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16. Abstract

Transverse cracking of pavements in West Texas initiates in the base course due to volumetric contraction caused by freezing temperatures. A computer program which predicts this transverse cracking requires two material properties of the frozen base course to be used as input data. (See Research Report 18-4F, "Thermal Pavement Cracking in West Texas.") The two properties are the elastic modulus and the tensile strength. A test program was conducted to determine how these properties are affected by such variables as suction, dry density, water content, and the number of freeze-thaw cycles the base course has experienced. An effective method of predicting both the elastic modulus and the tensile strength is presented in this report. It is now possible to determine these properties from the climatically-controlled values of suction and freeze-thaw cycles and the construction-controlled value of dry denisty. With this information, the computer program can be used to improve the design of pavements in West Texas.

An appendix of this report gives a detailed description of the measurement of suction with psychrometers. Another appendix gives all of the measured test data.

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PROPERTIES OF FROZEN BASE COURSES IN WEST TEXAS

by

William Raymond Campbell, Jr.
Robert L. Lytton

Research Report Number 207-4

Flexible Pavement Evaluation and Rehabilitation

Research Study 2-8-75-207

Conducted for

State Department of Highways
and Public Transportation

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by the

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ABSTRACT

Transverse cracking of pavements in West Texas initiates in the base course due to volumetric contraction caused by freezing temperatures. A computer program which predicts this transverse cracking requires two material properties of the frozen base course to be used as input data. (See Research Report 18-4F, "Thermal Pavement Cracking in West Texas.") The two properties are the elastic modulus and the tensile strength. A test program was conducted to determine how these properties are affected by such variables as suction, dry density, water content, and the number of freeze-thaw cycles the base course has experienced. An effective method of predicting both the elastic modulus and the tensile strength is presented in this report. It is now possible to determine these properties from the climatically-controlled values of suction and freeze-thaw cycles and the construction-controlled value of dry density. With this information, the computer program can be used to improve the design of pavements in West Texas.

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DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

PREFACE

This report gives the properties of frozen base course that occur in West Texas. These properties must be known in order to use the computer program which is presented in TTI Research Report 18-4F. The program is capable of predicting the rate of appearance of thermal fatigue cracks using U. S. Weather Bureau data tapes to input the daily variation of air temperature and solar radiation. The frozen elastic modulus and tensile strength of the base course are primarily functions of suction, dry density, and the number of freeze-thaw cycles endured by the base course.

This report concludes all experimental and theoretical work initiated in the study entitled, "Environmental Deterioration of Pavement," which was sponsored by the State Department of Highways and Public Transportation with the cooperation of the Federal Highway Administration. The work was finished with funds committed for the study entitled, "Flexible Pavement Evaluation and Rehabilitation," which has the same sponsors.

IMPLEMENTATION STATEMENT

This report gives a simple method of predicting the elastic modulus and tensile strength of frozen base course. It was found in an earlier study presented in TTI Research Report 18-4F that a reduction in the tensile strength of the base course is the most effective means of reducing the severity of the thermal cracking problem in West Texas. This study has shown that:

1. an increase of suction (e.g., by dry compaction)
2. a reduction in dry unit weight (e.g., again by dry compaction)

can do exactly that.

The computer program in Research Report 18-4F requires both of these properties of frozen base course to be used as input data. This will permit sensitivity studies to be made with the program in order to determine how the thermal fatigue life of pavements in West Texas may be increased if a different method of base course compaction is adopted. In addition, now that realistic values of frozen base course properties are available, further studies can be made to investigate new pavement materials to use in West Texas to reduce or prevent thermal cracking of pavements in that area of the state.

LIST OF REPORTS

Research Report No. 207-1, "Determining Stiffness Coefficients and Elastic Moduli of Pavement Materials from Dynamic Deflections," by C. H. Michalak, D. Y. Lu, and G. W. Turman, is a summary in one document of the various methods of calculating in situ stiffness coefficients and elastic moduli in simple two-layer and multi-layer pavement structures using surface pavement deflections.

Research Report No. 207-2, "Measurements of Pavement Performance Using Statistical Sampling Techniques," by J. P. Mahoney and R. L. Lytton, examines two methods for obtaining performance related data on the Texas highway system and the associated results of using the methods.

Research Report No. 207-3, "The Texas Rehabilitation and Maintenance District Optimization System," by N. V. Ahmed, D. Y. Lu, R. L. Lytton, J. P. Mahoney, and D. T. Phillips, describes in detail the rehabilitation and maintenance optimization system (RAMS) that has been developed for use by District offices in the state of Texas.

Research Report No. 207-4, "Properties of Frozen Base Courses in West Texas," by William Raymond Campbell, Jr., and Robert L. Lytton, presents an effective method of predicting both the elastic modulus and the tensile strength of base course materials.

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INTRODUCTION

General

In Texas, the problem of transverse cracking is severest in the western portion of the state, as shown in Fig. 1 (3). Several models have been proposed and studied in an effort to explain in what way environmental factors cause the cracking to occur. Of the environmental factors considered, two stand out. Either low temperature cracking or moisture shrinkage is considered in all of these models. Low temperature works through two mechanisms: thermal contraction and thermal fatigue. Thermal contraction can occur in the asphalt concrete (6, 7, 9), base course, or subgrade (6, 13). Temperature drops produce tensile stresses in the material. When these tensile stresses exceed the material's tensile strength, it cracks. In thermal fatigue, as the asphalt concrete goes through freeze-thaw cycles, it is fatigued in a manner similar to the way it is fatigued through repeated traffic loading (3).

Moisture shrinkage occurs in lime or cement stabilized materials because the hydration of the admixture removes moisture from the soil. As the moisture is removed, the soil suction increases thus inducing greater and greater tensile stresses in the material. When the tensile strength of the material is exceeded, it cracks. Eventually the crack will be reflected into the asphalt concrete and work its way to the surface (5).

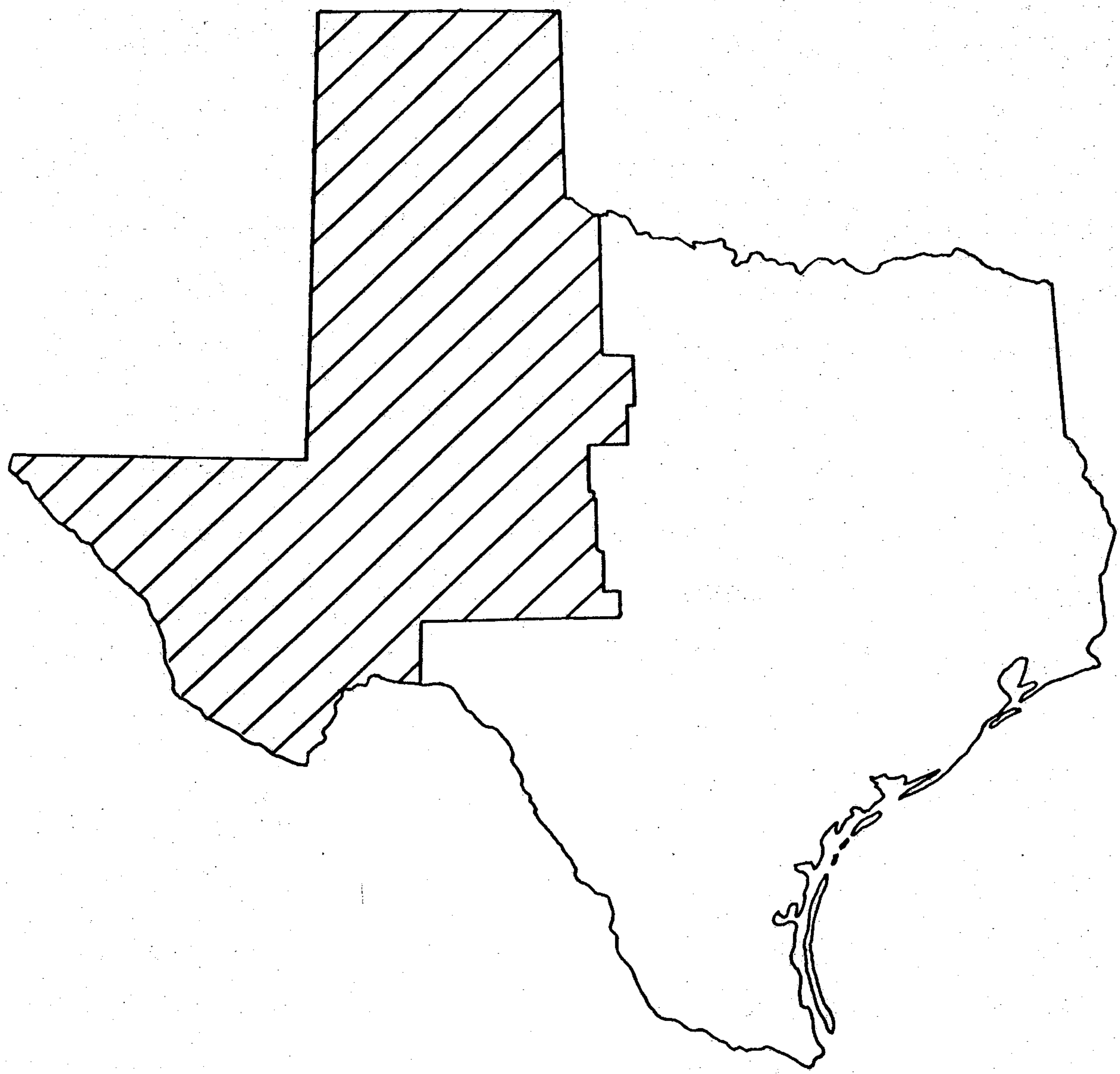

FIG. 1. - West Texas Area Exhibiting Extensive Transverse Cracking

A variation of this occurs when the subgrade has a much greater suction than the untreated base course above it. Moisture migrates toward the subgrade because of its higher suction level and thus produces tensile drying stresses in the base course. If the suction differential between the base course and the subgrade is great enough, it will cause the base course to crack just as hydration will cause it to crack (3).

Carpenter has conducted research to determine which, if any, of the aforementioned mechanisms are causing transverse cracking in West Texas (2, 3, 4). He concluded that thermal contraction cracking in the asphalt and moisture shrinkage in the base course do not occur because the necessary conditions do not exist in this part of the state. Carpenter found that a freeze-thaw mechanism working in the base course, rather than in the asphalt concrete or subgrade, is causing the transverse cracking to occur in West Texas (3, 4).

In his research, Carpenter subjected samples representative of the base course materials used in West Texas to a number of freeze-thaw cycles and measured the height of each during each of the freeze and thaw periods. This resulted in some significant findings concerning the thermal activity of the base course. The research showed that the two types of deformation, freeze deformation and residual deformation, act on the material as it goes through freeze-thaw cycles. Fig. 2, which is from Carpenter's work, shows the height change for the same material at different moisture contents. It shows that material having a moisture content greater than optimum moisture expands as it freezes and material with a moisture content less than optimum contracts upon freezing. However, regardless of a sample's moisture content it experiences both freeze and residual deformations.

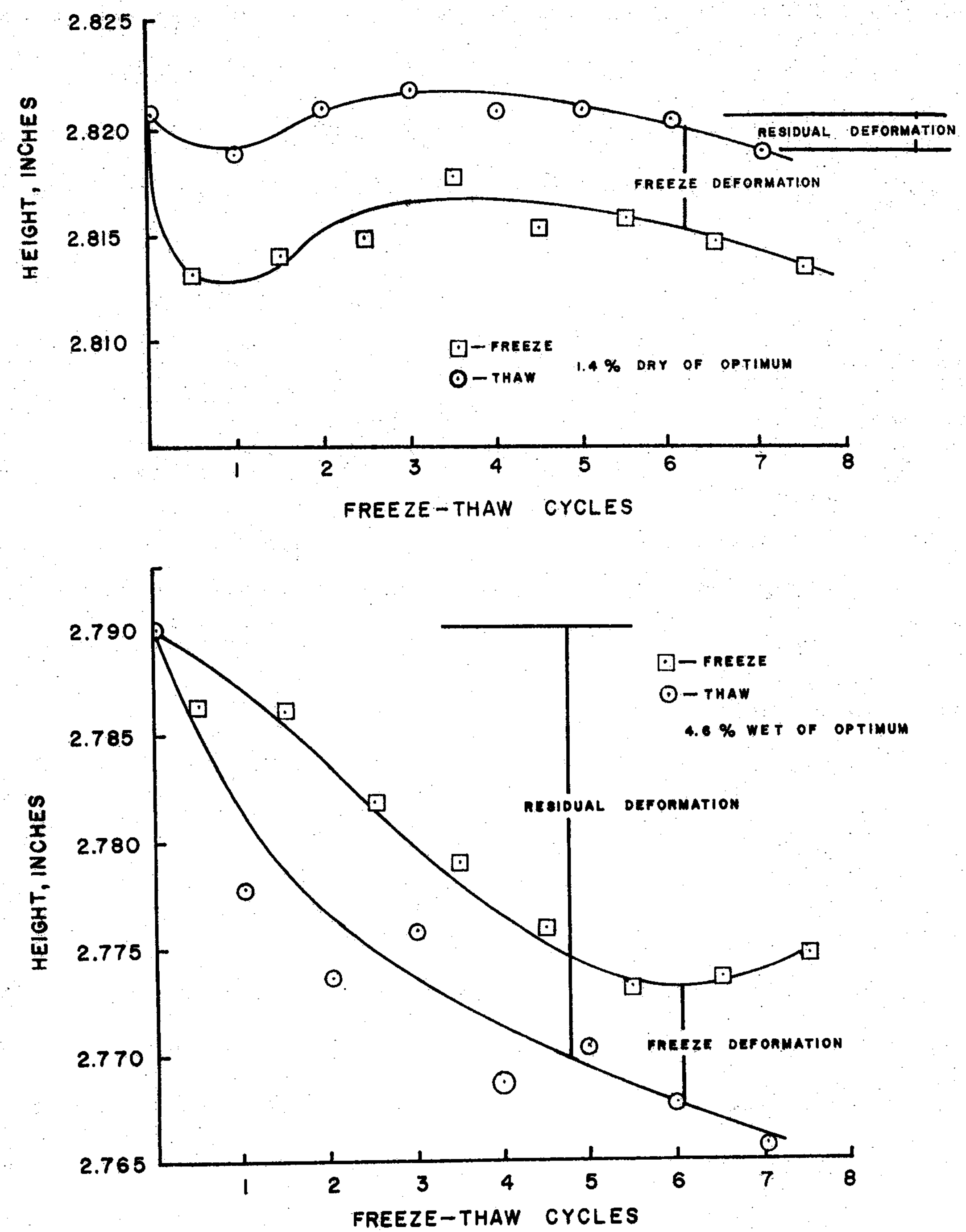

FIG. 2. - Sample Height as a Function of Freeze Thaw Cycles (3)

Freeze deformation is caused by the freeze portion of the freeze-thaw cycle. The change in height from a thawed condition to a frozen condition is shown in Fig. 2 (p. 4). Typically, part of the freeze deformation is recovered when the sample is thawed. The portion that is not recovered is the residual deformation which is permanent. An example of this can be seen in Fig. 2 (p. 4) as the difference between the original height and the thawed height (3). These two deformations work together to produce stresses in the base course which will eventually cause it to crack.

After carefully investigating the nature of the freeze-thaw mechanism which causes the base course to crack, Carpenter was able to develop a computer program which predicts crack spacing in the base course, thermal stresses, crack propagation rates through the overlying asphalt surface course, and the time at which the cracks are expected to appear at the surface of the asphalt concrete. The equation which predicts crack spacing is:

$$\log L = \frac{4.508 \times 10^{-12} (\sigma_T)^{1.4578} (E_B)}{(\Delta T)^{2.1199} (\alpha_B)^{1.1496}} + 8.151 \times 10^{-2} \qquad (1)$$

where

E = elastic modulus of the frozen base course material

L = 2 x the crack spacing

ΔT = the value of the temperature drop below freezing at the top of the base course

α_B = freeze coefficient of the base course

σ_T = tensile strength of the frozen base course material.

The rest of the program builds upon this equation (4).

Purpose

Two of the properties needed for Equation (1) are the elastic modulus and tensile strength of the frozen base course material. The purpose of this study has been to determine these properties for four sources of base course material from West Texas. The study will also be used to determine if other more easily measured parameters, such as moisture content, dry density, and soil suction can be used to predict the elastic modulus and tensile strength. The parameters which have the most significant effects will then be used to develop accurate methods for predicting the tensile strength and elastic modulus. Emphasis will also be placed on making these predictive relationships as simple as possible.

MATERIALS AND TESTING METHODS

Sample Preparation

Samples of base course material were taken from four different borrow areas in West Texas. Their locations are shown in Fig. 3 along with the State Department of Highways and Public Transportation districts in which they are located. This material is excavated from the borrow pit, hauled to the road site, dumped, spread, and compacted with no stabilizing agents added to it.

When the samples reached the laboratory, they were sieved and only material passing the 3/8-inch sieve was used for the tests. This will be discussed later in this section. Visual observations showed only a small portion of the sample being retained on the 3/8-inch sieve. Each sample was then divided into smaller portions and different amounts of water were added to vary the moisture content. After hand mixing, they were stored in the moisture room overnight to allow the water to diffuse uniformly throughout the entire sample.

Each of the smaller portions was used to make two moisture-density samples. The samples were made using the procedure specified by AASHTO specification T 180-74, Method A with a few modifications. The samples were compacted in three layers rather than five. However, since all samples were compacted in a similar manner, it is believed that the final results should still be acceptable for the intended purposes of these experiements. (It should be noted that AASHTO specification T99-74, Method A does specify compaction in three layers with less compactive effort.)

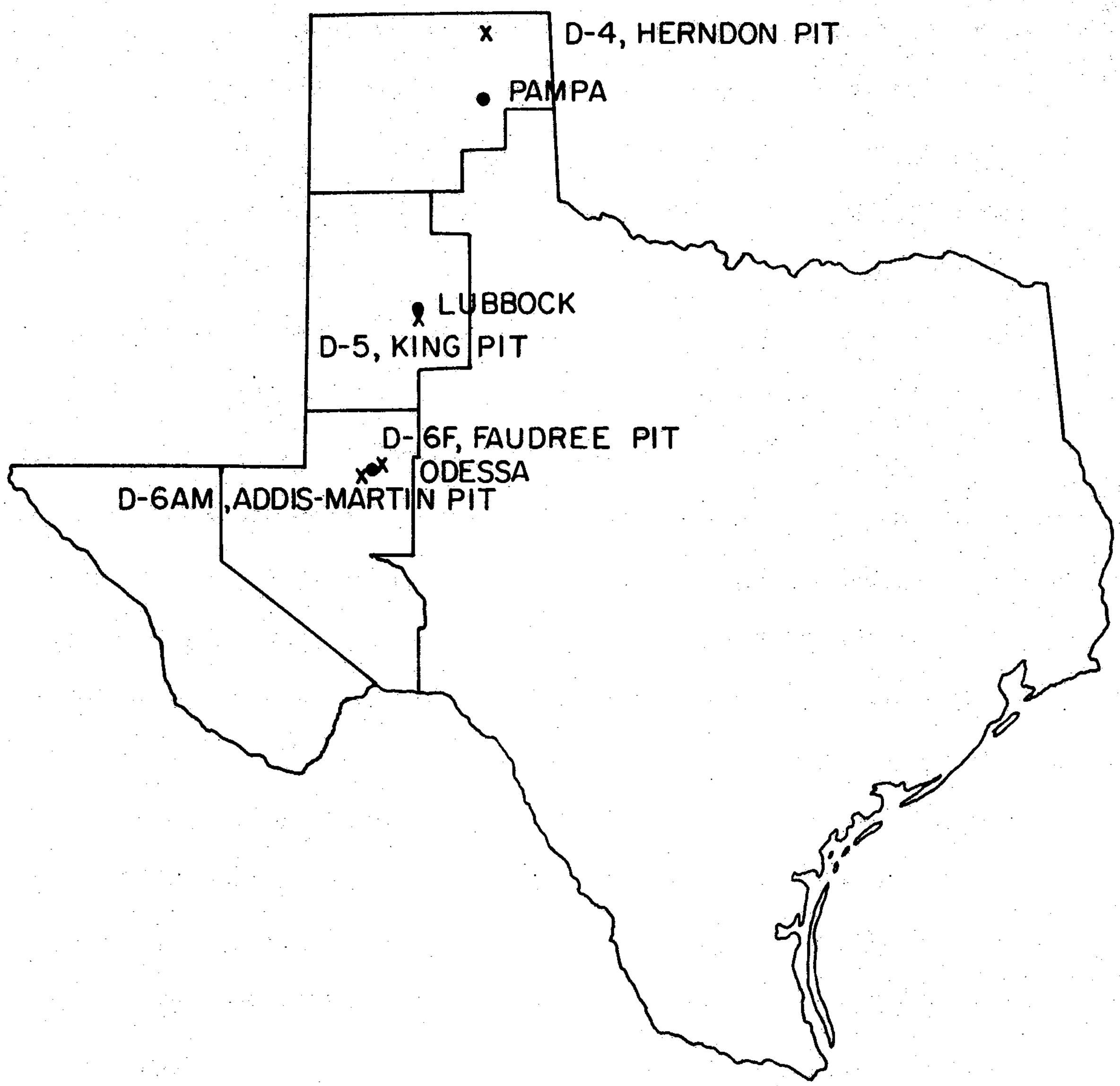

FIG. 3. - Base Course Pit Locations and TSDHPT Districts

Moisture content was not determined in the usual manner as this would have destroyed the sample. Normally, the sample would be cut in two and a moisture sample taken from the center. For this testing, however, a small moisture sample was taken from each of the three layers before it was compacted. The three moisture samples were used to determine an average moisture content for the whole sample.

The final variation was in the size of the material tested. Instead of testing just the material passing the No. 4 sieve, everything passing the 3/8-inch sieve was used. This was done in order to better simulate actual conditions in the field.

Moisture-density curves were plotted for the four sample groups and are shown in Figs. 4 through 7. The curves were then divided into five moisture groups with approximately equal numbers of samples in each. These groups were numbered 1 through 5 and are delineated on each of the moisture-density curves. Each group was then subdivided into three subgroups, each having an equal number of samples as far as was practicable. These subgroups were designated as F1, F3, or F5 according to the number of freeze-thaw cycles they would go through - one, three, or five respectively.

Testing Procedure

After the samples had been made, they were labeled with an identifying number and enclosed in a plastic freezer bag. All F1 samples from a particular borrow pit were then placed at a common location in an environmental room to begin their first freeze. The F3 and F5 samples were treated in a similar manner. Sample heights

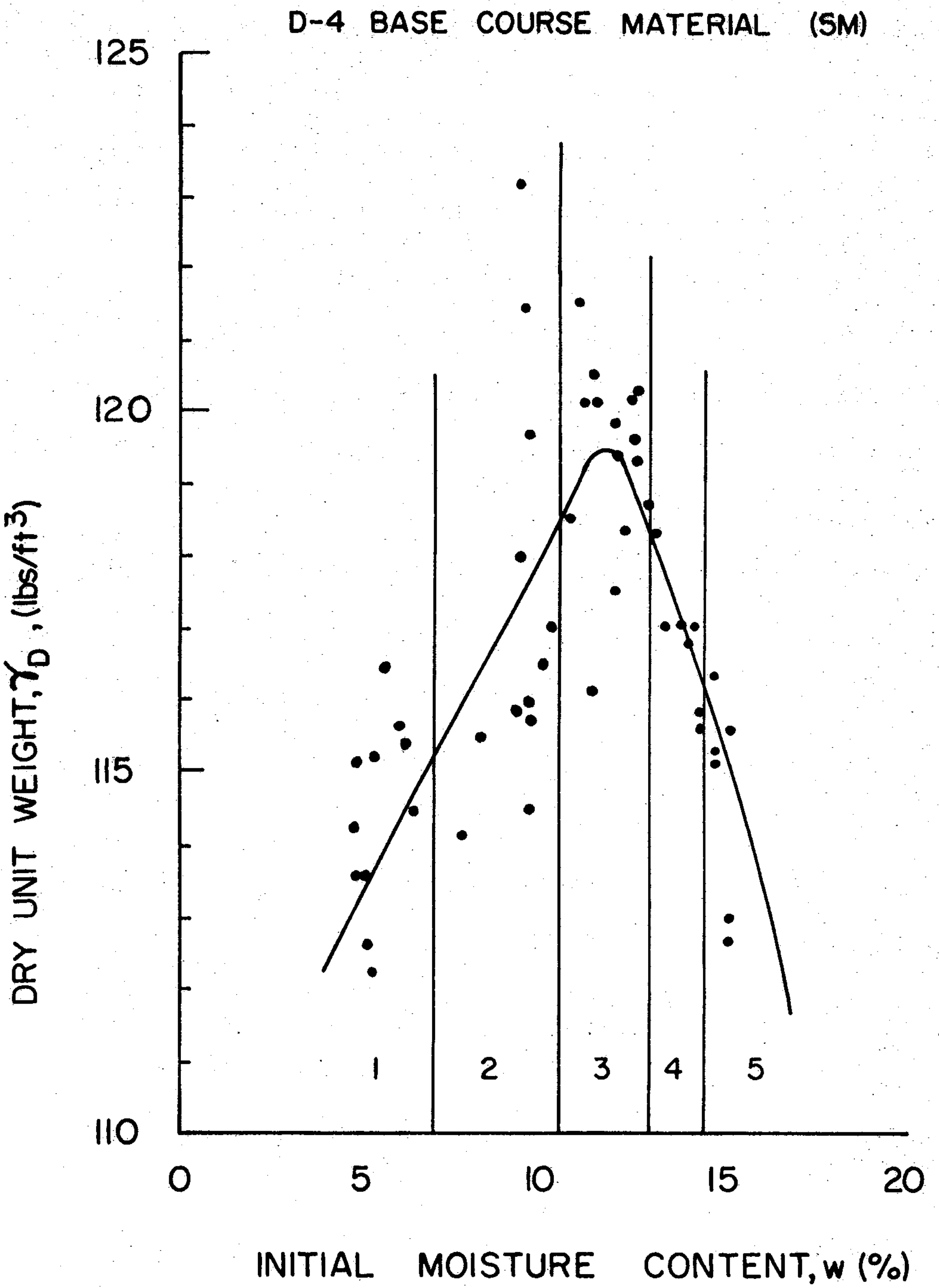

FIG. 4. - Compaction Curve For D-4 Base Course Material

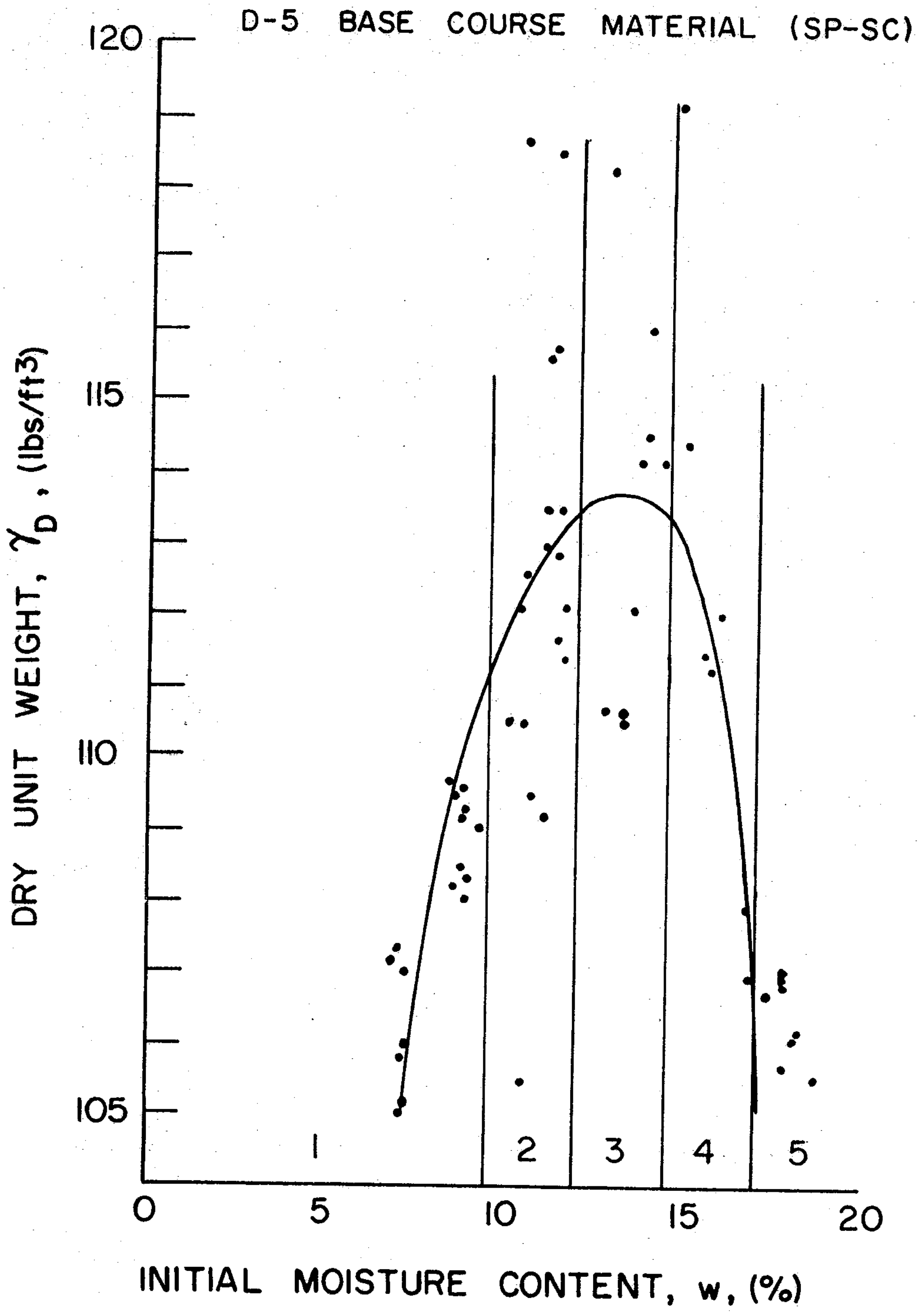

FIG. 5. - Compaction Curve For D-5 Base Course Material

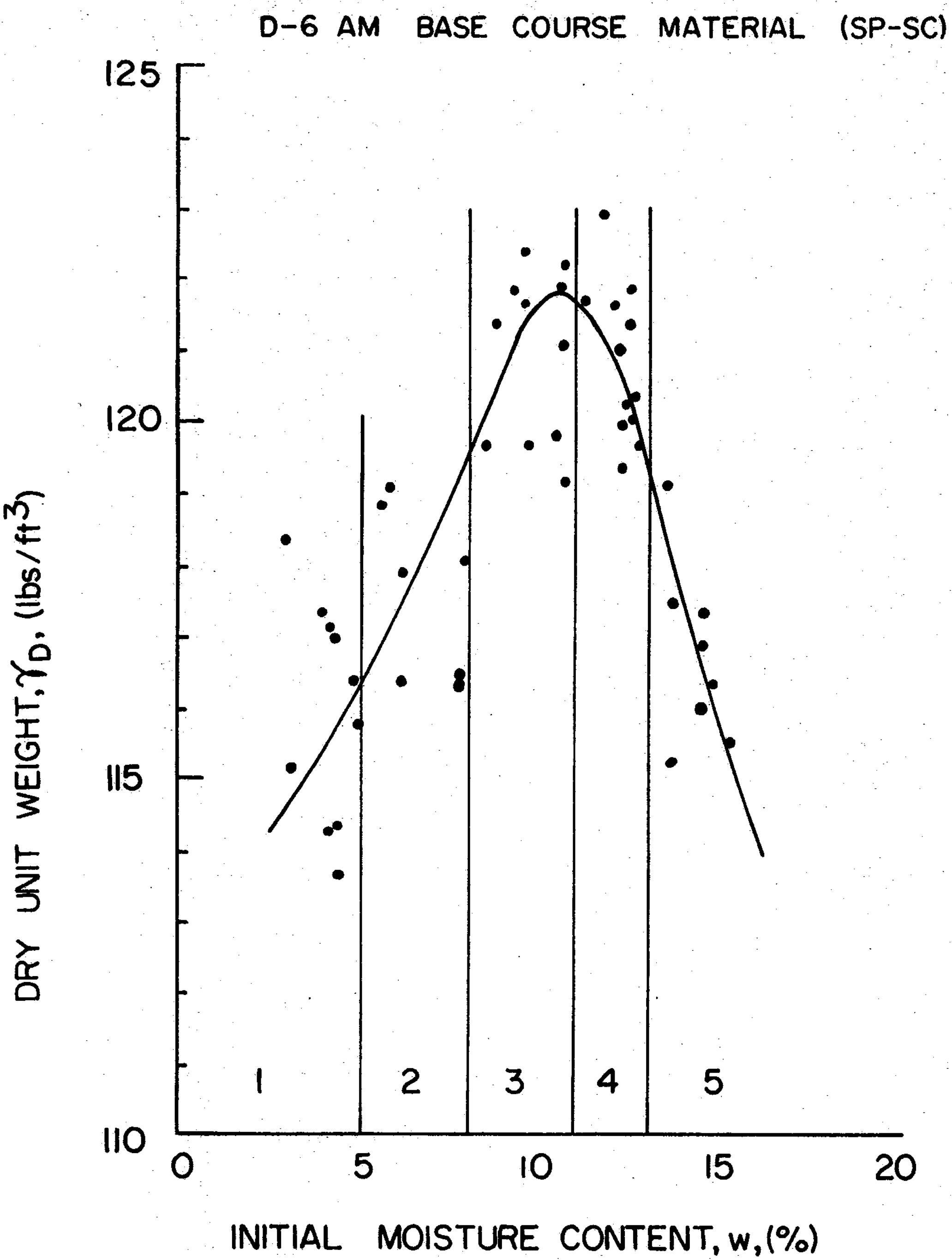

FIG. 6. - Compaction Curve For D-6AM Base Course Material

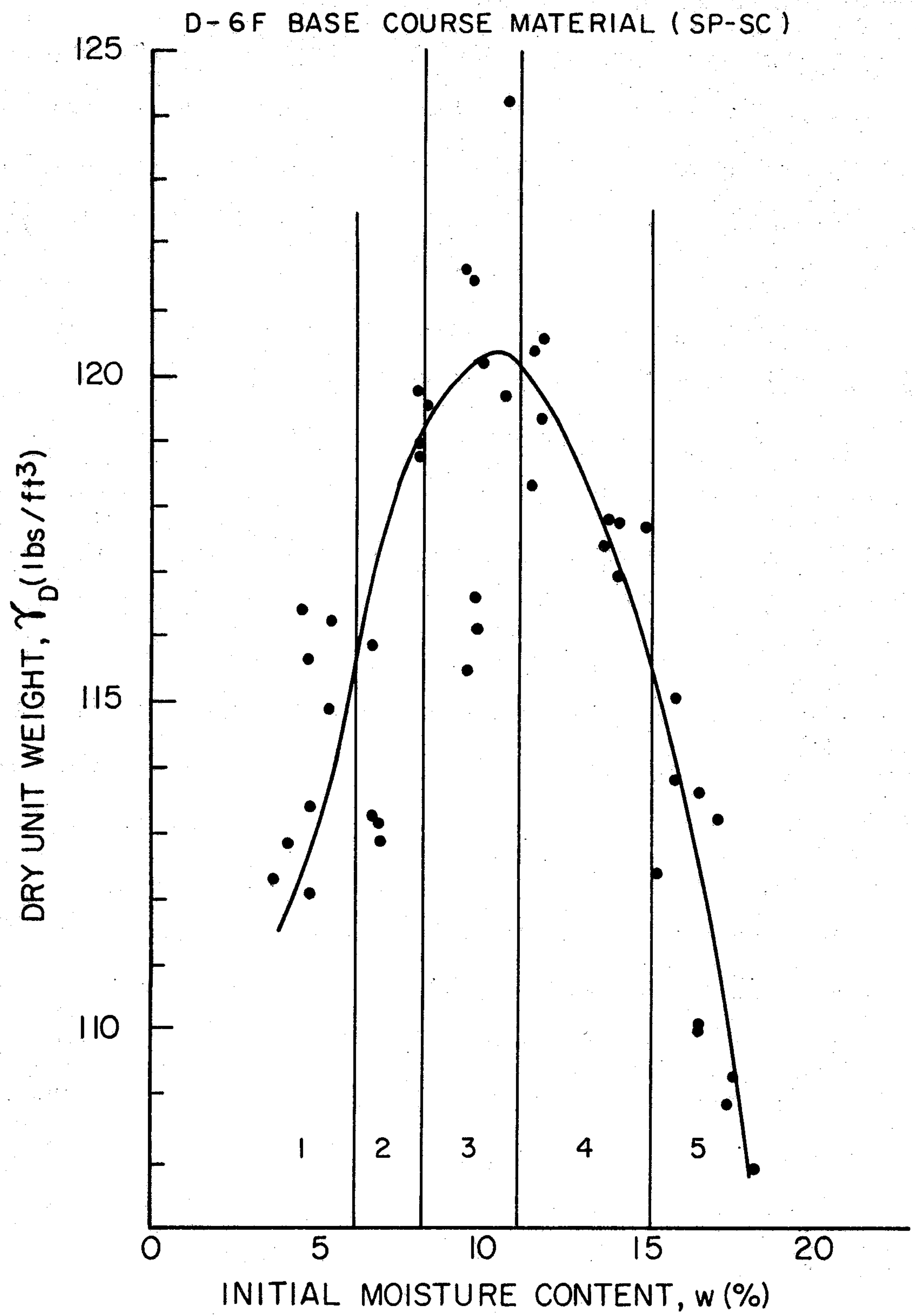

FIG. 7. - Compaction Curve For D-6F Base Course Material

were determined during one of the freeze cycles.

Freezing took place in an environmental room that was maintained at 0°F (-17.8°C). A study by Hamilton had previously determined that virtually all volume change can be brought about by a low temperature of 20°F (6.7°C) (8). The 0°F room was chosen because it was the one closest to 20°F without exceeding it. Thawing took place in the 77°F (25°C) environmental room. All samples were frozen or thawed for a minimum of twenty-four hours before they were tested.

All samples were subjected to the Schmidt Test during each of the freeze periods. The F3 and F5 samples were also tested during their final thaw cycles. The Schmidt Test measures the resilient modulus which is a value of the elastic modulus for a viscoelastic material subjected to a short-duration dynamic load.

The term "resilient modulus" is used here to refer to the modulus measured in the Schmidt test, which should be approximately equal to the Young's modulus of the material, a material property which is normally measured in tension.

After the samples went through the last Schmidt Test, they remained frozen until a splitting tensile test was run on each. For this test, each sample was loaded in diametrical compression to failure. This creates a fairly uniform tensile stress along the plane perpendicular to the loaded plane. Deformation in the direction the tensile stresses act and the load were recorded on a dual channel recorder. From these data, the ultimate tensile strength and elastic modulus could be calculated. A detailed progress chart and test data for each of the cycles are shown in Appendix IV.

The moisture content was again determined for each of the samples. Finally, the material from each pit was classified according to the Unified Soil Classification System. The material classification and a summary of some of the test data are in Table 1. Complete mechanical analysis charts are given in Appendix IV.

Soil Suction Tests

Five samples, one from each of the moisture groups, were taken from each of the F5 subgroups. These twenty samples were designated for soil suction measurements. In order to obtain accurate measurements of suction, these samples had to have special preparation. A psychrometer was placed next to the edge of the sample which was wrapped in foil. The entire sample was then sealed in wax to prevent changes in the moisture content. Fig. 8 illustrates the manner in which these samples were prepared.

A thermocouple type of psychrometer was used in conjunction with the dew point method of determining soil suction. This method was chosen because it is easy to use and it is the most accurate method presently available. Before the psychrometers were installed in the base course samples, they were calibrated using potassium chloride salt solutions. Further details on the theory, operation, and calibration of the psychrometers may be found in Appendix III.

Soil suction measurements were taken during the first and fourth thaw periods. A record of these data may be found in Appendix IV, Table 4-1. Changes in the ambient temperature can have an adverse effect upon the psychrometer readings so the thawed samples were kept in the 77°F environmental room where they were less subject to

TABLE 1. - Base Course Material Classification and Summary of Test Data

Borrow Pit	Unified Classification	Liquid Limit	Plastic Index	Percent Fines[a]	Percent Clay[b]
4	SM	22	3	15.5	9.3
5	SP - SC	40	17	7.2	5.0
6A&M	SP - SC	23	5	7.7	2.5
6F	SP - SC	23	9	10.8	8.1

[a] Percent passing the No. 200 sieve.

[b] Percent that is 2μ or smaller.

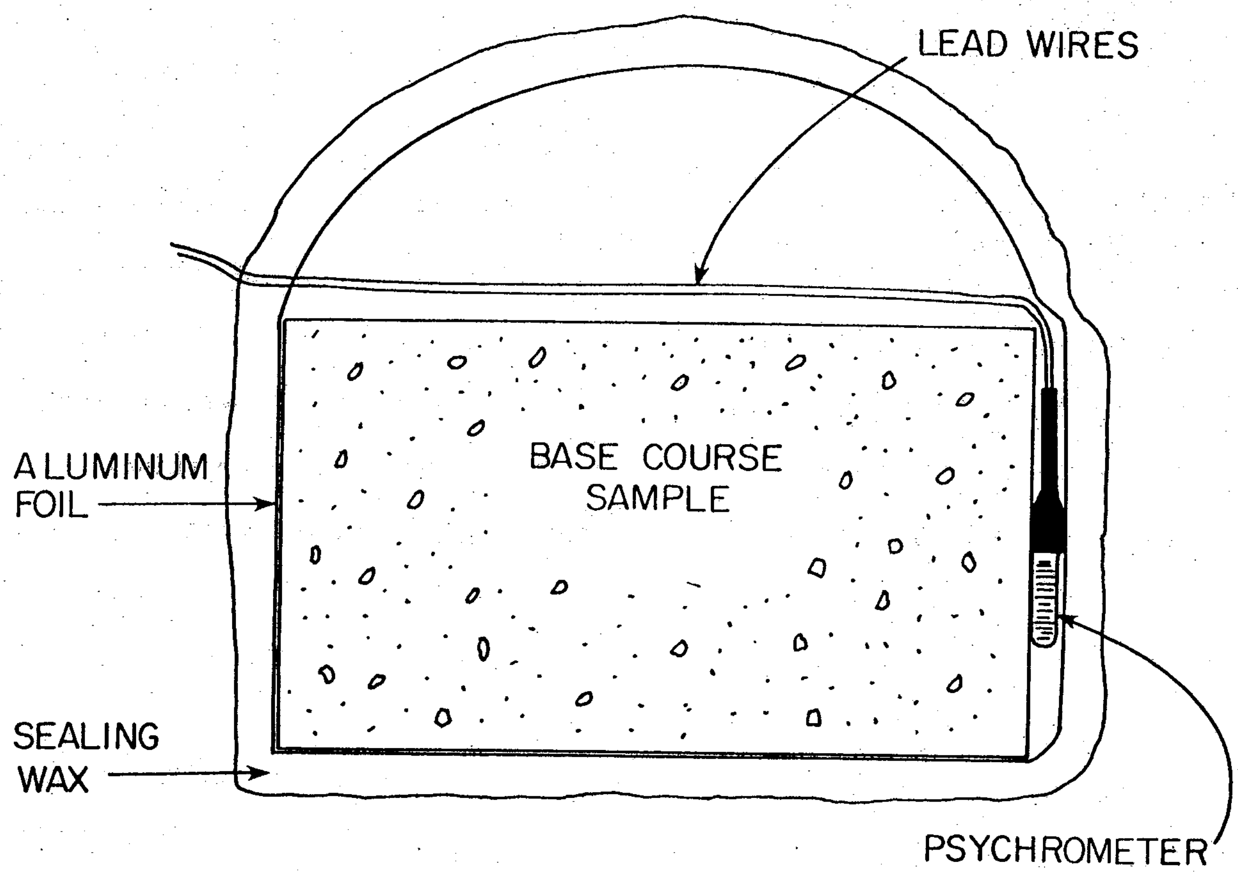

FIG. 8. - Cross-Section of Psychrometer Sample

temperature fluctuations. Each time the psychrometers were read, the ambient room temperature was also recorded using an electronic thermometer that was independent of the environmental room's controls. After the final suction level was measured, these samples were tested to determine their thawed and frozen resilient moduli and ultimate strength.

Summary

This section gives details of sample preparation and the testing procedures. After compaction, all samples were then subjected to different numbers of freeze-thaw cycles. The majority of the samples were tested to determine their resilient modulus and ultimate strength while in the frozen state and in the thawed state. The remaining twenty samples were used to determine the soil suction levels.

EXPERIMENTAL RESULTS

The testing program produced a large amount of data which was analyzed by linear regression techniques. All models had one dependent variable, but the number of independent variables ranged from one to eight. This section describes these analyses and the results obtained.

Preliminary Correlations

Moisture Content

As the final moisture contents were determined, it became clear that they had changed appreciably from the initial moisture content. An analysis of this produced a simple linear relationship of the form:

$$w_f = a + b\,(w_i) \qquad (2)$$

where

w_f = final moisture content, percent

w_i = initial moisture content, percent

a, b = regression constants

Table 2 summarizes equations derived for each of the four samples as well as the R^2 values for each of the regression analyses.

For the remainder of this thesis, the term "final moisture content" will mean the value that was actually measured at the end of the testing program rather than the value predicted by Equation (2). All regression analyses performed on the soil suction, elastic modulus, tensile strength,

TABLE 2. - Regression Equations to Predict Final Moisture Content (w_f) as a Function of Initial Moisture Content (w_i)

Material Number (1)	Equation (2)	R^2 (3)
D-4	$w_f = 0.30 + 0.72\ w_i$	0.43
D-5	$w_f = 0.12 + 0.93\ w_i$	0.91
D-6AM	$w_f = -0.33 + 0.85\ w_i$	0.71
D-6F	$w_f = 0.08 + 0.86\ w_i$	0.82

w_f, w_i in percent

and resilient modulus used the test values. In the future it may not always be possible to subject samples to freeze-thaw cycles and then determine their final moisture content because of time and budget limitations. In situations such as this, Equation (2) could prove to be very useful. The importance of the final moisture content will be shown shortly.

Soil Suction

Soil suction is in actuality a negative quantity; however, for the purpose of simplicity in this discussion it will be considered in the absolute value sense as a positive number. Although suction is affected by a number of things, such as grain size, clay minerals present, soil fabric, and dissolved ions present, for a given type of material, it can be effectively predicted by the moisture content. A plot of Initial Suction vs. Final Moisture Content can be found in Fig. 9 and Final Suction vs. Final Moisture Content in Fig. 10. Final moisture content was chosen rather than initial moisture because this was the moisture content at the time the tensile strength and elastic modulus were determined.

A typical expression for relating moisture content to suction is:

$$h = 10^{\left\{a + b(w_f)\right\}} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where

h = suction , psi

w_f = final moisture content, percent

a, b = regression constants

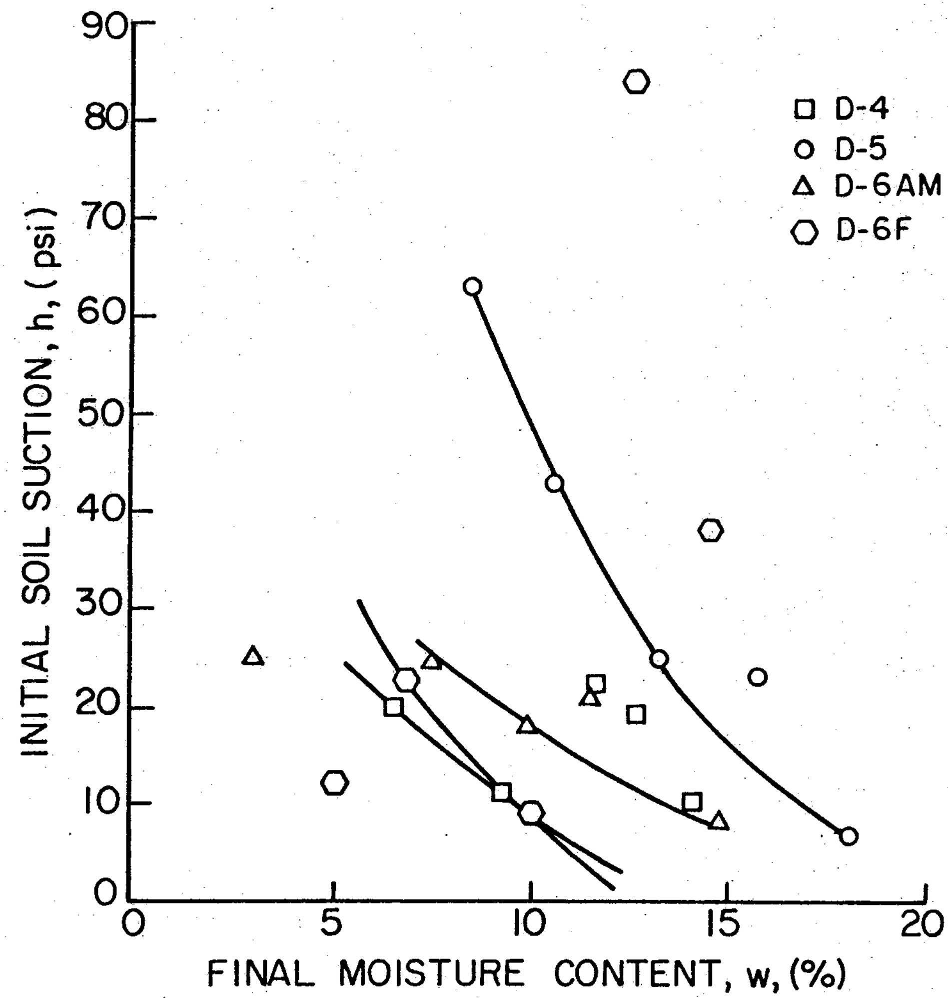

FIG. 9. - Initial Suction as a Function of the Final Moisture

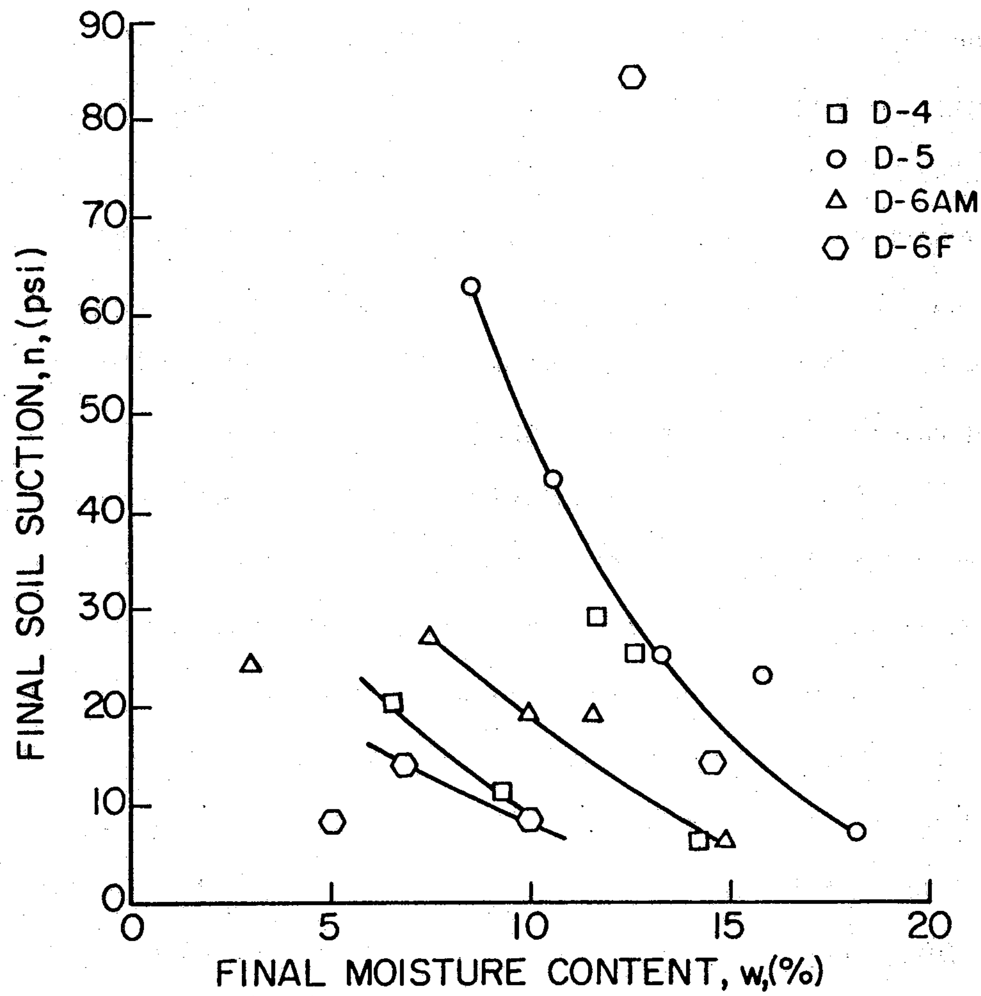

FIG. 10. - Final Suction as a Function of the Final Moisture

Since this relationship is widely used, it was decided to use it to determine the suction of each of the samples rather than assigning the value measured in a particular psychrometer sample to each of the samples within its moisture group. The regression coefficients for the initial suction equations are given in Table 3 and the coefficients for final suction are listed in Table 4. The values obtained from these equations are the values used in the analysis of the tensile strength, resilient modulus, and elastic modulus.

The D-5 samples did not have a change in suction and produced a very good fit as is evidenced by the R^2 of 0.90. The D-6AM samples also produced good results; however data for sample number 35 were deleted from both analyses. A sample with a moisture content this low should have exhibited a much larger value of suction than it did.

The D-4 and D-6F suction data were very scattered and inconsistent. As a result of this, the suction equations for these materials were derived in a different manner. For initial suction, the data points for all four materials were plotted as a function of moisture as in Fig. 9 (p. 22). Two points from the D-4 data and two points from the D-6F data were chosen which exhibited slopes similar to the slopes of the D-5 and D-6AM data. Points from the final suction data were chosen in a similar way. The data points chosen for material D-4 were from samples No. 14 and No. 33. For D-6F the points were from samples No. 15 and No. 18. These points were then used in the regression analyses to develop the suction equations. Since only two points were used in each regression analysis, the R^2 values are meaningless and so were deleted from Tables 3 and 4.

TABLE 3. - Regression Coefficients for Equation (3) to Predict Initial Suction as a Function of Final Moisture Content

Material Number (1)	Coefficients a (2)	Coefficients b (3)	R^2 (4)
D-4	1.9151	-0.0948	----
D-5	2.7019	-0.0978	0.90
D-6AM	2.0903	-0.0798	0.80
D-6F	2.2582	-0.1314	----

TABLE 4. - Regression Coefficients for Equation (3) to Predict Final Suction as a Function of Final Moisture Content

Material Number (1)	Coefficients a (2)	Coefficients b (3)	R^2 (4)
D-4	2.0532	-0.1310	-----
D-5	2.7019	-0.0978	0.90
D-6AM	2.2778	-0.0995	0.88
D-6F	1.6808	-0.0784	----

Primary Correlations

Introduction

Once the preliminary relationships were established, it was possible to begin the analysis of the data to determine which parameters had the greatest effect upon the tensile strength and elastic modulus. A total of eleven independent variables were considered in each of the analyses. They were as follows: the number of freeze-thaw cycles, final moisture content, dry density, initial suction, final suction, final moisture content squared, first resilient modulus, final resilient modulus, $\log_{10}$ of freeze-thaw cycles, $\log_{10}$ of initial suction, and $\log_{10}$ of dry density.

This data analysis was performed on a computer using the Statistical Analysis System (SAS). The regression was done by a procedure called STEPWISE with the Maximum R^2 Improvement option. This procedure first finds the one variable model which produces the highest R^2 value. Then it proceeds to find the two variable model with the highest R^2 value, then the three variable model and so forth. When the program adds a new variable it uses the previous "best" model as a starting point. After the variable that produces the greatest increase in R^2 is found, the program then goes back and checks to see if replacing any of the previous variables with one that is not being used will increase the R^2 value even more. In other words, the "best" four variable model may or may not contain the three variables which produced the "best" three variable model.

As was expected, some of the variables had a significant effect on the property being studied while others had very little. At the beginning of this report it was stated that simplicity as well as accuracy were of primary importance in developing the equations that would predict the tensile strength and elastic modulus for the four base course materials. Therefore, it was decided that the final equation would use only three variables and that the same variables would be used for each equation. The following paragraphs describe in detail the variables which had the most significant effects upon the property being predicted and the final predictive equations. Summaries of all regression models considered may be found in Appendix V.

Elastic Modulus

The variables which have the greatest effect on the elastic modulus are initial suction, dry density, freeze-thaw cycles, and final moisture content squared. In three of the four materials, initial suction is in the best single variable model and for the D-4 material, it is in the best two variable model. Dry density is in three of the best two variable models and for the D-5 material it is in the best three variable model. Finally, freeze-thaw cycles appear in three of the best three variable models and for the D-6F material it is found in the best four variable model. Therefore, it was decided that the elastic modulus could best be predicted by initial suction, dry density, and freeze-thaw cycles. The form of the equation which predicts it is:

$$E = 10^{\left[a + b(h_i) + c(\gamma_D) + d(FTCYC)\right]} \times 10^3 \quad . \; . \; . \; . \; . \; (4)$$

where

E = elastic modulus, psi

h_i = initial suction, psi

γ_D = dry unit weight of compacted base course material, lbs/ft^3

FTCYC = No. of freeze-thaw cycles to which the material has been exposed

a, b, c, d = regression constants

The regression constants and the values of R^2 for Equation (4) can be found in Table 5. Complete details of all the regression models developed for the elastic modulus can be found in Appendix V, Tables 5-2 through 5-5.

Tensile Strength

The tensile strength is affected by practically the same factors as the elastic modulus. These factors are dry density, initial suction, final suction, freeze-thaw cycles, and final moisture content. Again, initial suction appears in the best single variable model for three of the four materials. For the D-6AM material, the best single variable model uses final suction. Thus, suction appears to have a significant effect on the tensile strength of the base course materials and it is chosen as one of the common variables which are used to predict tensile strength.

Dry density also proved to be a predictor of the tensile strength. It appears in the best two variable model for all four of the materials. Dry density is also chosen as one of the variables that best predicts the

TABLE 5. - Regression Coefficients for Equation (4) to Predict Elastic Modulus

Material Number	Coefficients				R^2
	a	b	c	d	
(1)	(2)	(3)	(4)	(5)	(6)
D-4	-12.1503	-0.0296	0.1209	0.0636	0.60
D-5	-0.7255	-0.0117	0.0274	-0.0722	0.84
D-6AM	-1.1633	-0.0250	0.0362	-0.0311	0.86
D-6F	0.03227	-0.0248	0.0219	-0.0270	0.85

tensile strength.

Final suction appears in the best three variable models for all of the materials except D-5. However, the number of freeze-thaw cycles appears in the best three variable models for materials D-5 and D-6AM. Since it has such a strong effect on the elastic modulus and since it is desirable to keep the variables consistent with the ones used for the elastic modulus, the number of freeze-thaw cycles was chosen as the third variable to predict the tensile strength.

The equation for tensile strength has the same form as the one for elastic modulus.

$$\sigma_{TB} = 10^{\left(a + b(h_i) + c(\gamma_D) + d(FTCYC)\right)} \quad . \; . \; . \; . \; . \; . \; . \quad (5)$$

where

σ_T = ultimate tensile strength, psi

h_i = initial suction, psi

γ_D = dry unit weight of compacted base course material, lbs/ft^3

FTCYC = No. of freeze-thaw cycles to which the material has been exposed

a, b, c, d = regression constants

A listing of the regression constants and the R^2 value for each of the four base course materials can be found in Table 6. A complete list of all of the regression models considered for tensile strength may be found in Appendix V, Tables 5-6 through 5-9.

TABLE 6. - Regression Coefficients for Equation (5) to Predict Ultimate Tensile Strength

Material Number (1)	Coefficients				R^2 (6)
	a (2)	b (3)	c (4)	d (5)	
D-4	-10.3253	-0.0493	0.1115	0.0098	0.81
D-5	-2.3664	-0.0120	0.0455	0.0265	0.92
D-6AM	-1.8040	-0.0214	0.0394	0.0068	0.91
D-6F	-0.2338	-0.0240	0.0249	-0.0042	0.93

Resilient Modulus

Since the data were available, an analysis of the resilient modulus was also made. This was done by defining the last resilient modulus value obtained for each sample as the final resilient modulus. The final resilient modulus was then used as the dependent variable and was regressed on most of the same variables as the tensile strength and elastic modulus. This analysis produced no usable correlations. One possible explanation is that the testing procedure for determining the resilient modulus was not suitable for base course material.

Summary

In this section, equations for final moisture content, initial suction, and final suction were determined. Then, the parameters which had the greatest effect on the tensile strength and elastic modulus were discussed. Finally, equations which predict these two properties were developed. These equations had three independent variables; initial suction, dry density, and the number of freeze-thaw cycles. Since these base course materials are soils which have not been altered by admixture, the equations for elastic modulus and the tensile strength are very good as is evidenced by the high R^2 values.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

A study to determine the elastic modulus and ultimate tensile strength for frozen base course material has been conducted. This was done by varying certain measurable parameters and then determining the two properties which are of interest. The testing and analyses have led to the following conclusions:

1) The cominant parameters affecting the elastic modulus and the tensile strength of the soil are
   a) soil suction
   b) dry density of the compacted material
   c) number of freeze-thaw cycles experienced and
   d) final moisture content squared.
2) Of these, the first three can be used effectively to predict the elastic modulus and ultimate tensile strength of frozen base course material.

Recommendations

The testing and analyses have led to several recommendations. Some concern testing while others have to do with future research possibilities. The recommendations are as follow:

1) A testing procedure which will produce more consistent resilient modulus data for base course material needs to be developed. Perhaps more stringent controls over the mechanics of the existing testing procedure is all that is needed.

2) For the splitting tensile strength, the samples were taken one at a time from the 0°F environmental room to the Instron machine and immediately tested. While this procedure produced good results, it is believed that even better results could be obtained by performing this test in the 0°F environmental room.

3) Further research of this nature should be done on other base course materials from west Texas. Then, from all of the data, determine if there is any relationship between the regression coefficients for equations (4) and (5) and other parameters such as Atterberg Limits, the percent of material passing the No. 200 sieve, and the types and percentages of clay minerals.

APPENDIX I - REFERENCES

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APPENDIX II - NOTATION

a, b, c, d	=	regression coefficients
E	=	elastic modulus
emf	=	electromotive force
h	=	soil suction
h_f	=	final soil suction
h_i	=	initial soil suction
I	=	current
k	=	proportionality constant representing effective thermal conductivity
L	=	2 x crack spacing
R	=	ideal gas constant
RH	=	relative humidity
T	=	temperature
T_k	=	Temperature, ^oK
ΔT	=	temperature differential
ΔT_m	=	temperature differential resulting from the flow of the specified nominally optimum cooling current
μv	=	microvolts, 10^{-3} volts
w_f	=	final moisture content
w_i	=	initial moisture content
$\frac{dW_s}{dt}$	=	rate of heat transfer from surroundings to dry thermocouple

$\frac{dW_p}{dt}$ = rate of energy transfer due to Peltier effect

α = thermocouple sensitivity

α_B = freeze coefficient of the base course material

ν = specific molar volume of water

π = Peltier coefficient

π_V = cooling coefficient

σ_T = tensile strength

APPENDIX III - SOIL SUCTION MEASUREMENTS

Thermocouple Psychrometer Theory

A thermoelectric electromotive force (emf) can be produced in a thermocouple junction by a temperature difference between the two metals in the junction. The magnitude and direction of the *emf* are given by:

$$\text{emf} = \alpha \Delta T \quad \ldots\ldots\ldots\ldots \quad (1)$$

where

ΔT = temperature differential between metals

α = thermocouple sensitivity in volts/degree

When a current is passed through the junction in the same direction as the thermoelectric *emf*, the junction is cooled. This was discovered by Peltier in 1834 and is named the Peltier effect. The rate of the energy transfer $\frac{dW_p}{dt}$ caused by the Peltier effect is:

$$\frac{dW_p}{dt} = -\pi I \quad \ldots\ldots\ldots\ldots \quad (2)$$

where

I = current

π = the Peltier coefficient

Simultaneous heating of the thermocouple junction occurs as a result of the Joule effect, and Equation (2) must be modified to account for this in this manner:

$$\frac{dW_p}{dt} = -\pi I + RI^2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (3)$$

where

R = electrical resistance of the junction and lead wires in the immediate vicinity of the junction.

Since this is a quadratic function of the current it can be seen that there is some optimum value of current which will produce a maximum degree of cooling (11).

Work by Smith, Jones, and Chasmar (12) has shown that the coefficients α and π are related in the following manner:

$$\pi = T\alpha \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

where

T = temperature of thermocouple before current flows through it.

While these two coefficients remain identical for the same two metals, the maximum cooling capacity will vary from one junction to another. This is due to microscopic differences in the geometry and alloy makeup of each junction which causes the resistance to vary. The maximum realizable temperature depression is also influenced by heat flowing into the junction from its surroundings because of the Peltier cooling. This maximum temperature depression is very important in thermocouple psychrometry and will be considered again later on in this discussion.

It becomes clear from the preceding discussion that the Peltier coefficient is not the only factor which controls the maximum temperature depression of a thermocouple. Therefore, a new coefficient called the cooling coefficient will be defined. "The cooling coefficient π_v for a given thermocouple psychrometer shall be the differential *emf* in microvolts which results from the passage of a specified nominally optimum cooling current through the junction." (14). This may be stated mathematically as:

$$\pi_v = \alpha \, \Delta T_m \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (5)$$

where

ΔT_m = temperature differential resulting from the given current.

Dew Point Method

The relative humidity of the air that is in equilibrium with a soil sample can be related to the soil's suction level in the following manner:

$$h = \frac{RT_k}{\nu} \ln RH \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (6)$$

where

R = ideal gas constant

RH = relative humidity

T_k = Kelvin temperature

h = soil suction

ν = specific molar volume of water.

This relationship assumes that water vapor is an ideal gas (10). For all practical purposes this relationship between suction and relative humidity is linear from 0 to approximately -725 psi. A thermocouple psychrometer actually measures the relative humidity of the air in equilibrium with the soil sample.

A conventional psychrometer works in the following manner. The thermocouple is cooled below the dew point by the Peltier effect and water condenses on the junction. Then the current is stopped and the water evaporates back to the atmosphere. This evaporation process depresses the temperature of the junction below that of the surrounding air. The magnitude of the depression is dependent upon the ambient temperature of the air and the relative humidity. The temperature differential between the air and the junction generates an *emf* which is calibrated with the relative humidity in sealed flasks, as described later. Since it is a direct function of the relative humidity, the soil suction can be determined.

A dew point psychrometer determines the relative humidity by keeping the thermocouple junction at the dew point and sensing the difference between the temperatures of the ambient air and the junction. This temperature differential is also directly proportional to the relative humidity and thus the soil suction. This method is considered to be superior to the conventional method because it provides a continuous reading rather than an instantaneous one as in the conventional method.

In the dew point method, a situation is electronically simulated in which the thermocouple junction's temperature is determined exclusively by the heat transferred to or away from it by condensation or vaporization of water on it. When the measuring process is taking place, the junction's temperature is lower than the surrounding atmosphere (because it is at dew point); thus heat moves from the atmosphere into the junction. Peltier cooling is used to set up a counter flow whose magnitude is adjusted electronically to exactly equal the heat inflow. The result is a net heat transfer of zero. This balanced condition is set up on the dry junction before it is cooled and condenses water. In this way, all heat transfer mechanisms except for the condensation or evaporation of water are accounted for, so the temperature of the junction will only be affected by the water.

The general mathematical model for conductive and radiative heat transfer mechanisms to and from the thermocouple junction are quite complex. However, for small temperature differentials between the junction and the surroundings, the following linear model is sufficiently accurate (12):

$$\frac{dW_s}{dt} = k \, \Delta T \qquad (7)$$

where

$\frac{dW_s}{dt}$ = rate of heat transfer from surroundings to dry thermocouple

k = proportionality constant representing effective thermal conductivity

ΔT = temperature differential between surroundings and thermocouple junction.

The maximum temperature depression ΔT_m will be achieved when the optimum cooling current is used (recall Equation (3)). If this optimum cooling current is consistently switched on and off by an electronic timing pulse, the actual cooling effect can be varied linearly between zero and one, and the average temperature depression ΔT of the thermocouple junction will be:

$$\Delta T = L \, \Delta T_m \quad \text{. . . . .} \quad (8)$$

where

L = cooling duty cycle ratio.

The cooling duty cycle ratio is given by:

$$L = \frac{t_a}{t_b} \quad \text{. . . . .} \quad (9)$$

where

t_a = "on" time of cooling current

t_b = period of electronic timing pulses.

It is a dimensionless number that varies between zero and one.

It can be seen now that by precisely controlling the value of L, the magnitude of the cooling effect, Equation (3), can be adjusted to exactly balance the heat inflow, Equation (7). Under these conditions Equations (5), (7) and (8) can be combined to give Equation (10).

$$\frac{dW_p}{dt} = \frac{dW_s}{dt} = \frac{k L \pi_v}{\alpha} \quad \text{. . . . .} \quad (10)$$

The relationship stated in Equation (9) can be interpreted in the following way. $\alpha \Delta T$ is the output voltage from the thermocouple junction. If it is used to control L in the following manner:

$$L = \frac{\alpha \Delta T}{\pi_V} \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (11)$$

then the energy balance stated in Equation (10) is satisfied (14).

A cross-sectional view of a psychrometer is shown in Fig. A-3-1 (3). The shell is made of a semi-permeable ceramic which only allows water vapor to enter the chamber. The thermocouple bead is where the water is condensed and where the dew point temperature is maintained and monitored. The smaller temperature sensing thermocouple is where the ambient temperature is measured. A microvoltmeter is used to measure the difference in these two temperatures and displays this difference on a meter. The temperature difference, which is actually a differential microvoltage, is recorded and converted to suction by an equation that is unique to the psychrometer used.

It should be noted that the initial ambient temperature is the one used to determine the dew point depression. If the ambient temperature shifts during the test procedure, the meter output will be affected by a proportionate amount. Thus, the importance of testing the samples in the environmental room where a constant temperature can be better maintained is seen. The foil and wax seal used in this testing program also helped insulate the samples from ambient temperature changes (14).

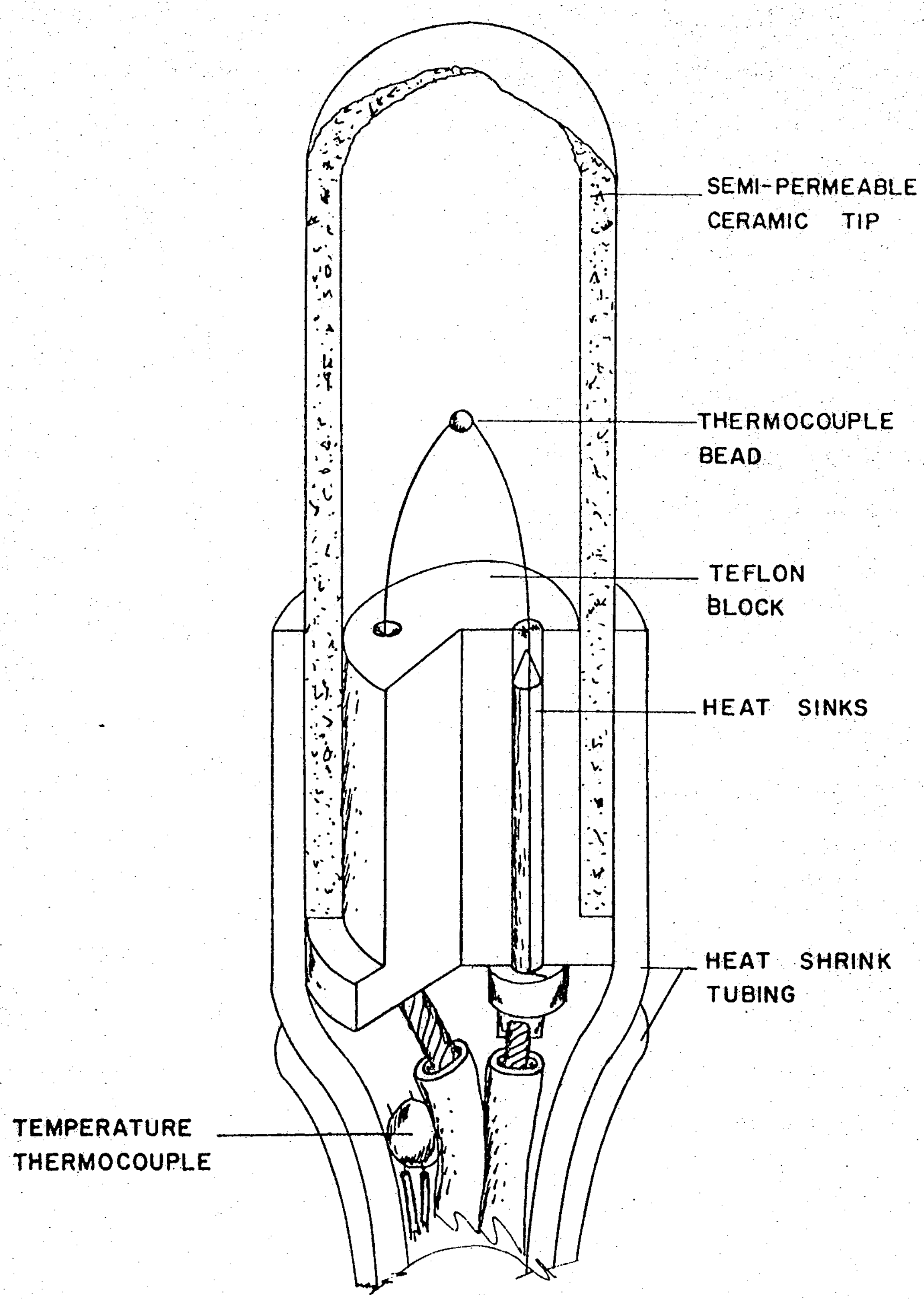

FIG. A-3-1. - Cross-Section View of a Psychrometer (3)

Psychrometer Calibration

Because of variations in the thermocouple geometry, psychrometers must be individually calibrated. This is usually done with solutions of potassium chloride (KCl). The suction of the solution varies with the molality. This can be seen in Table 3-1. Calibration can be done with any solution in which the suction level varies with the molality, however, KCl seems to be the most common.

The psychrometers are placed in a flask which is partially filled with KCl of a known molality (and thus a known suction). The psychrometers may be suspended above or immersed in the solution and are sealed in by a rubber stopper which has holes punched in it to allow the lead wires to be connected to the microvoltmeter and control box. The flask is then placed in an environmental chamber where the temperature is carefully maintained at 25°C. The psychrometers are allowed to sit at least two hours so that all temperature gradients can be eliminated and to achieve temperature and vapor equilibrium (1). The psychrometer is then read in the normal fashion. This procedure is repeated for a number of solutions having different suction levels. For each solution the microvoltmeter is read and recorded. Then, a regression analysis is performed on the microvoltmeter readings and the suction levels which gives a relationship of this form:

$$h = a + b\,(\mu v) \qquad (12)$$

where

h = suction, psi

μv = microvoltmeter reading

a, b = regression constants.

TABLE 3-1. - Suction of KCl and NaCl Solutions at 25°C (1)

Molality (1)	Suction, psi	
	KCl (2)	NaCl (3)
0.1	- 66.57	- 67.01
0.3	-195.51	-198.70
0.5	-323.15	-330.98
0.7	-451.51	-466.01
1.0	-645.28	-672.54
1.2	-775.24	-812.65
1.4	-906.35	-956.53
1.6	-1040.52	-1105.77

Table 3-2 lists the psychrometers used in this study, their calibration equations, and their R^2 values from the regression.

As previously mentioned, psychrometers are quite sensitive to temperature changes. The calibration is also affected by temperature changes. If readings of suction are made at temperatures other than the one at which the psychrometer is calibrated, the calibration is changed. This can be compensated for by changing the π_V value which is electronically set into the control equipment before each reading is made. The π_V value is altered in the following manner:

$$\pi_{V_T} = \pi_V + (T^{o}C - 25^{o}C)(0.7) \quad . . . . \quad (13)$$

where

π_{V_T} = cooling coefficient at any temperature other than $25^{o}C$

π_V = cooling coefficient at $25^{o}C$

T = temperature at which psychrometer will be read.

Values of π_V can be found in Table 3-2.

TABLE 3-2. - Psychrometer Calibration Equations and Cooling Coefficients

Psychrometer (1)	a (2)	b (3)	R^2 (4)	π_v (5)
K	7.60	21.19	0.92	62
V	5.31	17.48	0.86	71
Y	3.32	17.60	0.89	74
G	11.38	22.73	0.89	57
M	13.96	18.11	0.85	64
X	4.01	21.46	0.86	73
H	13.60	14.21	0.82	57
J	11.53	21.97	0.99	62
E	-4.17	29.67	0.99	56
C	9.20	26.70	0.99	55
50	-10.16	21.19	0.99	60
Ø	5.22	19.78	0.99	65
A	3.45	19.81	0.99	53

$$h = a + b\ (\mu V)$$

APPENDIX IV

TEST DATA AND RESULTS

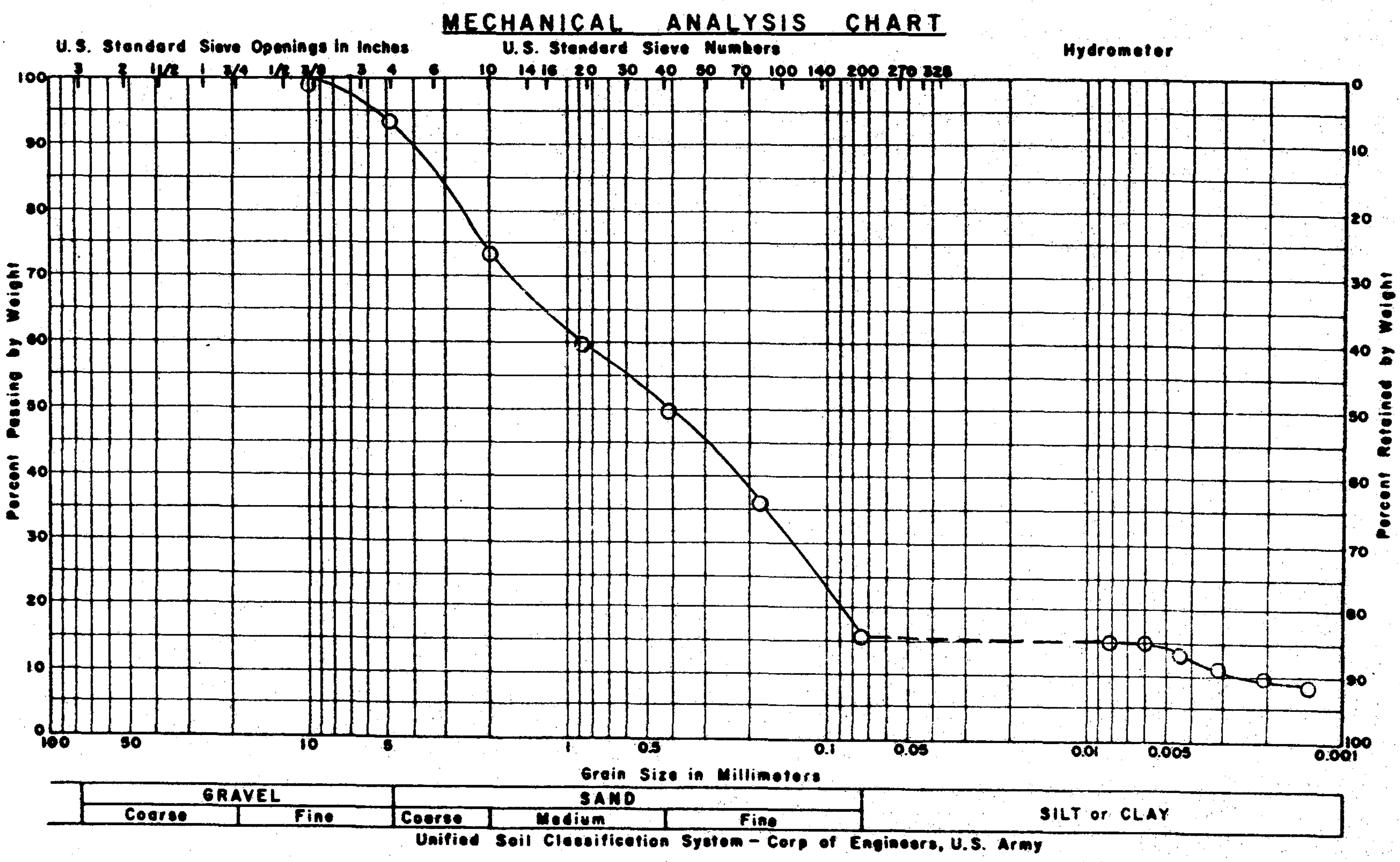

FIG. A-4-1. - Grain Size Distribution of the D-4 Material (SM)

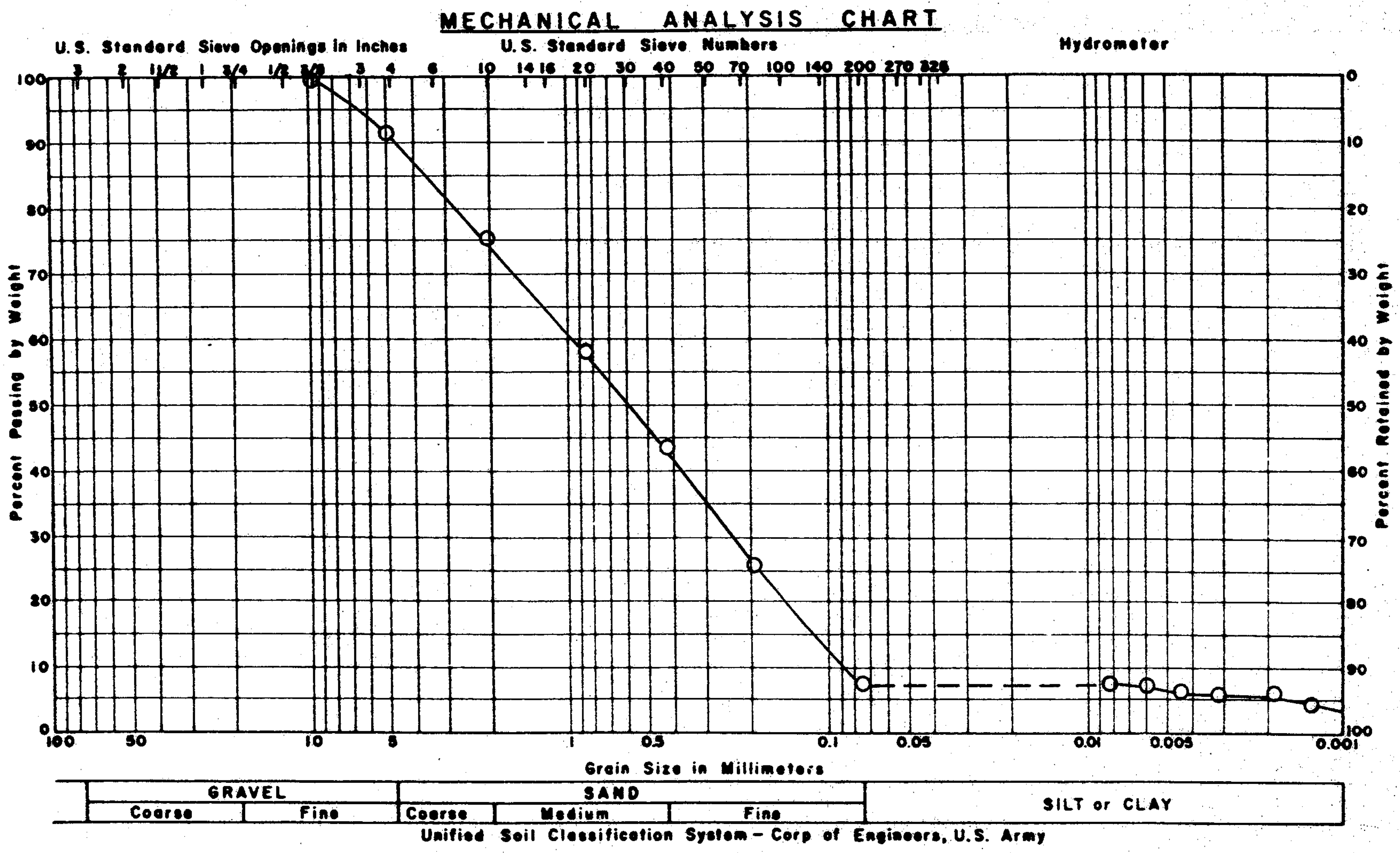

FIG. A-4-2. - Grain Size Distribution of the D-5 Material (SP-SC)

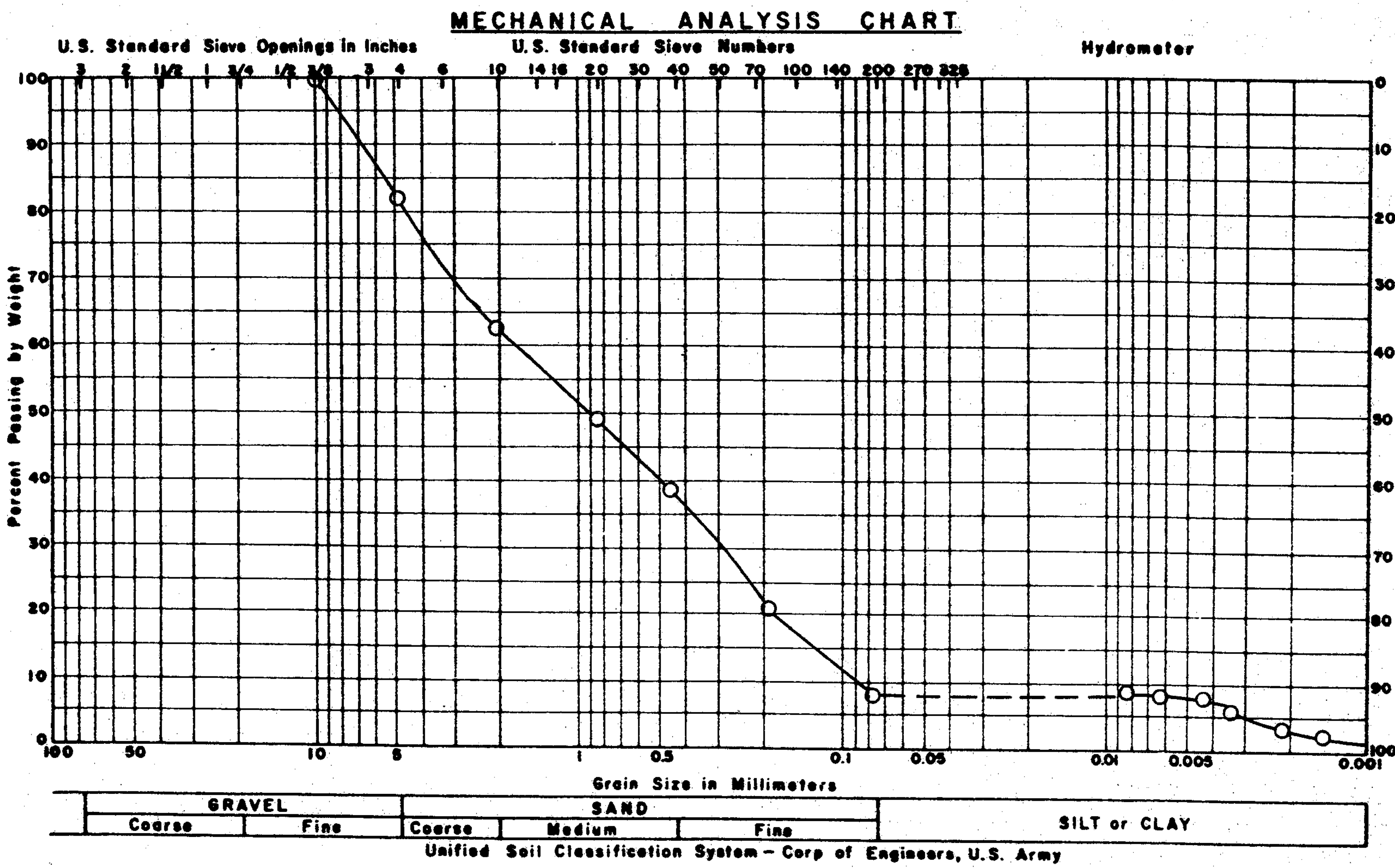

FIG. A-4-3. - Grain Size Distribution of the D-6AM Material (SP-SC)

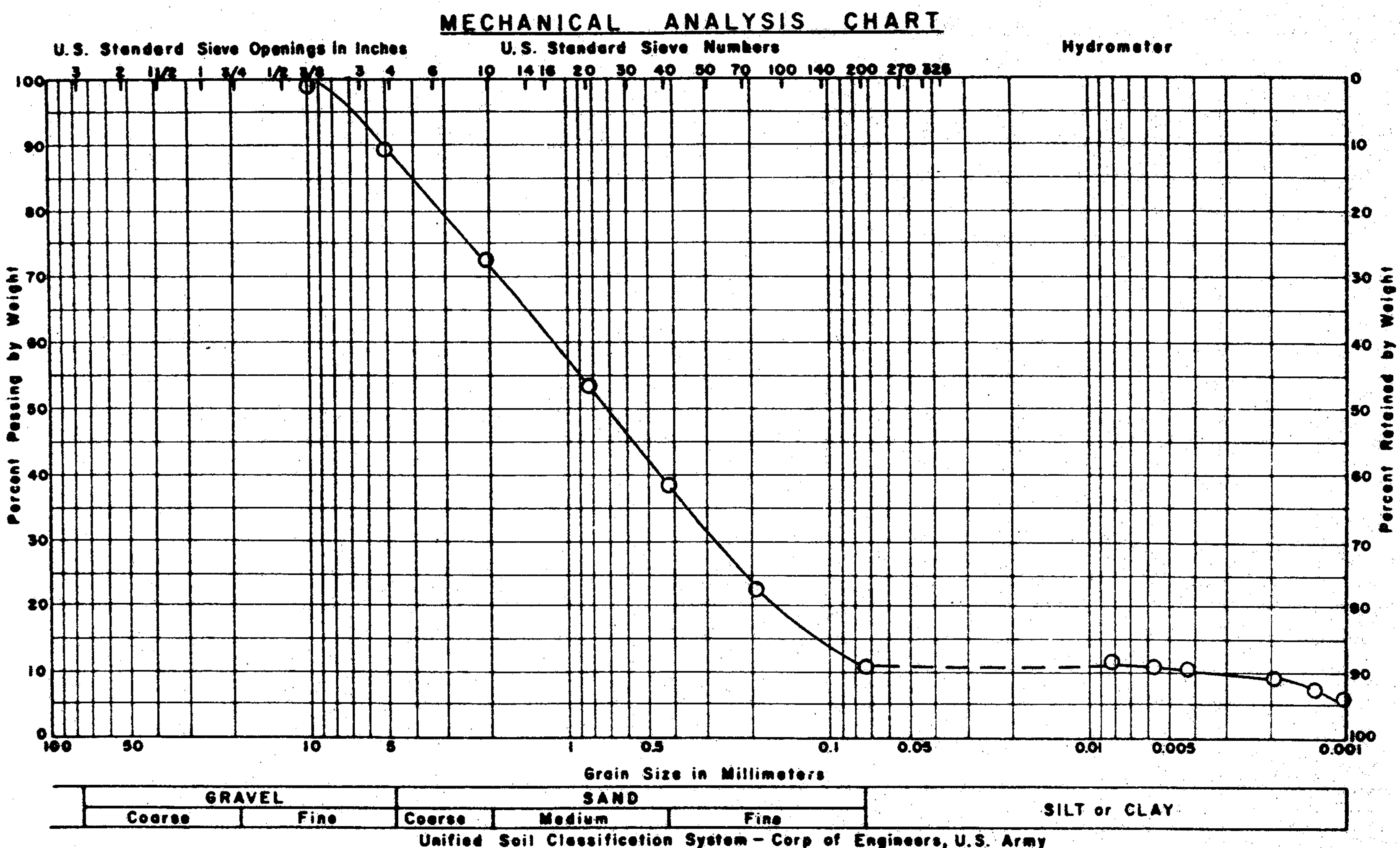

FIG. A-4-4. - Grain Size Distribution of the D-6F Material (SP-SC)

PROGRESS CHART

MATERIAL NUMBER	SUB-GROUP	F_1	T_1	F_2	T_2	F_3	T_3	F_4	T_4	F_5	SPLIT. TENS.	FINAL w %
D-4	FI	9/27/77									1/19/78	5/30/78
	F3	10/3/77	10/6/77	10/22/77	11/2/77	11/15/77					1/19/78	5/30/78
	F5	10/6/77	10/21/77	10/24/77	11/4/77	11/10/77	11/15/78	11/27/77	12/7/77	12/10/77	5/15/78	5/24/78
	PSY	6/1/77	5/24/78	5/30/78	5/31/78	6/1/78	6/2/78	6/4/78	7/6/78	7/11/78	7/11/78	7/12/78
D-5	FI	4/13/77									4/16/77	4/18/77
	F3	4/19/77	—	5/26/77	6/6/77	6/14/77					9/19/77	10/11/77
	F5	4/16/77	—	4/23/77	—	6/9/77	—	7/14/77	7/20/77	7/27/77	9/19/77	10/11/77
	PSY	—	8/5/77	—	8/11/77	8/19/77	8/23/77	8/26/77	11/5/77	11/8/77	—	5/24/78
D-6AM	FI	8/10/77									5/13/78	5/23/78
	F3	8/25/77	8/29/77	9/15/77	10/11/77	10/31/77					5/13/78	5/24/78
	F5	8/27/77	—	10/19/77	11/4/77	11/8/77	—	11/19/78	11/30/78	12/8/78	5/15/78	5/24/78
	PSY	—	3/17/78	3/18/78	3/19/78	3/20/78	3/22/78	—	4/22/78	5/15/78	5/15/78	5/24/78
D-6F	FI	8/23/77									5/12/78	5/23/78
	F3	8/23/77	8/26/77	10/12/77	10/20/77	10/27/77					5/15/78	5/23/78
	F5	7/15/77	8/26/77	10/26/77	11/1/77	11/3/77	11/10/77	11/16/77	11/29/77	12/7/77	5/12/78	5/22/78
	PSY	9/30/77	3/17/78	3/18/78	3/19/78	3/20/78	3/22/78	—	6/2/78	5/15/78	7/8/78	7/7/78

FIG. A-4-5. - Testing Program Progress Chart

TABLE 4-1. - Soil Suction Data From Psychrometer Samples

Material Number (1)	Sample Number (2)	Final Moisture Content, % (3)	Initial Suction psi (4)	Final Suction psi (5)
D - 4	33	6.48	20	16
	14	9.22	11	7
	44	11.63	22	29
	71	14.06	10	6
	53	12.63	19	25
D - 5	29	8.43	63	63
	27	10.58	43	43
	20	13.25	25	25
	24	15.76	23	23
	62	18.12	7	7
D - 6AM	35	3.01	25	24
	2	7.46	25	27
	20	9.90	18	19
	32	11.54	21	19
	29	14.75	8	6
D - 6F	11	4.95	12	8
	15	6.82	23	14
	18	9.92	9	8
	5	12.50	84	84
	6	14.52	38	14

TABLE 4-2. - Computer Variables Used in TABLES 4-3 through 4-6.

SAMPNO	=	sample number;
FTCYC	=	total number of freeze-thaw cycles sample experienced;
MR1	=	resilient modulus x 10^{-3} at first freeze period, psi;
MR2	=	resilient modulus x 10^{-3} at second freeze period, psi;
MR3	=	resilient modulus x 10^{-3} at third freeze period, psi;
MR4	=	resilient modulus x 10^{-3} at fourth freeze period, psi;
MR5	=	resilient modulus x 10^{-3} at fifth freeze period, psi;
MRT	=	resilient modulus x 10^{-3} at last thaw period, psi;
EMOD	=	Elastic modulus x 10^{3} of frozen material as measured in splitting tensile test, psi;
STRESS	=	ultimate stress of frozen material as measured in splitting tensile test, psi;
WI	=	initial moisture content, %;
WF	=	final moisture content, %;
DRYDEN	=	dry density, lbs/ft^{3};
SUCI	=	initial suction predicted from equations in TABLE 3, psi; and
SUCF	=	final suction predicted from equations in TABLE 4, psi.

TABLE 4-3. - Test Data From D-4 Base Course Material

SAMPNO	FTCYC	MR1	MR2	MR3	MR4	MR5	MRT	EMOD	STRESS	WI	WF	DRYDEN	SUCI	SUCF
1	5	117.0	171.0	170.0	1140.0	361.0	224.00	22.600	18.00	9.40	3.87	121.43	35.3467	35.1648
2	1	87.1	.	.	.	.	.	120.000	149.00	10.23	7.27	117.01	16.8334	12.6068
3	3	96.5	297.0	508.0	.	.	52.30	108.000	199.00	11.42	11.25	120.51	7.0637	3.7941
4	5	640.0	100.0	939.0	312.0	424.0	207.00	25.400	15.40	10.87	4.00	118.52	34.3582	33.8123
6	3	229.0	277.0	1305.0	.	.	160.00	133.000	212.00	9.41	7.29	123.23	16.7601	12.5310
8	5	177.0	86.7	179.0	776.0	141.0	207.00	11.100	22.00	9.75	5.00	116.02	27.6231	25.0060
9	1	140.0	.	.	.	.	.	146.000	284.00	10.02	9.32	116.53	10.7626	6.7920
10	1	.	.	.	.	.	.	.	.	9.78	.	119.70	.	.
12	3	707.0	256.0	476.0	.	.	57.40	39.600	79.60	9.67	6.74	115.70	18.8970	14.7929
13	3	309.0	218.0	403.0	.	.	143.00	119.000	139.00	9.42	7.23	117.98	16.9809	12.7599
14	5	.	.	.	.	81.5	24.10	86.300	168.00	9.23	9.22	115.86	11.0000	7.0000
16	3	102.0	562.0	.	.	.	107.00	31.400	28.90	9.77	7.05	114.54	17.6611	13.4720
18	5	99.6	59.7	175.0	75.8	39.2	35.60	2.950	1.05	6.79	4.33	108.91	31.9713	30.6080
19	5	104.0	72.1	579.0	72.9	98.7	86.80	2.350	3.59	6.39	3.61	114.50	37.4098	38.0343
21	1	.	.	.	.	.	.	.	.	8.23	.	115.50	.	.
22	5	745.0	133.0	130.0	531.0	116.0	308.00	9.450	4.95	7.86	4.24	114.27	32.6053	31.4505
24	1	23.1	.	.	.	.	.	2.510	5.20	5.32	5.39	113.57	25.3698	22.2302
25	3	49.8	.	.	.	.	.	.	.	5.17	3.44	112.69	38.8235	40.0360
26	5	36.5	39.1	14.2	17.9	13.4	15.90	0.885	0.64	4.78	3.16	114.26	41.2693	43.5652
27	1	.	.	.	.	.	.	.	.	4.91	.	115.16	.	.
28	1	131.0	.	.	.	.	.	7.270	8.80	5.26	4.74	115.21	29.2354	27.0466
31	3	42.7	42.2	20.1	.	.	10.60	1.280	2.13	5.28	3.82	112.31	35.7344	35.6993
32	3	47.3	35.8	75.7	.	.	25.20	1.090	2.30	5.04	5.71	113.56	23.6589	20.1843
33	5	.	.	.	.	347.0	25.20	13.100	21.40	6.20	6.48	115.44	20.0000	16.0000
34	1	116.0	.	.	.	.	.	19.200	29.40	6.09	.	115.66	.	.
36	3	110.0	312.0	132.0	.	.	50.30	5.410	9.06	5.70	4.22	116.48	32.7479	31.6408
37	1	132.0	.	.	.	.	.	118.000	357.00	11.51	10.83	120.12	7.7416	4.3067
39	5	194.0	148.0	218.0	101.0	331.0	83.90	141.000	252.00	11.32	7.83	120.21	14.8973	10.6471
41	3	307.0	81.5	237.0	.	.	71.50	138.000	300.00	11.07	9.48	121.46	10.3934	6.4719
43	3	62.5	67.1	233.0	.	.	53.70	106.000	298.00	12.06	2.84	119.82	44.2537	47.9809
44	5	.	.	.	.	310.0	16.90	164.000	311.00	12.07	11.63	118.56	6.5017	3.3831
45	1	167.0	.	.	.	.	.	79.700	367.00	12.18	11.64	119.30	6.4375	3.3729
47	1	233.0	.	.	.	.	.	.	.	12.00	11.19	117.47	7.1568	3.8634
48	3	102.0	125.0	161.0	.	.	59.90	132.000	287.00	11.45	9.82	116.05	9.6502	5.8409
49	5	149.0	120.0	304.0	702.0	125.0	244.00	94.900	38.50	12.24	5.16	118.30	26.6754	23.8276
50	5	76.0	117.0	244.0	325.0	223.0	440.00	78.600	7.97	14.22	3.90	117.03	35.1161	34.8479
51	1	59.9	.	.	.	.	.	103.000	363.00	13.16	13.09	118.32	4.7280	2.1778
52	3	61.9	55.6	127.0	.	.	9.78	177.000	355.00	13.83	12.22	117.04	5.7163	2.8314
53	5	.	.	.	.	82.3	13.60	88.800	286.00	14.48	12.63	115.56	5.2272	2.5020
54	5	108.0	130.0	88.4	214.0	212.0	188.00	75.700	138.00	14.00	8.12	116.77	13.9838	9.7551
55	1	.	.	.	.	.	.	79.900	267.00	14.84	13.91	115.20	3.9535	1.7005
56	3	478.0	73.1	118.0	.	.	26.00	58.900	247.00	15.15	11.43	112.97	6.7917	3.5935
58	5	144.0	232.0	1178.0	244.0	71.1	174.00	62.600	121.00	13.39	7.39	117.06	16.3983	12.1586

TABLE 4-3. - (Continued)

SAMPNO	FTCYC	MR1	MR2	MR3	MR4	MR5	MRT	EMOD	STRESS	WI	WF	DRYDEN	SUCI	SUCF
59	1	98.6	.	.	.	.	.	102.0	384.00	12.57	11.97	119.62	6.0368	3.0533
60	1	127.0	.	.	.	.	.	91.1	305.00	14.46	14.04	116.88	3.8429	1.6351
61	3	76.9	183.0	195.0	.	.	40.60	247.0	248.00	14.41	9.55	115.82	10.2358	6.3366
63	5	62.7	150.0	216.0	658	644	79.50	106.0	145.00	15.07	7.93	112.67	14.5757	10.3306
64	1	62.3	.	.	.	.	.	108.0	351.00	14.60	13.90	114.67	3.9621	1.7056
65	5	56.3	173.0	220.0	120	191	55.50	48.8	85.70	14.18	6.56	116.58	19.6539	15.6184
67	3	139.0	104.0	48.5	.	.	2.87	100.0	344.00	14.79	12.24	116.30	5.6915	2.8144
68	5	114.0	60.7	147.0	261	690	45.80	93.1	230.00	15.19	9.25	115.56	10.9282	6.9369
69	1	.	.	.	.	.	.	.	.	14.78	.	115.26	.	.
71	5	.	.	.	.	184	.	74.7	278.00	14.06	14.11	116.66	3.7846	1.6009
72	3	79.1	.	256.0	.	.	84.70	111.0	250.00	12.49	9.30	120.20	10.8097	6.8331
73	1	97.0	.	.	.	.	.	104.0	366.00	12.63	12.26	120.24	5.6667	2.7975
75	1	55.2	.	.	.	.	.	60.6	299.00	13.79	12.08	117.32	5.8937	2.9536
76	1	.	.	.	.	.	.	.	.	12.93	.	118.71	.	.
77	5	343.0	185.0	622.0	1847	223	135.00	224.0	7.57	12.67	2.34	119.28	49.3547	55.7935
80	3	53.3	173.0	1111.0	.	.	41.10	107.0	245.00	12.98	9.48	116.60	10.3934	6.4719

N=59

TABLE 4-4. - Test Data From D-5 Base Course Material

SAMPNO	FTCYC	MR1	MR2	MR3	MR4	MR5	MRT	EMOD	STRESS	WI	WF	DRYDEN	SUCI	SUCF
1	3	49.3	111.0	105.0	.	.	23.30	6.85	48.7	9.02	8.84	108.35	68.688	68.688
2	5	50.4	163.0	191.0	82.4	177.0	47.20	.	45.7	8.66	8.27	109.46	78.100	78.100
3	1	48.9	.	.	.	.	.	32.40	72.9	9.28	10.90	109.10	43.183	43.183
5	1	133.0	.	.	.	.	.	36.90	101.0	11.10	11.59	109.24	36.965	36.965
6	3	54.2	207.0	55.9	.	.	22.70	15.90	156.0	10.77	10.17	109.52	50.902	50.902
7	1	54.3	.	.	.	.	.	53.70	122.0	10.55	10.54	105.51	46.831	46.831
8	5	86.5	50.0	46.0	154.0	163.0	28.90	46.00	249.0	14.63	13.42	109.16	24.475	24.475
9	1	86.5	.	.	.	.	.	76.50	303.0	13.32	12.86	110.51	27.767	27.767
10	5	40.1	89.8	89.1	147.0	108.0	33.10	42.10	264.0	12.65	12.32	110.58	31.359	31.359
11	1	316.0	.	.	.	.	.	73.00	285.0	13.87	13.60	114.53	23.503	23.503
12	3	121.0	66.3	38.9	.	.	48.10	.	.	12.71	11.58	118.25	37.049	37.049
13	3	40.6	108.0	87.4	.	.	23.20	159.00	401.0	15.04	12.98	114.42	27.026	27.026
15	3	232.0	54.3	221.0	.	.	45.60	33.30	282.0	11.08	10.57	115.61	46.516	46.516
16	5	67.0	64.7	120.0	105.0	40.5	68.90	26.80	179.0	11.24	10.34	115.75	48.990	48.990
17	5	84.4	55.8	103.0	285.0	92.2	75.50	42.00	319.0	13.76	13.22	114.15	25.603	25.603
18	1	72.5	.	.	.	.	.	121.00	368.0	13.88	14.78	115.97	18.016	18.016
20	5	.	.	.	.	73.0	41.60	98.30	296.0	14.29	13.25	114.10	25.431	25.431
21	1	598.0	.	.	.	.	.	126.00	317.0	16.73	16.03	107.94	13.594	13.594
22	1	112.0	.	.	.	.	.	370.00	309.0	16.79	15.97	106.94	13.779	13.779
23	3	63.1	118.0	66.0	.	.	57.50	59.70	388.0	15.72	12.73	111.17	28.592	28.592
24	5	.	.	.	.	102.0	25.40	.	.	16.04	15.76	112.01	14.446	14.446
25	5	85.1	159.0	266.0	187.0	101.0	31.00	33.90	258.0	15.55	14.41	111.44	19.582	19.582
26	3	20.8	62.5	89.0	.	.	34.50	36.70	221.0	11.48	10.57	113.52	46.516	46.516
27	5	.	.	.	.	97.6	121.00	135.00	260.0	11.38	10.58	112.83	46.411	46.411
28	3	69.9	36.6	50.1	.	.	41.80	12.70	66.8	8.99	8.10	108.12	81.150	81.150
29	5	.	.	.	.	1018.0	42.30	25.10	76.0	9.04	8.43	109.28	75.335	75.335
30	3	45.7	44.8	87.6	.	.	39.50	6.01	38.1	8.64	7.62	108.17	90.418	90.418
31	1	89.4	.	.	.	.	.	31.20	58.2	8.79	9.58	108.53	58.139	58.139
32	3	120.0	60.9	60.3	.	.	51.60	30.40	179.0	11.56	9.23	111.37	62.910	62.910
33	5	67.6	27.9	165.0	128.0	124.0	54.40	46.00	226.0	11.06	10.49	113.46	47.362	47.362
34	3	99.4	101.0	284.0	.	.	57.40	15.20	154.0	11.04	10.07	113.48	52.062	52.062
35	5	95.8	91.1	117.0	148.0	100.0	49.90	34.80	180.0	11.63	9.84	112.09	54.831	54.831
36	1	85.9	.	.	.	.	.	4.57	14.3	7.26	7.46	105.15	93.737	93.737
37	5	66.7	71.8	42.8	27.8	38.2	7.94	1.43	11.9	7.15	7.14	105.09	100.745	100.745
38	5	143.0	70.8	133.0	206.0	62.7	21.90	.	.	8.89	8.57	109.23	72.996	72.996
39	5	64.2	40.4	63.3	74.1	89.5	29.70	7.17	41.6	9.00	7.26	109.33	98.058	98.058
40	3	226.0	31.1	136.0	.	.	62.40	26.40	70.2	8.92	7.89	109.62	85.082	85.082
41	1	77.0	.	.	.	.	.	38.40	63.3	8.40	8.99	109.73	66.405	66.405
43	1	30.0	.	.	.	.	.	10.10	13.4	7.29	7.18	106.96	99.841	99.841
44	3	54.1	43.3	31.2	.	.	34.70	.	.	7.06	5.44	107.40	147.764	147.764
45	5	79.2	47.0	52.0	65.6	50.8	10.60	2.08	12.1	6.83	6.31	107.22	121.461	121.461
46	1	1252.0	.	.	.	.	.	81.30	209.0	11.14	11.46	112.96	38.064	38.064
47	3	63.6	75.2	183.0	.	.	92.70	25.30	154.0	11.36	9.83	111.69	54.955	54.955

TABLE 4-4. - (Continued)

SAMPNO	FTCYC	MR1	MR2	MR3	MR4	MR5	MRT	EMOD	STRESS	WI	WF	DRYDEN	SUCI	SUCF
48	5	56.7	37.6	111.0	100.0	109.0	58.8	18.00	61.90	10.09	7.41	110.56	94.799	94.799
49	1	92.1	.	.	.	.	.	61.90	145.00	10.44	10.36	110.50	48.769	48.769
50	5	19.4	92.7	126.0	148.0	304.0	35.5	44.00	157.00	10.37	10.31	112.14	49.322	49.322
51	1	500.0	.	.	.	.	.	102.00	202.00	10.63	10.87	112.61	43.475	43.475
52	5	65.7	63.3	88.9	44.3	51.0	16.8	1.77	9.93	7.13	5.84	105.78	135.029	135.029
53	5	71.4	32.6	132.0	67.9	96.8	15.3	2.67	7.75	7.24	5.74	105.99	138.106	138.106
54	3	37.2	53.8	64.4	.	.	47.3	39.40	306.00	14.19	11.92	111.51	34.316	34.316
55	1	368.0	.	.	.	.	.	82.90	244.00	13.51	13.69	112.08	23.031	23.031
56	5	50.1	47.3	60.1	92.9	79.0	21.4	40.70	295.00	17.73	16.37	106.93	12.591	12.591
57	3	63.5	58.4	86.6	.	.	35.0	.	.	17.75	13.98	107.01	21.574	21.574
58	1	31.8	.	.	.	.	.	125.00	276.00	17.68	17.19	106.79	10.467	10.467
60	5	.	45.7	42.3	103.0	49.2	26.6	43.00	293.00	18.15	14.98	106.27	17.222	17.222
61	1	49.3	.	.	.	.	.	96.20	96.70	17.37	17.90	106.70	8.920	8.920
62	5	.	.	.	.	148.0	21.8	176.00	309.00	18.74	18.12	105.56	8.489	8.489
63	3	66.8	164.0	190.0	.	.	20.3	62.00	335.00	17.85	17.27	105.70	10.280	10.280
64	1	115.0	.	.	.	.	.	.	.	18.11	18.14	106.12	8.450	8.450

N=59

TABLE 4-5. - Test Data From D-6AM Base Course Material

SAMPNO	FTCYC	MR1	MR2	MR3	MR4	MR5	MRT	EMOD	STRESS	WI	WF	DRYDEN	SUCI	SUCF
1	3	173.0	69.0	235.0	.	.	62.70	64.00	71.30	7.90	6.64	118.01	36.3527	41.395
2	5	.	.	.	.	79.5	4.67	50.10	126.00	7.80	7.46	116.38	31.2686	34.304
3	1	90.1	.	.	.	.	.	150.00	190.00	7.96	8.18	115.69	27.3942	29.087
4	3	52.6	51.2	79.4	.	.	32.30	146.00	144.00	7.81	6.33	116.47	38.4832	44.443
5	1	64.9	.	.	.	.	.	706.00	407.00	9.82	10.01	119.66	19.5723	19.124
6	3	83.5	120.0	64.3	.	.	28.50	236.00	287.00	10.39	7.91	119.84	28.7874	30.943
7	5	72.1	151.0	47.5	54.1	215.0	5.27	311.00	368.00	10.64	8.96	119.17	23.7368	24.326
8	1	98.0	.	.	.	.	.	710.00	384.00	10.68	9.92	121.12	19.8986	19.522
9	1	69.6	.	.	.	.	.	768.00	402.00	14.50	14.23	116.88	9.0141	7.271
10	3	24.6	25.3	107.0	.	.	5.97	575.00	359.00	14.54	11.91	117.32	13.8051	12.373
11	5	44.3	108.0	66.0	51.9	40.5	2.65	656.00	366.00	13.73	11.96	117.48	13.6789	12.232
12	1	51.8	.	.	.	.	.	819.00	388.00	14.37	13.71	115.96	9.9178	8.191
13	1	99.0	.	.	.	.	.	753.00	456.00	12.40	12.06	121.32	13.4298	11.955
14	3	106.0	57.3	70.1	.	.	33.30	418.00	339.00	12.62	10.20	120.11	18.9009	18.309
15	5	296.0	76.9	51.5	54.2	66.0	7.65	602.00	406.00	11.98	11.26	121.58	15.5562	14.361
16	1	73.0	.	.	.	.	.	748.00	455.00	12.07	11.64	120.99	14.5072	13.163
17	3	175.0	88.4	82.7	.	.	18.80	323.00	388.00	12.45	10.40	121.86	18.2189	17.489
18	1	91.2	.	.	.	.	.	25.00	22.40	4.18	3.89	114.39	60.2505	77.737
19	3	29.1	28.6	115.0	.	.	34.70	254.00	309.00	9.53	8.44	121.68	26.1164	27.404
20	5	.	.	.	.	132.0	18.80	417.00	367.00	9.55	9.90	122.36	19.9719	19.612
21	1	145.0	.	.	.	.	.	94.10	84.20	6.06	5.91	116.42	41.5704	48.933
22	3	297.0	54.4	1332.0	.	.	127.00	62.50	40.10	5.83	3.78	119.06	61.4806	79.722
23	5	146.0	229.0	170.0	72.7	565.0	6.51	58.70	65.40	6.13	4.79	117.89	51.0681	63.250
24	1	47.6	.	.	.	.	.	83.90	99.20	5.39	5.83	118.83	42.1859	49.838
25	3	24.4	76.3	46.4	.	.	28.40	2.97	5.12	4.15	2.86	116.97	72.8024	98.432
26	5	58.2	405.0	90.8	100.0	51.5	9.85	56.60	99.40	4.07	2.81	117.06	73.4742	99.566
27	1	179.0	.	.	.	.	.	24.10	30.60	3.90	4.22	117.35	56.7061	72.076
28	3	141.0	42.2	59.7	.	.	3.50	377.00	344.00	15.19	11.96	115.51	13.6789	12.232
29	5	.	.	.	.	50.3	.	643.00	342.00	14.95	14.75	116.42	8.1925	6.454
30	5	24.1	133.0	117.0	131.0	113.0	61.90	67.90	73.40	8.69	4.61	121.41	52.7851	65.914
31	1	111.0	.	.	.	.	.	470.00	349.00	9.21	8.24	121.84	27.0939	28.689
32	5	.	.	.	.	127.0	3.54	206.00	222.00	12.99	11.54	119.52	14.7762	13.468
33	5	74.4	70.3	61.3	69.5	175.0	7.98	142.00	226.00	12.72	8.33	119.71	26.6496	28.104
34	3	63.0	93.6	85.0	.	.	126.00	2.75	4.22	4.34	1.31	113.68	96.7879	140.407
35	5	.	.	.	.	.	.	.	.	4.04	3.01	114.33	70.8234	95.106
36	1	175.0	.	.	.	.	.	1221.00	495.00	10.69	10.39	122.20	18.2524	17.529
37	3	92.5	49.5	273.0	.	.	176.00	71.70	116.00	10.49	5.34	121.92	46.1599	55.760
38	1	114.0	.	.	.	.	.	534.00	433.00	11.76	10.42	122.91	18.1521	17.409
39	3	66.2	647.0	142.0	.	.	132.00	126.00	113.00	11.24	5.46	121.70	45.1533	54.248
40	1	114.0	.	.	.	.	.	50.30	49.30	4.84	4.80	116.40	50.9743	63.105
41	3	68.7	237.0	64.3	.	.	99.00	2.78	2.58	4.94	1.19	115.77	98.9455	144.322
42	1	123.0	.	.	.	.	.	611.00	382.00	12.63	12.21	119.99	13.0648	11.551
43	3	107.0	114.0	79.8	.	.	81.00	67.00	60.00	12.30	3.96	120.25	59.4806	76.500

TABLE 4-5. - (Continued)

SAMPNO	FTCYC	MR1	MR2	MR3	MR4	MR5	MRT	EMOD	STRESS	WI	WF	DRYDEN	SUCI	SUCF
44	5	26.4	85.6	60.5	71.8	668	7.70	144.0	290.0	12.20	8.89	119.28	24.0440	24.719
45	1	88.6	.	.	.	.	.	748.0	442.0	12.55	12.20	120.28	13.0888	11.578
46	5	141.0	79.7	47.4	147.0	147	6.15	64.8	177.0	13.56	9.25	119.11	22.5052	22.762
47	3	38.6	112.0	145.0	.	.	82.70	98.9	66.8	13.68	4.65	115.21	52.3986	65.312
48	5	63.1	79.3	27.0	15.0	.	.	.	.	2.99	2.04	115.17	84.6397	118.779
49	5	51.3	72.4	19.3	15.0	.	4.47	.	.	2.91	1.59	118.37	91.9348	131.681

N=49

TABLE 4-6. - Test Data From D-6F Base Course Material

SAMPNO	FTCYC	MR1	MR2	MR3	MR4	MR5	MRT	EMOD	STRESS	WI	WF	DRYDEN	SUCI	SUCF
1	1	112.0	.	.	.	.	.	122.00	383.0	15.16	15.61	112.38	1.6081	2.8642
2	3	93.2	45.8	45.2	.	.	.	345.00	321.0	16.51	14.00	109.95	2.6178	3.8302
3	1	58.5	.	.	.	.	.	234.00	336.0	13.85	14.71	117.74	2.1116	3.3694
4	3	44.7	200.0	352.0	.	.	4.46	262.00	341.0	13.99	12.35	116.92	4.3135	5.1592
5	5	.	.	.	.	47.4	21.30	337.00	399.0	13.75	12.50	116.78	4.1220	5.0213
6	5	.	.	.	.	97.7	2.95	245.00	356.0	16.55	14.52	110.00	2.2366	3.4870
7	1	64.8	.	.	.	.	.	160.00	438.0	17.28	16.63	108.85	1.1810	2.3825
8	3	100.0	79.9	453.0	.	.	.	562.00	266.0	17.61	15.48	109.29	1.6726	2.9322
9	5	45.4	54.6	206.0	36.8	272.0	33.40	122.00	242.0	18.11	10.94	107.90	6.6095	6.6546
10	3	39.0	364.0	83.5	.	.	23.30	22.10	27.3	5.07	3.81	114.89	57.1983	24.1052
11	5	.	.	.	.	288.0	33.90	22.00	21.5	5.27	4.95	116.24	40.5073	19.6216
12	1	379.0	.	.	.	.	.	.	.	8.15	6.53	119.46	25.1100	14.7524
13	3	66.9	416.0	188.0	.	.	56.50	94.50	126.0	8.01	6.96	119.01	22.0458	13.6506
14	1	56.9	.	.	.	.	.	436.00	331.0	17.08	16.17	113.18	1.3574	2.5888
15	5	.	.	.	.	88.6	111.00	38.40	112.0	7.97	6.82	118.75	23.0000	14.0000
16	1	292.0	.	.	.	.	.	.	.	7.96	7.87	119.67	16.7382	11.5827
17	1	411.0	.	.	.	.	.	271.00	464.0	9.38	10.75	121.55	7.0007	6.8568
18	5	.	.	.	.	360.0	57.30	331.00	447.0	9.66	9.92	121.44	9.0000	8.0000
19	1	89.0	.	.	.	.	.	327.00	431.0	12.01	11.81	122.04	5.0793	5.6874
20	3	51.0	161.0	137.0	.	.	46.00	94.30	383.0	10.84	8.03	123.03	15.9469	11.2529
21	1	122.0	.	.	.	.	.	146.00	231.0	8.68	8.22	118.27	15.0557	10.8735
22	3	51.4	537.0	149.0	.	.	78.70	204.00	254.0	8.68	8.22	118.27	15.0557	10.8735
23	5	83.8	169.0	195.0	169.0	138.0	116.00	164.00	214.0	9.55	8.17	119.55	15.2853	10.9721
24	1	156.0	.	.	.	.	.	445.00	444.0	10.93	10.87	123.32	6.7510	6.7392
25	3	72.8	396.0	117.0	.	.	50.10	382.00	393.0	10.91	10.53	122.26	7.4827	7.1658
26	3	68.2	77.2	58.8	.	.	5.91	301.00	306.0	14.30	13.29	116.70	3.2454	4.3540
27	5	41.8	41.9	1413.0	73.6	.	31.80	81.30	266.0	14.53	11.98	116.76	4.8246	5.5155
28	5	248.0	105.0	132.0	1336.0	.	125.00	.	.	9.95	4.55	120.32	45.7206	21.0909
29	1	66.8	.	.	.	.	.	305.00	450.0	10.71	10.60	124.17	7.3259	7.0738
30	1	308.0	.	.	.	.	.	129.00	506.0	14.84	9.39	117.69	10.5660	8.8032
31	3	85.8	69.7	140.0	.	.	2.96	302.00	327.0	14.02	12.37	117.76	4.2874	5.1406
32	3	57.7	58.6	296.0	.	.	19.80	33.70	55.8	6.80	5.88	112.92	30.5695	16.5891
33	5	109.0	71.4	112.0	133.0	92.5	73.50	6.64	22.8	6.53	4.50	115.80	46.4178	21.2821
34	1	136.0	.	.	.	.	.	75.80	70.4	6.58	6.54	113.26	25.0342	14.7258
35	3	115.0	219.0	332.0	.	.	22.10	38.00	50.7	6.77	5.69	113.16	32.3790	17.1680
36	3	104.0	276.0	173.0	.	.	25.60	217.00	245.0	9.58	8.70	116.08	13.0199	9.9710
37	5	133.0	116.0	626.0	308.0	68.6	59.80	160.00	246.0	9.77	8.84	116.60	12.4797	9.7221
38	1	89.5	.	.	.	.	.	685.00	394.0	10.62	11.37	119.69	5.8029	6.1576
39	5	82.8	48.4	204.0	67.6	196.0	145.00	146.00	361.0	11.77	9.98	120.53	8.8380	7.9138
40	1	74.1	.	.	.	.	.	451.00	389.0	11.42	11.70	120.31	5.2513	5.8015
41	3	82.3	139.0	72.2	.	.	38.40	410.00	464.0	11.68	10.30	119.34	8.0222	7.4696
42	1	129.0	.	.	.	.	.	24.00	32.1	4.72	4.79	112.11	42.5172	20.1966
43	1	50.6	.	.	.	.	.	30.90	29.4	4.67	4.53	113.43	45.9982	21.1672

TABLE 4-6. - (Continued)

SAMPNO	FTCYC	MR1	MR2	MR3	MR4	MR5	MRT	EMOD	STRESS	WI	WF	DRYDEN	SUCI	SUCF
44	3	69.3	73.1	41.0	.	.	20.6	1.00	3.23	3.62	3.34	112.35	65.942	26.2396
45	5	38.8	43.8	59.4	53.1	.	20.3	.	.	3.97	1.94	112.93	100.737	33.7845
46	5	213.0	64.9	91.7	89.2	76.6	62.5	1.85	2.62	4.31	1.64	116.36	110.312	35.6646
47	5	44.1	91.2	108.0	148.0	.	56.2	.	.	4.67	2.19	115.64	93.396	32.2936
48	5	71.0	36.5	130.0	388.0	.	66.5	.	.	15.90	13.82	114.99	2.764	3.9567
49	5	82.1	113.0	54.8	308.0	.	37.6	.	.	16.37	9.04	113.58	11.747	9.3774

N=49

APPENDIX V

REGRESSION ANALYSIS SUMMARY

TABLE 5-1. - Computer Variables Used in Appendix V

SAMPNO	=	sample number;
FTCYC	=	total number of freeze-thaw cycles sample experienced;
MR1	=	resilient modulus x 10^{-3} at first freeze period, psi;
MR2	=	resilient modulus x 10^{-3} at second freeze period, psi;
MR3	=	resilient modulus x 10^{-3} at third freeze period, psi;
MR4	=	resilient modulus x 10^{-3} at fourth freeze period, psi;
MR5	=	resilient modulus x 10^{-3} at fifth freeze period, psi;
MRT	=	resilient modulus x 10^{-3} at last thaw period, psi;
EMOD	=	Elastic modulus x 10^{3} of frozen material as measured in splitting tensile test, psi;
STRESS	=	ultimate stress of frozen material measured in splitting tensile test, psi;
WI	=	initial moisture content, %;
WF	=	final moisture content, %;
DRYDEN	=	dry density, lbs/ft^3;
SUCI	=	initial suction predicted from equations in TABLE 3, psi;
SUCF	=	final suction predicted from equations in TABLE 4, psi;
LFTCYC	=	log (FTCYC);
LSUCI	=	log (SUCI);
LDRYDEN	=	log (DRYDEN);
MRF	=	final resilient modulus; and
WF2	=	final moisture content squared.

TABLE 5-2. - Summary of Regression Models Considered for Predicting Elastic Modulus for the D-4 Material

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
1	log	DRYDEN	0.1412	-14.8775	.35	43
2	log	DRYDEN	0.1191	-11.8123	.58	43
		SUCI	-0.0256			
3	log	DRYDEN	0.1197	-13.7325	.61	43
		FTCYC	0.1150			
		WF	0.1273			
4	log	DRYDEN	0.1090	-12.4729	.62	43
		FTCYC	0.0983			
		WF	0.1245			
		MRF	0.0003			
5	log	DRYDEN	0.1081	-12.4158	.62	43
		FTCYC	0.0936			
		WF	0.1259			
		MRF	0.0003			
		MR1	0.0003			
6	log	DRYDEN	0.0926	81.5685	.74	43
		FTCYC	0.0790			
		WF	-9.7253			
		WF2	0.2865			
		SUCF	1.8011			
		SUCI	-3.4453			

TABLE 5-2. - (Continued)

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
7	log	DRYDEN FTCYC WF WF2 SUCF SUCI MR1	0.0904 0.0719 -9.6915 0.2853 1.8019 -3.4427 0.0004	81.5480	.75	43
8	log	DRYDEN FTCYC WF WF2 SUCF SUCI MR1 MRF	0.0891 0.0703 -9.5710 0.2818 1.7821 -3.4029 0.0003 0.00005	80.5822	.75	43
9	log	LDRYDEN	37.1113	-75.0666	.33	50
10	log	LDRYDEN LSUCI	31.7219 -0.9630	-62.8331	.57	50
11	log	LDRYDEN LSUCI LFTCYC	32.2945 -1.1359 0.4387	-64.0172	.60	50

TABLE 5-3. - Summary of Regression Models Considered for Predicting Elastic Modulus for the D-5 Material

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
1	log	SUCI	-0.0138	2.1995	.78	46
2	log	SUCI FTCYC	-0.0128 -0.0615	2.3211	.82	46
3	log	SUCI FTCYC DRYDEN	-0.0117 -0.0722 0.0274	-0.7255	.84	46
4	log	SUCI FTCYC DRYDEN WF2	-0.0094 -0.0759 0.0353 0.0009	-1.8148	.84	46
5	log	SUCI FTCYC DRYDEN WF2 MR1	-0.0097 -0.0720 0.0334 0.0009 0.00008	-1.6186	.84	46
6	log	SUCI FTCYC DRYDEN WF2 MR1 WF	-0.0120 -0.0716 0.0338 0.0023 -0.00009 -0.0447	-1.2843	.84	46

TABLE 5-3. - (Continued)

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
7	log	SUCI FTCYC DRYDEN WF2 MR1 WF MRF	-0.0120 -0.0716 0.0338 0.0023 0.00009 -0.0446 0.0000007	-1.2848	.84	46
8	log	LSUCI	-1.2981	3.5939	.62	51
9	log	LSUCI LDRYDEN	-1.2753 14.4163	-25.8714	.73	51
10	log	LSUCI LDRYDEN LFTCYC	-1.1952 15.2023 -0.3818	-27.4525	.78	51

TABLE 5-4.- Summary of Regression Models Considered for Predicting Elastic Modulus for the D-6AM Material

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
1	log	SUCI	-0.0271	3.1459	.86	41
2	log	SUCI DRYDEN	-0.0255 0.0339	-0.9450	.87	41
3	log	SUCI DRYDEN FTCYC	-0.0250 0.0362 -0.0311	-1.1523	.88	41
4	log	DRYDEN FTCYC WF2 SUCF	0.0434 -0.0262 0.0027 -0.0129	-2.5	.88	41
5	log	DRYDEN FTCYC SUCF SUCI WF	0.0468 -0.0232 -0.0722 0.1129 0.2080	-5.8823	.88	41
6	log	DRYDEN FTCYC SUCF SUCI WF WF2	0.0435 -0.0250 -0.2889 0.5984 2.1261 -0.0552	-24.5003	.88	41

TABLE 5-4. - (Continued)

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
7	log	DRYDEN	0.0429	-24.1625	.89	41
		FTCYC	-0.0264			
		SUCF	-0.2839			
		SUCI	0.5886			
		WF	2.1035			
		WF2	-0.0547			
		MRF	0.00005			
8	log	DRYDEN	0.0430	-24.4334	.89	41
		FTCYC	-0.0266			
		SUCF	-0.2869			
		SUCI	0.5953			
		WF	2.1303			
		WF2	-0.0555			
		MRF	0.00005			
		MR1	-0.00003			
9	log	LSUCI	-2.0592	5.1693	.78	45
10	log	LSUCI	-1.8840	-33.6892	.84	45
		LDRYDEN	18.6077			
11	log	LSUCI	-1.8447	-34.1781	.85	45
		LDRYDEN	18.8562			
		LFTCYC	-0.2285			

TABLE 5-5. - Summary of Regression Models Considered for Predicting Elastic Modulus for the D-6F Material

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
1	log	SUCI	-0.0258	2.5527	.84	35
2	log	DRYDEN SUCF	0.0299 -0.0748	-0.6133	.87	35
3	log	DRYDEN SUCF WF2	0.0210 -0.0897 -0.0018	0.7704	.88	35
4	log	SUCF SUCI WF FTCYC	-0.3278 0.0484 -0.2397 -0.0422	7.0842	.88	35
5	log	SUCF SUCI WF FTCYC MR1	-0.3640 0.0566 -0.2683 -0.0518 -0.0006	7.6742	.89	35
6	log	SUCF SUCI WF FTCYC MR1 MR2	-0.8334 0.1207 -1.4306 -0.0555 -0.0007 0.0321	19.2586	.89	35

TABLE 5-5. - (Continued)

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
7	log	SUCF SUCI WF FTCYC MR1 WF2 DRYDEN	-0.7694 0.1088 -1.3491 -0.0485 -0.0006 0.0310 0.0075	17.2334	.89	35
8	log	SUCF SUCI WF FTCYC MR1 WF2 DRYDEN MRF	-0.7797 0.1113 -1.3706 -0.0538 -0.0008 0.0317 0.0099 0.0003	17.1411	.89	35
10	log	LSUCI	-0.9898	3.0433	.62	41
11	log	LSUCI LDRYDEN	-1.0356 14.2497	-26.3569	.75	41
12	log	LSUCI LDRYDEN LFTCYC	-1.0278 14.1341 -0.01072	-26.1072	.75	41

TABLE 5-6. - Summary of Regression Models Considered for Predicting Tensile Strength for the D-4 Material

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
1	log	SUCI	-0.0533	2.8363	.66	43
2	log	SUCI DRYDEN	-0.0485 0.1108	-10.2120	.80	43
3	log	SUCI DRYDEN SUCF	-0.1104 0.1057 0.0542	-9.3370	.81	43
4	log	SUCI DRYDEN SUCF WF	-0.5568 0.0906 0.3474 -0.4394	-0.5160	.84	43
5	log	SUCI DRYDEN SUCF WF WF2	-2.2800 0.0896 1.1888 -6.1848 0.1795	50.3872	.85	43
6	log	SCUI DRYDEN SUCF WF WF2 MR1	-2.2729 0.0887 1.1860 -6.1541 0.1786 0.0002	50.2006	.85	43

TABLE 5-6. - (Continued)

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
7	log	SUCI DRYDEN SUCF WF WF2 MR1 MRF	-2.1904 0.0863 1.1445 -5.9075 0.1715 0.0002 0.00009	48.1691	.85	43
8	log	SUCI DRYDEN SUCF WF WF2 MR1 MRF FTCYC	-2.1884 0.0865 1.1433 -5.9042 0.1715 0.0001 0.00009 0.0026	48.0977	.85	43
9	log	LSUCI	-1.9359	4.0592	.64	50
10	log	LSUCI LDRYDEN	-1.7810 29.8363	-57.8006	.78	50
11	log	LSUCI LDRYDEN LFTCYC	-1.8577 30.0905 0.1947	-58.3262	.78	50

TABLE 5-7. - Summary of Regression Models Considered for Predicting Tensile Strength for the D-5 Material

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
1	log	SUCI	-0.0130	2.7507	.82	47
2	log	SUCI DRYDEN	-0.0114 0.0487	-2.694	.91	47
3	log	SUCI DRYDEN FTCYC	-0.0120 0.0455 0.0265	-2.3868	.92	47
4	log	SUCI DRYDEN FTCYC WF2	-0.0141 0.0377 0.0299 -0.0009	-1.3098	.92	47
5	log	SUCI DRYDEN FTCYC WF2 MR1	-0.0142 0.0364 0.0328 -0.0010 0.00006	-1.1670	.92	47
6	log	SUCI DRYDEN FTCYC WF2 MR1 MRF	-0.0144 0.0361 0.0358 -0.0010 0.0003 -0.0002	-1.1183	.92	47

TABLE 5-7. - (Continued)

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
7	log	SUCI DRYDEN FTCYC WF2 MR1 MRF WF	-0.0135 0.0358 0.0355 -0.0021 0.0003 -0.0002 0.0350	-1.3791	.92	47
8	log	LSUCI	-1.1341	3.9149	.59	52
9	log	LSUCI LDRYDEN	-1.1017 19.3562	-35.6493	.84	52
10	log	LSUCI LDRYDEN LFTCYC	-1.1229 19.1656 0.0949	-35.2645	.85	52

TABLE 5-8. - Summary of Regression Models Considered for Predicting Tensile Strength for the D-6AM Material

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
1	log	SUCF	-0.0159	2.8235	.90	41
2	log	SUCF DRYDEN	-0.0148 0.0337	-1.2316	.91	41
3	log	SUCF DRYDEN FTCYC	-0.0150 0.0323 0.0187	-1.1074	.92	41
4	log	SUCF DRYDEN FTCYC MR1	-0.0150 0.0346 0.0181 -0.0004	1.3363	.92	41
5	log	SUCF DRYDEN FTCYC MR1 WF2	-0.0146 0.0356 0.0189 -0.0004 0.0003	-1.4917	.92	41
6	log	SUCF DRYDEN FTCYC MR1 WF2 MRF	-0.0146 0.0356 0.0184 -0.0004 0.0003 0.00002	-1.4946	.92	41

TABLE 5-8. - (Continued)

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
7	log	SUCF DRYDEN FTCYC MR1 WF2 SUCI WF	-0.1056 0.0348 0.0184 -0.0004 -0.0217 0.2020 0.7738	-9.1551	.91	41
8	log	SUCF DRYDEN FTCYC MR1 WF2 SUCI WF MRF	-0.1069 0.0348 0.0178 -0.0005 -0.0223 0.2053 0.7924 0.00002	-9.3097	.92	41
9	log	LSUCI	-1.6905	4.6046	.74	45
10	log	LSUCI LDRYDEN	-1.5123 18.9259	-34.9183	.82	45
11	log	LSUCI LDRYDEN LFTCYC	-1.5150 18.9089 0.0156	-34.8848	.82	45

TABLE 5-9. - Summary of Regression Models Considered for Predicting Tensile Strength for the D-6F Material

Model Number (1)	Dependent Variable Transformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
1	log	SUCI	-0.0243	2.6721	.91	35
2	log	SUCI DRYDEN	-0.0235 0.0262	-0.3969	.94	35
3	log	DRYDEN SUCF WF	0.0227 -0.0980 -0.0595	1.1938	.95	35
4	log	DRYDEN SUCF WF MR1	0.0211 -0.0989 -0.0608 0.0004	1.3522	.96	35
5	log	DRYDEN SUCF WF SUCI WF2	0.0196 -1.0243 -2.2968 0.1289 0.0611	24.0269	.96	35
6	log	DRYDEN SUCF WF SUCI WF2 MR1	0.0196 -0.9725 -2.1896 0.1208 0.0584 0.0003	22.8631	.97	35

TABLE 5-9. - (Continued)

Model Number (1)	Dependent Variable Tranformation (2)	Independent Variables in Model (3)	Regression Coefficients (4)	Intercept (5)	R^2 (6)	Total Degrees of Freedom (7)
7	log	DRYDEN SUCF WF SUCI WF2 MR1 FTCYC	0.0182 -1.0101 -2.2559 0.1272 0.0598 0.0002 -0.0087	23.8114	.97	35
8	log	DRYDEN SUCF WF SUCI WF2 MR1 FTCYC MRF	0.0181 -1.0098 -2.2552 0.1271 0.0598 0.0002 -0.0085 -0.00001	23.8145	.97	35
9	log	LSUCI	-0.9206	3.1335	.64	41
10	log	LSUCI LDRYDEN	-0.9670 14.4389	-26.6569	.80	41
11	log	LSUCI	-0.9721	-26.8192	.80	41