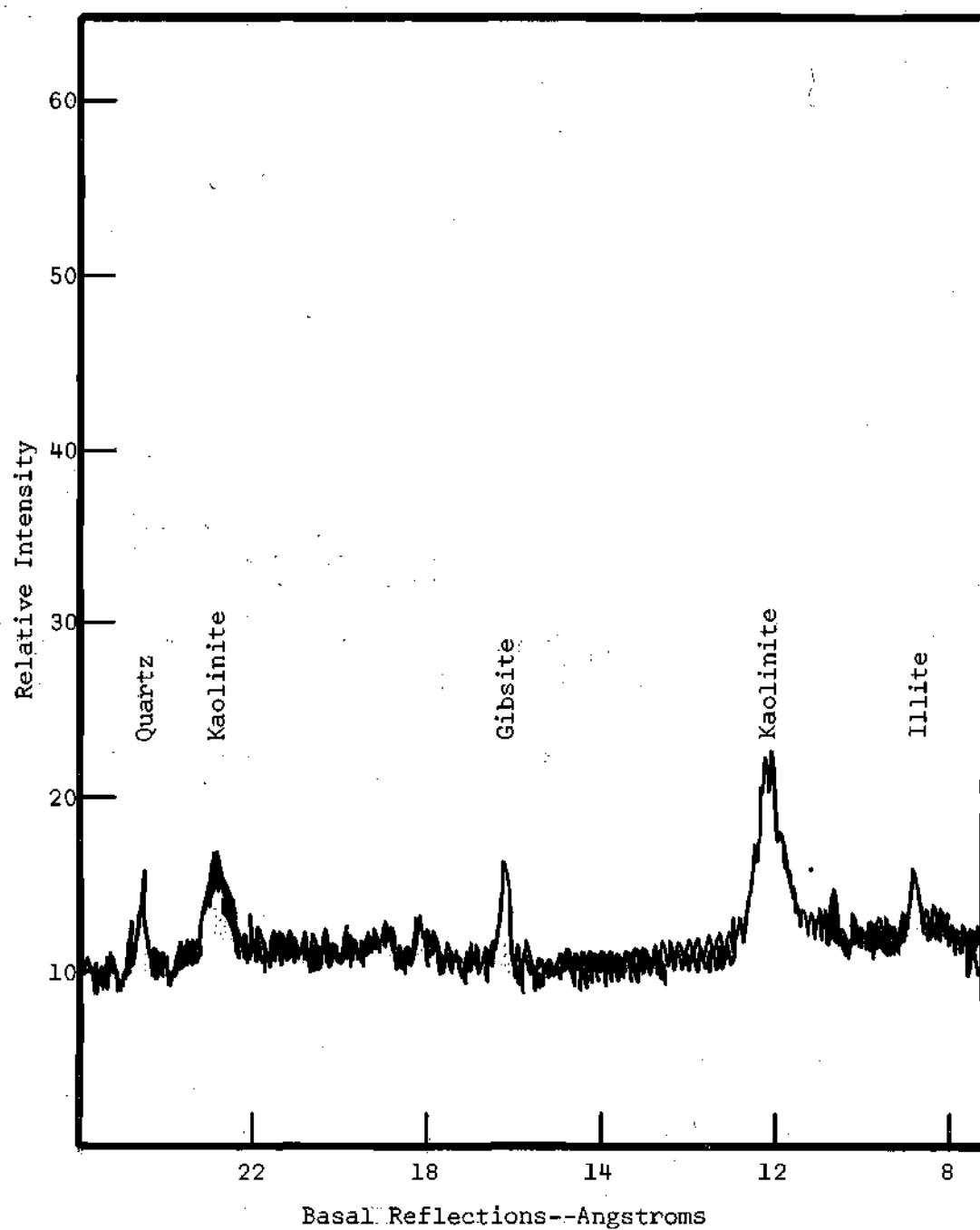


Figure 2. X-Ray Analysis of Soil I.

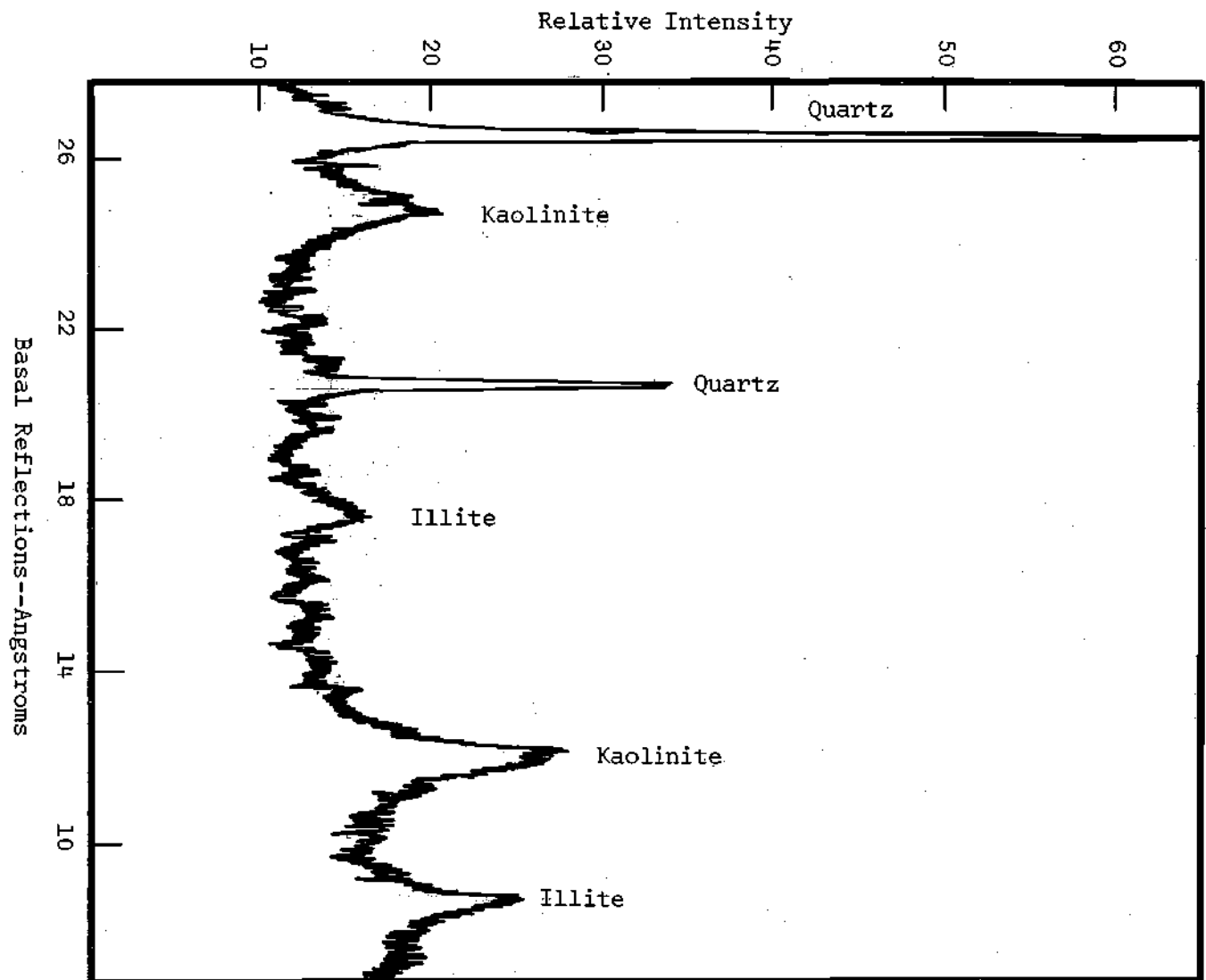


Figure 3. X-Ray Analysis of Soil II.

Table 3. Wetting Agent Data

| Product Name | Ionic Type | Chemical Type | Manufacturer | Remarks |
|---------------|------------|--|--------------|--|
| Alkanol 189-S | Anionic | Long Chain Hydrocarbon Sodium Sulfonate | Dupont | Reddish-brown Liquid |
| Alkanol B | Anionic | Alkyl naphthalene Sodium Sulfonate | Dupont | Light cream Powder |
| Alkanol DW | Anionic | Alkylaryl Sodium Sulfonate | Dupont | Clear yellow Liquid |
| Duponol WN | Anionic | Short Chain Fatty Alcohol Sodium Sulfate | Dupont | Pale yellow Liquid |
| Duponol WA | Anionic | Lauryl Sodium Sulfate | Dupont | White opaque Paste |
| Avitex SF | Anionic | Cetyl Sodium Sulfate | Dupont | White paste |
| Alkanol OJ | Nonionic | Ethoxylated Fatty Alcohol | Dupont | Soft light tan Paste |
| Product BCO | Amphoteric | Cetyl Botaine | Dupont | Clear brown Liquid |
| Avitex Y | Cationic | Fatty Acid Amine Condensate Quaternary | Dupont | Yellow viscous liquid 70° to 100°F: non-pourable paste at 50°F. |

Table 3. Wetting Agent Data (Continued)

| Product Name | Ionic Type | Chemical Type | Manufacturer | Remarks |
|--------------------|------------|--|-------------------|---|
| Hydroxyacetic Acid | | Alpha Hydroxy Carboxylic Acid | Dupont | 70% technical aqueous solution; clear yellow liquid |
| Tergitol NPX | Nonionic | Nonyl Phenyl Polyethylene Glycol Ether | Union Carbide | Slightly viscous Clear liquid |
| Tergitol TP-9 | Nonionic | Nonyl Phenyl Polyethylene Glycol Ether | Union Carbide | Slightly viscous Clear liquid |
| Aerosol OT-75% | Anionic | Sodium Dioctyl Sulfosuccinate | American Cyanamid | Clear slightly Viscous liquid |
| Polytergent B-300 | Nonionic | Ethoxylated Nonylphenol | Olin Mathieson | Pale yellow, slightly Viscous liquid |
| Polytergent L-405 | Nonionic | Polyalkoxy Ether | Olin Mathieson | Pale yellow Slightly viscous Liquid |
| Nacconol NR | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | White flake, dry strength 40% |
| Nacconol DB | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | Dense bead dry, Strength 40% |
| Nacconol 40 DB | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | Fine white beads, Dry strength 40% |

Table 3. Wetting Agent Data (Continued)

| Product Name | Ionic Type | Chemical Type | Manufacturer | Remarks |
|-----------------|------------|-----------------------------|------------------|--|
| Nacconol DBX | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | Extra dense bead, Dry strength 40% |
| Nacconol 40 DBX | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | Extra dense bead, Dry strength 40% |
| Nacconol Beads | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | Light bead, dry strength 40% |
| Nacconol Z | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | Ivory flake, dry strength 85% |
| Nacconol NRSF | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | Light yellow flake, dry strength 92.5% |
| Nacconol 40 lb | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | White beads, dry strength 40% |
| Nacconol 90 F | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | Ivory flake, dry strength 90% |
| Nacconol 40 F | Anionic | Sodium Alkyl Aryl Sulfonate | National Aniline | White powder 40% dry strength |
| Ivory Liquid | | | Proctor & Gamble | Commercial detergent, slightly viscous white opaque liquid |

CHAPTER III

TESTING PROCEDURE

General

The basic testing program was designed to measure the change in density of the two soils when compacted at a specified moisture content with water treated with the various admixtures. Some of the desirable features in this testing program were:

1. A standard size sample and method of compaction which is suitable for testing the various types soils.
2. An admixture that is water soluble.
3. Evaluation by comparing the density of the treated soil to the density of the untreated soil.
4. Consistency in compacting the mold samples.

Preparation of Soil and Mixing

Soil I was air dried to a uniform moisture content and sieved through a No. 4 sieve with only the material passing being used in the tests. Soil II was oven dried at 110°F for 48 hours and sieved through a No. 4 sieve with only the material passing being used in the test. Both soils were predominantly minus four material with the majority of the discarded material being hardened lumps and roots. The initial moisture content of both soils before mixing began was approximately 2 per cent.

Mixing was done in a Reco Two-Speed mixer at a speed of 72 RPM.

Both soils were mixed for three minutes after the prepared solution had been added. To ensure a uniform moisture content throughout the soil before compaction, the soil was further mixed by hand using 20 strokes with a large spoon.

Establishment of a Standard for Comparison

The Standard Proctor moisture-density curve for both soils was determined by performing a minimum of eight tests for each soil. The moisture density curve for Soil I can be found in Figure 4 and for Soil II in Figure 5. From these curves the maximum density and optimum moisture content of both soils can be determined. The moisture content and dry density selected as a standard of comparison for the treated soils is less than the optimum moisture content and maximum dry density for each soil. The decision to compact all the test samples at a moisture content less than optimum was entirely arbitrary. The density of Soil I produced at the specified moisture content is 98.5 per cent of the maximum Standard Proctor Density at optimum moisture content for Soil I. The density of Soil II produced at the specified moisture is 98.6 per cent of the maximum Standard Proctor Density at optimum moisture content for Soil II. The moisture contents used in the compaction of the samples were:

Soil I 13%

Soil II 25%

Therefore, the standard for comparison for Soil I is the dry density of Soil I at 13 per cent moisture or 102.65 pounds per cubic foot, and for Soil II the dry density of Soil II at 25 per cent moisture of 90.05

pounds per cubic foot.

Preparation of Chemicals

Special handling and preparation of the chemicals was not required. The weight of chemical required to give the per cent solution of moisture to be added to the soil was added to the water prior to mixing of the water with the soil. The water and chemical were mixed for 30 seconds in a Hamilton Beach Model 33 mixer and then added to the soil. The per cent of admixture to be added to the compaction moisture was computed on a per cent by weight of total moisture content basis (e.g., 100 grams of moisture to produce a 13 per cent moisture content would be comprised of 10 grams of admixture and 90 grams of water and would constitute a 10 per cent solution). Regardless of the initial moisture content at the time of sample preparation, the weight of agent was based on the total moisture that would be required for compaction. For clarity an example calculation using Soil I is shown below:

Weight of air dry soil per sample.....4.6 lbs.

Initial moisture content.....2 per cent

Solution strength desired.....1 per cent

Water required to produce a
13 per cent m/c sample.....223 grams

$$\frac{4.6 \text{ lbs}}{1.02} = 4.4 \text{ lbs} = \text{dry weight of soil.}$$

$$4.4 \times 454 \text{ gm/lb} \times 13 \text{ per cent} = 259 \text{ grams total water required for } 13\% \text{ m/c.}$$

$$259 \times 1 \text{ per cent} = 2.6 \text{ grams-weight of chemical for required concentration.}$$

Thus for a 1 per cent solution, 2.6 grams of chemical and 223 grams of

water would be added and mixed with 4.5 pounds of air-dried soil. This would yield a sample treated with a 1 per cent solution and compacted at 13 per cent moisture.

Control of Variance in Moisture Content

Any appreciable variance in the moisture content of the compacted sample would affect the density, thus leading to a misinterpretation of the performance of the wetting agent. To guard against this occurrence a moisture content sample was taken from the center of each compacted sample. If the actual moisture content did not vary more than 1 per cent above or below the specified value it was considered acceptable. Those samples exceeding these limits were discarded.

Selection of Per Cent Solutions to be Used

Technical data furnished by the chemical manufacturers did not provide any information concerning recommended concentrations. The first six agents tested were mixed in solutions with concentrations ranging from 0 per cent to 12 per cent. Evaluation of these tests showed that percentages above 3 per cent produced insignificant changes in the dry density; therefore, the remaining chemicals were tested in solutions ranging from 0-3 per cent. The test increments were 0.25, 0.50, 0.75, 1.0 and 3.0 per cent solutions. Throughout the body of this report the percentages of admixtures mentioned are computed on a per cent by weight of final moisture content basis. The corresponding percentages in terms of the dry weight of the soil for both soils are shown below:

| <u>Soil I and II</u> | <u>Soil I</u> | <u>Soil II</u> |
|---|---|---|
| <u>Per Cent by Weight of Final Moisture Content</u> | <u>Per Cent by Dry Weight of Soil</u> | <u>Per Cent by Dry Weight of Soil</u> |
| 0.25 | 0.028 | 0.06 |
| 0.50 | 0.05 | 0.12 |
| 0.75 | 0.084 | 0.18 |
| 1.00 | 0.110 | 0.25 |
| 3.00 | 0.330 | 0.75 |

Reliability of Value Selected as Standard

To insure the accuracy of the values chosen as standards from the moisture density curves in Figures 4 and 5 the first sample compacted in the testing of a chemical was at 0 per cent solution, i.e., pure water. Each of these values has been included on the respective moisture-density curve in an effort to define more precisely that portion of the moisture density curve used for evaluating the treated samples.

Mixing Equipment

All mixing equipment and implements were thoroughly washed and dried after their use in testing one specific chemical. This precaution was taken to remove any residual amounts of chemicals from the equipment before testing began with another chemical.

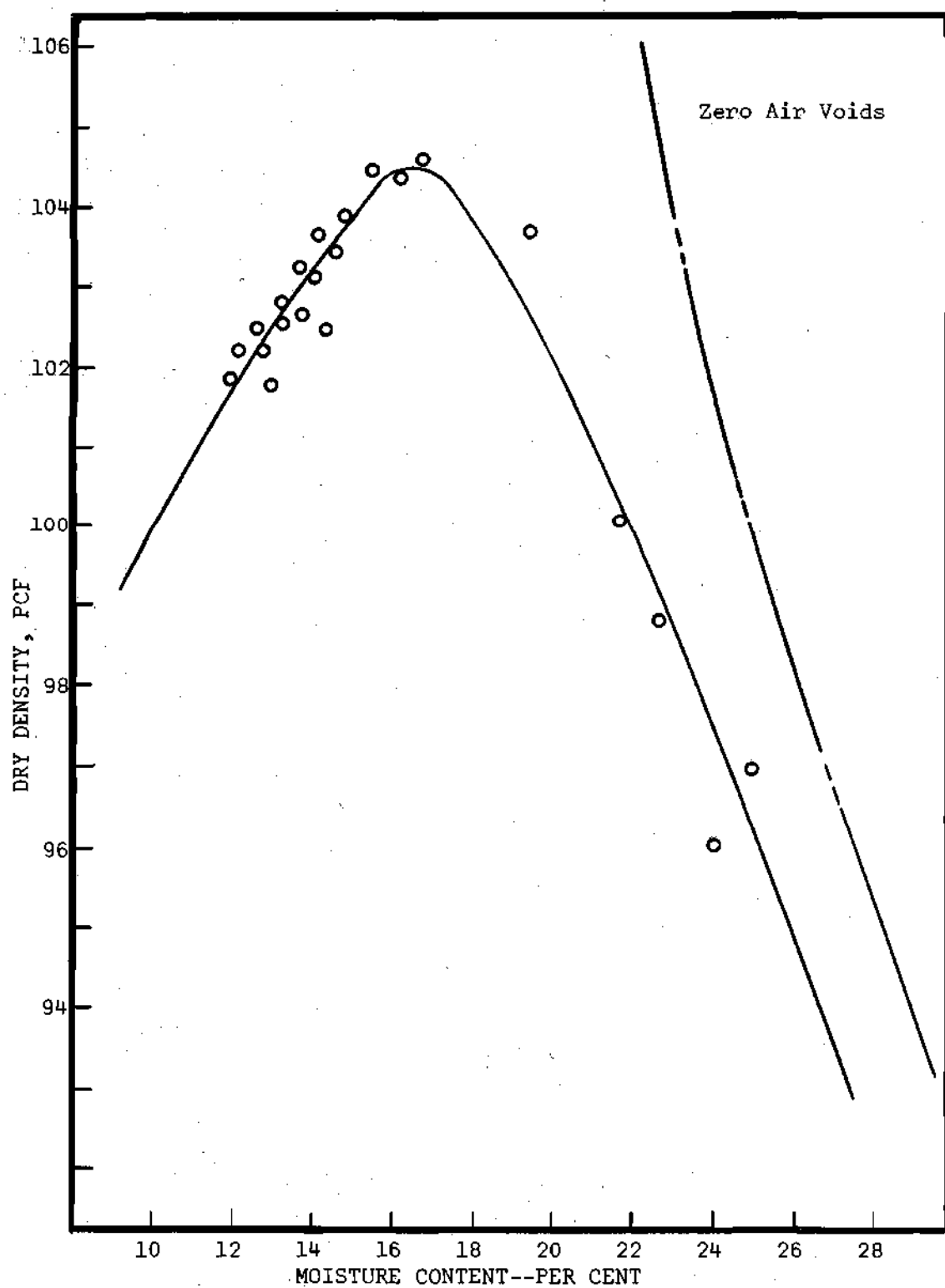


Figure 4. Standard Proctor Moisture-Density Curve for Soil I.

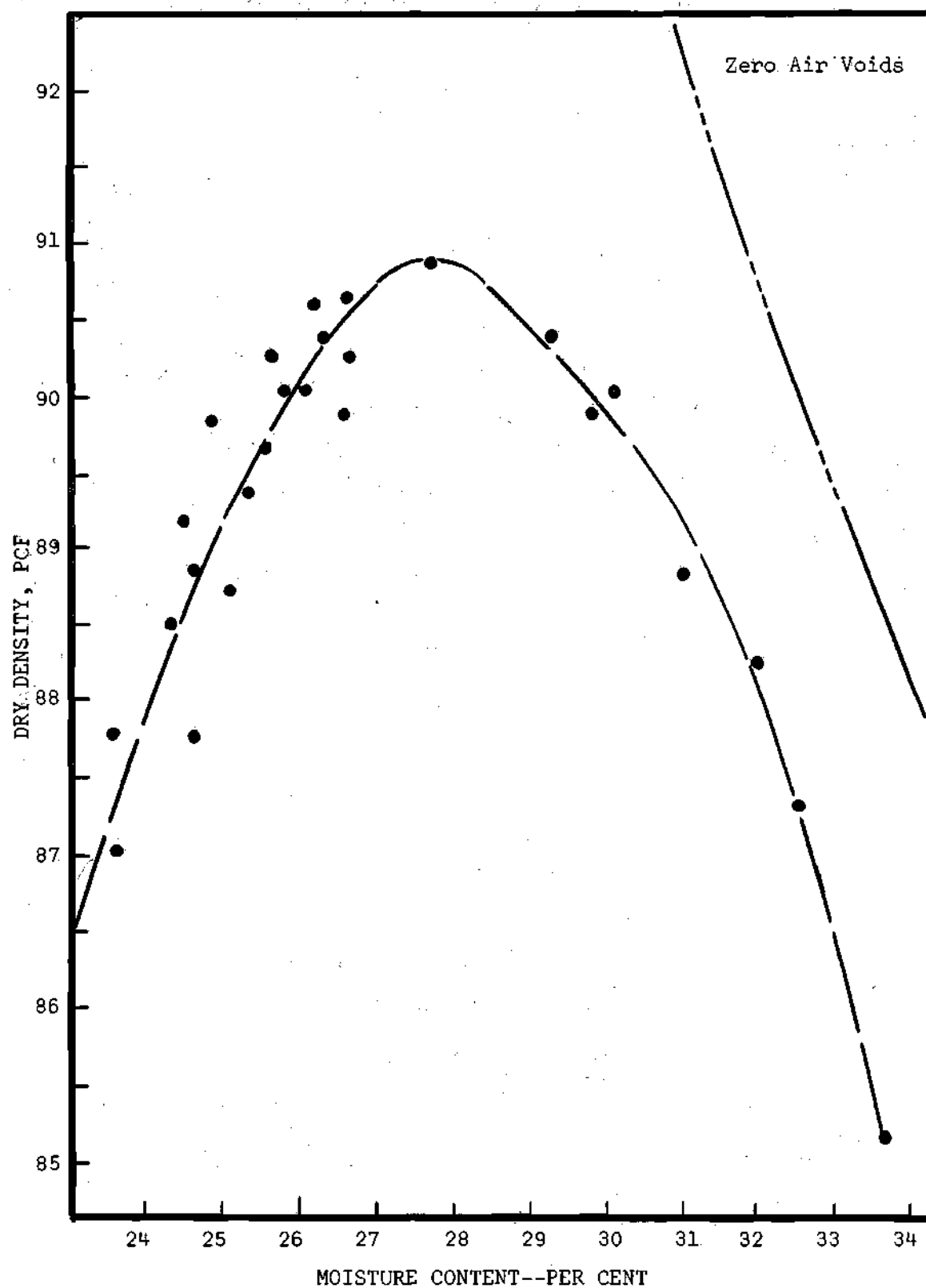


Figure 5. Standard Proctor Moisture-Density Curve for Soil II.

CHAPTER IV

EVALUATION OF TEST RESULTS

General

Testing of the two soils and the soils combined with the various admixtures involved determining the dry density of the soils at the moisture contents selected, both with and without the admixture.

Each soil used in this study was compacted to its Standard Proctor density for the specified moisture content with the water used for compaction treated with the various admixtures in the following increments: 0.25, 0.5, 0.75, 1 and 3 per cent. All percentages of admixtures were based on the total amount of water required to produce the specified final moisture content.

Admixture-Density

An admixture-density curve was plotted for each soil with the test increments of admixture as noted above. Exceptions to this were admixtures Alkanol DW, Alkanol OJ, Avitex Y, Alkanol 189-S, Product BCO and Ivory Liquid which were tested at increments of 0.5, 1, 3, 5, 7, and 9 per cent.

For clarity in discussion the admixtures have been grouped in the following categories:

1. Amphoteric
2. Anionic
3. Cationic

4. Nonionic

5. Miscellaneous

Product BCO is the only admixture that falls in the category of an amphoteric surface active agent. Evaluation of Figure 6 for Soil I shows that increasing percentages of admixture cause a slight decrease in density. This decrease is approximately 1.5 per cent and occurs at a 9 per cent concentration of admixture. For Soil II increasing percentages of admixture cause an increase of density up to 3 per cent admixture while at higher percentages the density gradually declined to a value only 5.5 per cent larger than the untreated density. The density of Soil II at 3 per cent admixture was 8.5 per cent greater than the untreated density.

Within the category of anionic surface active agents, 18 admixtures were tested. Of this total, 11 are of the trade name Nacconol. These 11 are all the same chemically with the only difference between them being their dry strength and physical appearance.

Evaluation of Figure 7 shows that increasing percentages of Aerosol OT-75 per cent causes and increases in density of both Soils I and II, with Soil II experiencing the greatest increase; approximately 11 per cent. Both soils experienced the greatest increase in density at percentages of admixture below 0.50. Percentage admixtures above this value cause a diminishing increase in density.

Figure 8 shows that increasing percentages of Alkanol 189-S cause an increase in density of Soil II. Soil I experienced a decrease in density of 0.50 per cent at 1 per cent admixture but increased in density above its untreated value by 2 per cent at 9 per cent admixture. The

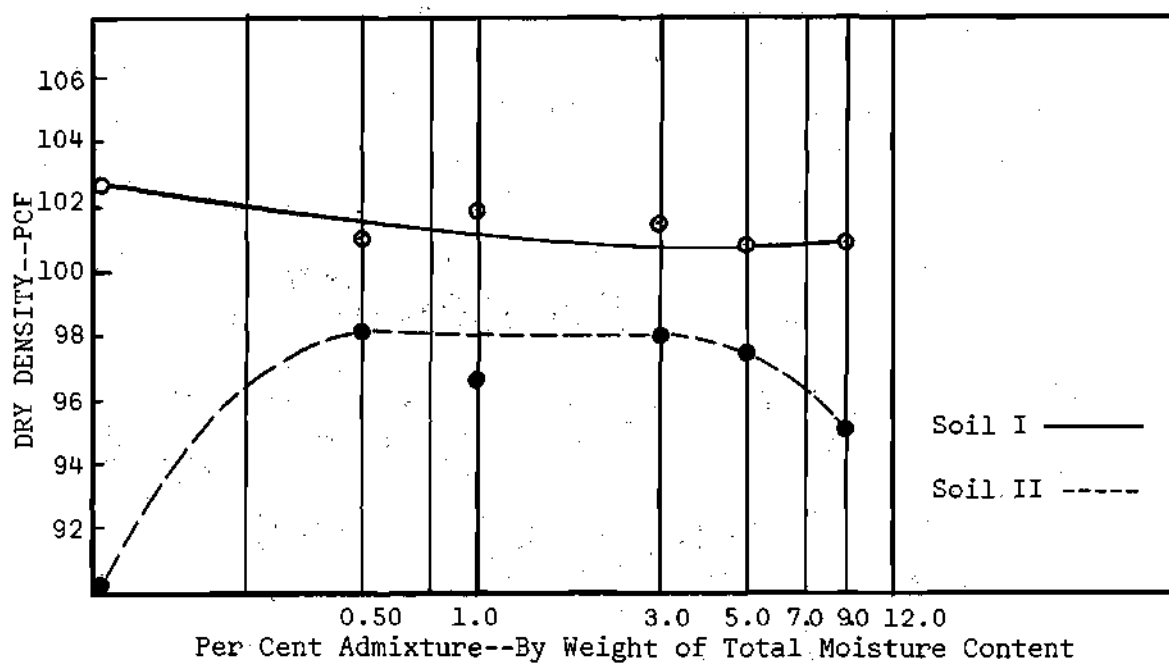


Figure 6. Relationship of Dry Density and Admixture Product BCO for Soils I and II.

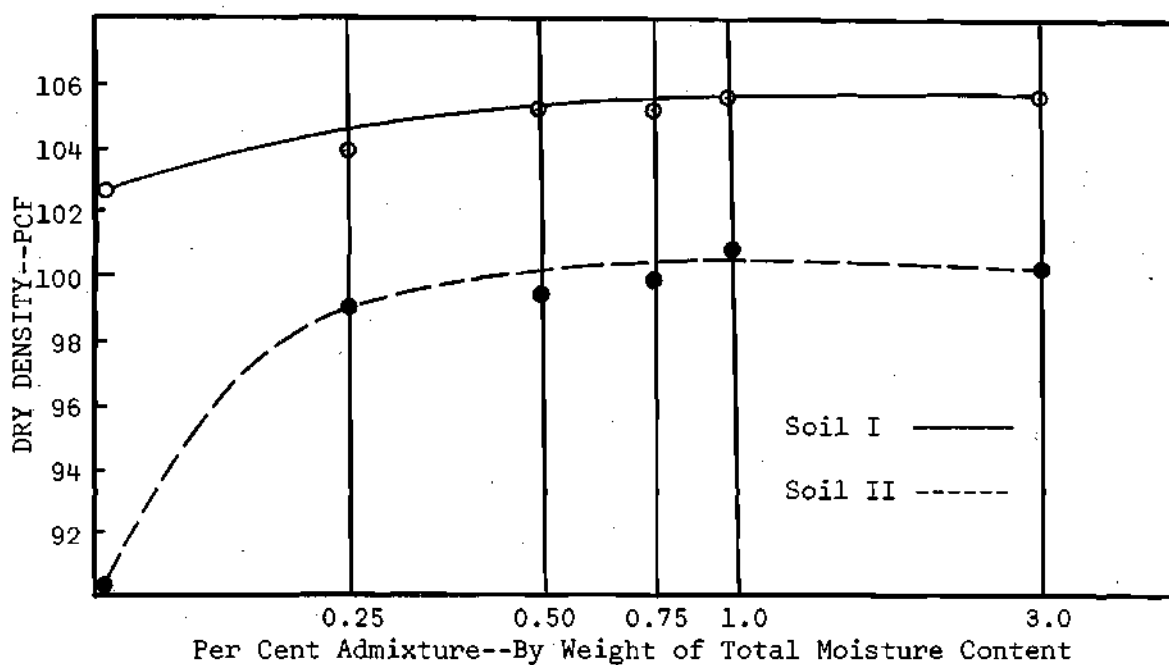


Figure 7. Relationship of Dry Density and Admixture Aerosol OT-75% for Soils I and II.

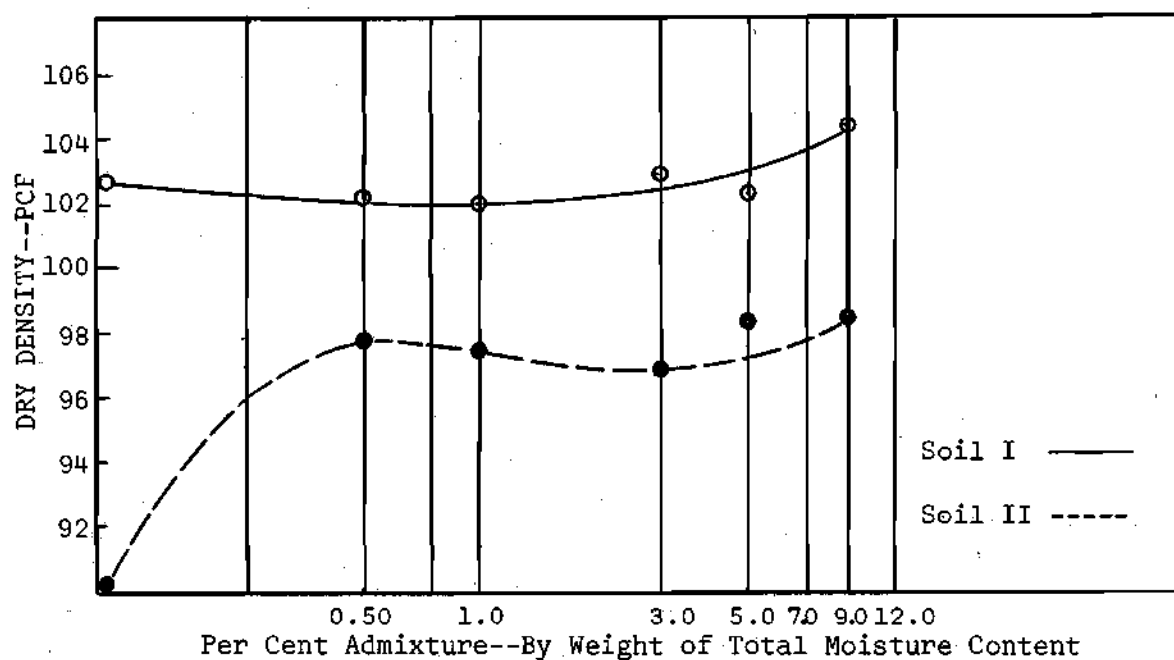


Figure 8. Relationship of Dry Density and Admixture Alkanol 189-S for Soils I and II.

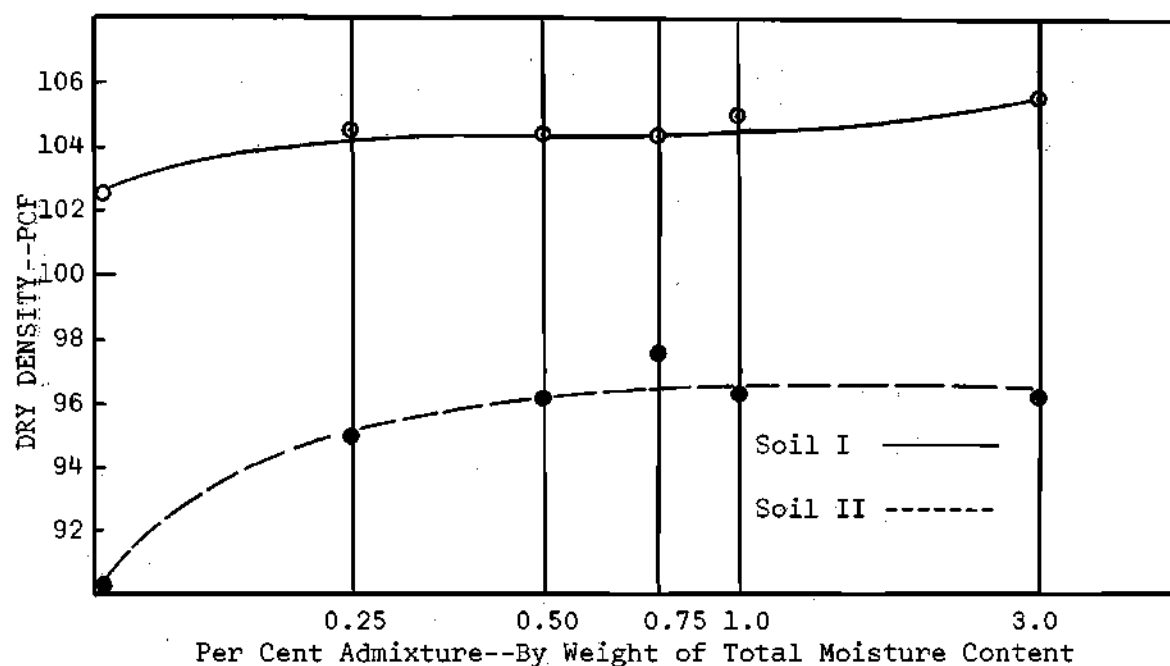


Figure 9. Relationship of Dry Density and Admixture Alkanol B for Soils I and II.

density of Soil II was increased 8.75 per cent at 0.25 per cent admixture with percentages above that value causing a diminishing increase in density.

The effect of Alkanol B on Soils I and II is shown in Figure 9. Increasing percentages of admixture cause increasing density in both soils with Soil II the most responsive to the admixture. Again the greatest increase in density is caused at relatively small admixture percentages. Percentages higher than 0.25 per cent cause only an additional increase of 1.5 per cent in Soil II. The increase in density over untreated soil at 0.25 per cent admixture is 5.5 per cent for Soil II.

Of all the anionic wetting agents tested, Alkanol DW caused the least response in Soil II. Figure 10 shows that a percentage of 0.5 per cent increased the dry density at 25 per cent moisture from 90.05 pcf to 93.4 pcf, an increase of 3.5 per cent. Increasing the concentration from 0.5 to 9 per cent caused a further increase in density of 1.25 per cent to a density of 94.7 pcf. The density of Soil I increased from 102.7 pcf to 104.3 pcf at 5 per cent admixture, an increase of 1.6 per cent over the untreated soil. Further increases in concentration caused a gradual decrease in density towards the untreated value of 102.7 pcf.

With increases in concentration of Avitex SE, the density of Soil II increased sharply at low concentrations and increased at a decreasing rate at higher concentrations. (Figure 11) Soil I was only slightly affected with a 3 per cent concentration causing an increase in density of 1 per cent.

Evaluation of Figure 12 shows that increases in concentration of Duponol WA cause an increase in the density of Soil II to 99.4 pcf at

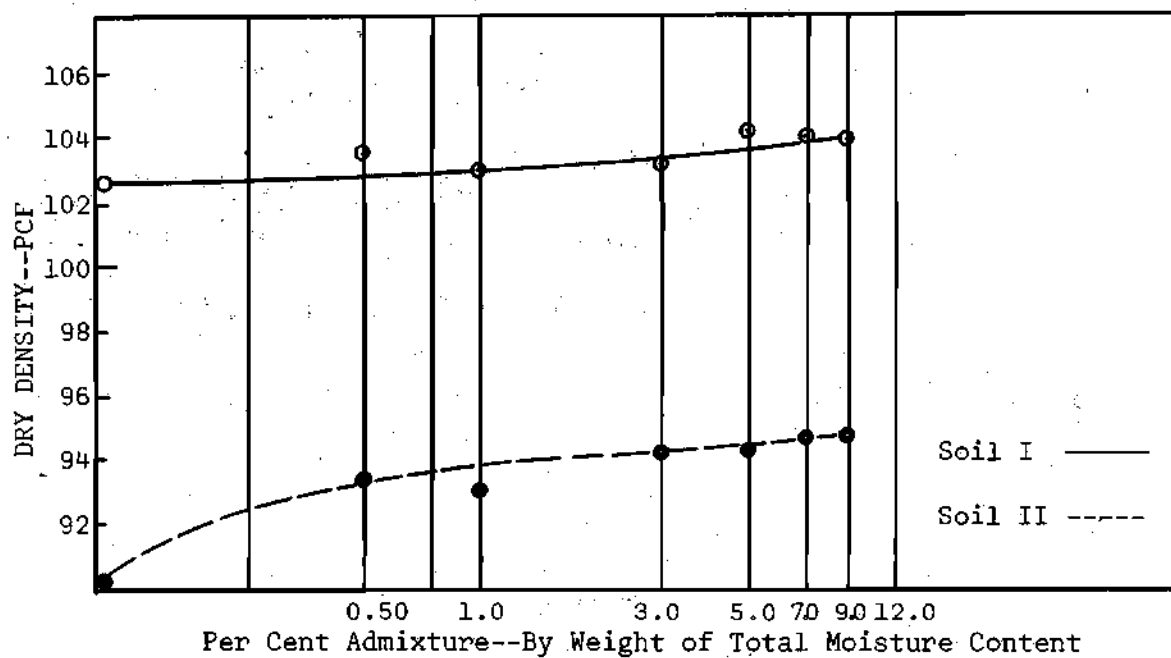


Figure 10. Relationship of Dry Density and Admixture Alkanol DW for Soils I and II.

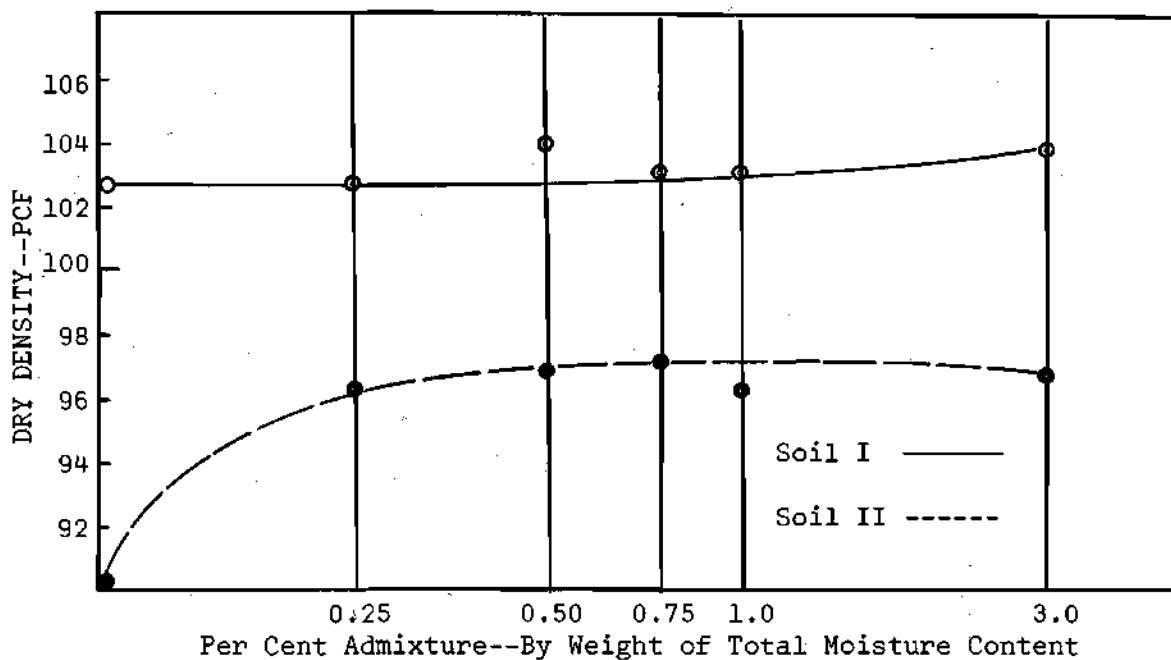


Figure 11. Relationship of Dry Density and Admixture Avitex SF for Soils I and II.

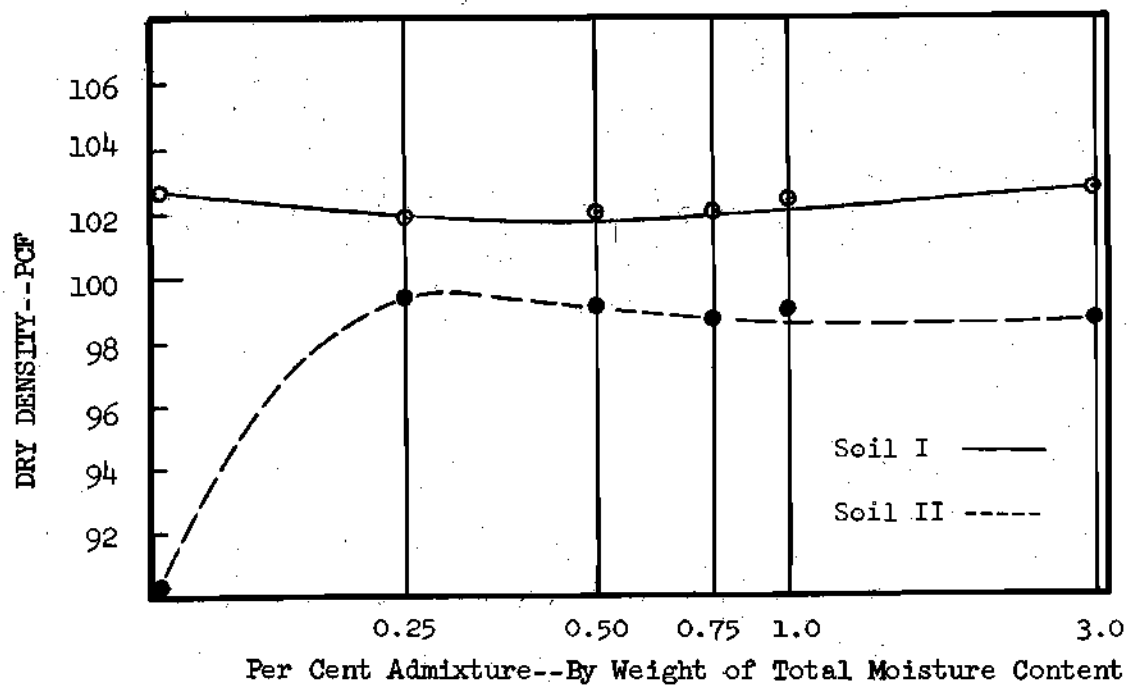


Figure 12. Relationship of Dry Density and Admixture Duponol WA for Soils I and II.

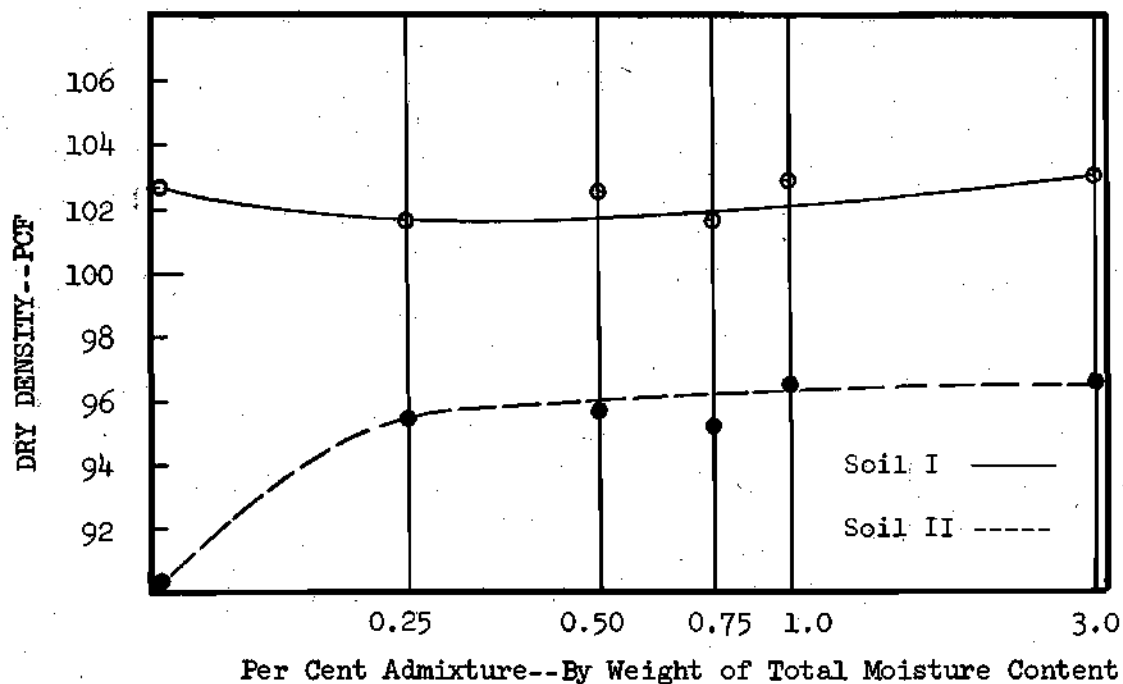


Figure 13. Relationship of Dry Density and Admixture Duponol WN for Soils I and II.

0.25 per cent admixture, increasing concentrations above this value causes a slight decrease in density to 98.7 pcf at 3 per cent admixture. This is a total increase of 9.5 per cent over the untreated value of 90.05 pcf. The density of Soil I is decreased from 102.7 pcf to 101.9 pcf by increasing the concentration from 0 to 0.25 per cent. Further increases in concentration cause a gradual increase of density back to the untreated value of 102.7 at a concentration of 3 per cent.

Figure 13 shows that increasing concentrations of Duponol WN cause an increase in the density of Soil II to 95.5 pcf at 0.25 per cent concentration. Increasing the percentage concentration to 3 per cent causes a further increase in density of just 1.25 per cent. The density of Soil I is decreased with increasing concentrations of admixture to a minimum value of 101.6 pcf at 0.75 per cent concentration. Concentrations above this value cause a gradual increase to a value slightly above that for the untreated soil.

Figures 14 through 21 are for the Nacconol surface active agents having a dry strength of 40 per cent. Examination of these figures show that the density of Soil II is increased to a minimum value of 96.9 pcf at 3 per cent for Nacconol 40 LB and a maximum value of 98.9 pcf at 3 per cent for Nacconol 40 F. For concentrations of 0.25 per cent the minimum density was 96.3 pcf for Nacconol 40 LB and the maximum value 98.5 pcf for Nacconol NR. The density of Soil I varied from a minimum value of 103.9 pcf to a maximum value of 106.3 pcf for a 3 per cent concentration. This is a range of increase from 1.2 to 3.5 per cent over the untreated soil.

Figure 22 shows the effect of Nacconol Z on the dry density of

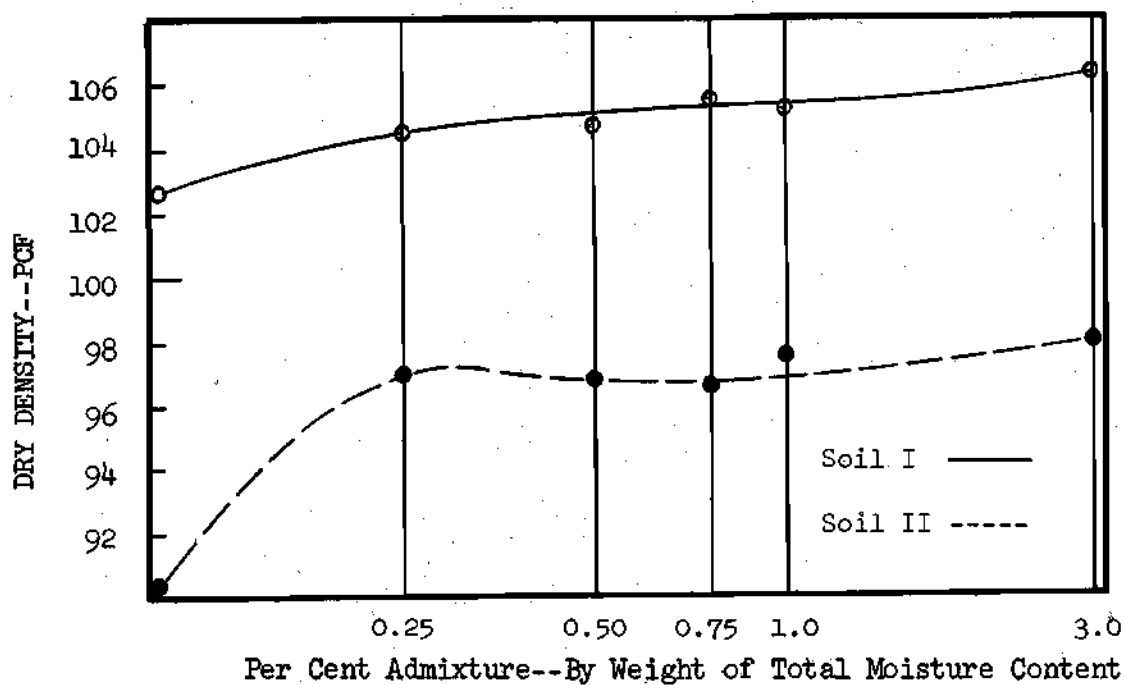


Figure 14. Relationship of Dry Density and Admixture Nacconol 40 DB for Soils I and II.

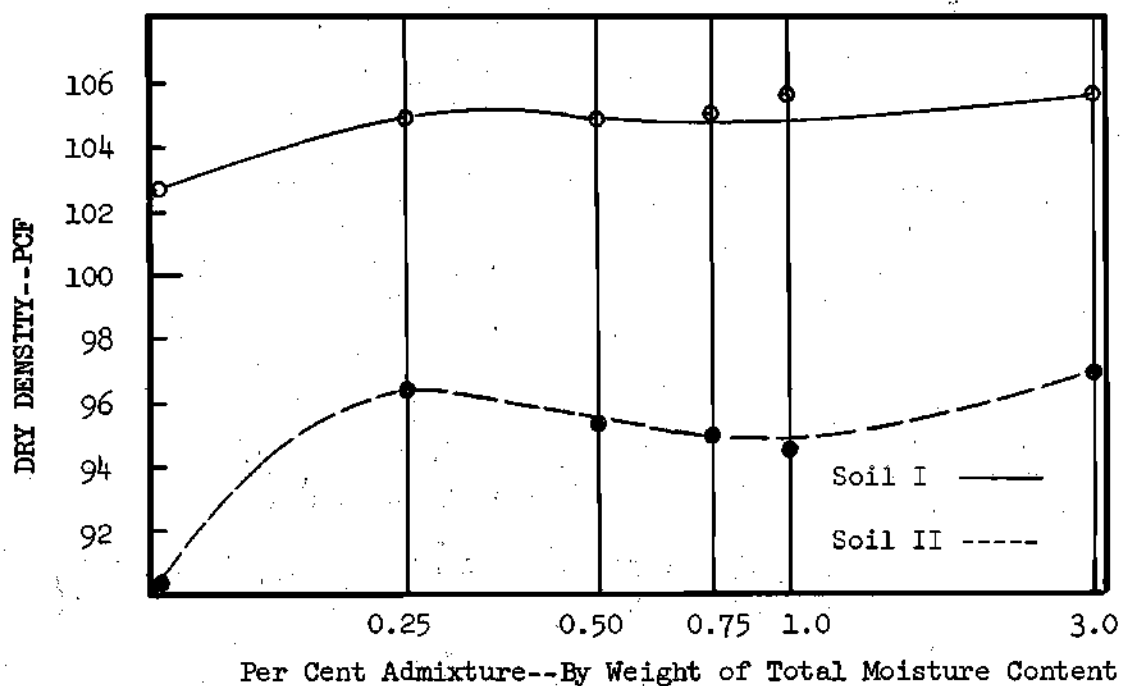


Figure 15. Relationship of Dry Density and Admixture Nacconol 40 LB for Soils I and II.

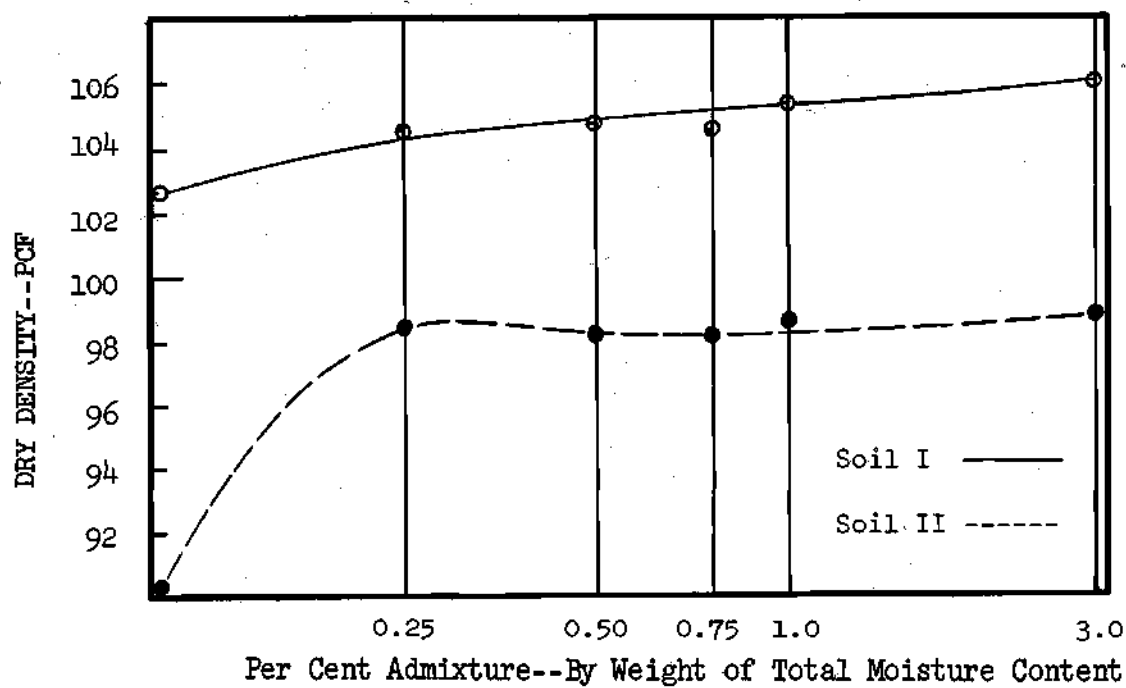


Figure 16. Relationship of Dry Density and Admixture Nacconol NR for Soils I and II.

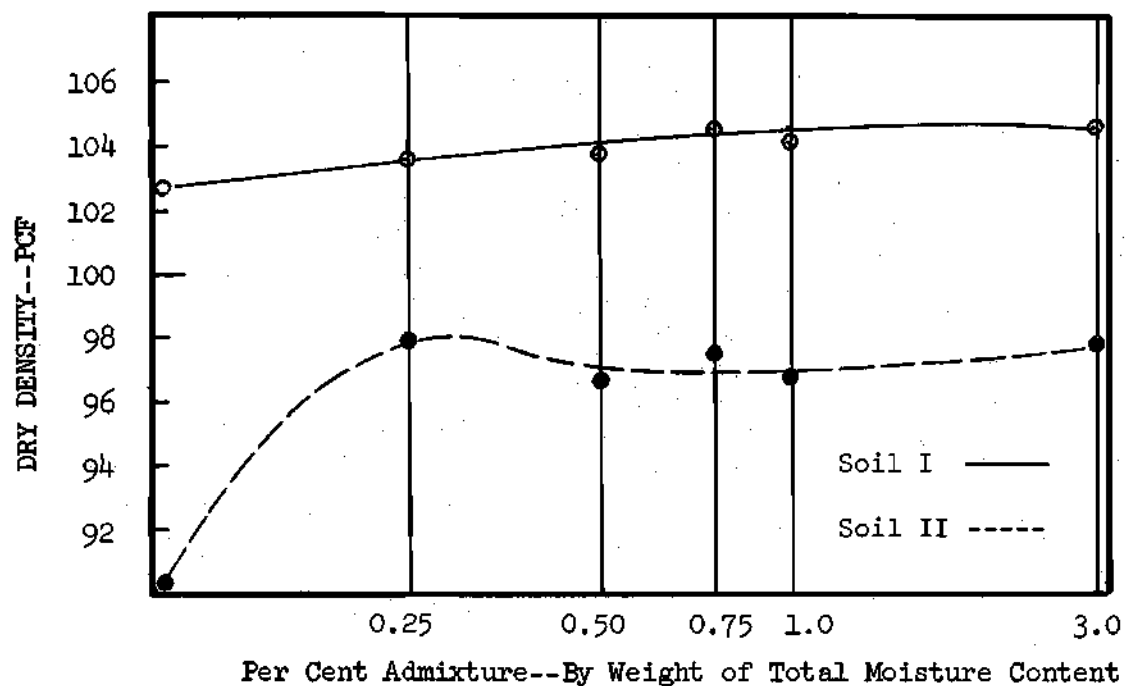


Figure 17. Relationship of Dry Density and Admixture Nacconol DB for Soils I and II.

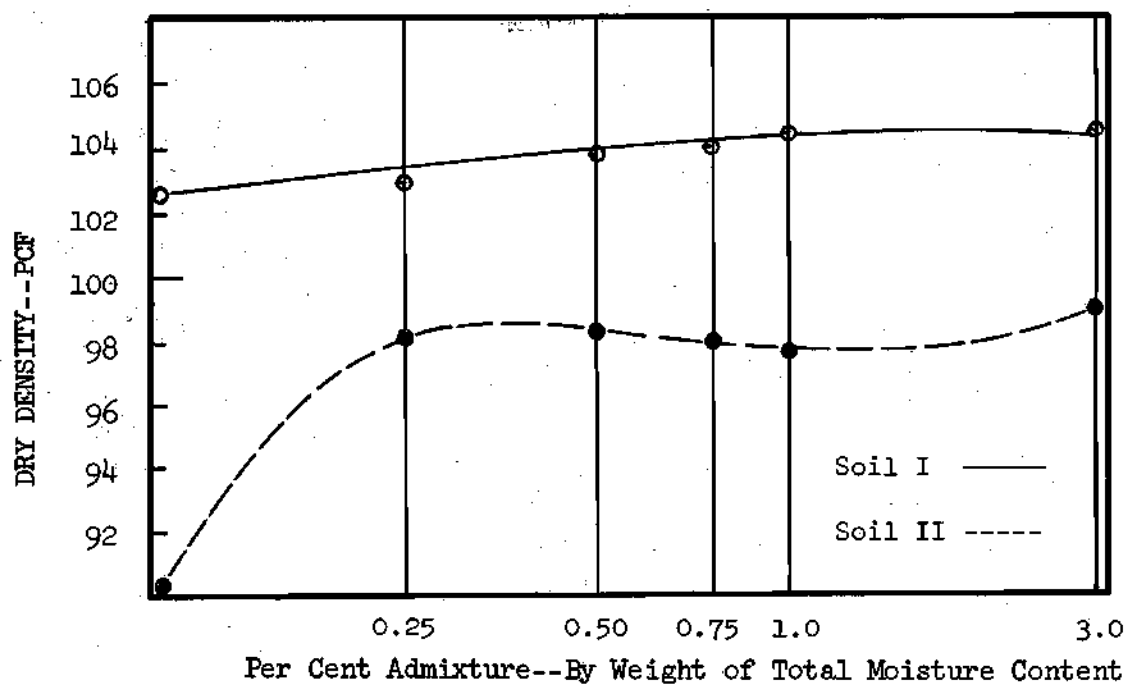


Figure 18. Relationship of Dry Density and Admixture Nacconol 40 F for Soils I and II.

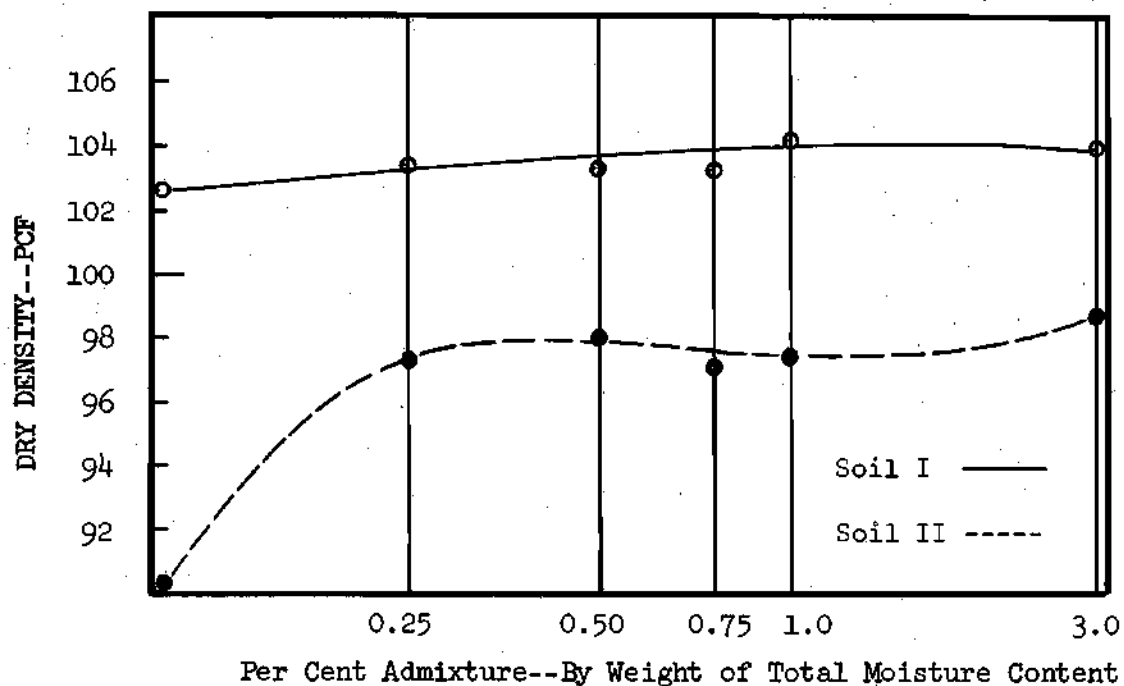


Figure 19. Relationship of Dry Density and Admixture Nacconol 40 DBX for Soils I and II.

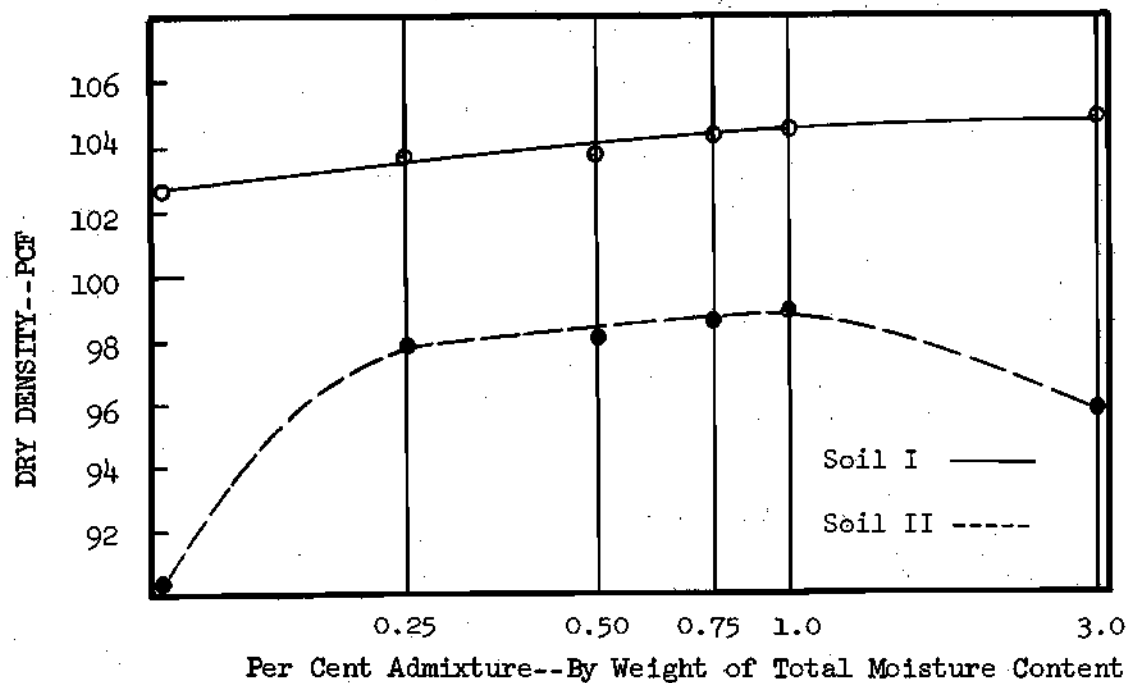


Figure 20. Relationship of Dry Density and Admixture Nacconol Beads for Soils I and II.

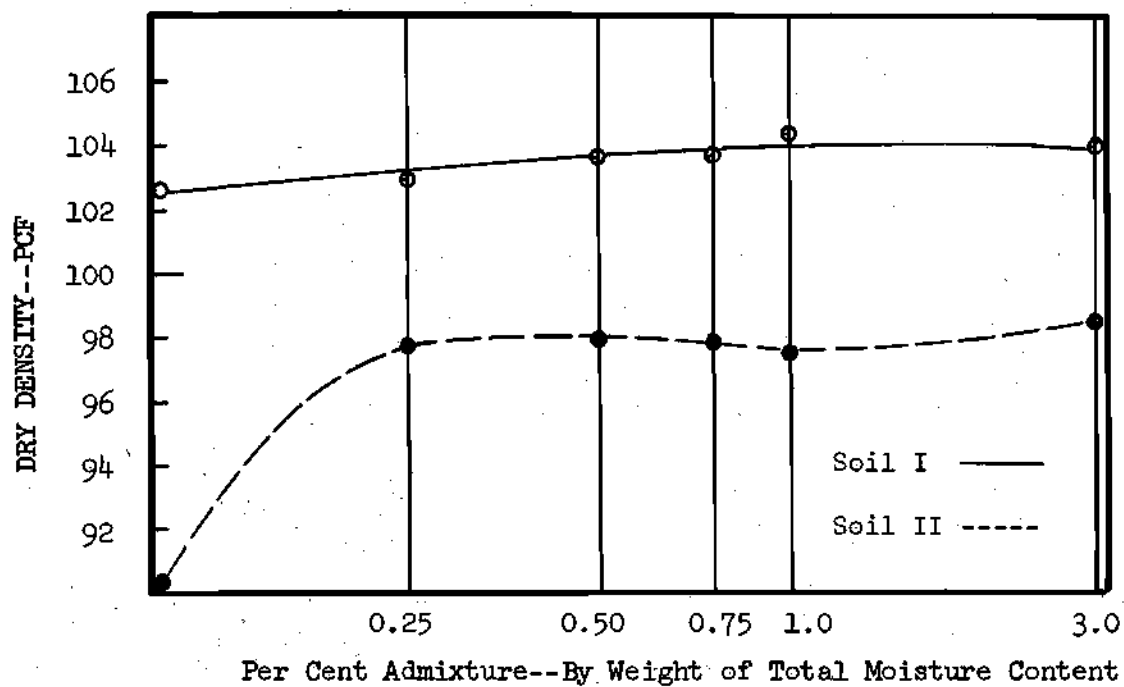


Figure 21. Relationship of Dry Density and Admixture Nacconol DBX for Soils I and II.

Soils I and II. The density of Soil II is increased some 8.3 per cent to a value of 97.6 pcf at a concentration of 3 per cent. A concentration of 0.25 per cent caused an increase to 96.5 pcf, only 1.1 per cent less than at a 3 per cent concentration. Soil I showed little response to treatment with the agent. The density was increased a maximum of 1 per cent at 3 per cent concentration of admixture.

Nacconol 90 F had a dry strength of 90 per cent and caused the largest increase in density of Soil II of all the Nacconol agents tested. Figure 23 shows that the density of Soil II was increased to 99.4 pcf at a concentration of 3 per cent, an increase of 10.5 per cent over the value of the untreated soil. The density at 0.25 per cent concentration was increased to 98.1 pcf an increase of 9 per cent over the untreated soil. The density of Soil I was increased by only 1 per cent at a concentration of 3 per cent.

Figure 24 shows that increasing the admixture causes an increase in density of Soils I and II. Nacconol NRSF has a dry strength of 92.5 per cent. This admixture, like Nacconol 90 F, causes the greatest increase in density of Soil II to occur at concentrations less than 0.5 per cent. Increased concentrations above this value cause a diminishing increase in density. Soil I responded only slightly with a total increase in density of 0.75 per cent.

Avitex Y was the only cationic surface active agent that was available for testing. Its effect on Soils I and II is shown in Figure 25. As the per cent concentration increases the density increases until a concentration of 1 per cent. Increases above this value cause a decrease in the density to a value of 95 pcf at 9 per cent. This is an

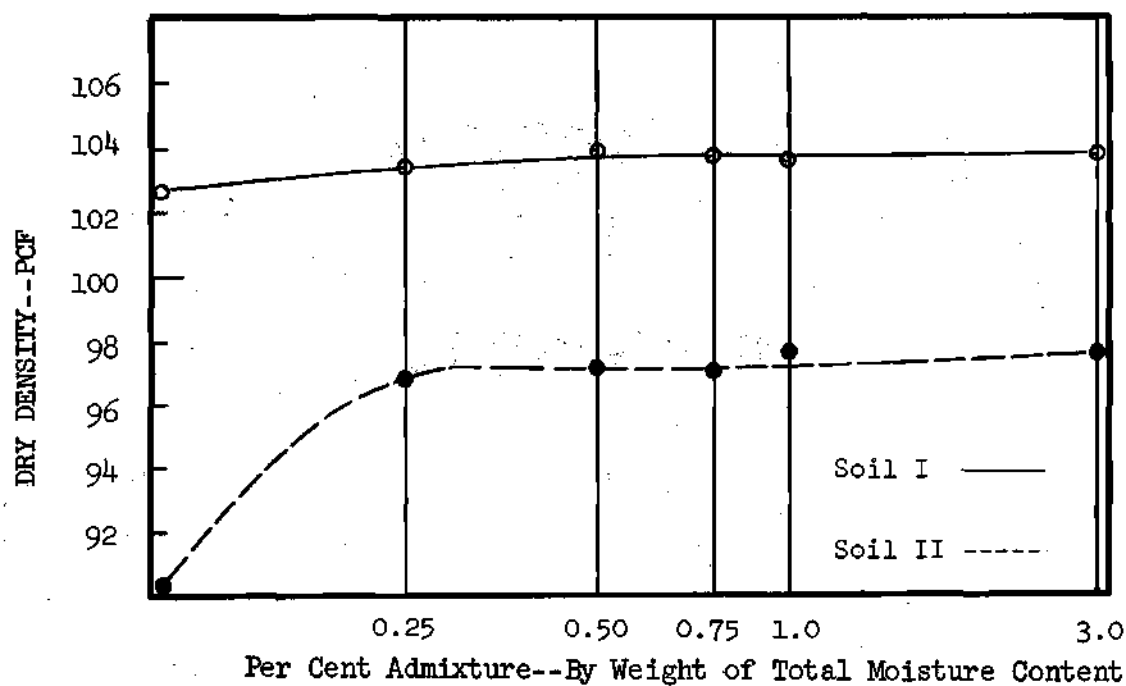


Figure 22. Relationship of Dry Density and Admixture Nacconol Z for Soils I and II.

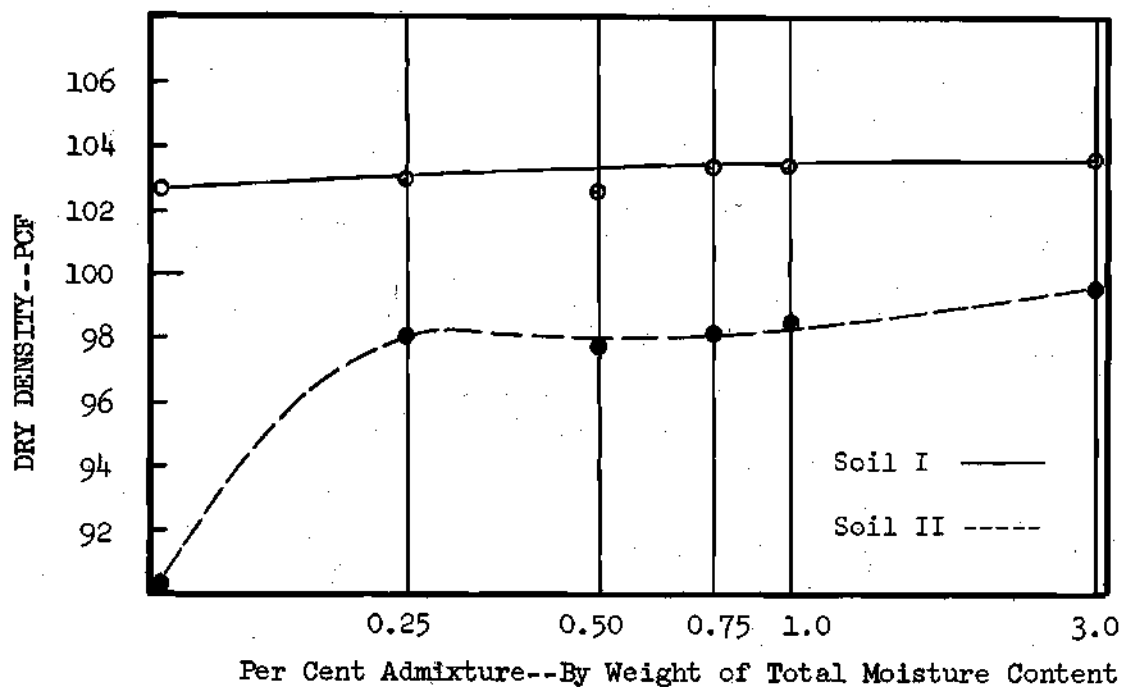


Figure 23. Relationship of Dry Density and Admixture Nacconol 90 F for Soils I and II.

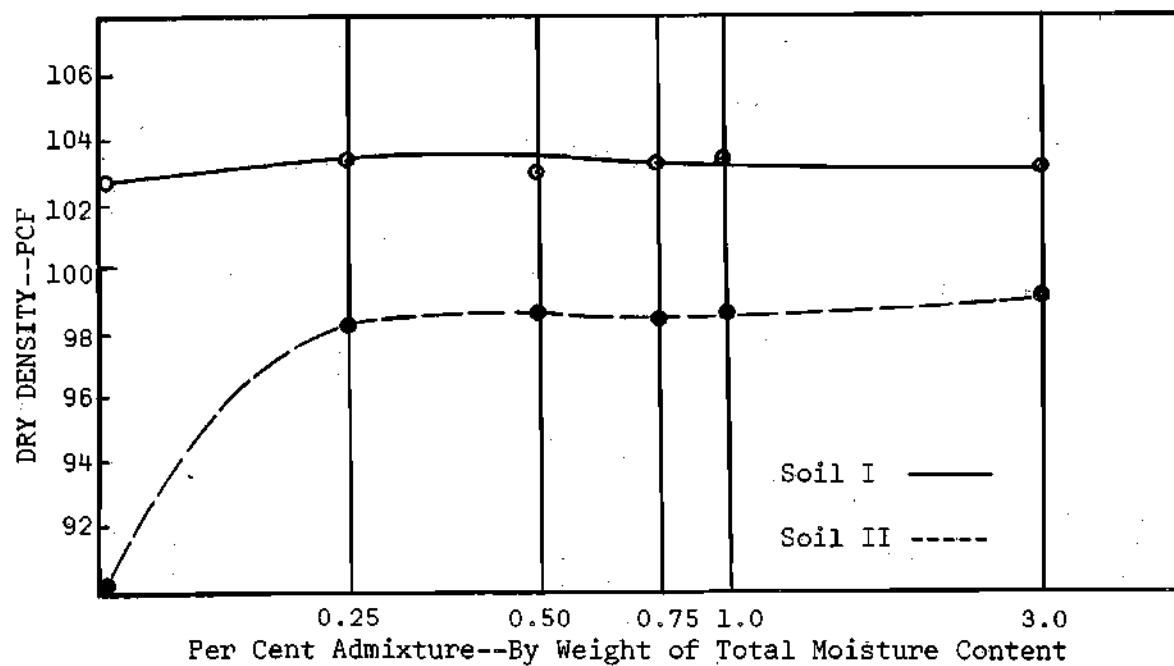


Figure 24. Relationship of Dry Density and Admixture Nacconol NRSF for Soils I and II.

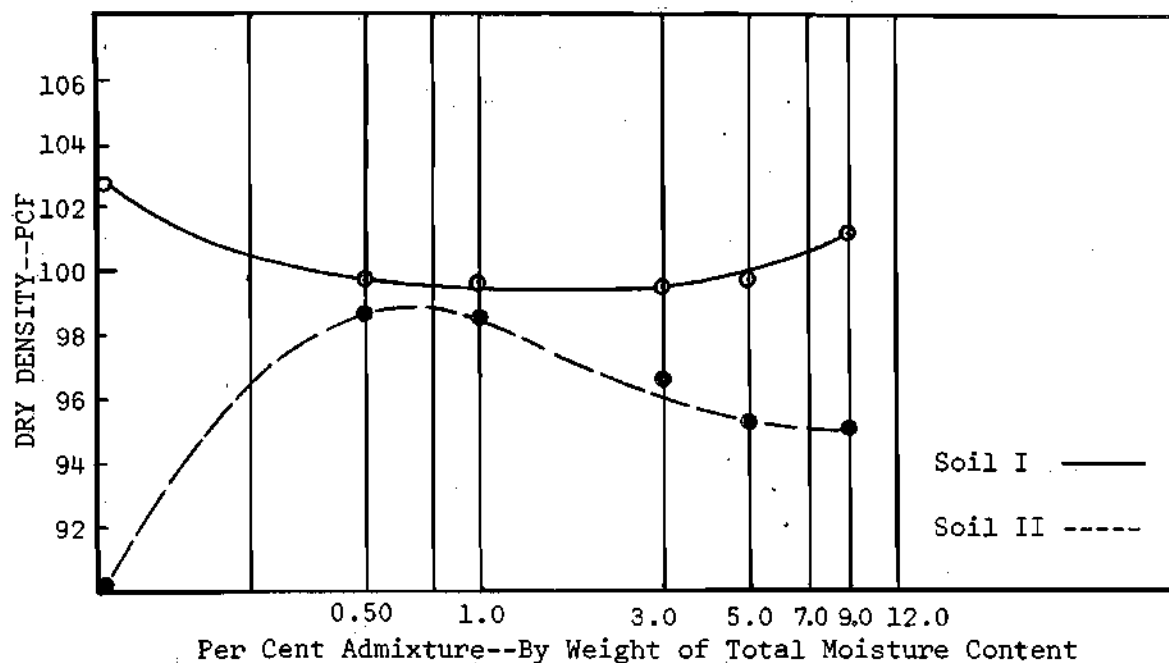


Figure 25. Relationship of Dry Density and Admixture Avitex Y for Soils I and II.

increase of 5.6 per cent over the untreated density. The density of Soil I is decreased as the concentration increases until a concentration of 1 per cent. Further increases in concentration of admixture increase the density to a value 1.5 per cent less than the untreated density. The response of both soils to treatment with Avitex Y is quite similar to that of both soils treated with Product BCO, the amphoteric agent. This would indicate that Product BCO had been used in an acid media thus reacting as a cationic surface active agent. The tap water used proved to be slightly acidic when tested with litmus.

The results of tests with the nonionic wetting agents are shown in Figures 26 through 30. As a general rule, the nonionic types are chemically less efficient than the cationic and anionic types. However at small percentages of admixture their effect on the density was as significant as the other type agents.

Figure 26 shows that increasing percentages of admixture cause an increase in density for both Soils. In contrast to previous agents discussed, the effect of Alkanol OJ on Soil II was not as pronounced at low concentrations of admixture. At 1/2 per cent admixture the per cent increase in density was only 3.5 per cent. The same concentration for Soil I caused an increase in density of 2.3 per cent.

Polytergent 300 (Figure 27) was a very effective admixture. The density of Soil II was increased 11 per cent to a value of 99.9 pcf with the addition of 0.75 per cent admixture. Increases above this value cause a gradual decrease in density to a minimum value of 99.2 pcf at 3 per cent admixture. Soil I increased in density with increasing admixture to a value of 103.9 pcf at 3 per cent admixture. This was an

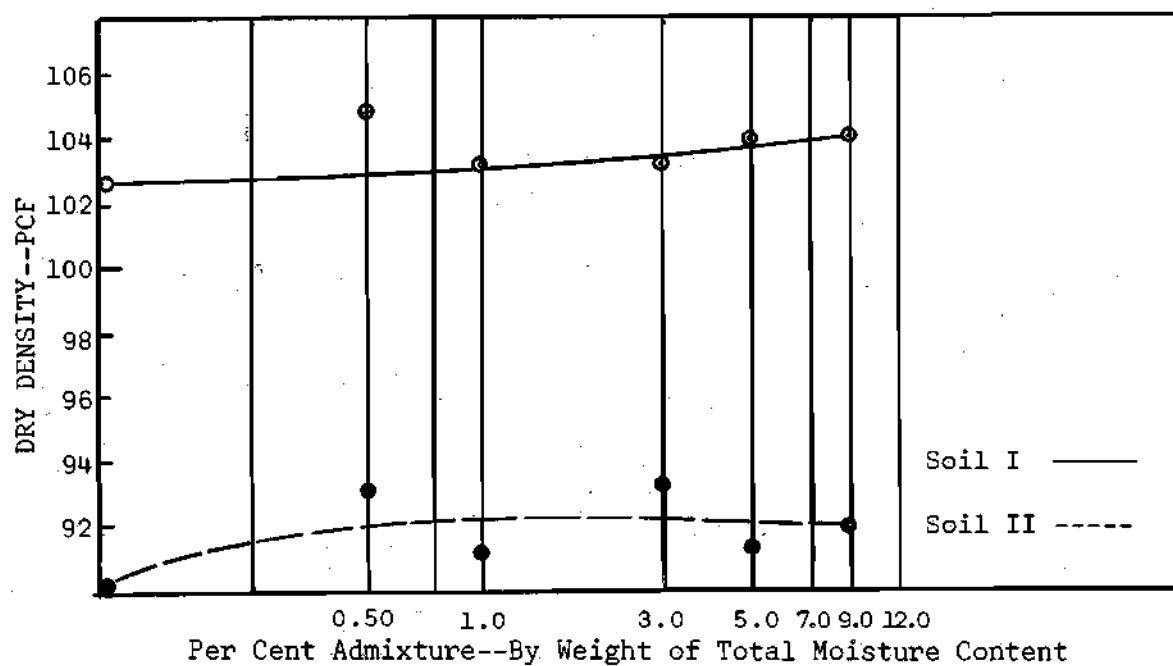


Figure 26. Relationship of Dry Density and Admixture Alkanol OJ for Soils I and II.

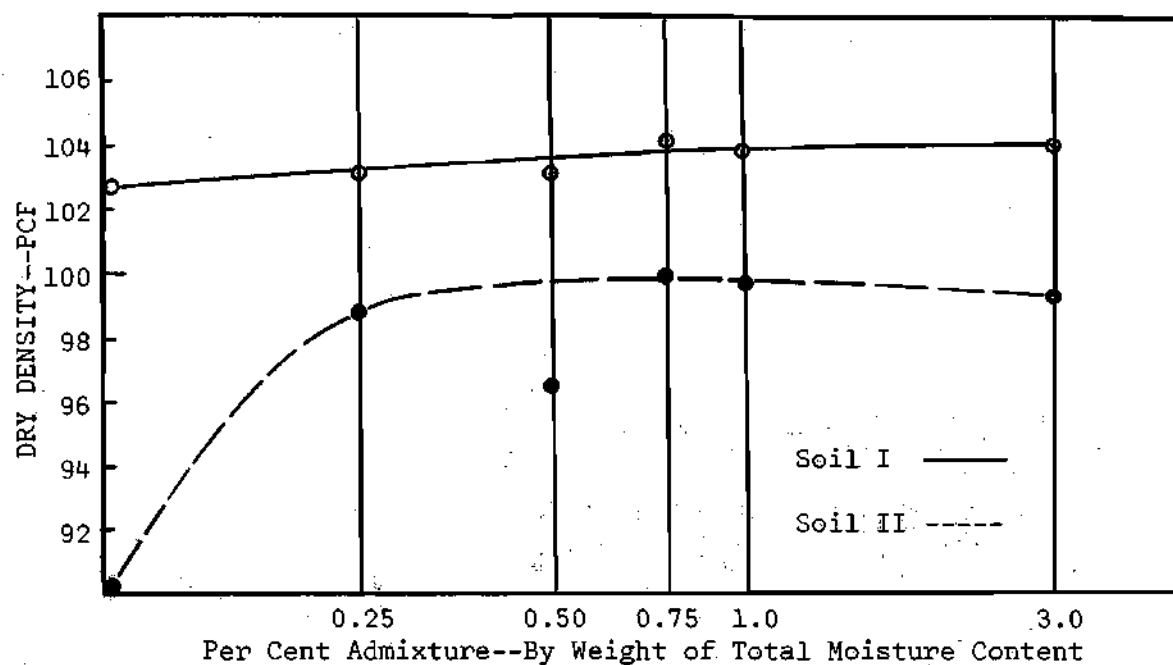


Figure 27. Relationship of Dry Density and Admixture Polytergent B-300 for Soils I and II.

increase of 1 per cent over the untreated density.

Figure 28 shows that increasing percentages of Polytergent L-405 cause increases in the density of Soil II. The maximum increase of 8.8 per cent occurs at 0.25 per cent admixture. Increasing the concentration to 3 per cent causes a further increase in density of only 0.6 per cent. The density of Soil I increased a total of 0.8 per cent with increasing percentages of admixture.

Evaluation of Figure 29 shows that increasing the percentages admixture of Tergitol NPX causes the density of Soil II to increase to a maximum value of 98.4 pcf at 3 per cent admixture. The largest per cent increase though, occurs at an admixture percentage of 0.25. This is an increase in density of 6.7 per cent over the untreated density. Increasing the percentage admixture to 3 per cent raises the density only an additional 2.7 per cent. The density of Soil I increases slightly with increases in admixture but percentages above 0.50 per cent cause only a diminishing increase in density.

Figure 30 shows that increasing percentages of admixture Tertitol TR-9 causes an increase in density of Soil II to a maximum value of 99.5 pcf at 0.75 per cent admixture. Increases in admixture above this value cause a gradual decrease in the density. The density of Soil I is increased 0.8 per cent with the percentage admixture at 0.25 per cent. Further increases produced no changes in the density of Soil I.

The admixtures Ivory Liquid and Hydroxyacetic Acid are catagorized as miscellaneous agents.

Figure 31 shows that increasing the percentage of Ivory Liquid to a value of 5 per cent caused a 7 per cent increase in density of Soil II.

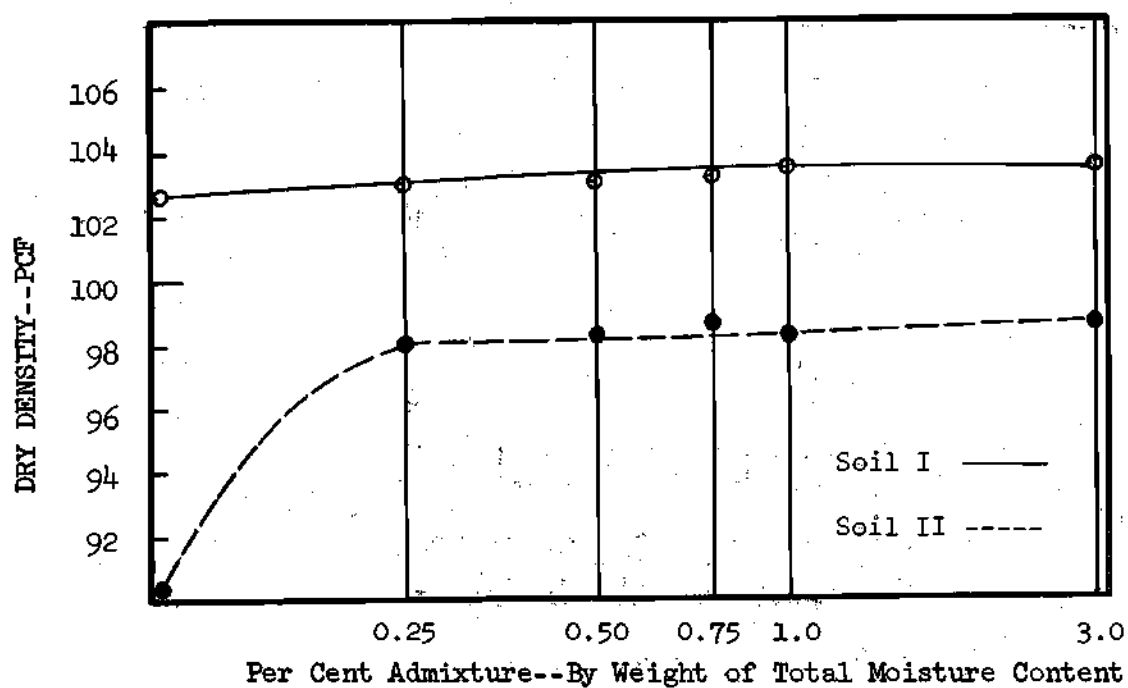


Figure 28. Relationship of Dry Density and Admixture Polytergent L-405 for Soils I and II.

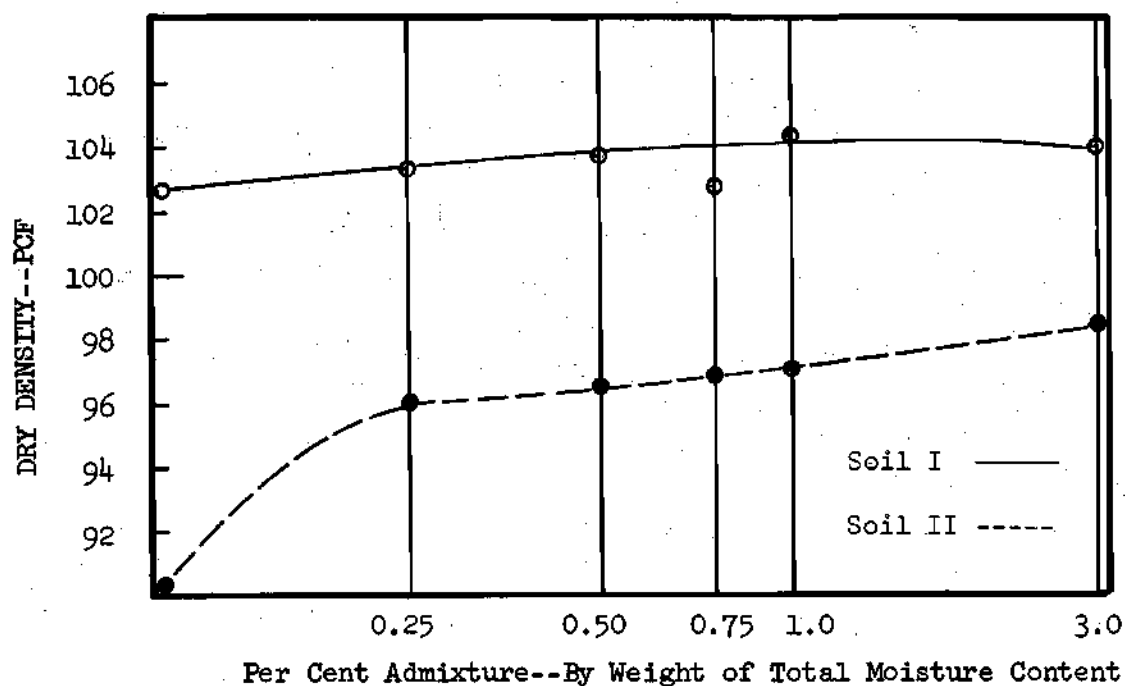


Figure 29. Relationship of Dry Density and Admixture Tergitol NPX for Soils I and II.

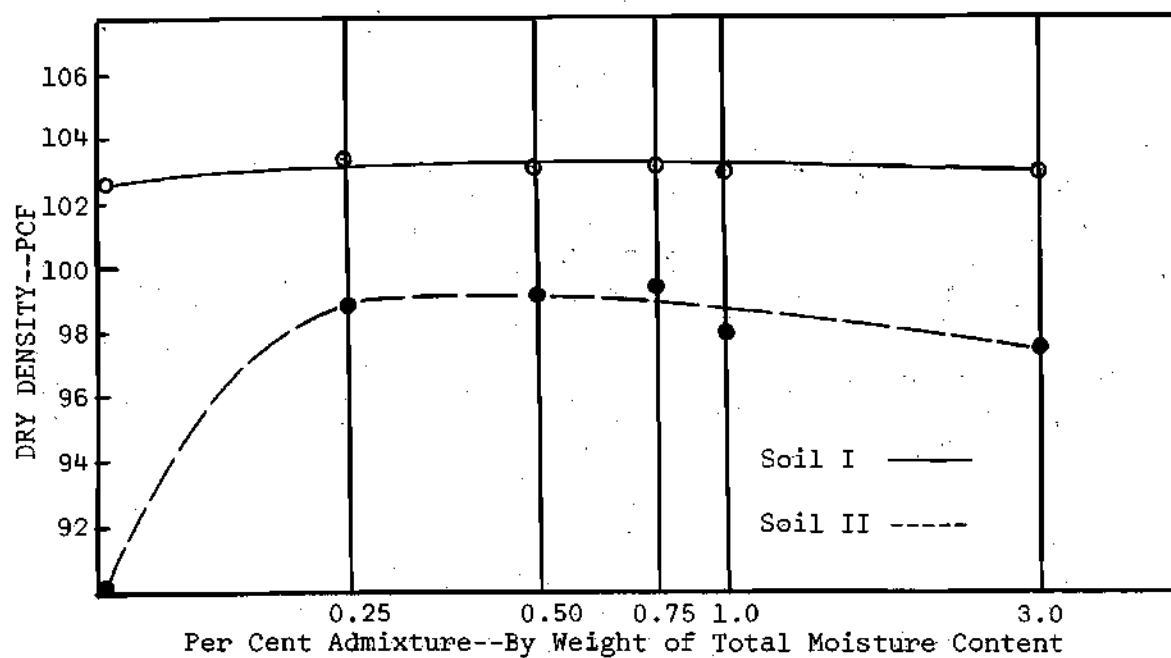


Figure 30. Relationship of Dry Density and Admixture Tergitol TP-9 for Soils I and II.

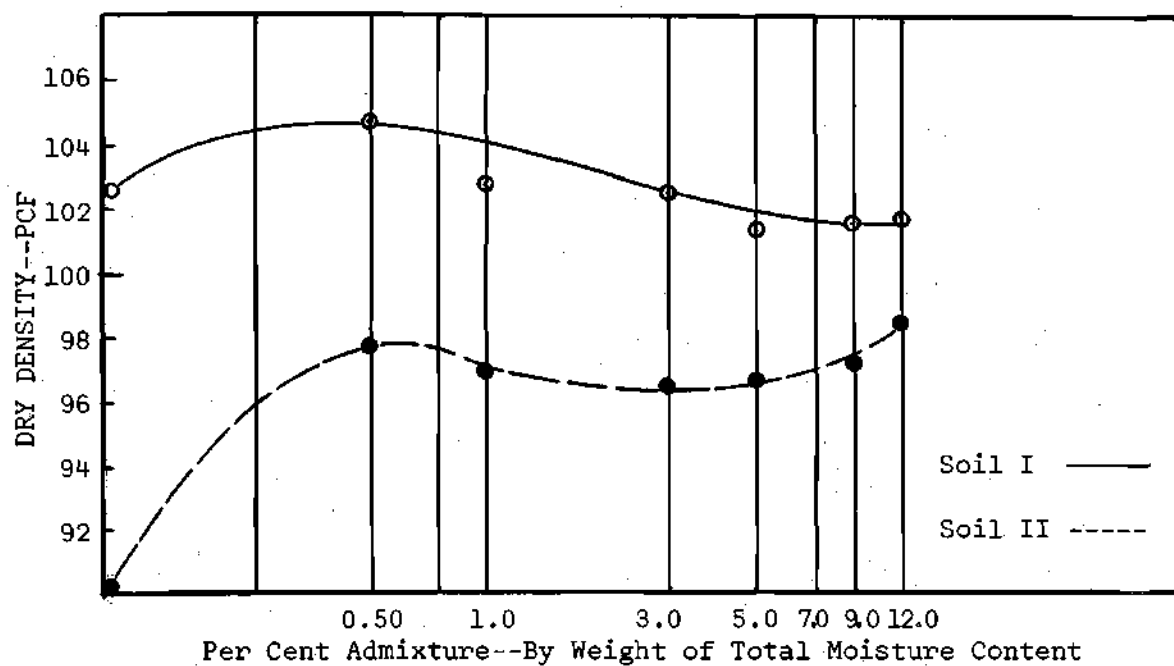


Figure 31. Relationship of Dry Density and Admixture Ivory Liquid for Soils I and II.

Increases of admixture above this value cause a further increase in density of only 2 per cent. The maximum density obtained for Soil II was 98.4 pcf, an increase over the untreated density of 9.3 per cent. The density of Soil I was first increased then decreased as the percentage admixture increased.

The results of testing with Hydroxyacetic Acid are shown in Figure 32. The density of Soil II was increased with increasing percentages of admixture. Percentages above 0.25 per cent caused only a slight increase in density. The density of Soil I was decreased some 0.75 per cent as the percentage of admixture increased.

Evaluation of all the surface active agents tested shows that the density of Soil I is only slightly influenced by the addition of a wetting agent during compaction. This can be attributed to the relatively large particle size of Soil I or the clay minerals present. As the particle size increases from clay size to silt size the importance of particle surface charge or forces becomes less significant. Thus the addition of admixtures to reduce surface and interfacial tension on individual soil particles has little or no effect on the particles whose gravitational forces are predominant in controlling the density.

Soil II, as shown throughout the discussion, is quite sensitive to the surface active agents. This soil has been classified as fine grained, thus its behavior is influenced to a marked degree by particle surface force phenomenon. The primary purpose of adding water in compaction of clays is to reduce these surface forces to allow (1) easy manipulation of the soil particles and (2) to allow tighter packing which produces an increase in density. The addition of a surfactant to the

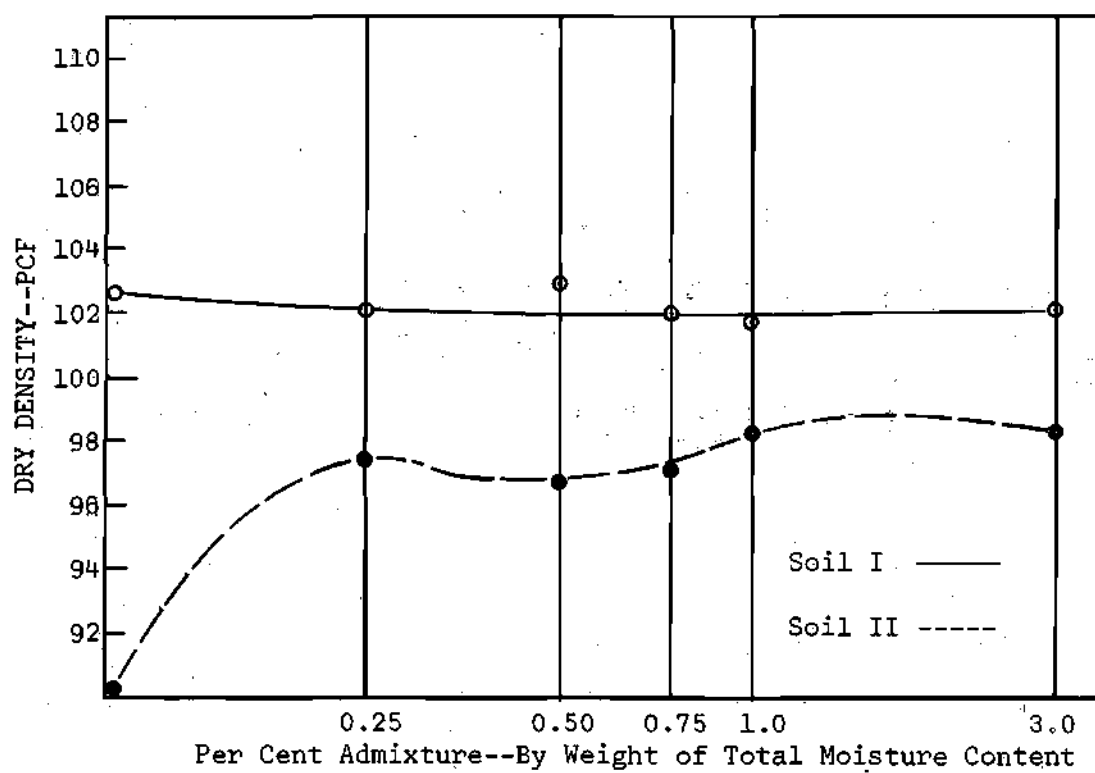


Figure 32. Relationship of Dry Density and Admixture Hydroxyacetic Acid for Soils I and II.

compaction moisture would reduce both water-surface tension and water-soil particle interfacial tension. This would cause a more uniform coating of each soil particle as well as more efficient wetting of each particle, and in turn a further decrease of particle surface attractive forces. The final result would be an increase in density for the same moisture content and compactive effort over the soil compacted with water not treated with a surfactant.

The clay minerals present in Soil II were Kaolinite and Illite. Both clay minerals would not be subject to isomorphous substitution with the surfactants added. Therefore any increase in density of Soil II could not be attributed to this phenomenon. Even if the clay minerals present had been of the Montmorillonite family and had expanded lattices, isomorphous substitution with the surfactant to produce a contracted lattice probably would not have occurred, since the majority of the surfactants are of a sodium base. It is possible that if the lattice were collapsed initially it would have expanded in the presence of the surfactants, thus producing a decrease in density. The listing of the surfactants in Table 3 shows that the majority are of the sulfonate family. The sulfonate materials are one of a wide variety of chemicals that are used as dispersants.

The surfactants, in addition to reducing the mixing water surface tension, also act as a dispersant, which increases the electric repulsion between the adjacent clay particles, reducing the cohesion between them and causing the particles to disperse slightly.

When reacting with the soil the surfactant (acting as a dispersant), employs the following three mechanisms:

1. Sequestration--the polyanionic part of the surfactant removes and insolubilizes any monovalent exchangeable ions.
2. Ion Exchange--the surfactant furnishes monovalent ions for exchange reaction with the soil.
3. Anion Adsorption--the surfactant furnishes polyanionic groups for adsorption by the soil particles.

The adsorbed water decreases the particle attractive forces and the secondary dispersant action of the surfactant increases particle repulsion which causes an apparent decrease in particle size. Thus adjacent soil particles in the treated soil do not tend to cohere as strongly, but repel each other so they can be moved easily relative to each other. Therefore, for the same compactive effort and moisture content, Soil II when treated with the surfactant was forced into a mass of higher density than for the same soil without the surfactant. In all cases the compacted samples were characterized by a laminated appearance of the compacted soil. The laminations appear in a plane perpendicular to the plane of application of the compactive effort, and are to be expected in fine grained soils treated with dispersants since a nearly parallel arrayed soil structure is produced.

When Soil II and the treated water were mixed, the soil appeared to be finer grained (although it did not act as such) than when the soil was mixed with untreated water. This phenomenon supports the previous statement concerning the apparent decrease in particle size of a soil when treated with a dispersant.

Thus the increases in density caused in Soil II were the combined result of reduced surface tension in the water giving increased wetting

efficiency and the secondary dispersant effects of the surfactants.

All of the surface active agents tested caused the largest increases in density in Soil II between admixture percentages of 0.25 and 0.75 per cent. This result can be attributed primarily to the surfactants themselves. The surface tension value for a particular liquid by a surface active agent is a function of the cohesive forces acting between the molecules in the film. If a liquid film is under compressive forces due to surface crowding the surface tension is affected. It is important to note that the surface crowding obtained by high concentrations of the surfactant, can be carried too far, resulting in the piling up of the surfactant in local drops. Hence, higher concentrations than the critical are valueless in effecting increased reduction of surface tension.

Figure 32 shows the relationship between per cent change in density and admixture concentrations for the surface active agent categories for Soil I. Of the two surfactants causing a decrease in density, the cationic type caused the largest decrease, a total of 3 per cent at 3 per cent admixture. The amphoteric type caused a decrease of 1 per cent at 3 per cent concentration. Those surfactants causing increases in density were the anionic and nonionic types. Of these two, the anionic was the more effective causing 1.5 per cent more increase than the nonionic.

Evaluation of Figure 34 shows that, by type surfactant, the most effective surfactant at 3 per cent admixture was the anionic type for Soil II. The nonionic types were some 2 per cent less effective than the anionic. The cationic was the least effective of all tested.

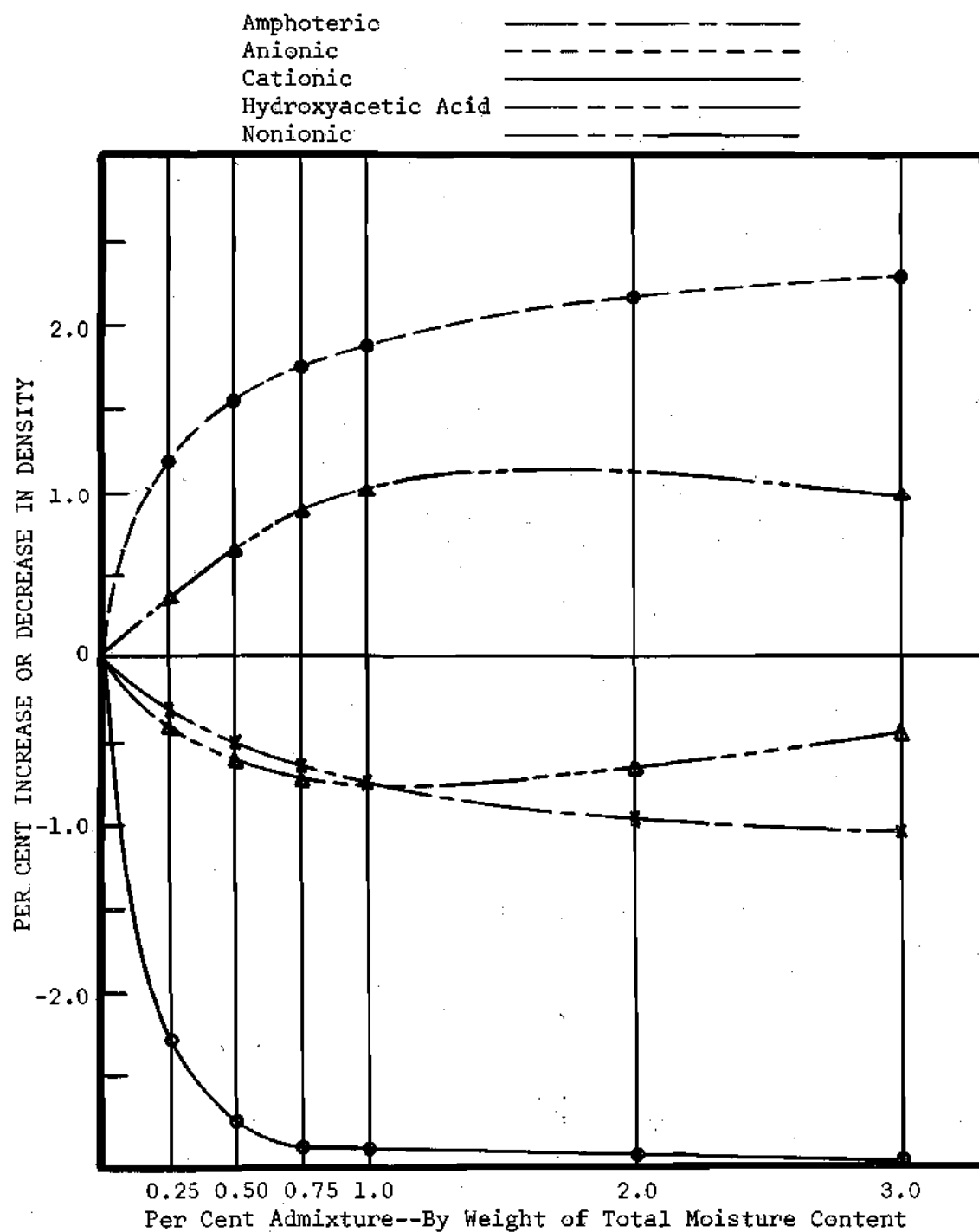


Figure 33. Relationship of Per Cent Increase or Decrease Over Standard and Admixture Type for Soil I.

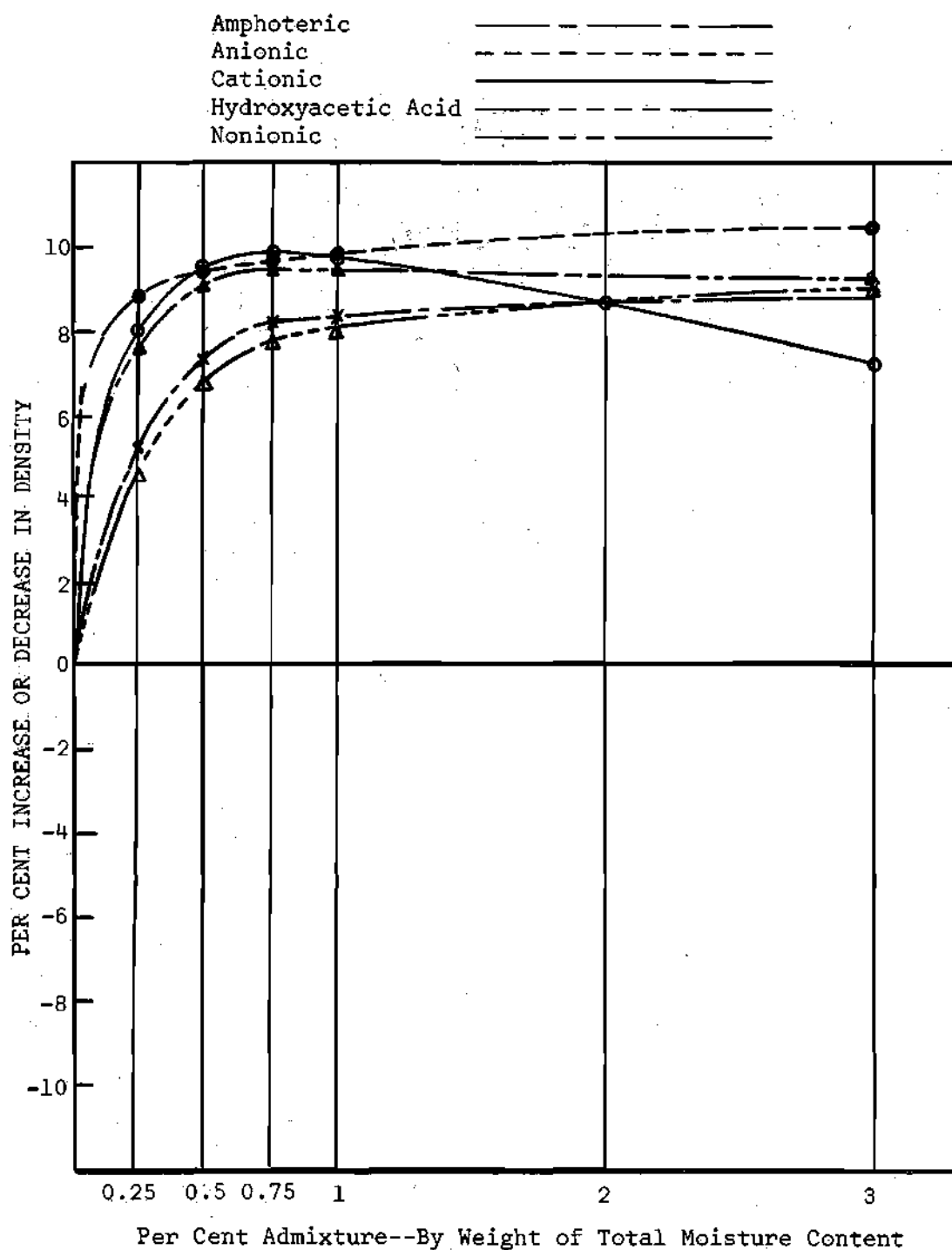


Figure 34. Relationship of Per Cent Increase or Decrease Over Standard and Admixture Type for Soil II.

At a percentage admixture of 0.5 per cent the anionic, cationic and nonionic all cause an increase in density of approximately 9 per cent.

Any study dealing with admixtures used in soil stabilization is not complete until the cost of the stabilizing admixture can be compared to costs of currently used methods. Tank truck carload prices were obtained for the following surfactants:

| | |
|-------------------|-------------|
| Polytergent B-300 | \$0.158/lb. |
| Polytergent L-405 | \$0.345/lb. |

Examination of Figure 27 shows that the largest percentage increase in density of Soil II was caused by a per cent admixture (by weight of soil moisture) of 0.25 per cent. In terms of dry soil weight this is 0.06 per cent. Therefore the cost per cubic yard for treatment of Soil II at 0.06 per cent admixture is as follows:

From Figure 5:

| | |
|--|--------|
| Maximum dry density at optimum moisture content | 91 pcf |
|--|--------|

$91 \text{ pcf} \times 27 \text{ ft}^3/\text{yd}^3 = 2,457 \text{ lbs}/\text{yd}^3$
Pounds of Polytergent B-300
Required at 0.06%

$2,457 \text{ lbs}/\text{yd}^3 \times 0.0006 = 1.47 \text{ lbs}/\text{yd}^3$

Cost per cubic yard

$1.471 \text{ lbs}/\text{yd}^3 \times \$0.158/\text{lb} = 23.2 \text{ cents}/\text{yd}^3$

This unit cost is somewhat higher than the unit cost of most conventional methods used currently to obtain higher densities but under certain soil and weather conditions, it would possibly be used competitively with current methods.

CHAPTER V

CONCLUSIONS

The following conclusions have been reached as a result of this study:

1. The addition of surface active agents affects the density of a soil when molded at a constant moisture content.
2. The density of certain soils can be increased by the addition of certain surface active agents.
3. The density of Soil CL was increased by all the surface active agents.
 - a. Density increased with increased amounts of surface active agent.
 - b. The greatest rate of increase is at percentages of admixture less than 0.50 per cent.
 - c. Higher percentages of admixture caused a diminishing rate of increase in density.
 - d. Soil CL was the most responsive to treatment by the surface active agents.
 - e. The anionic type surface active agent effected the greatest increase in density.
4. The density of Soil ML was increased and decreased by some of the surface active agents.
 - a. Density increased a maximum of 2 per cent with increased

amounts of anionic and nonionic surface active agents.

- b. Density decreased a maximum of 3 per cent with increased amounts of amphoteric and cationic surface active agents.

CHAPTER VI

RECOMMENDATIONS

The following recommendations are made for further study:

1. Further testing of effects on soil density treated with surface active agents at very low percentage admixture.
2. An evaluation of the long-term effect of surface active agents on soil serviceability under actual weather conditions.
3. A study of the effects of surface active agents on the angle of internal friction and cohesion of a soil.
4. A study of the effect of surface active agents on the pore water pressure in compacted clays.
5. A study of the effect of surface active agents on soil permeability.

APPENDIX

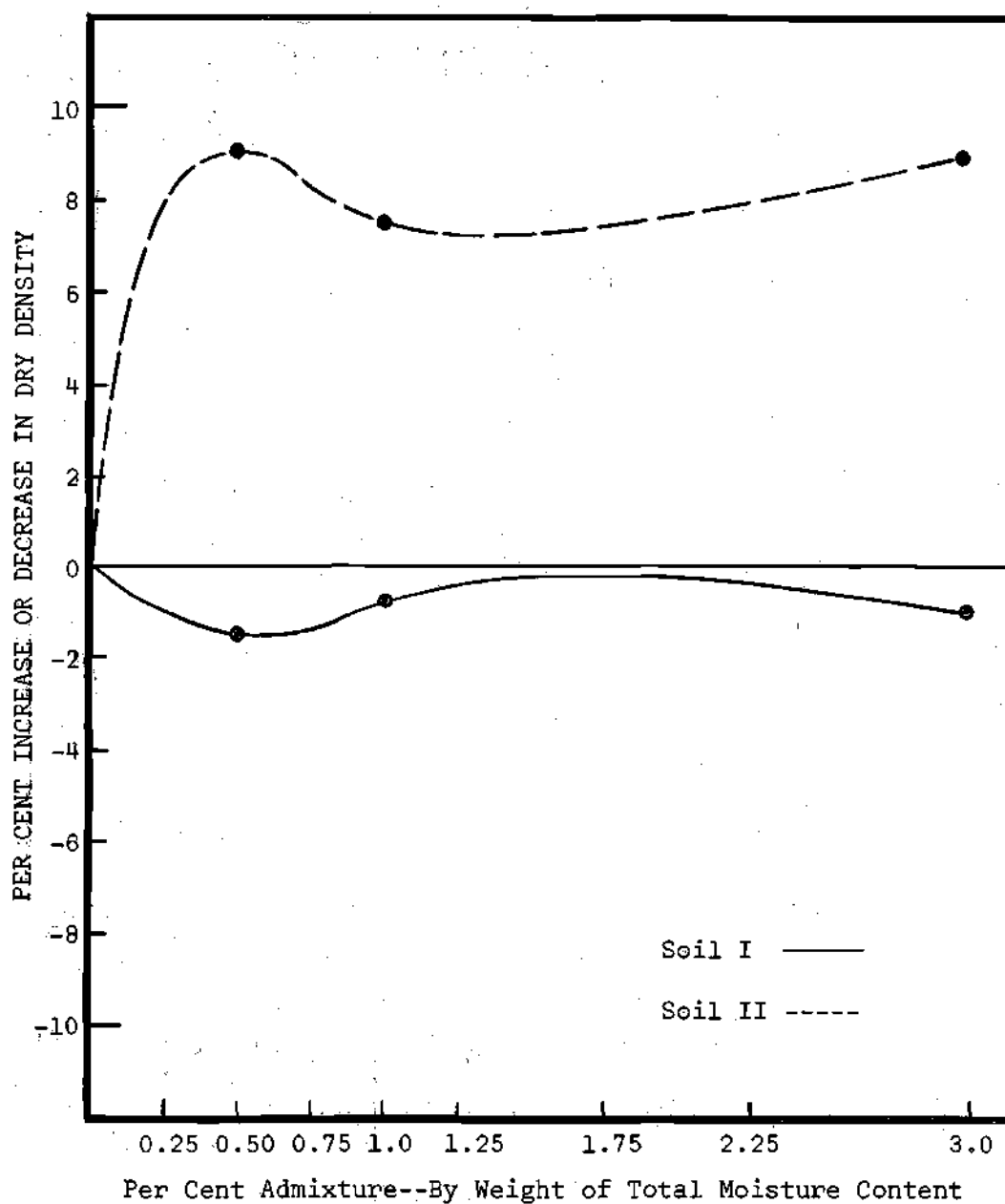


Figure 35. Relationship of Per Cent Increase or Decrease in Dry Density and Admixture Product BCO for Soils I and II.

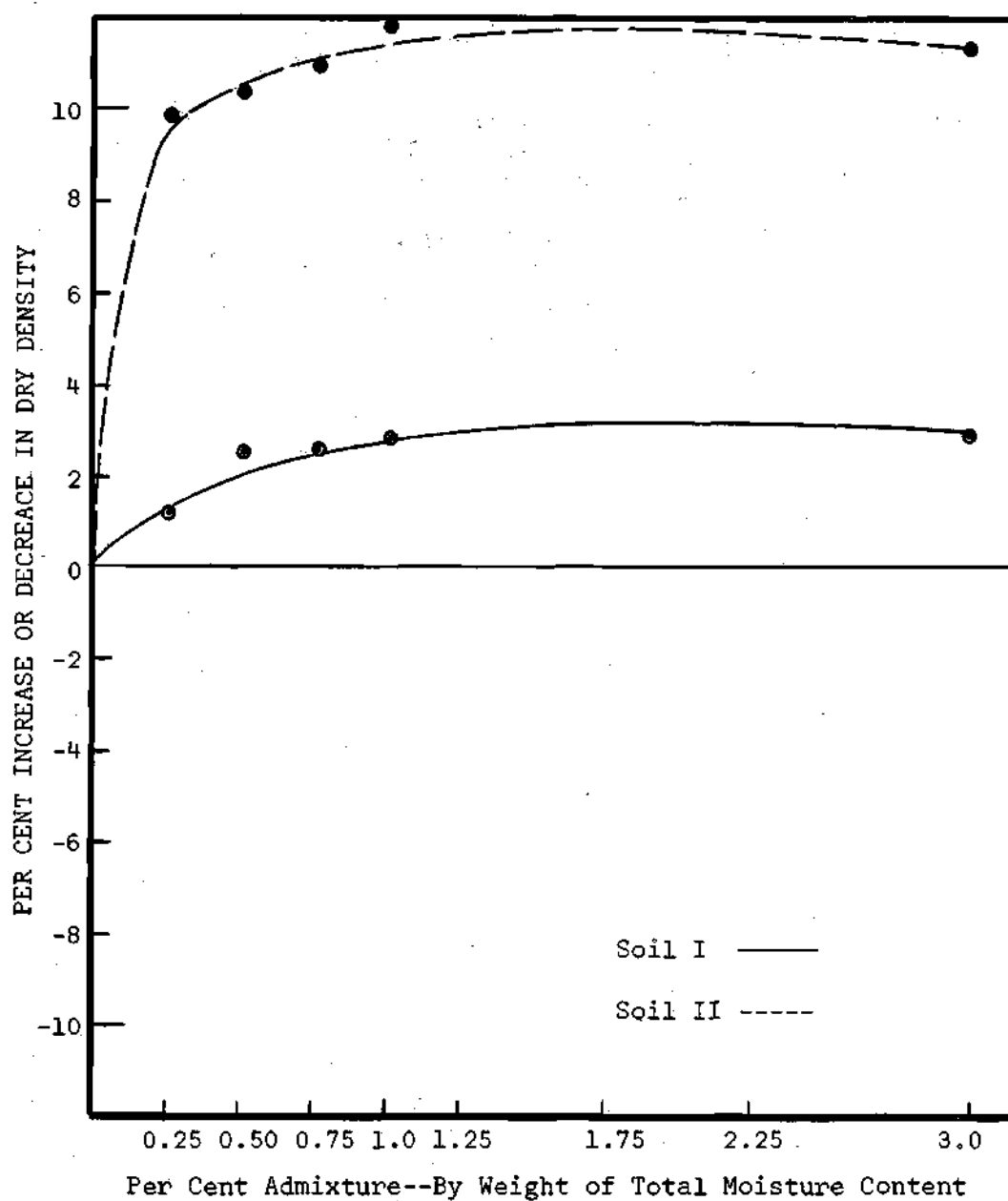


Figure 36. Relationship of Per Cent Increase or Decrease in Dry Density and Admixture Aerosol OT-75 for Soils I and II.

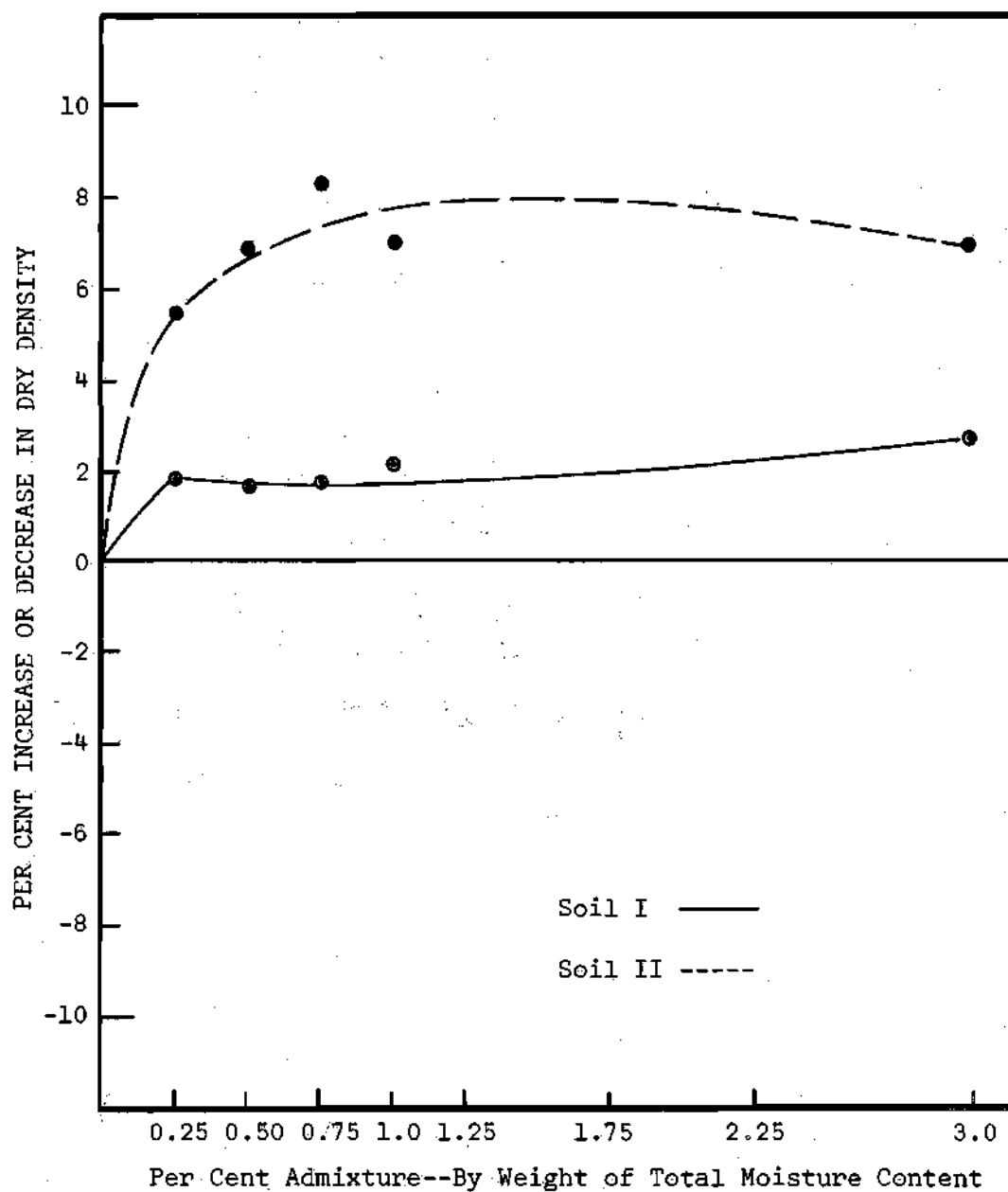


Figure 37. Relationship of Per Cent Increase or Decrease in Dry Density and Admixture Alkanol B for Soils I and II.

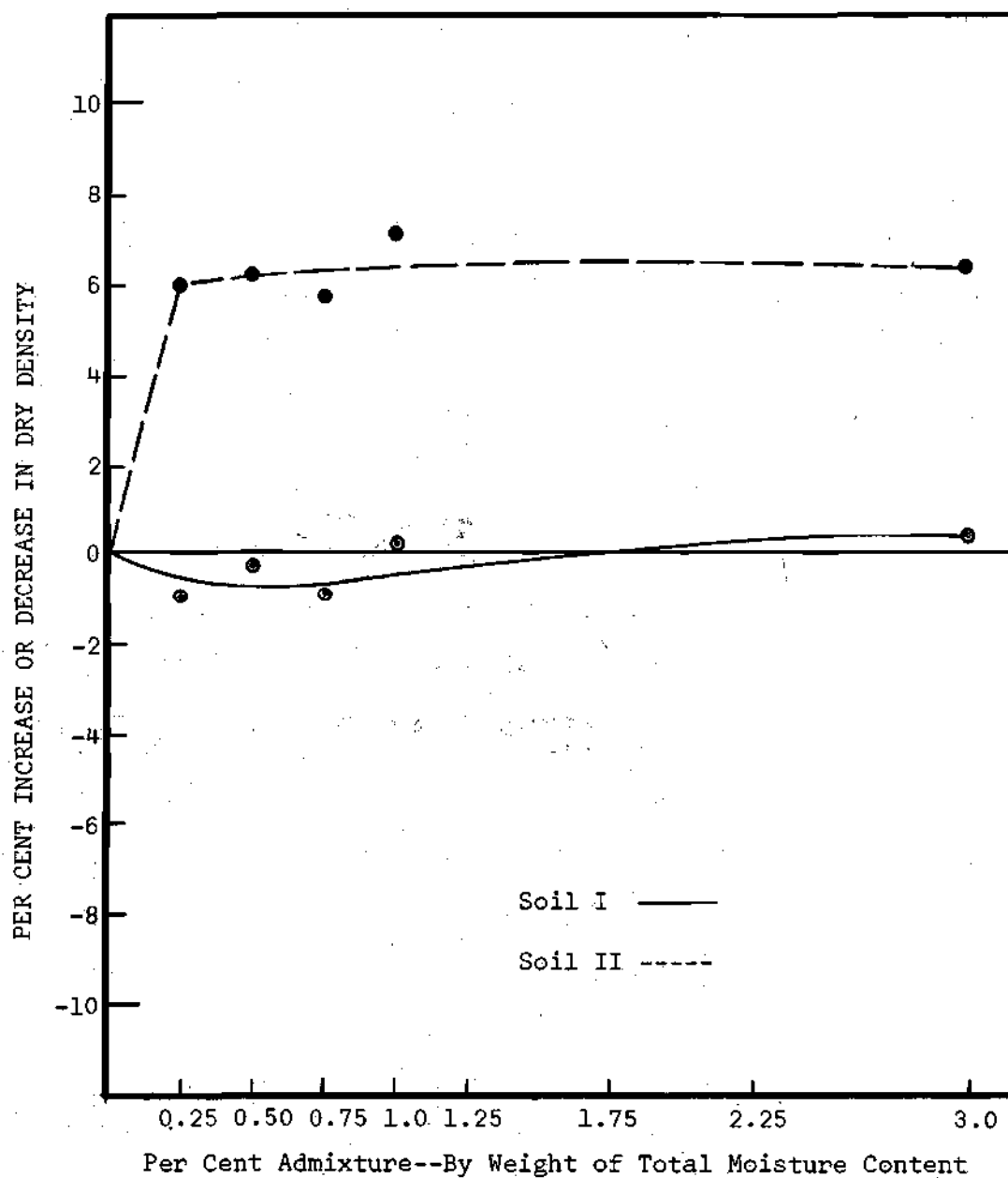


Figure 38. Relationship of Per Cent Increase or Decrease in Dry Density and Admixture Duponol WN for Soils I and II.

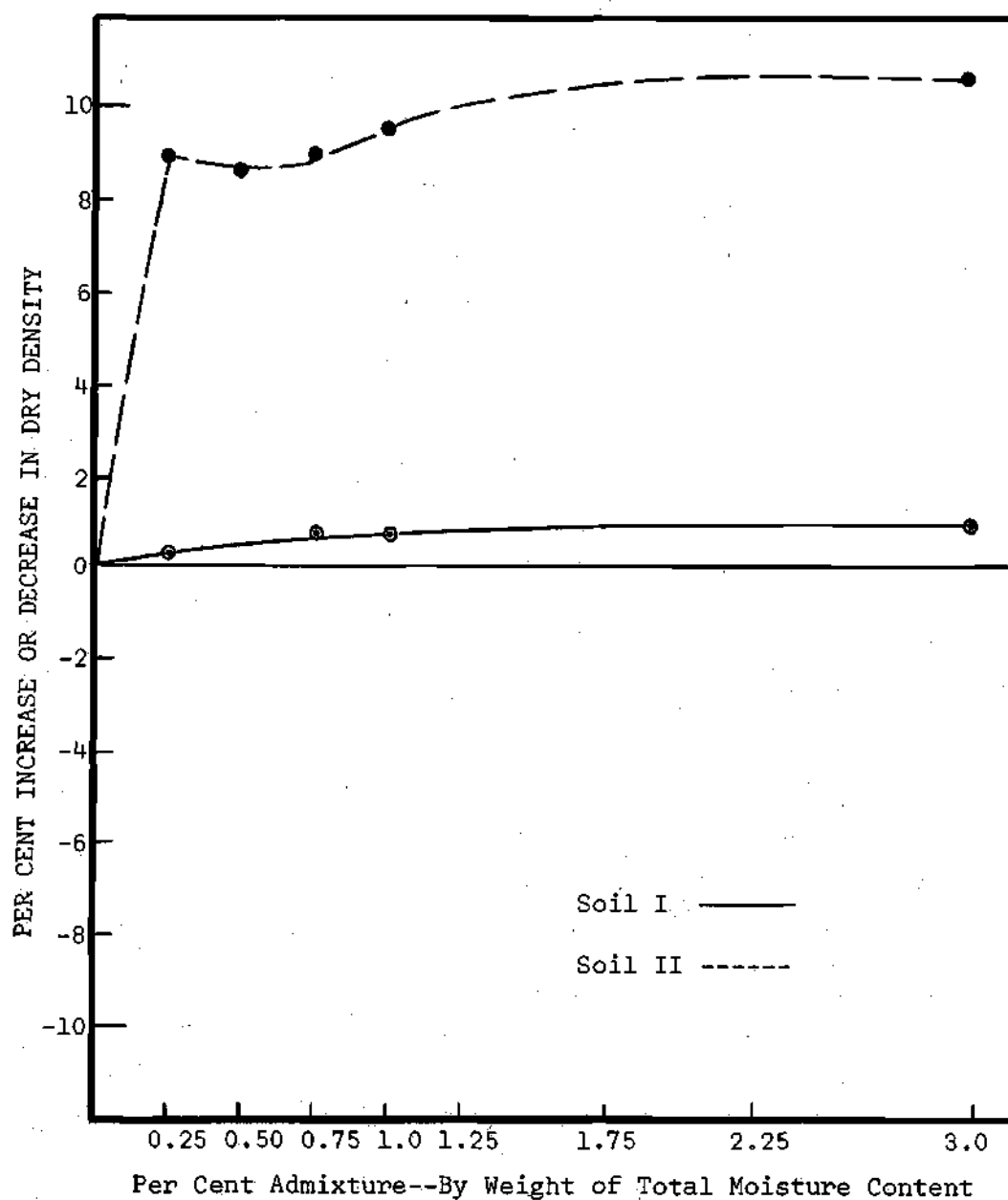


Figure 39. Relationship of Per Cent Increase or Decrease in Dry Density and Admixture Nacconol 90F for Soils I and II.

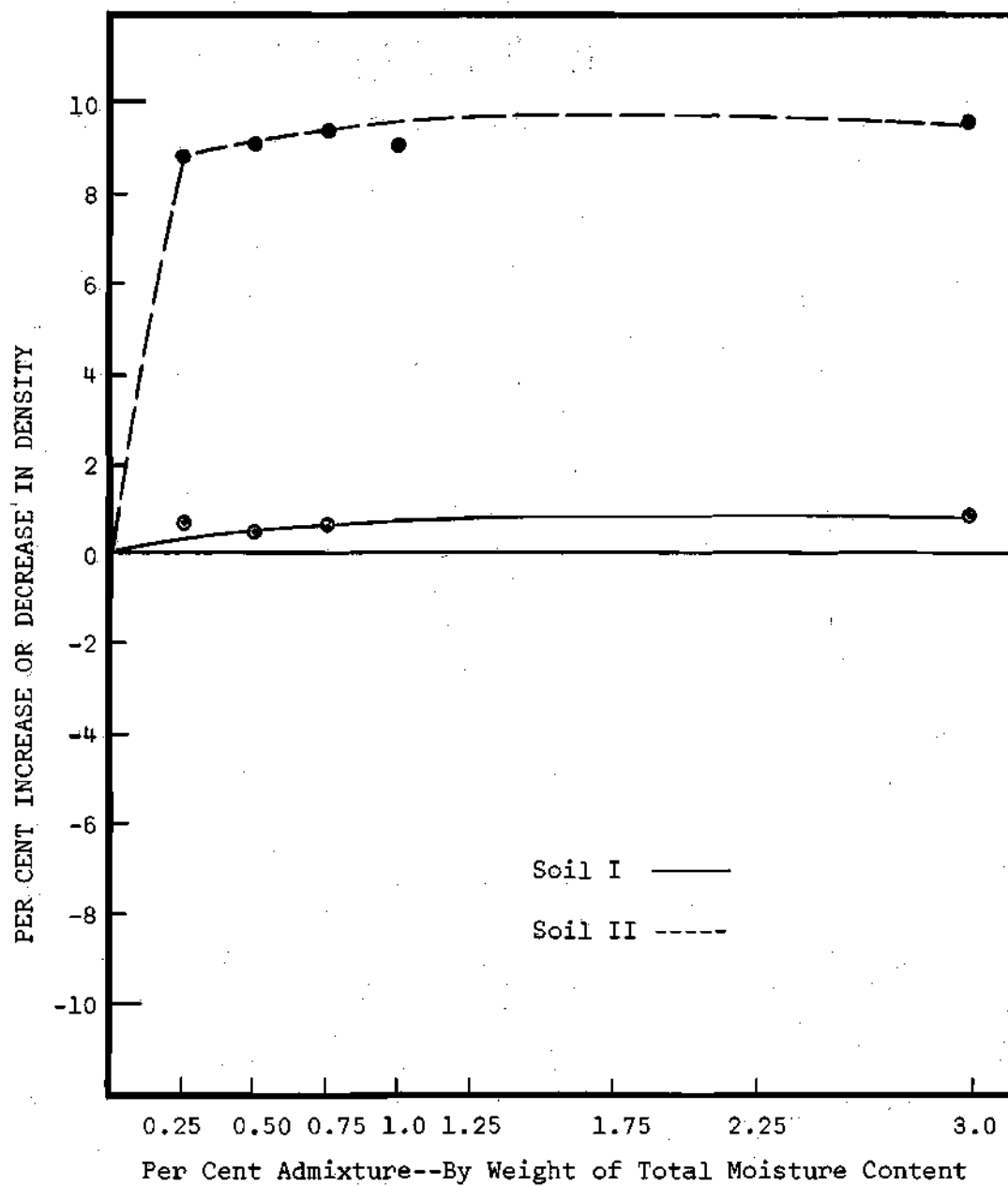


Figure 40. Relationship of Per Cent Increase or Decrease in Dry Density and Admixture Polytergent L-405 for Soils I and II.

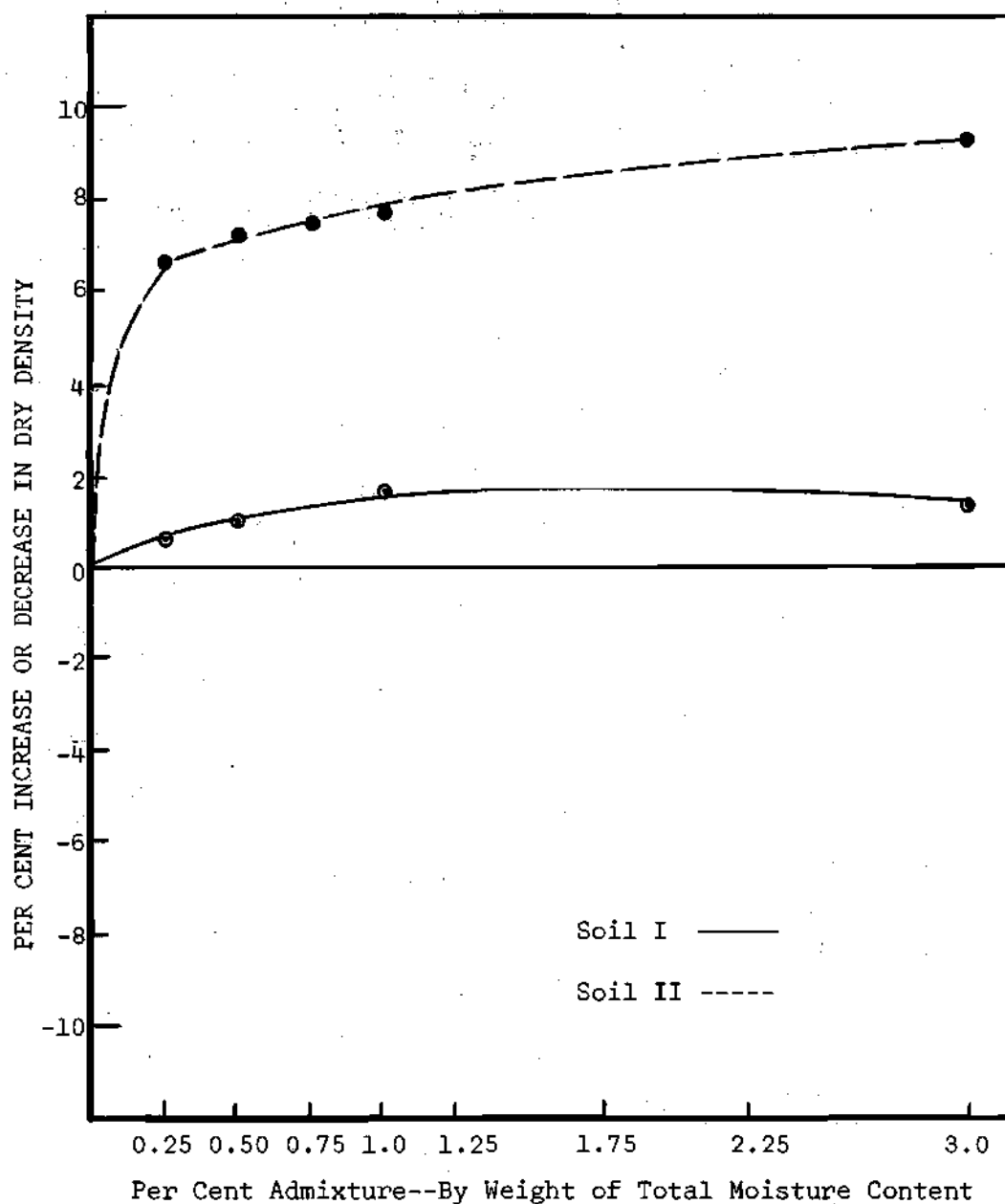


Figure 41. Relationship of Per Cent Increase or Decrease in Dry Density and Admixture Tergitol NPX for Soils I and II.

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