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A STUDY OF THE SOIL STABILIZING PROPERTIES OF TUNG OIL

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A STUDY OF THE SOIL STABILIZING PROPERTIES OF TUNG OIL

SUMMARY

This report describes the results obtained from a laboratory investigation of the soil stabilizing properties of tung oil, a study undertaken during the war period to determine the suitability of local materials, available in the combat areas, for use in the construction of airfields and roads.

In order to evaluate the effectiveness of the tung oil throughout a wide range of soil types, eight soils were employed representing textural differences from sand to silty clay. Samples of each soil, treated with 0.5 to 5.0 percent of admixture (based on the dry weight of the soil) were subjected to four types of laboratory exposure tests; namely, capillary absorption, immersion, alternate wetting and drying, and alternate freezing and thawing. The compressive strength and the amount of moisture absorption at the end of such tests were used to indicate the relative effectiveness of each treatment.

Additional tests were conducted to determine: (a) the effect of different curing and molding methods on the stability of the treated soil samples; (b) the effectiveness of various chemical admixtures in improving the stability of the tung oil-soil systems and; (c) the comparison of the stabilizing effectiveness of tung oil with that of other admixtures.

The primary conclusions from this investigation may be summarized as follows:

1. The addition of tung oil improved the stability of all soils but the effectiveness varied considerably with the type of soil treated. Clay soils were improved but slightly.

2. To obtain maximum benefits from the tung oil it was necessary to air dry the treated samples to a moisture content unlikely to be attained in average field construction.

3. Up to a treatment of five percent, the maximum amount used for these studies, the stabilizing effectiveness of tung oil increased with the percentage employed.

4. Various chemicals, when added to the soil-tung oil mixture, improved the stability of air dried samples. The most effective were potassium sulfate, zinc stearate, calcium stearate, and stearic acid.

5. Under air dried conditions, tung oil compared favorably with other type admixtures when used in comparable quantities.

INTRODUCTION

The study of tung oil as a possible soil stabilizing agent was undertaken as part of a war time project conducted by the Airport Development Division, Technical Development, of the Civil Aeronautics Administration for the purpose of developing materials and methods for improving the engineering properties of natural soils as used in the construction of roads and airfields. Emphasis was placed on the utilization of materials available in particular combat areas and/or those showing effectiveness when used in relatively small quantities. Due to the reported availability of tung oil in the China area and to the various references in the literature to the possible soil stabilizing properties of this material it was decided to include it in our investigations.

Preliminary testing, described in a previous report,[1] indicated that both the strength and waterproofing characteristics of a fine sandy loam soil were greatly improved by the addition of tung oil, the effectiveness of treatment being proportional to the quantity of admixture employed, up to an optimum treatment of between five and ten percent, based on the dry weight of the soil. The conclusions drawn from these tests, however, were limited by the fact that only one soil type was used and that the treated samples were subjected to but one form of laboratory exposure - water absorption - prior to testing for strength.

The present study was undertaken to evaluate more fully the soil stabilizing properties of tung oil by studying its effectiveness throughout a wide range of soil types when subjected to several forms of laboratory exposure tests, including alternate wetting and drying, and alternate freezing and thawing. In addition, it was recognized that before proper evaluation tests could be made it would be necessary to study certain characteristics of the soil-tung oil-water mixtures, especially regarding methods of curing and molding. In order to determine the effectiveness of the admixture when used in small quantities an arbitrary maximum limit of five percent treatment was selected for study with emphasis placed on lower percentages.

All of the testing described in this report was conducted in the soils laboratories of the Airport Development Division of Technical Development. Valuable suggestions for the conduct of this work were received from Dr. H. F. Winterkorn of Princeton University, W. L. Lawton of the Airport Development Division and G. W. McAlpin formerly of the Airport Development Division.

It was realized during this investigation that the use of tung oil as a soil stabilization agent would be limited, in general, to areas in which the material might be readily available and that its peacetime use in this country would be restricted by economic considerations for some time to come. The results of the study are published at the present time in order to record the results of the work in this field and to present data and test methods that may be beneficial to other soil stabilization studies.

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[1]Mainfort, R. C. "A Laboratory Study of the Effectiveness of Various Chemicals as Soil Stabilizing Agents," CAA Technical Development Note No. 40, October, 1945.

DESCRIPTION OF MATERIALS

Soils

Eight different soil types were used in this investigation ranging in texture from sand to silty clay and representing locations in four different states. The characteristics of the soils and their grain size analysis are shown in Table I and Figure 1 respectively. Only the soil fractions passing the number 10 sieve were used throughout these tests. The soils are designated by letter in descending order of their maximum density, the symbols having no reference to the soils used in our other reports.

Tung Oil

Tung oil, sometimes referred to as China wood oil, is a drying oil consisting essentially of the glyceride of eleomargeric acid, an unsaturated fatty acid of the linolic series represented by the general formula $C_{18}H_{32}O_2$. When exposed to the air, tung oil absorbs oxygen forming a hard resinous material with a slight increase in weight. The specific gravity of tung oil is 0.940 to 0.943.

For this study two different supplies of tung oil were used. One supply was several years old and had been stored in the laboratory during that time. This sample was clear and quite free from cloudiness unless disturbed. In cases where cloudiness did appear the material was filtered, by gravity, through a number 4 Whatman filter paper and the filtrate used for the tests. The second supply of tung oil was obtained from a commercial source, just prior to using, and was sold as meeting A.S.T.M. requirements. Comparative tests, however, showed that there was no appreciable difference in the effectiveness of either type oil as long as it was clear.

Chemical Agents

All of the chemicals used as admixtures with the tung oil were of C.P. grade as obtained from commercial supply houses. Distilled water was used for all tests involving the chemical admixtures. Comparative tests, however, showed no significant difference between samples molded with laboratory tap water and those molded with distilled water.

PREPARATION OF SAMPLES AND TESTING PROCEDURES

The basic testing procedures used in the investigation were similar to those followed in our previous work with resin treated soil samples.[1]

[1]Winterkorn, Hans F. and McAlpin, George W. "Soil Stabilization By the Use of Rosin" CAA Technical Development Note No. 34, February, 1946, McAlpin, George W., Mainfort, Robert C., Winterkorn, Hans F. "A Laboratory Study of the Soil Stabilizing Effectiveness of a Complex Salt of Abietic Acid" CAA Technical Development Note No. 35, July, 1934; Winterkorn, Hans F. "A Laboratory Study of the Soil Stabilizing Effectiveness of Artificial Resins with Special Emphasis on the Aniline-Furfural Resins" CAA Technical Development Note No. 43, January, 1947.

Since no established testing procedure fulfills the requirements for evaluating all chemical admixtures it was necessary to modify some of these and to adopt new procedures as the test work progressed. This was particularly true regarding the preparation and curing of samples prior to weathering tests.

Preparation of Test Specimens

All quantities of soil used in the preparation of test specimens were representative of material passing the number 10 sieve. The optimum moisture and maximum density were determined by the standard Proctor method (A.S.T.M. designation D698-42T) for both the natural soils and those treated with various percentages of tung oil. For the tung oil treated samples, the required amount of admixture was thoroughly mixed with the air dried soil prior to the incremental additions of water. The results of the Proctor determinations are shown in Figure 2. Table II shows the comparative quantities required to mold a single sample of each soil type as computed from the Proctor curves for untreated soil, and from similar curves for soils treated with two and five percent tung oil. An analysis of these data indicates that the optimum values for the treated soils are practically equal to those obtained by considering the tung oil as part of the mix water and molding to untreated soil conditions; that is, the increase in dry density obtained for the treated samples is equal to the weight of the added tung oil. Since the bulk of the work performed in this study was concerned with treatments of two percent or less, it was decided to mold all samples to untreated soil conditions and to consider the tung oil as part of the mix water. In this way all samples of the same soil type were molded to constant weight but the dry weight varied with the percent admixture contained in each sample.

The treated soil was prepared for molding by mixing a proportioned weight of soil, water, and tung oil. Tests indicated that the order of mixing these materials had no appreciable effect on the resulting stability of the samples. In order to more nearly simulate field conditions all batches were mixed by first adding the required water to the soil and then adding the tung oil. Where additional chemicals were used the water soluble chemicals were added with the mix water, in solution, while the water insoluble chemicals were mixed with the dry soil prior to the addition of water. All mixing was accomplished by the use of a paddle-type dough mixer, and a thorough dispersion of the admixtures was obtained in a two minute mixing period.

At the end of the mixing period the quantity of material required to mold a sample was weighed and placed in the compaction mold. All samples were molded into cylinders two-inch high by two-inch in diameter. The compaction device employed was a modification of that used by the Portland Cement Association for compacting similar size samples of soil-cement.[1]

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[1]"Soil Cement Mixtures" - Laboratory Handbook, Portland Cement Association.

This apparatus permits the dynamic compaction of the sample from both top and bottom by the use of a double piston method. Compaction in this manner permitted a very close control of the molded weights of each sample, and an accuracy of within plus or minus 0.2 grams was usually attained.

Tests were performed to determine whether the tung oil would tend to set up immediately after mixing. The results showed that the stability of samples molded within a period of eight hours after mixing were the same as for those molded immediately after mixing. The samples were maintained in a moist condition throughout this test.

Curing of Test Specimens

In the study of soils treated with chemical admixtures it has been found from our previous studies that the amount and type of curing of the treated sample, prior to its subjection to the exposure tests are critical.[1] Different admixtures react to curing in different manners. Depending upon the type of material being tested it is customary to cure the sample either by moist curing, air drying to constant weight, oven drying to constant weight at temperatures not exceeding 140 degrees F., or by various partial drying of the sample. In order to determine the characteristics of the tung oil treated samples in this respect tests were conducted to determine the optimum curing conditions. For this investigation samples treated with two percent tung oil were tested at moisture contents ranging from molding moisture to oven dried conditions. All samples were moist cured for twenty-four hours, dried to the required moisture content in air or oven, and moist cured for another twenty-four hour period to balance the moisture throughout the specimens. The samples were then subjected to seven days capillary absorption at the end of which the compressive strength was determined. Figure 3 shows the result of this test for the different soil types, and clearly indicates the beneficial effect of air drying the samples. The maximum stability was reached at approximately the hygroscopic or air dried moisture for each soil type. Further drying at a temperature of 140 degrees F. was detrimental to all soils tested.

The results of similar tests performed to determine the effect of various periods of moist curing of the samples prior to exposure is shown in Figure 4. These tests indicate that the stability of samples is greatly improved by moist curing.

As a result of these tests it was decided to use both air dried and moist cured samples for this study.

[1]McAlpin, George W., Mainfort, Robert C., Winterkorn, Hans F., "A Laboratory Study of the Soil Stabilizing Effectiveness of a Complex Salt of Abietic Acid" CAA Technical Development Note No. 35, July, 1934; Mainfort, R. C., "A Laboratory Study of the Effectiveness of Various Chemicals as Soil Stabilizing Agents" CAA Technical Development Note No. 40, October, 1945.

Laboratory Exposure Tests

In order to evaluate the relative effectiveness of the various percentages of admixture and chemicals employed, treated soil samples were subjected to four laboratory exposure tests during which the moisture absorption was periodically determined. At the end of each exposure test the samples were broken in unconfined compression on a Southwark-Emery testing machine at a constant rate of loading of five hundred pounds per minute. Except when modified for special or exploratory investigations the laboratory exposure tests were conducted at the end of the curing period as follows:

Capillary Absorption. The samples were placed on blotting paper resting on a moist sand pad with a constant water level maintained just touching the bottom of the samples, the whole being enclosed in a moist cabinet. Seven days of such exposure constituted the test.

Immersion. The samples were subjected to seven days total immersion in water.

Alternate Wetting and Drying. The samples were subjected to eight hours of total immersion followed by eighteen hours of oven drying at a temperature of 140 degrees F. The samples were broken at the end of the seventh wetting cycle of the test.

Alternate Freezing and Thawing. All air dried samples were subjected to three days capillary absorption prior to beginning the freezing and thawing cycles. The moist cured samples were not subjected to preliminary soaking. One cycle consisted of eight hours of freezing at a temperature of -10 degrees F. followed by 18 hours of capillary absorption. The samples were broken after the seventh capillary absorption cycle. Tests showed that the samples were thoroughly frozen in less than four hours at the -10 degrees F. temperature.

TEST RESULTS

All of the tests were performed according to the methods discussed, which may be summarized briefly as follows:

1. All test specimens were molded to densities obtained for the untreated soil but using the required tung oil as part of the mixing moisture.

2. Samples were either air dried for seven days in laboratory air or moist cured for seven days prior to beginning the exposure tests.

3. Four general exposure tests were employed and the moisture content determined periodically during the test. The unconfined compressive strength was obtained after the last wet cycle of the exposure test.

In order to more clearly present the test results, the evaluation data have been divided into four groups; untreated samples, treated samples not exposed to laboratory weathering, air dried samples, and moist cured samples.

Untreated Samples.

In order to properly evaluate the tung oil treatment it was necessary to study the characteristics of the untreated raw soil samples under the same exposure test condition as applied to the treated samples. For this study, however, very little test data can be shown since none of the untreated soil samples, regardless of the method of curing, were able to withstand even the preliminary stages of the exposure tests. All samples failed completely within a matter of minutes when subjected to immersion thus eliminating the possibility of further exposure by the immersion or the wetting and drying tests. The capillary absorption test was less severe and, with the exception of air dried samples of soil H, all specimens were still intact after seven days capillary absorption. However, the rate of water intake was very high and the samples became soft even after a short exposure. The periodic absorption rate during the first twenty-four hours of the test for both air dried and moist cured samples of each soil type are shown in Figure 5. From the capillary test it was found that only soils C, D, and E were in a condition to warrant further exposure. Specimens of these soils, however, succumbed rapidly to the freezing and thawing test and were unable to withstand more than two or three cycles of such exposure.

Treated Samples Not Exposed to Laboratory Weathering

This test was conducted to determine the effect of various percentages of tung oil on the strength of samples before they were subjected to exposure, that is, when they were in their most stable condition. The results are shown in Figure 6 for both moist cured and air dried samples treated through a range of from zero to five percent tung oil. These data show that the compressive strength of all soils increased with the percentage of admixture employed and all treated samples were better than untreated soil.

Evaluation Tests for Air Dried Samples

After a preliminary investigation to determine the range of the quantities of tung oil to be used in the evaluation tests it was decided that three percentages of admixture, 0.5, 1.0, and 2.0 percent based on the dry weight of the soil, would yield significant results. Although treatments as low as 0.2 percent showed good results with soils B, C, and F this percentage of treatment was not effective with the other soils.

The results of these evaluation tests, using the eight different soil types, are shown in Figures 7 through 14. Each Figure shows the complete data for all four exposure tests as applied to one soil and indicate the periodic moisture content of the samples from the start to finish of the exposure tests and the final breaking load in pounds per square inch. The values for the untreated samples are indicated either as "failed" when they were unable to complete their exposure cycles or by a very small breaking load, indicating that the sample survived the exposure tests although, as previously discussed, such samples were in very poor condition. The moisture absorption for the untreated samples can best be studied from Figure 6 since in many cases the values were too high to show on the graphs used to plot data for the treated samples.

From these data it can be seen that tung oil improved the resistance of all soils to laboratory exposure to a degree proportional to the amount of admixture employed. For all soils the capillary absorption was the least severe test, with the destructive forces of the other tests varying with the soil type. The detrimental influence of the wetting and drying was increased by the fact that the required oven drying at 140 degrees F. has been shown to effect adversly the treated samples as compared to air drying.

Evaluation Tests for Moist Cured Samples

From preliminary investigations it was soon obvious that the moist cured samples were far inferior to the air dried. All treatments below two percent yielded very poor results so the maximum percentage used was increased to five. Four soils, A, B, D, and F, representative of entire group, were selected for study at treatments of two and five percent. Soil H was not considered since it did not appear suitable for treatment either air dried or moist cured.

The results of the moist cured tests are presented in Figures 15 through 18 in the same manner as were the air dried samples. These data clearly indicate the relatively poor stability obtained when the samples are tested without being allowed to dry prior to exposure, even with treatments as high as five percent. This fact is further brought out by a study of Figure 19 which shows a comparison of the air dried and moist cured samples for all the soils, treated with two percent tung oil and subjected to capillary absorption prior to breaking.

With moist cured samples, as well as with air dried, the capillary absorption was the least severe of the exposure tests, although, due to the drying cycle, good results were obtained for some soils with the wetting and drying test. In this case the improvement obtained from the drying more than compensated for the detrimental effects of oven drying. The first moist cycle of the test, however, was conducted on the undried samples. No preliminary absorption was given the moist cured samples prior to the freezing and thawing test.

ADDITIONAL LABORATORY TESTS

In addition to the evaluation tests described, supplemental investigations were conducted to study more fully the properties of tung oil treated samples, and to attempt the improvement of the stabilizing characteristics of such combinations by the addition of chemical admixtures. These additional tests will be discussed separately.

Stability of Soils as a Function of the Percent Treatment

Soils C, D, F, G, and H were treated with increasing amounts of tung oil up to a quantity of five percent. The samples were air dried, subjected to 24 hours immersion, and the compressive strength determined. As shown in Figure 20 the stability of all soils increased with the percentage of admixture employed. The data are presented as a function of the compressive strength obtained for the one percent treatment, and show that the rate of strength increase varies for the different soils, being higher for the more plastic types D and H, soils which were relatively unimproved by the lower percentages of treatment.

Sixty Day Immersion Test

Four of the soils - B, C, F and G - treated with two percent tung oil were subjected to sixty days total immersion. Both moist cured and air dried samples were used in the test. At the end of this period of soaking the samples were in good condition and there was no sign of leaching of the admixture from the soil. The compressive strengths were only slightly lower than those obtained for seven day immersion, indicating that continuing the immersion test beyond this period does not further weaken the samples to an appreciable degree.

Treatment of Clay Soils

In addition to the eight soil types reported for the evaluation tests exploratory studies were conducted on additional soils classified as clays. They were subjected to the capillary absorption and the immersion tests. All results indicated that the clay type soils could not be effectively treated with tung oil.

Comparison of Dynamic and Static Methods of Molding

In order to determine the effectiveness of different molding procedures as reflected by the resulting stability of the samples comparison was made between the dynamic method of molding described in this report and a static load method.

For the static determination the same mold and methods were employed as for the dynamic procedure with the exception that the load was applied slowly by the head of a Southwark-Emery testing machine at a rate of five hundred pounds per minute, rather than by the falling weight method used for the dynamic molding.

Seven different soils treated with two percent tung oil, were molded by each method, air dried, and subjected to the exposure tests. Although uniform samples were obtained by both methods of compaction slightly higher strengths were obtained in all cases for soils molded by the dynamic method. With both methods of compaction, however, the samples were not entirely uniform in density, there being a tendency to lower densities at the center of the specimens. This was more particularly noticeable in the silty clay soils D and E.

Stability of Re-Dried Samples After Exposure

This test was performed to determine how much of the dry strength of the treated soil could be regained by the samples after undergoing the detrimental effects of the laboratory exposure tests. Four soils, B, D, F, and G, treated with one percent tung oil were oven dried to constant weight at a temperature of 140 degrees F. The samples were then subjected to the usual four laboratory exposure tests. At the end of the tests two samples of each soil for each exposure test were broken in compression. Two other corresponding samples were again oven dried to constant weight after which they too were broken in compression. Figure 21 shows the result of this test for the four soils. The compressive strength at the end of exposure and after exposure and re-drying are shown expressed as a percentage of the original oven dried strength of the sample. It should be mentioned in this connection that the oven dried samples broken before exposure were considerably stronger than similar air dried samples. Only when subjected to exposure did the air dried samples prove to be stronger.

Comparison of Tung Oil with Other Stabilizing Agents

Tests were conducted to compare the soil stabilizing effectiveness of a fixed percentage of tung oil with other admixtures previously studied. All of the testing was performed as described with the exception that the capillary and the immersion tests were combined into one moisture absorption test consisting of three days capillary plus four days immersion. Two percent tung oil treated samples were compared to those treated with equal or optimum percentages of other admixture all portioned on a dry weight of soil basis. For some of the cement treated samples an arbitrary treatment of six percent was used. The aniline-furfural consisted of a 2 1 ratio of these chemicals mixed as described in a previous report.[1]

All samples were air dried prior to exposure with the cement and stabinol (which consists of about 80 percent cement) being moist cured for seven days prior to the drying. Six representative soil types were used in this comparison the results of which are shown in Figure 22.

The Effectiveness of Chemical Admixtures as Added to the Tung Oil Treated Soil

In an effort to improve the stabilizing effectiveness of the tung oil treatment various chemicals were added to the soil-tung oil-water mixture. A search of the literature indicated several materials that might improve the hardening rate of tung oil, and further, it was decided to study the effectiveness of various metallic salts that had proven effective in improving other resinous materials. In addition, purely exploratory tests were conducted.

[1]Winterkorn, Hans F., "A Laboratory Study of the Soil Stabilizing Effectiveness of Artificial Resins with Special Emphasis on the Aniline-Furfural Resins," CAA Technical Development Note No. 43, January, 1947.

Two percent tung oil treatment was used in the investigation plus the experimental chemical admixtures which were added to quantities of 20 percent based on the weight of the tung oil. If the chemicals were water soluble they were added to the soil in solution with the required mix water, if insoluble, the dry chemical was thoroughly mixed with the dry soil prior to the addition of tung oil and water.

Since many of the exploratory tests were conducted on samples subjected to exposure tests which varied from standard, it was decided to express all compressive strengths for treated samples as a percentage of that obtained for the control samples consisting of two percent tung oil treatment with no additional admixture. Control samples were included with each different test in order to offset the intentional or accidental variables introduced by the different curing and testing procedures.

Several chemicals were found to improve the air dried strengths of the samples but none were effective to an appreciable extent in benefiting the moist cured samples.

Table III shows the summary results of the first tests conducted with various chemical admixtures. All samples were air dried and broken after different degrees of exposure. The breaking load is expressed as a percent of that for the control sample. The most promising of the chemicals were selected for more thorough study by use of the absorption, wetting and drying, and freezing and thawing tests. These results are presented in Table IV.

From these tests several chemicals appear to be definitely beneficial. The effectiveness of any one chemical varied with the type soil used but in general potassium sulfate, calcium stearate, and zinc stearate were outstanding. Other very effective chemicals were stearic acid, potassium bisulfate, magnesium stearate and aluminum stearate. The stearates were particularly beneficial in the wetting and drying test.

Of these chemicals the sulfates were water soluble while the stearates were not. Additional study indicated that the 20 percent treatment was about optimum in effectiveness for the sulfates but that the effectiveness of the stearates increased with the percentage used up to 100 percent based on the weight of the tung oil.

Additional studies were made with other admixtures including cement, lime, synthetic resin "321" and a commercial powdered urea-formaldehyde resin. The cement and tung oil were mutually incompatible, a small amount of cement reducing the effectiveness of tung oil, while the addition of tung oil greatly reduced the strength of a normal soil-cement mix. Lime, when used in greater percentages than the tung oil improved the absorption strength of air dried and moist cured samples, but such samples failed rapidly when subjected to the wetting and drying and the freezing and thawing tests. The synthetic resins added in quantities of 20 percent of the tung oil were beneficial to most soils treated especially to soils B, D, E, and G.

Several solvents, including benzene, carbon bisulfide, chloroform, and alcohol, were mixed with the tung oil in an effort to improve its dispersion throughout the soil mass. None of these solvents were effective, all samples so treated being weaker than those treated with tung oil alone.

DISCUSSION

As has been found in other attempts to evaluate the properties of soil stabilizing materials the soil itself is one of the more significant variables encountered. No chemical analysis, other than pH determination, was made of the soils used in this study and neither these values nor the physical characteristics revealed trends from which definite conclusions could be drawn relative to the varying susceptibility of the soils to treatment.

The evaluation test data and that summarized in Figure 21 show the absolute values obtained when the different soils were treated with the admixture. However, since the untreated soil itself varied in stability these data do not give a complete picture of the relative susceptibility of the soils to treatment, so that other methods of comparison were selected.

Figure 23 shows the compressive strength of the weathered samples of treated soil expressed as a percentage of the compressive strength of the corresponding untreated, unweathered soil samples. In this manner a comparison is obtained between the treated soil samples in its most unstable condition - after exposure - to the raw soil in its best natural condition - air dried. The data presents an index of the percent effectiveness of the tung oil with each soil after each exposure test. As indicated by the average value of all four exposure tests the relative susceptibility of the soils to treatment by this method can be expressed as follows C, B, F, D, G, A, E, H. Two percent treatment and air dried samples were used in this test.

Another method for evaluating the effectiveness of tung oil with the different soils is shown in Figure 24. In this presentation the stability of the treated samples after exposure is expressed as a percentage of the corresponding treated soil in an air dried condition prior to exposure. Two percent treatment and air dried samples were used for this test also. These data particularly indicate the relative amount of stability retained by the treated soils after exposure as compared to their maximum stability when dry. The average of the four tests give a comparative rating to the soils of B, C, F, G, D, A, E, H.

From the above ratings it can be seen that the well graded sandy loam and loam soils, C and B, were the most easily stabilized, with the silty clay types least improved. This is consistent with findings in other stabilization studies. Soils F and G, predominantly silts, gave surprisingly good results especially in the tests involving capillary absorption. Soil A, consisting of 83 percent sand, yielded low strength values in unconfined compression as would be expected from the uncohesive nature of such a soil. Also, this type of soil is extremely susceptible to moisture absorption. The fact that soil A resisted the exposure tests at all indicates the effectiveness of the tung oil admixture.

For all of the tests described in this report, other than those of a purely exploratory nature, three different test runs were made for each condition of test and the results averaged. In general, good duplication of results was obtained for the different tests but exceptions were noted in the case of soils D, E, and G particularly in the wetting and drying tests. Samples of these soils tended to split through the center during the immersion cycles of this test and consequently allowed greater moisture absorption. The split sections, however, remained individually firm and stable. It is believed that this was due to the presence of entrapped air in the center of the silt and silty clay samples, a condition that might be improved by the use of a split mold rather than the solid one employed. Soils D, E and F, containing the highest percentage of clay for the group, were particularly noticeable for their variation of density throughout the samples, the top and bottom being more dense than the center. This condition could not be corrected with the various types of compaction employed. However, the addition of the more successful chemicals potassium sulfate and the stearates as described, appeared to correct this condition and all tests conducted with these treatments gave uniformly high results. Since these chemicals improved the wetting and drying characteristics of the silty clay soils to a much greater amount than the other soils and the other type exposure tests it is reasonable to suppose that most of the benefit obtained with some of the chemicals resulted from improved compaction characteristics of the tung oil treated samples rather than from chemical reaction alone, even when a reduction in swelling characteristics may have resulted.

Although the capillary absorption test was the least severe of the exposure tests, and gave good indication of the relative effectiveness of the treatments, it is believed that the more severe test such as the immersion gives a better indication of the value of the treatment. The tung oil imparted excellent resistance to capillary moisture in the soil samples but the immersion test indicated that this might be a retarding action rather than actual waterproofing. The wide difference between final moisture content in the capillary and immersion tests was particularly evident for the air dried samples.

The wetting and drying test, employing the detrimental oven drying, affected the soils to a similar degree except for occasional splitting of the samples as discussed. The moisture absorption, which reflects the compressive strength, followed the same pattern for each soil. The eight hour immersion cycle, although not severe in itself, when combined with the drying cycle broke down the initial resistance of the sample to absorption and after two or three cycles the soils reached varying degrees of saturation and maintained a constant moisture content after each subsequent cycle. There was very little loss of soil due to surface scaling during this test, and indications were that further cycles, within a reasonable number, would not materially reduce the stability of the samples.

On the other hand, there was a progressive increase in moisture absorption after each cycle of the freezing and thawing test indicating that additional cycles would cause continuing deteriation of the samples. Sand A was an exception, this soil rapidly absorbing moisture to saturation after which there was no increase during the test. Although the air dried samples were subjected to three days capillary absorption prior to test they were still relatively dry due to the resistance of the treated samples to capillary absorption. An immersion exposure prior to testing would undoubtedly provide a more severe test but even as conducted the destructive nature of the freezing and thawing cycles is clearly indicated.

Regarding exposure tests in general, Winterkorn[1] has found in testing soil-cement samples that the destructive forces of laboratory weathering were approximately four times as severe on the two inch by two inch samples as on those molded to the standard Proctor size as commonly employed.

A study of the evaluation test data indicates that, within the range of treatments studied, there was no intermediate optimum amount of treatment. All strengths and moisture absorption curves for all soils and all tests show that the beneficial effects of the tung oil were in proportion to the quantity employed. This is further indicated in a study of the treated dry samples where all compressive strengths, compared to those for untreated soil, showed an increase with the quantity of tung oil added.

One of the more significant facts shown by this study is that, unless allowed to dry a considerable amount before exposure, the tung oil treated samples yield relatively poor results, a condition holding true for the majority of resinous materials. Although moist cured samples treated with five percent admixture show resistance to laboratory weathering they do not in general compare favorably with much smaller percentages of treatment when the samples are air dried. The actual conditions obtained in the field would be difficult to predict depending as they do upon such variables as climate, soil type, drainage conditions, and other factors. An average condition would probably lie between the two extremes employed in this report. Therefore, although for comparative studies emphasis has been placed on the air dried samples their poorer performance when in a moist condition prior to exposure, should be born in mind.

In comparison with some other admixtures the tung oil showed well although it did not compare favorably to the higher percentages of cement, nor, in general, was it as effective as an equal percentage of aniline-furfural resin.

CONCLUSIONS

From the test results obtained in this study the following conclusions can be stated regarding the soil stabilizing effectiveness of tung oil

1. Tung oil was beneficial to all soils treated as compared to natural soil. The well graded soils, - sandy loam, and certain silts - responded well to treatment. Poor results were obtained with clays.

[1]Winterkorn, Hans F., and McAlpin, George W., "Soil Stabilization by the Use of Rosin" CAA Technical Development Note No. 34, February, 1946.

2. Tung oil acted as both a binder and a waterproofing agent, its effectiveness in both cases being proportional to the percentage employed. The dry strength of all the soils was increased by the addition of tung oil.

3. The effectiveness of treatment was proportional to the amount of air drying allowed to the samples prior to exposure. Moist cured samples yielded low compressive strengths as compared to air dried samples. Oven drying at 140 degrees F. was detrimental as compared to air drying.

4. The diverse characteristics of the natural soil itself was one of the greatest variables encountered.

5. Tung oil compared favorably with other soil stabilizers when used in approximately equal amounts, although, in general, it was not as effective as aniline-furfural resin.

6. The addition of various chemicals greatly improved the stability of the treated soil, especially in resistance to the alternate wetting and drying tests. The most beneficial chemicals were potassium sulfate, calcium stearate, zinc stearate, and stearic acid. No admixture was found that would appreciably improve the stability of the moist cured samples.

7. A comparison of the standard Proctor compaction data obtained for treated and untreated soil indicated that there was no increase in density obtained from the addition of tung oil other than that equal to the dry weight of the tung oil itself.

8. The capillary absorption was the least severe of the evaluation tests used. The severity of the other tests varied with the soil type.

TABLE I
Characteristics of the Soils Employed

Soil	Texture	Specific Gravity	Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit	Proctor Compaction		pH^1
							O.M.	M.D.	
A	Sand	2.71	N.P.	N.P.	N.P.	---	10.0	123.8	8.1
B	Sandy Loam	2.67	17.1	14.8	2.3	14.5	11.0	119.0	7.4
C	Loam	2.64	28.0	20.0	8.0	15.1	13.8	115.1	6.4
D	Clay Loam	2.69	33.4	20.0	13.4	15.9	14.0	114.6	5.0
E	Silty Loam	2.63	27.0	18.5	8.5	16.7	15.0	112.8	7.2
F	Silty Loam	2.71	27.0	18.5	8.5	17.2	16.7	108.1	7.3
G	Silt	2.70	30.7	25.5	4.2	22.1	16.9	106.6	7.6
H	Silty Clay Loam	2.66	29.4	20.7	8.7	17.6	20.0	102.0	6.7

[1]Determined by LaMotte-Morgan Soil Testing Method

TABLE II

Comparative Quantities Required to Mold Two-inch by Two-inch Soil Specimens - Based on Proctor Curves for Treated and Untreated Soil

Soil	Untreated Soil			Two Percent Tung Oil Treated Soil						Five Percent Tung Oil Treated Soil					
	From Standard Proctor Curves			From Untreated Soil Curves[1]			From Treated Soil Curves			From Untreated Soil Curves[1]			From Treated Soil Curves		
	Weight Soil	Weight Water	Molded Weight	Weight Soil	Weight Water	Molded Weight	Weight Soil	Weight Water	Molded Weight	Weight Soil	Weight Water	Molded Weight	Weight Soil	Weight Water	Molded Weight
A	204.1	20.4	224.5	208.2	16.3	224.5	214.2	10.2	224.4	214.3	10.2	224.5	213.5	11.9	225.4
B	196.4	21.6	218.0	200.3	17.7	218.0	206.0	9.7	217.7	206.2	11.8	218.0	202.2	14.2	216.4
C	190.0	26.2	216.2	193.8	22.4	216.2	199.6	16.7	216.3	199.5	16.7	216.2	197.8	13.7	211.5
D	189.1	26.4	215.5	192.9	22.6	215.5	198.5	16.9	215.4	198.6	16.9	215.5	196.1	15.7	211.8
E	186.0	27.8	213.8	189.7	24.1	213.8	195.3	18.6	213.9	195.3	18.5	213.8	192.0	19.0	211.0
F	178.4	29.8	208.2	182.0	26.2	208.2	187.4	20.8	208.2	187.3	20.9	208.2	189.5	18.6	208.1
G	175.8	29.6	205.4	179.3	26.1	205.4	184.6	20.8	205.4	184.6	20.8	205.4	181.5	21.4	202.9
H	168.2	33.6	201.8	171.6	30.2	201.8	176.7	25.4	202.1	176.6	25.2	201.8	179.0	23.3	202.3

[1] Computed from untreated soil data by adding weight of tung oil to weight of untreated soil, and deducting weight of tung oil from required moisture.

TABLE III

Effectiveness of Chemical Admixtures as Added to Soils Treated With Two Percent Tung Oil - Expressed as a Percentage of the Compressive Strength Obtained, After Exposure, For Corresponding Samples Treated With Tung Oil Alone

Chemical Admixture	Soil Type					
	A	B	D	E	F	G
Aluminum Acetate *	150	144	---	139	---	102
Aluminum Chloride	---	83	---	---	---	80
Aluminum Hydroxide *	250	115	145	145	---	96
Aluminum Stearate *	92	170	130	104	154	145
Aluminum Sulfate *	250	213	120	159	---	136
Ammonium Chloride	---	---	66	---	---	139
Ammonium Sulfate *	124	105	141	---	177	146
Barium Chloride	---	66	93	---	---	90
Calcium Carbonate	---	---	103	---	---	105
Calcium Chloride	---	---	100	---	---	78
Calcium Hydroxide *	---	---	100	---	---	100
Calcium Stearate *	322	150	151	---	---	131
Calcium Sulfate	91	103	112	---	101	120
Copper Ammonium Sulfate	---	50	31	---	---	---
Ferric Chloride	---	---	142	---	---	75
Ferric Sulfate *	95	210	---	236	---	138
Ferrous Sulfate	---	---	---	---	---	107
Lead Acetate *	87	112	139	87	208	120
Lead Oxide (Red)	---	---	---	---	---	105
Lead Oxide (Yellow)	---	---	---	---	---	118
Magnesium Chloride	---	---	100	---	---	60
Magnesium Oxide	---	---	50	---	---	122
Magnesium Stearate	77	100	154	---	150	136

Chemical Admixture	Soil Type					
	A	B	D	E	F	G
Magnesium Sulfate	---	55	116	---	---	90
Magnesium Trisilicate	---	78	122	---	---	128
Manganese Dioxide	---	42	137	---	---	134
Nickel(ous) Sulfate *	75	165	114	112	137	150
Potassium Acetate	---	---	100	---	---	---
Potassium Binoxalate	97	188	---	97	---	---
Potassium Bisulfate *	114	183	148	127	208	151
Potassium Chloride	---	63	90	---	---	110
Potassium Sulfate *	130	125	160	115	200	165
Silica Gel	---	55	124	---	---	106
Silicic Acid	---	66	128	---	---	---
Sodium Aluminate	---	---	---	---	---	65
Sodium Fluorosilicate	---	---	0	---	---	---
Sodium Oxylate	---	---	0	---	---	0
Sodium Silicate	---	---	50	---	---	40
Sodium Stearate	---	---	90	---	---	85
Sodium Sulfate	---	66	---	---	---	---
Stearic Acid *	342	---	145	585	---	106
Sulfur (Powder)	---	---	---	---	57	51
Sulfuric Acid	---	110	83	51	---	73
Zinc Oxide	---	---	56	---	---	125
Zinc Stearate *	95	157	123	---	167	134
Zinc Sulfate *	100	183	112	120	---	152

* These chemicals are more fully evaluated as shown in Table IV.

TABLE IV

Effectiveness of Chemical Admixtures on the Resistance of Tung Oil Treated Samples to Three Types of Exposure Tests - Expressed as a Percentage of the Compressive Strength Obtained for Corresponding Samples Without the Chemical Admixtures

Chemical Admixture	Soil B			Soil D			Soil E			Soil G		
	Imm	W-D	F-T	Imm	W-D	F-T	Imm	W-D	F-T	Imm	W-D	F-T
Aluminum Acetate	154	119	159	138	94	201	118	35	120	180	120	118
Lead Acetate	110	106	183	156	136	313	93	110	96	108	262	63
Aluminum Hydroxide	102	21	108	103	96	105	96	34	40	181	100	105
Calcium Hydroxide	90	71	45	80	59	37	57	40	41	170	181	25
Aluminum Sulfate	208	165	182	95	80	163	102	124	100	124	100	104
Ammonium Sulfate	127	129	80	184	240	160	160	182	280	260	200	200
Ferric Sulfate	161	146	172	100	112	66	96	195	145	200	100	128
Nickel(ous) Sulfate	126	123	130	106	83	72	89	107	70	158	130	122
Potassium Bisulfate	242	129	165	141	196	140	133	212	371	262	183	210
Potassium Sulfate	152	123	116	200	248	240	223	238	640	280	192	230
Stearic Acid	126	142	121	138	805	245	140	840	482	231	176	172
Aluminum Stearate	142	105	158	120	240	180	102	32	114	230	840	196
Calcium Stearate	120	106	128	143	995	264	138	996	388	172	226	160
Magnesium Stearate	105	129	124	106	83	72	150	1010	210	150	262	40
Zinc Stearate	131	103	136	120	940	202	103	580	172	172	570	132

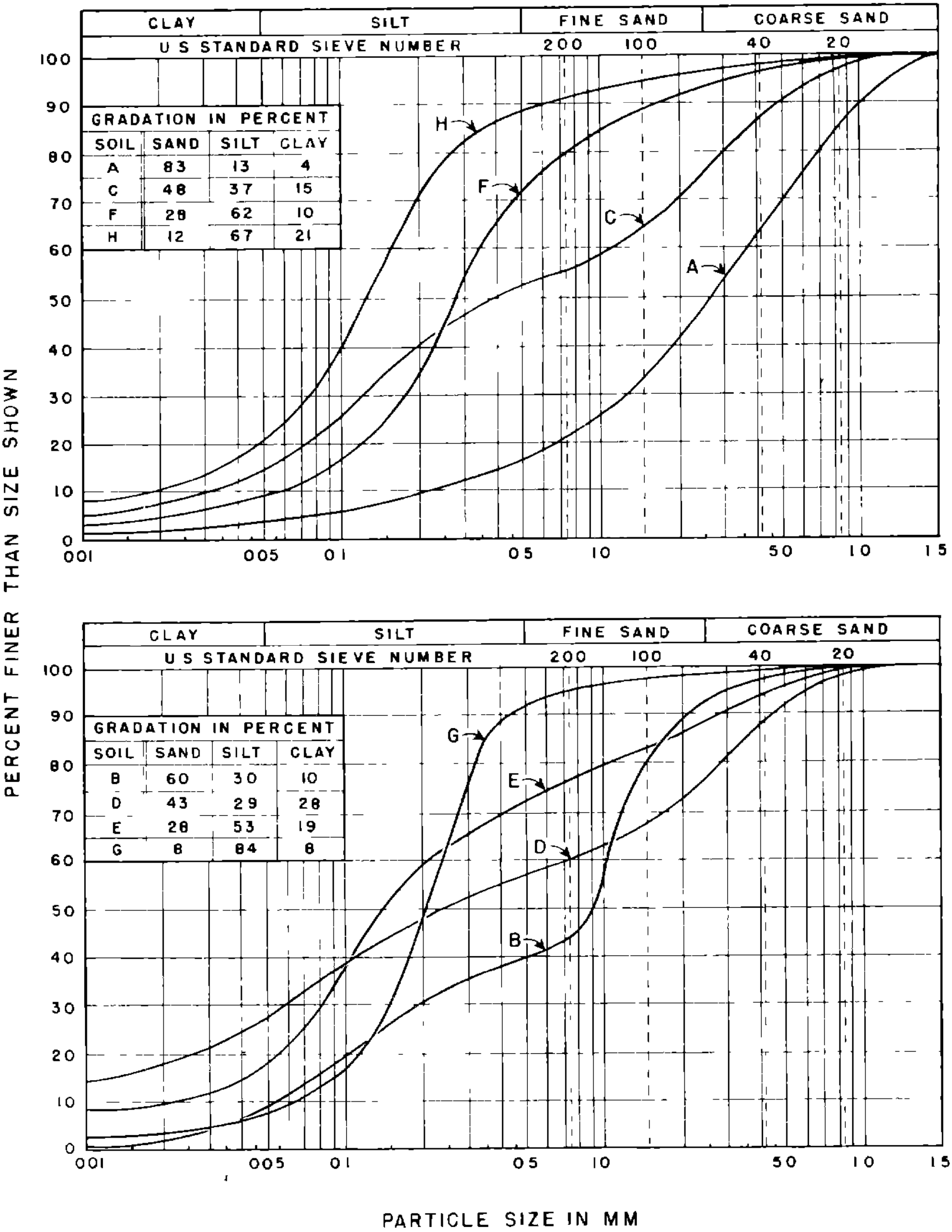


FIGURE I GRAIN SIZE - DISTRIBUTION CURVES FOR THE DIFFERENT SOILS

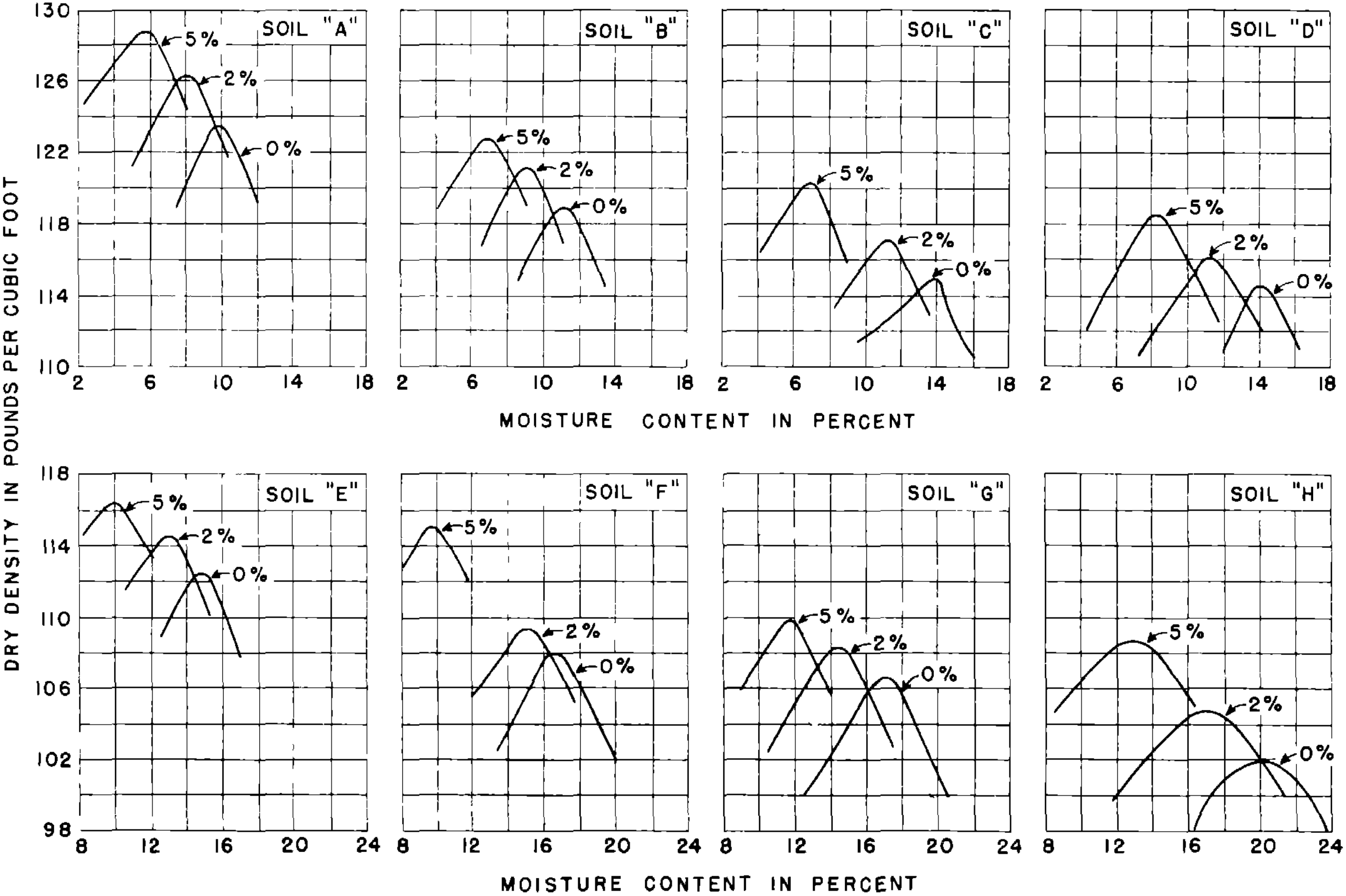


FIGURE 2 MOISTURE-DENSITY RELATIONSHIP FOR THE TREATED AND UNTREATED SOILS

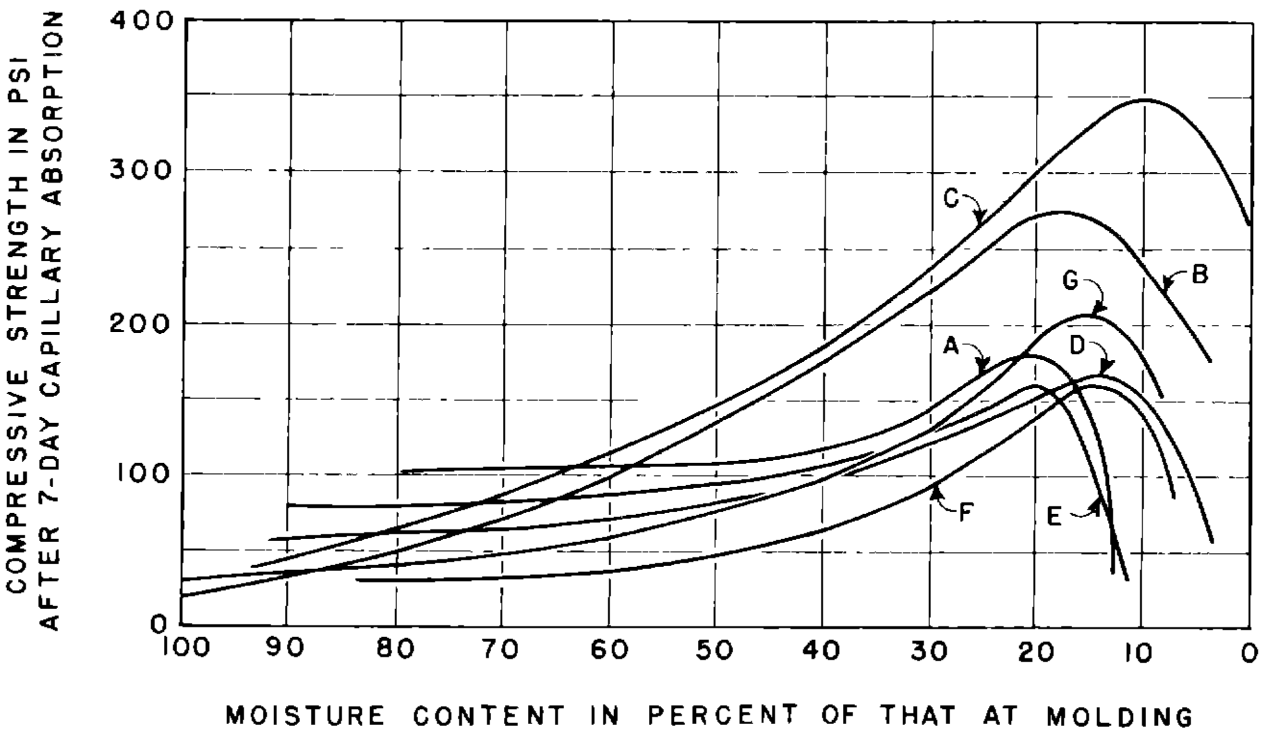


FIGURE 3 EFFECT OF MOISTURE CONTENT PRIOR TO EXPOSURE ON THE SUBSEQUENT COMPRESSIVE STRENGTH OF SOIL SAMPLES TREATED WITH TWO PERCENT TUNG OIL

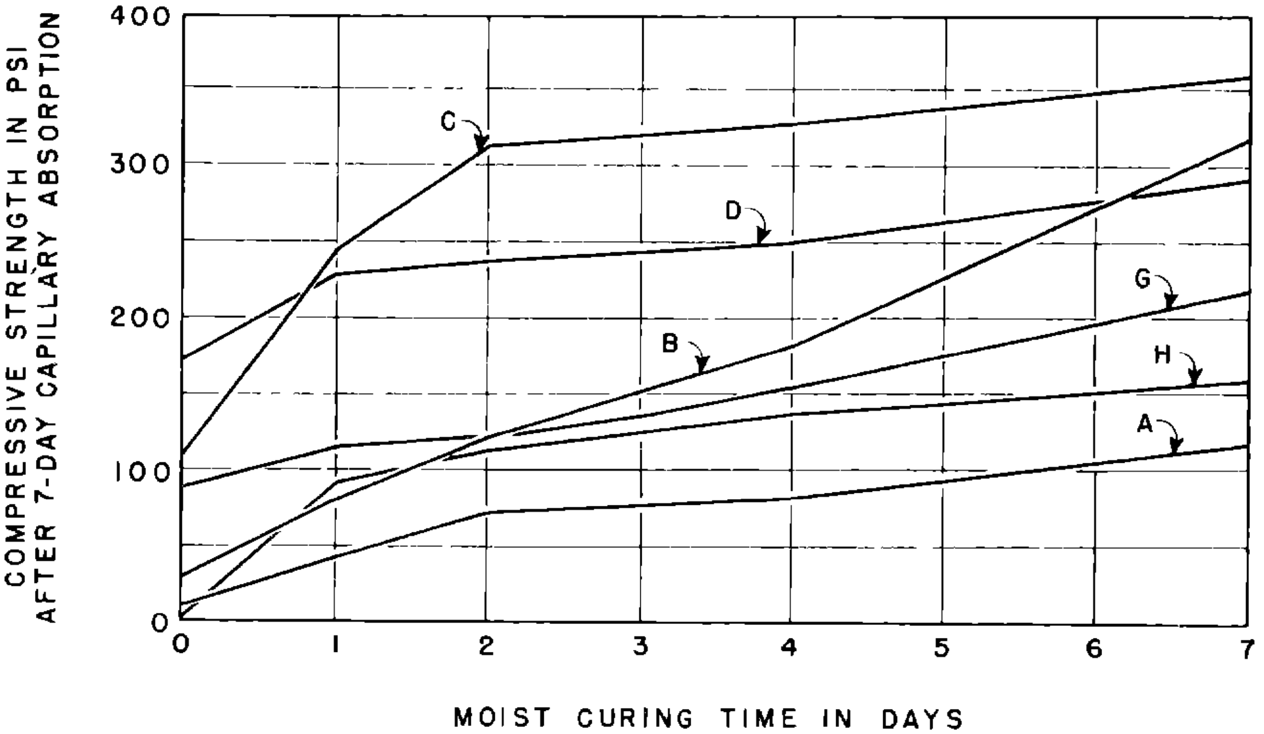
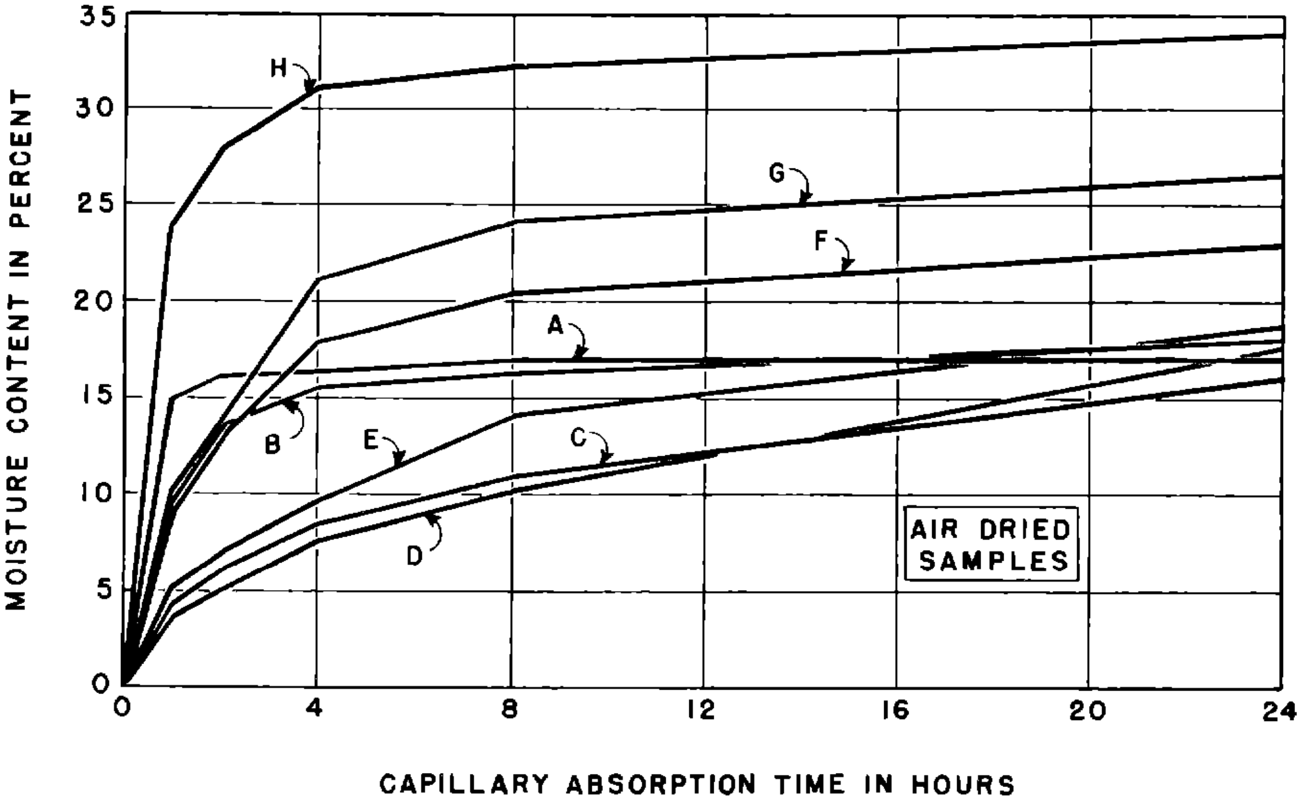


FIGURE 4 EFFECT OF MOIST CURING PRIOR TO EXPOSURE ON THE SUBSEQUENT COMPRESSIVE STRENGTH OF SOIL SAMPLES TREATED WITH TWO PERCENT TUNG OIL



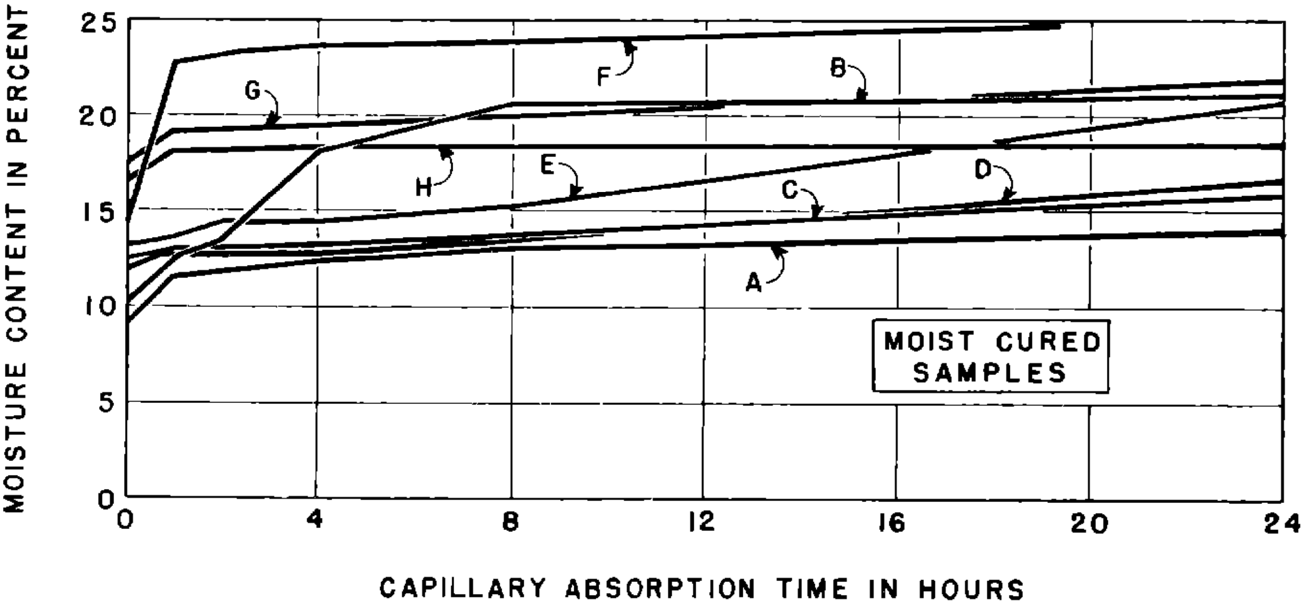


FIGURE 5 RATE OF CAPILLARY MOISTURE ABSORPTION OF THE UNTREATED SOIL SAMPLES

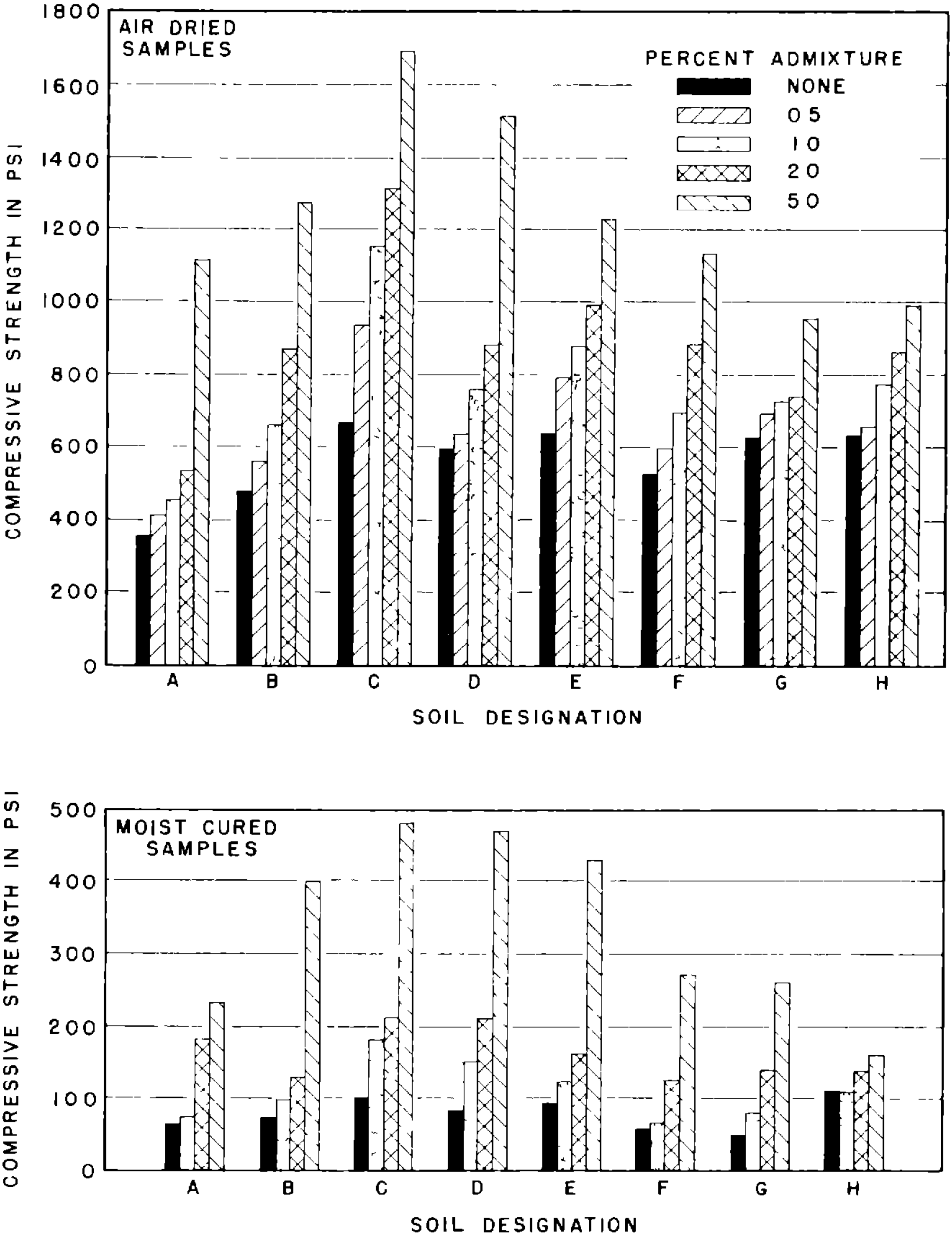


FIGURE 6 EFFECTIVENESS OF VARIOUS PERCENTAGES OF TUNG OIL ON THE COMPRESSIVE STRENGTH OF SOIL SAMPLES PRIOR TO EXPOSURE TESTS

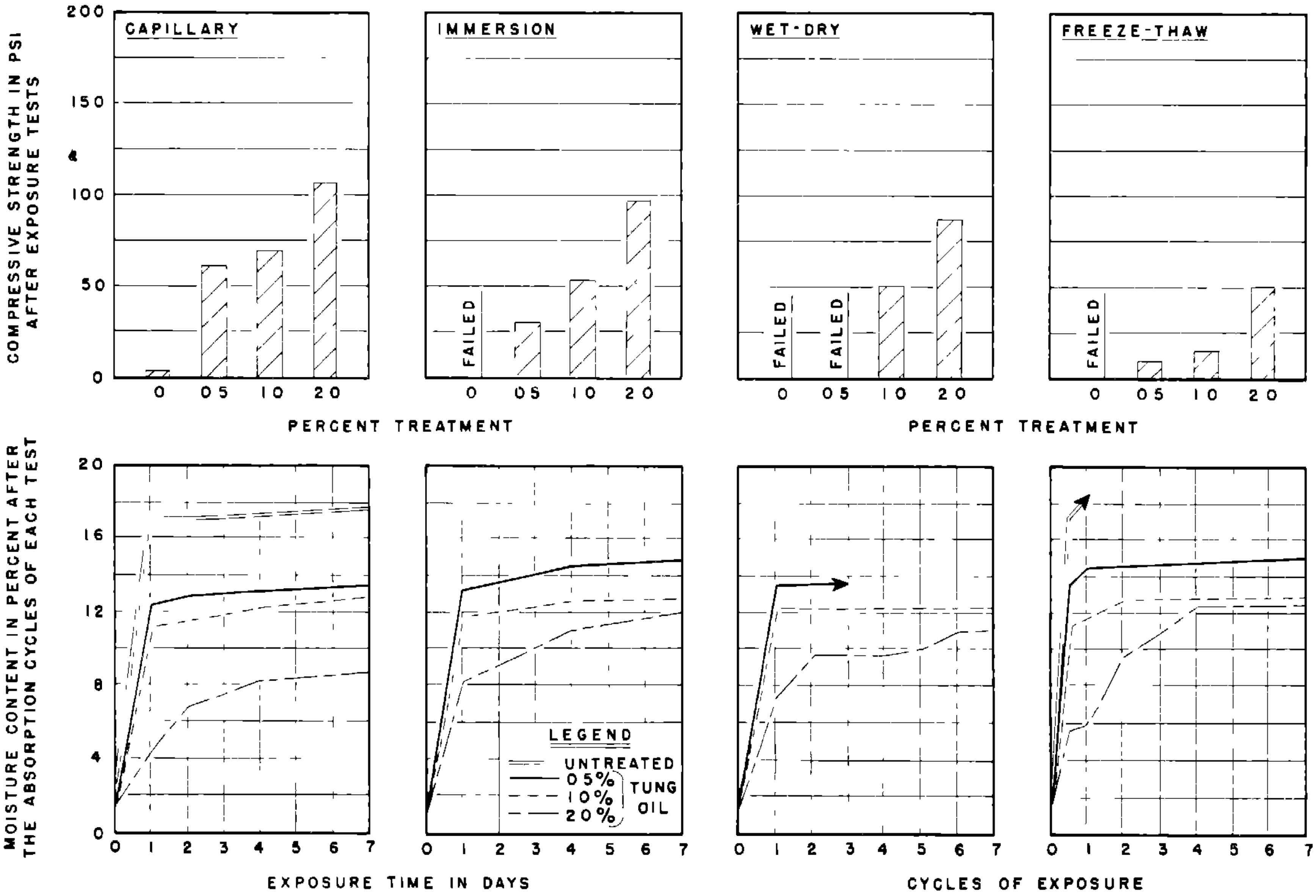


FIGURE 7 RESULTS OF THE LABORATORY EXPOSURE TESTS - AIR DRIED SAMPLES OF SOIL "A"

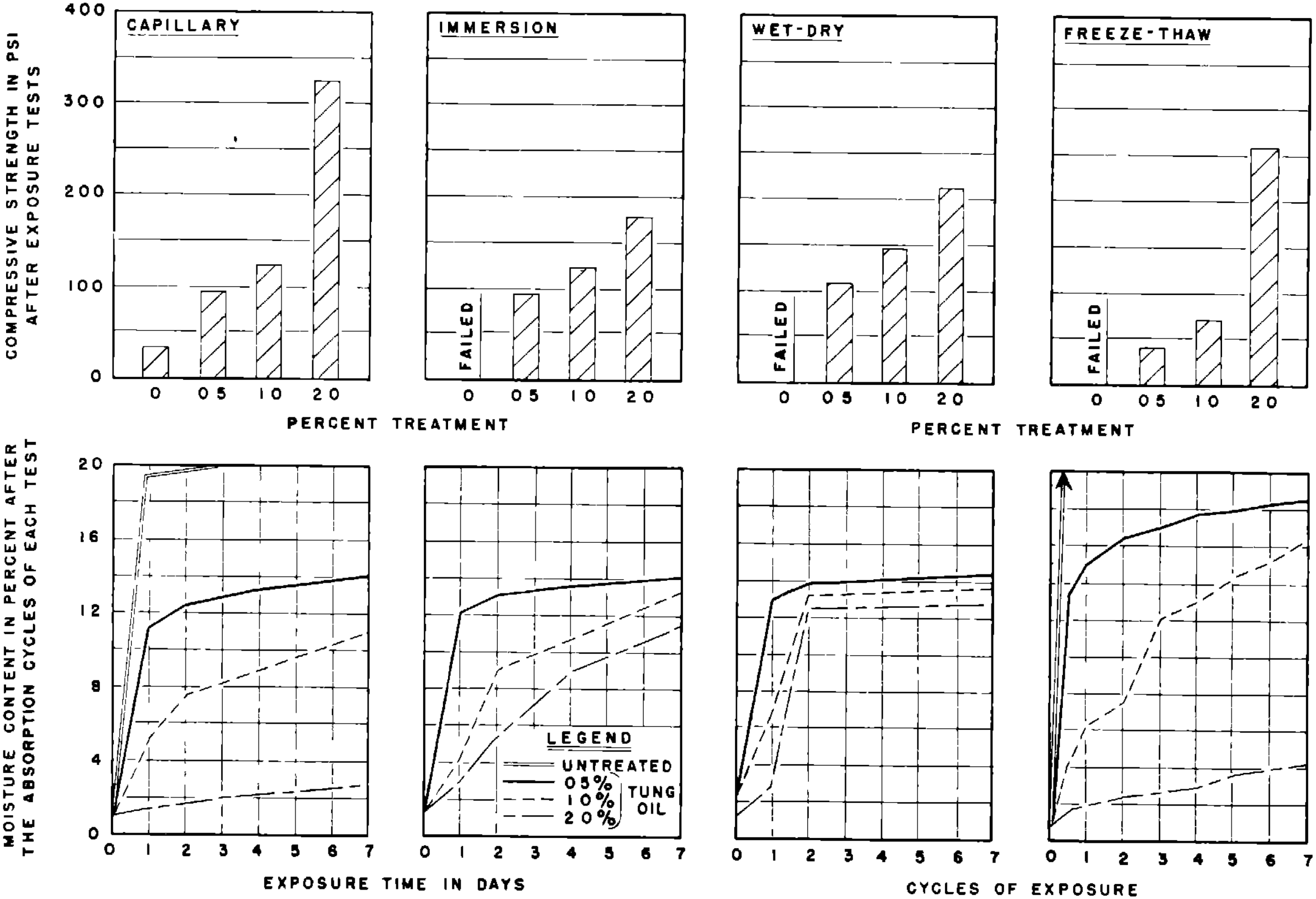


FIGURE 8 RESULTS OF THE LABORATORY EXPOSURE TESTS-AIR DRIED SAMPLES OF SOIL "B"

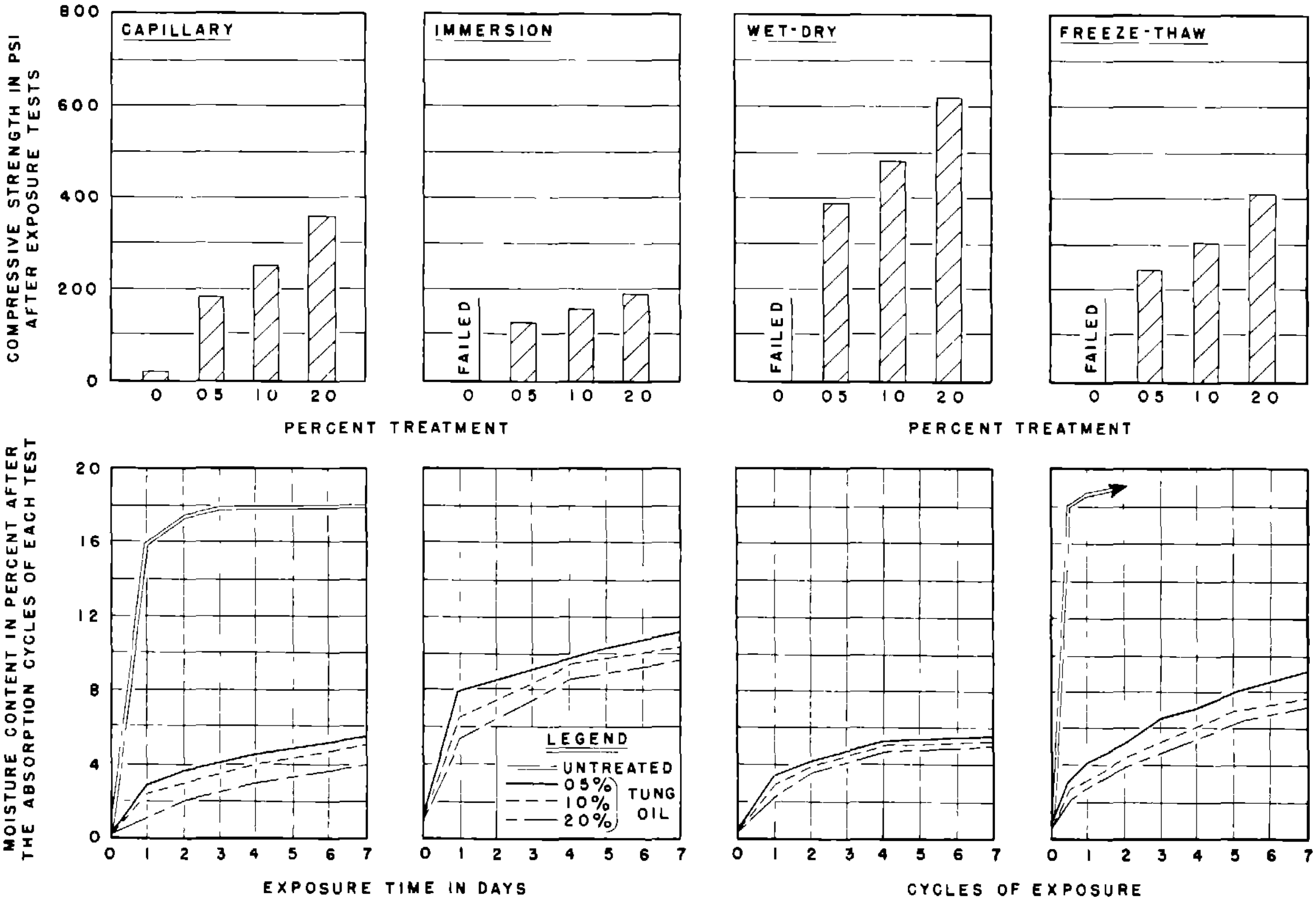


FIGURE 9 RESULTS OF THE LABORATORY EXPOSURE TESTS-AIR DRIED SAMPLES OF SOIL "C"

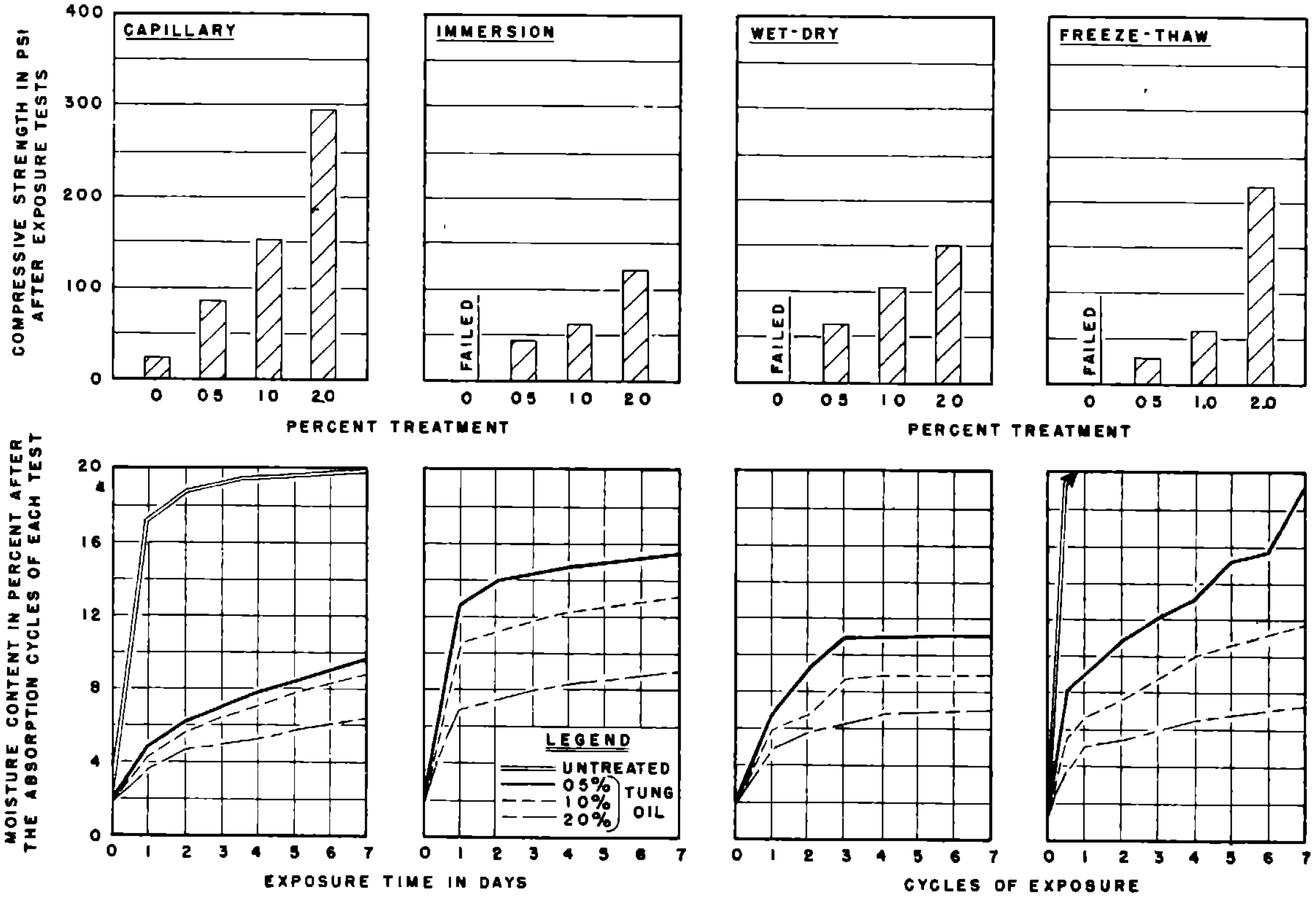


FIGURE 10 RESULTS OF THE LABORATORY EXPOSURE TESTS-AIR DRIED SAMPLES OF SOIL "D"

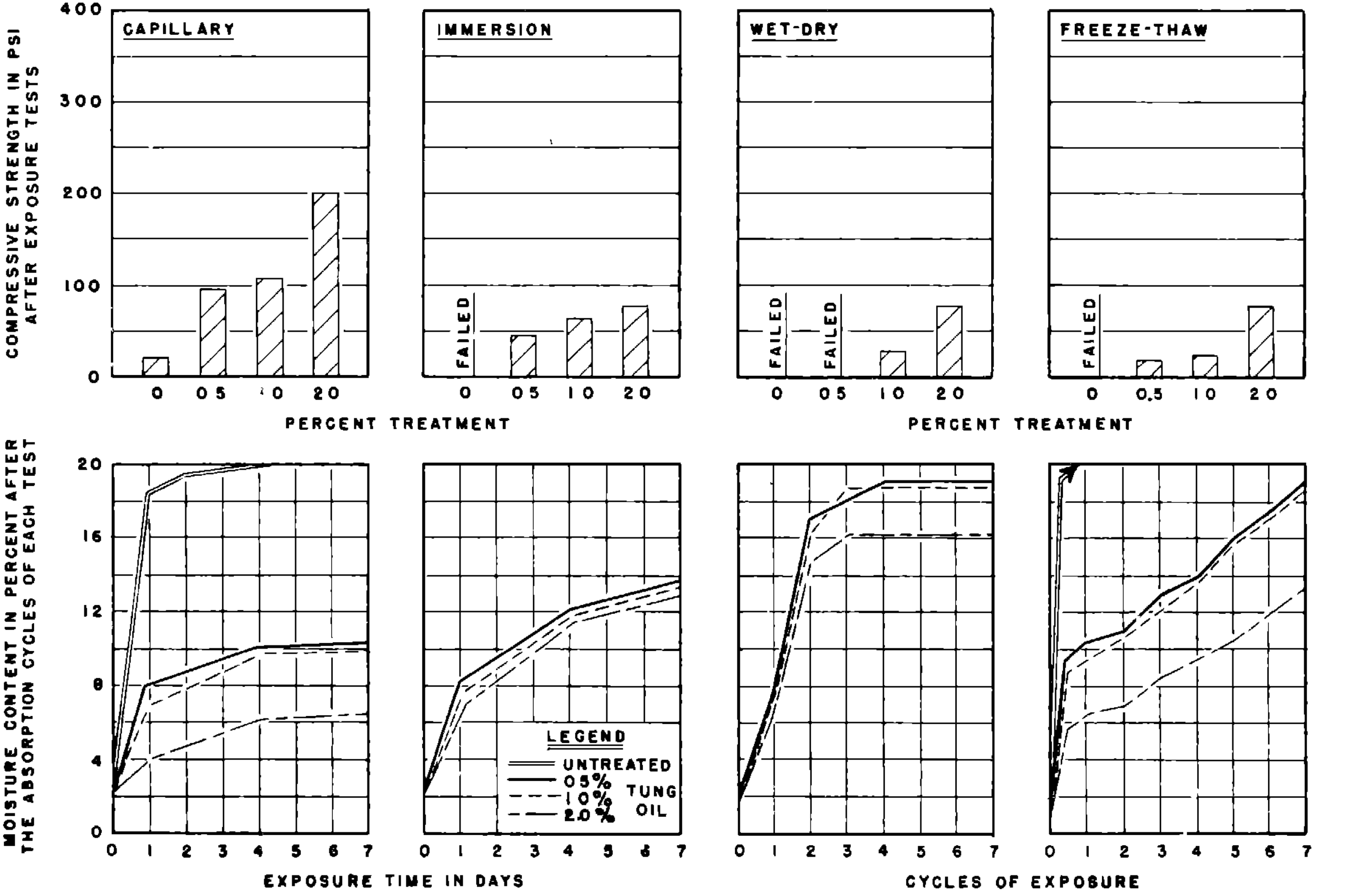


FIGURE 11 RESULTS OF THE LABORATORY EXPOSURE TESTS - AIR DRIED SAMPLES OF SOIL "E"

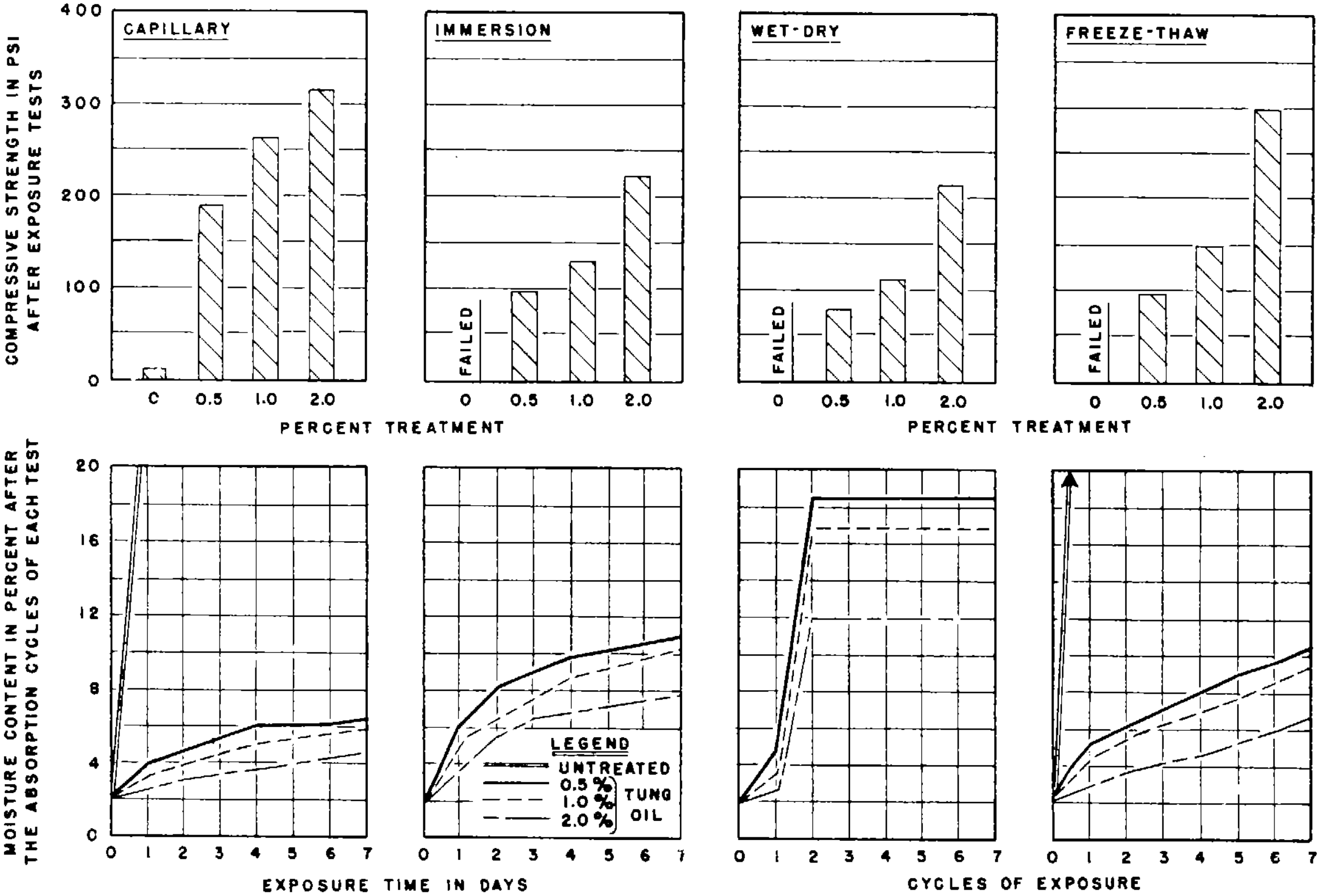


FIGURE 12. RESULTS OF THE LABORATORY EXPOSURE TESTS-AIR DRIED SAMPLES OF SOIL "F"

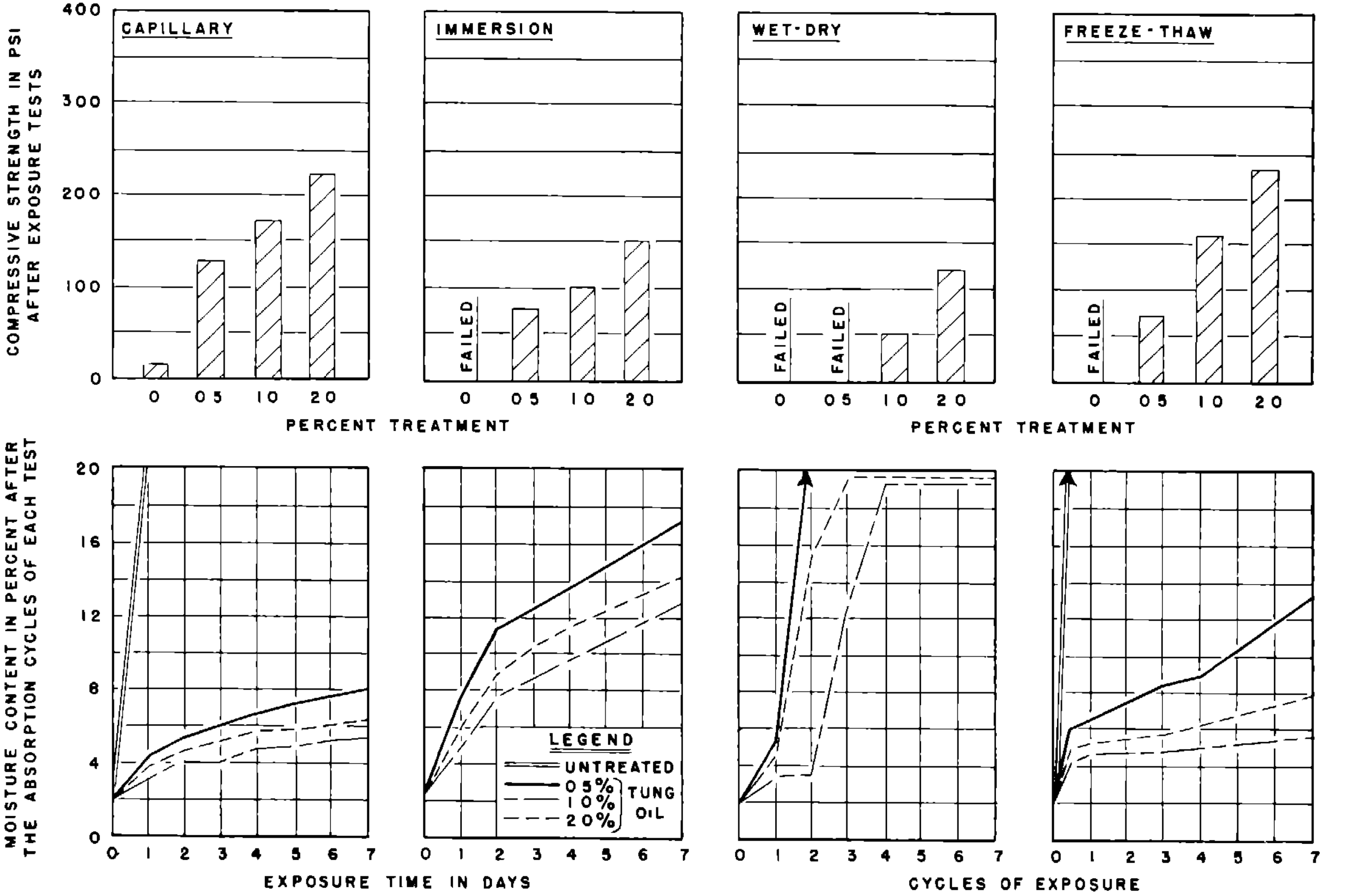


FIGURE 13 RESULTS OF THE LABORATORY EXPOSURE TESTS-AIR DRIED SAMPLES OF SOIL "G"

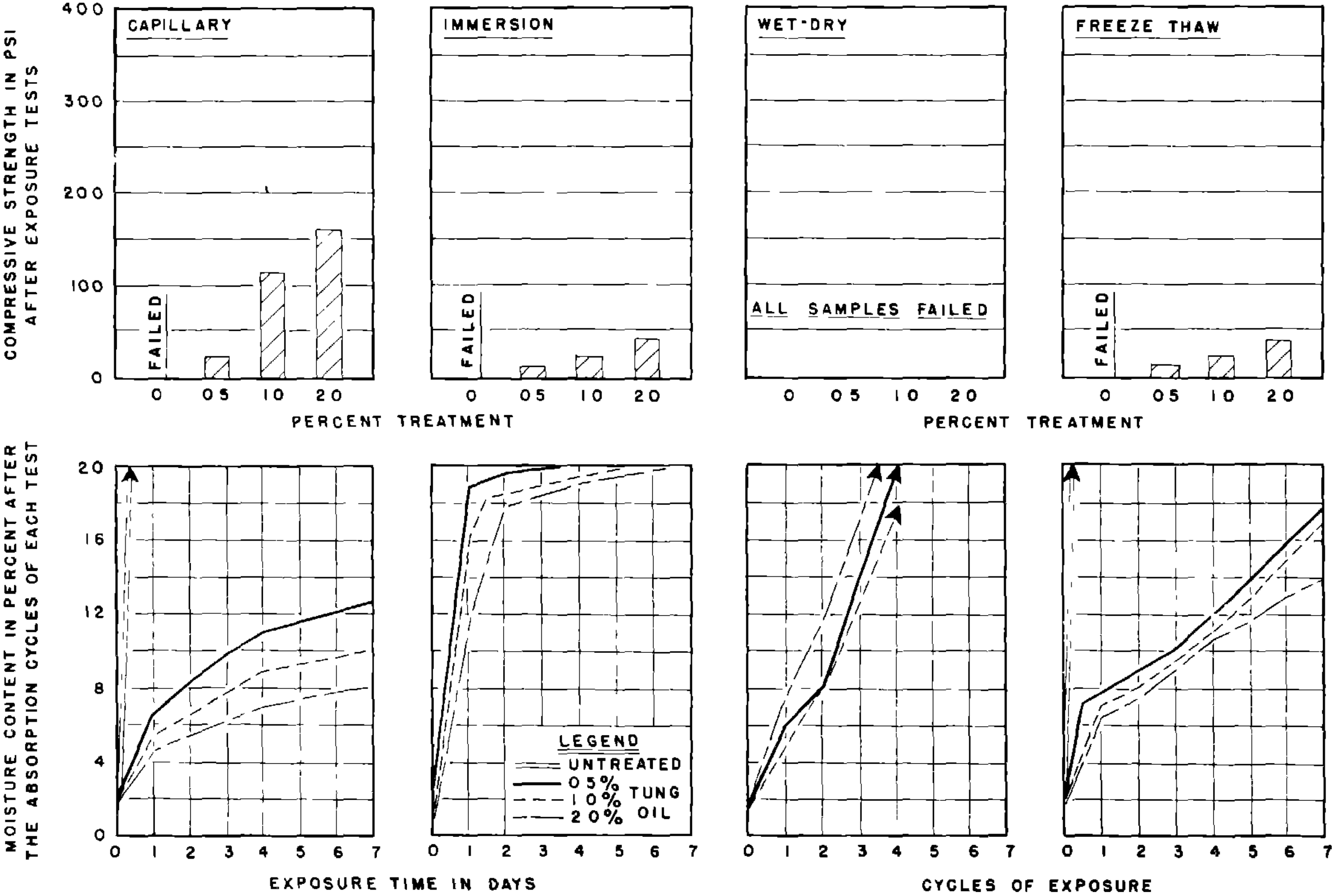


FIGURE 14 RESULTS OF THE LABORATORY EXPOSURE TESTS-AIR DRIED SAMPLES OF SOIL "H"

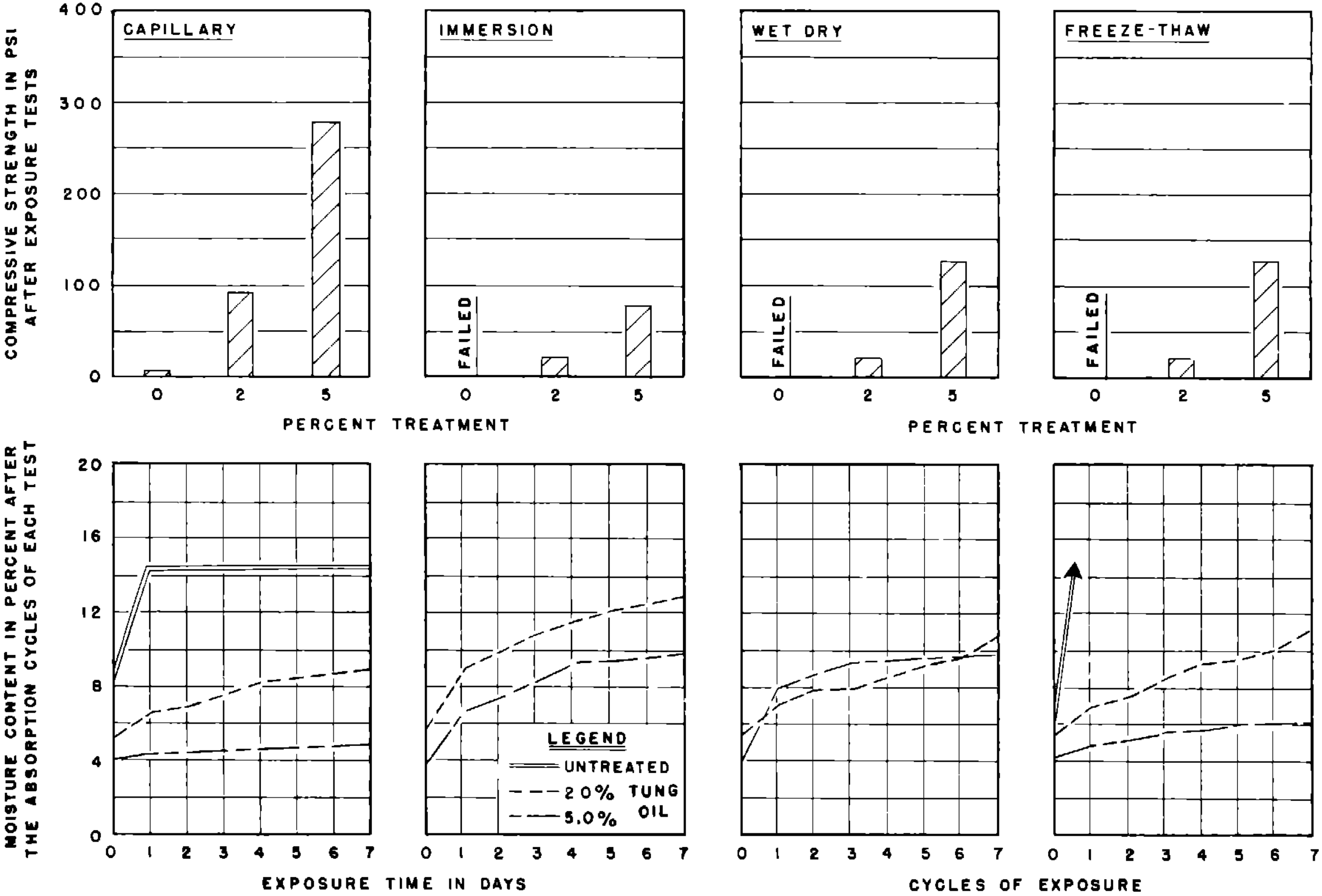


FIGURE 15 RESULTS OF THE LABORATORY EXPOSURE TESTS-MOIST CURED SAMPLES OF SOIL "A"

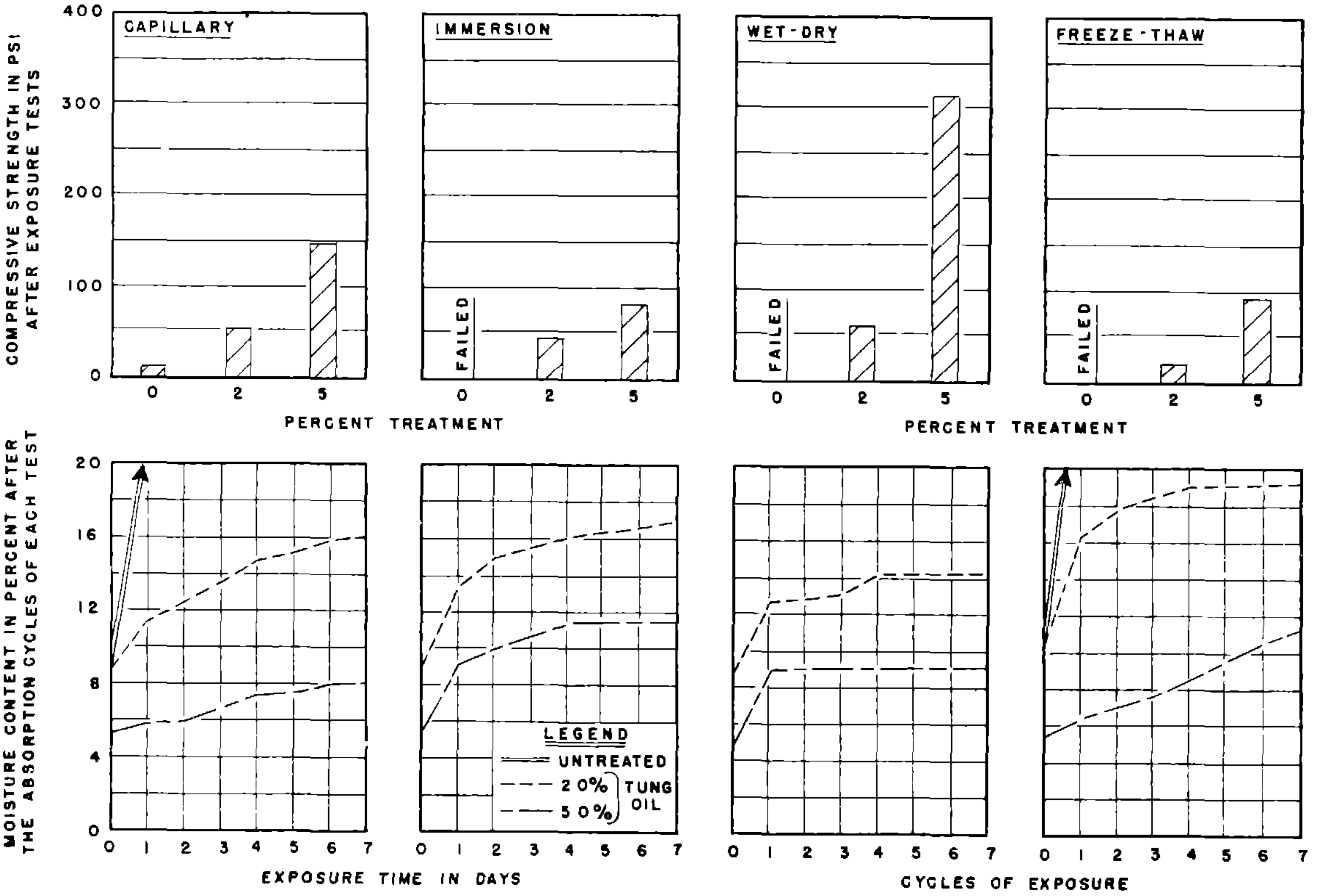


FIGURE 16 RESULTS OF THE LABORATORY EXPOSURE TESTS-MOIST CURED SAMPLES OF SOIL "B"

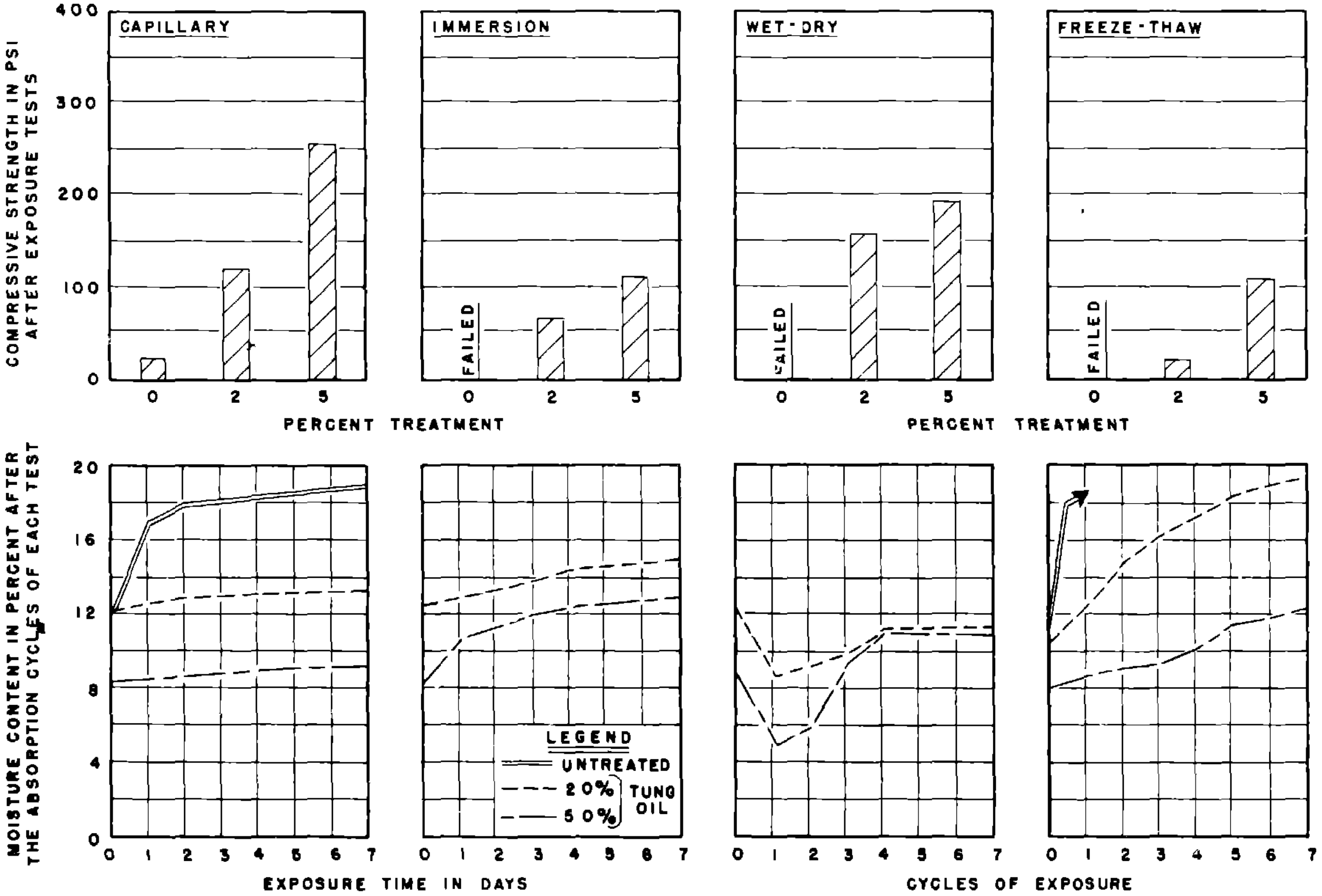


FIGURE 17. RESULTS OF THE LABORATORY EXPOSURE TESTS-MOIST CURED SAMPLES OF SOIL "D"

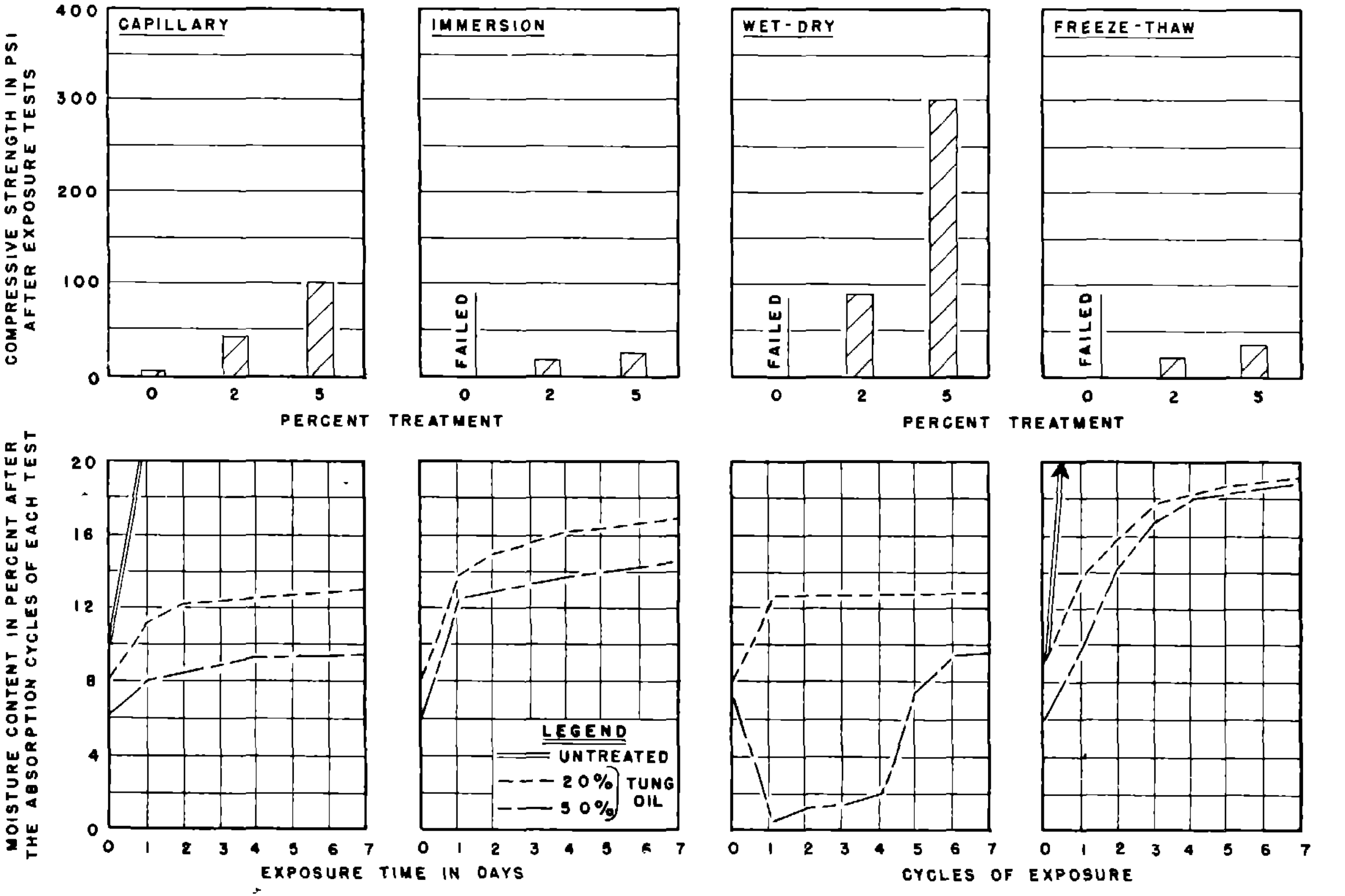


FIGURE 18. RESULTS OF THE LABORATORY EXPOSURE TESTS-MOIST CURED SAMPLES OF SOIL "F"

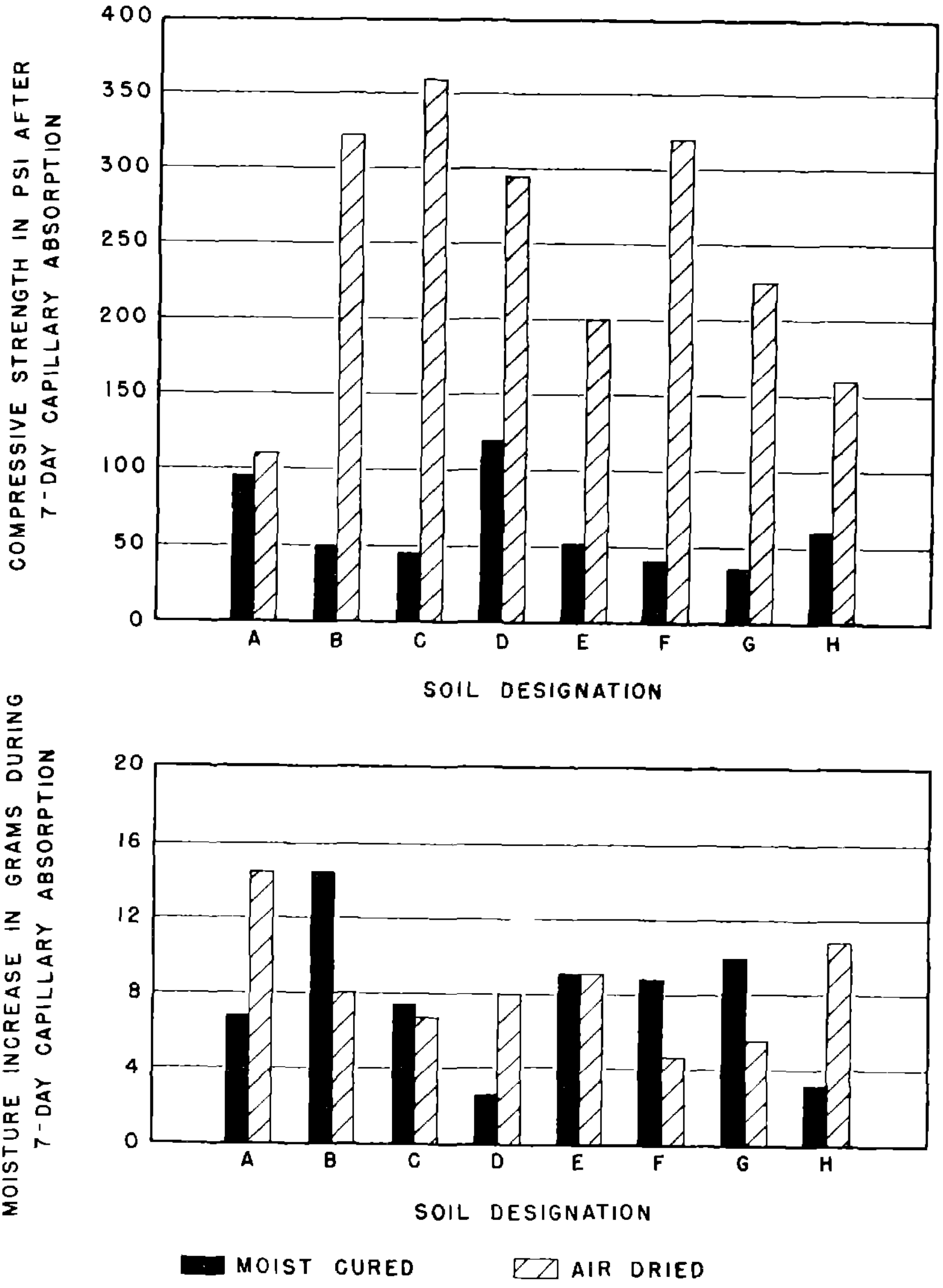


FIGURE 19 COMPARATIVE STABILITY OF AIR DRIED AND MOIST CURED SAMPLES WHEN TREATED WITH TWO PERCENT TUNG OIL

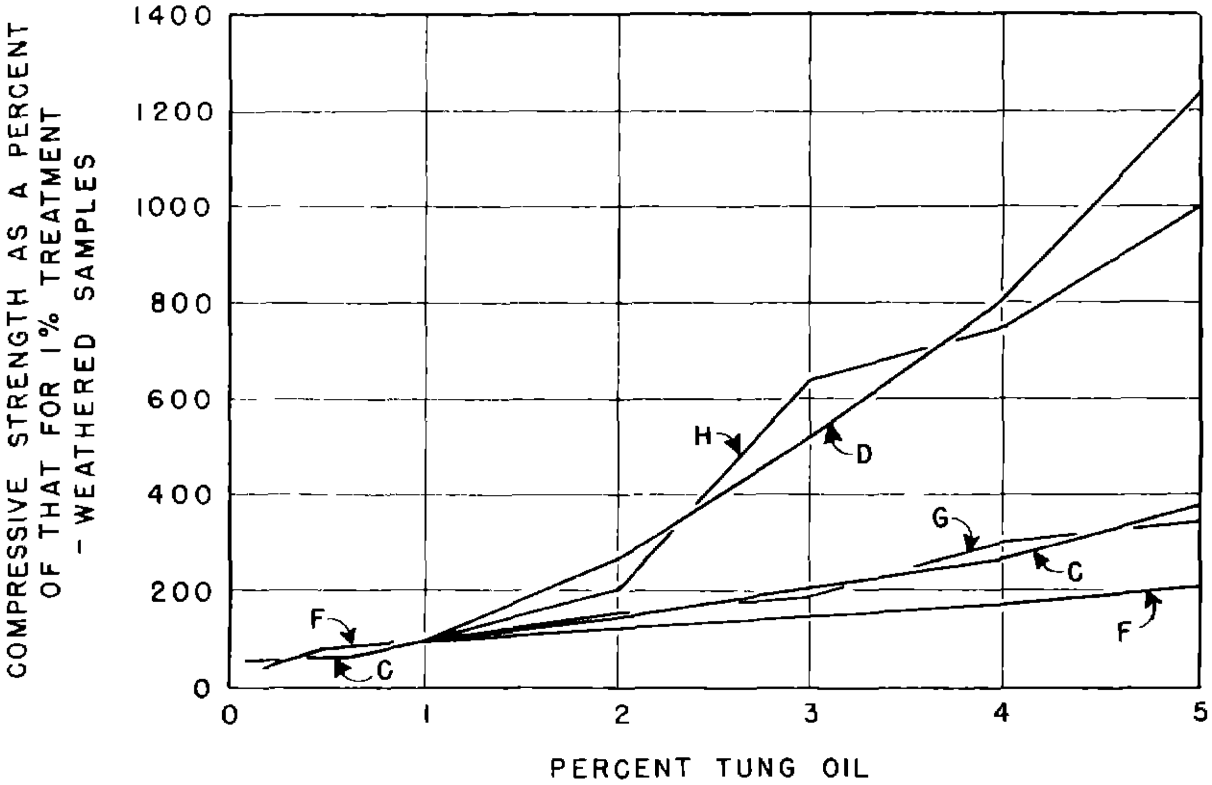


FIGURE 20 STABILITY OF THE SOIL SAMPLES AFTER CAPILLARY ABSORPTION AS A FUNCTION OF THE PERCENT TUNG OIL EMPLOYED

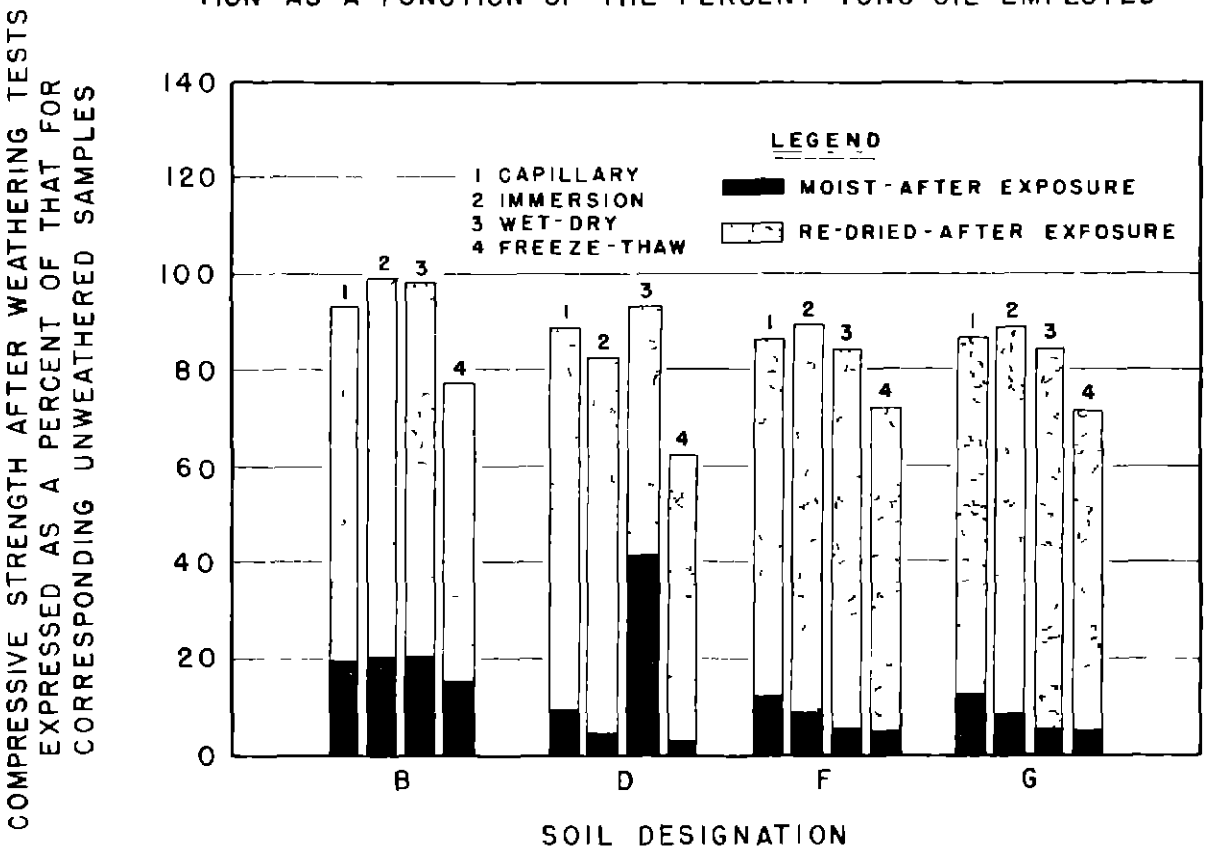


FIGURE 21 RECOVERY IN STABILITY OF ONE PERCENT TUNG OIL TREATED SAMPLES RE-DRIED AFTER EXPOSURE TESTS

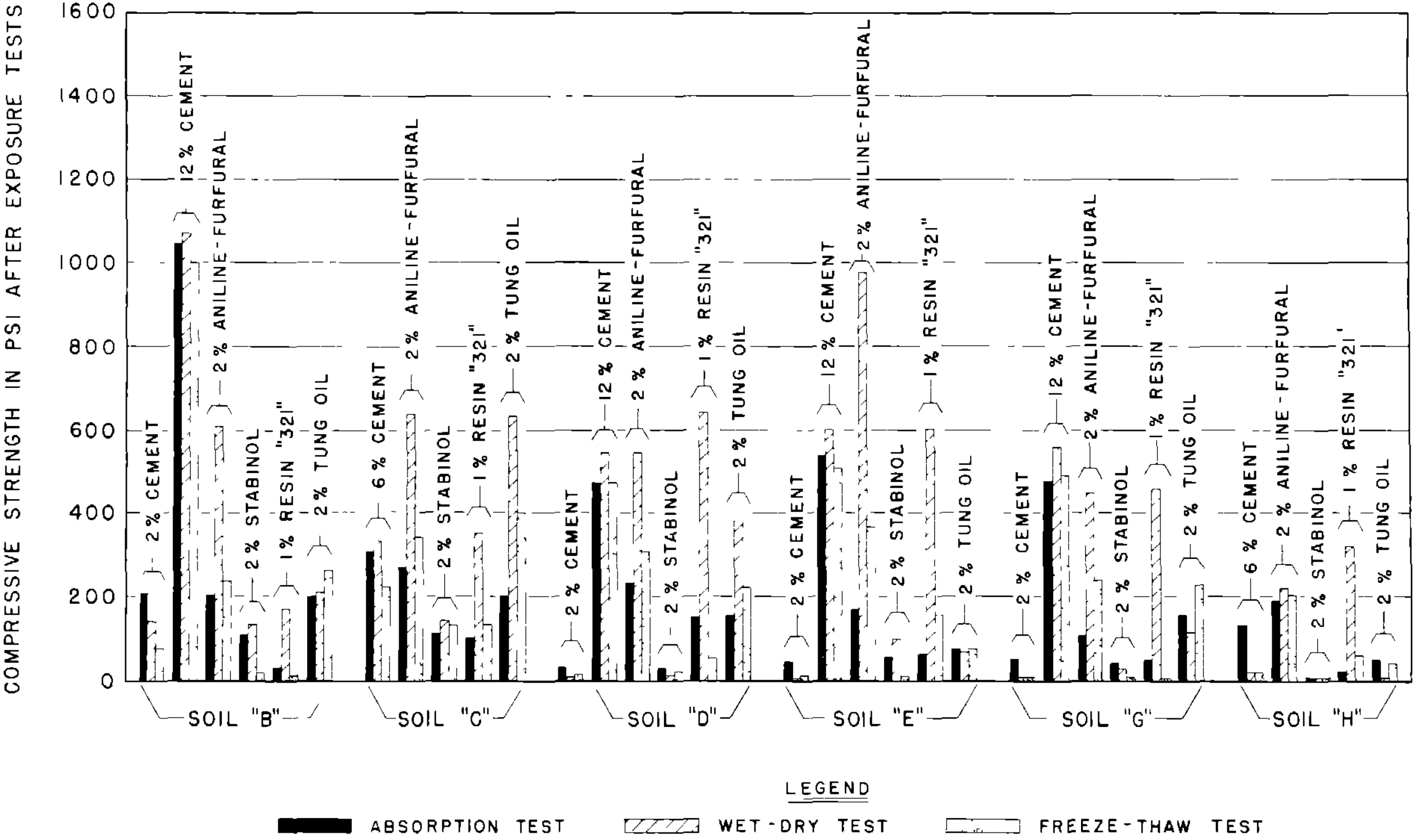


FIGURE 22 COMPARISON OF TUNG OIL WITH OTHER SOIL STABILIZING AGENTS - AIR DRIED SAMPLES

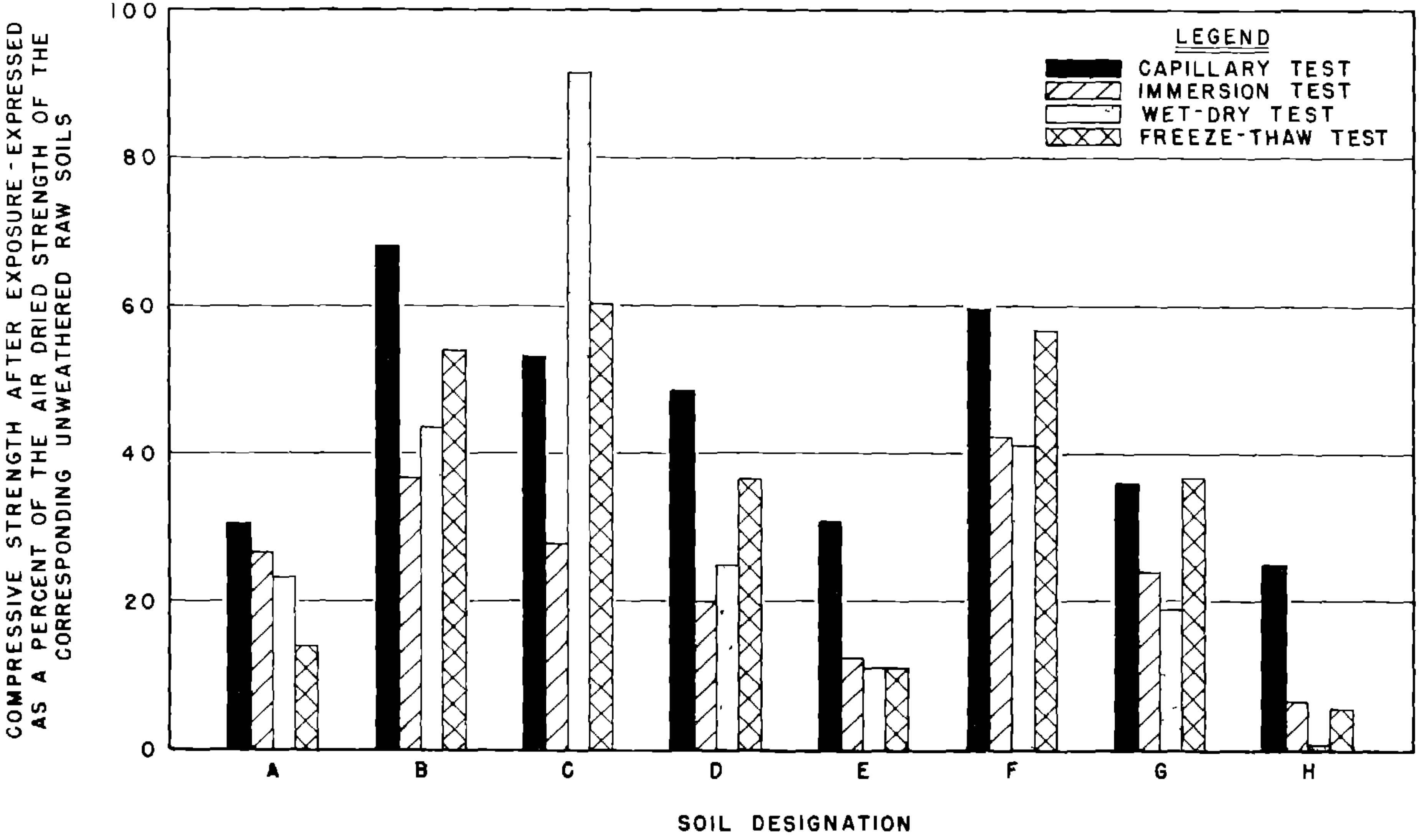


FIGURE 23 RELATIVE SUSCEPTIBILITY OF THE AIR DRIED SOILS TO TREATMENT - EXPRESSED AS A RATIO OF THE COMPRESSIVE STRENGTHS OF TREATED WEATHERED SOILS TO CORRESPONDING UNWEATHERED RAW SOILS

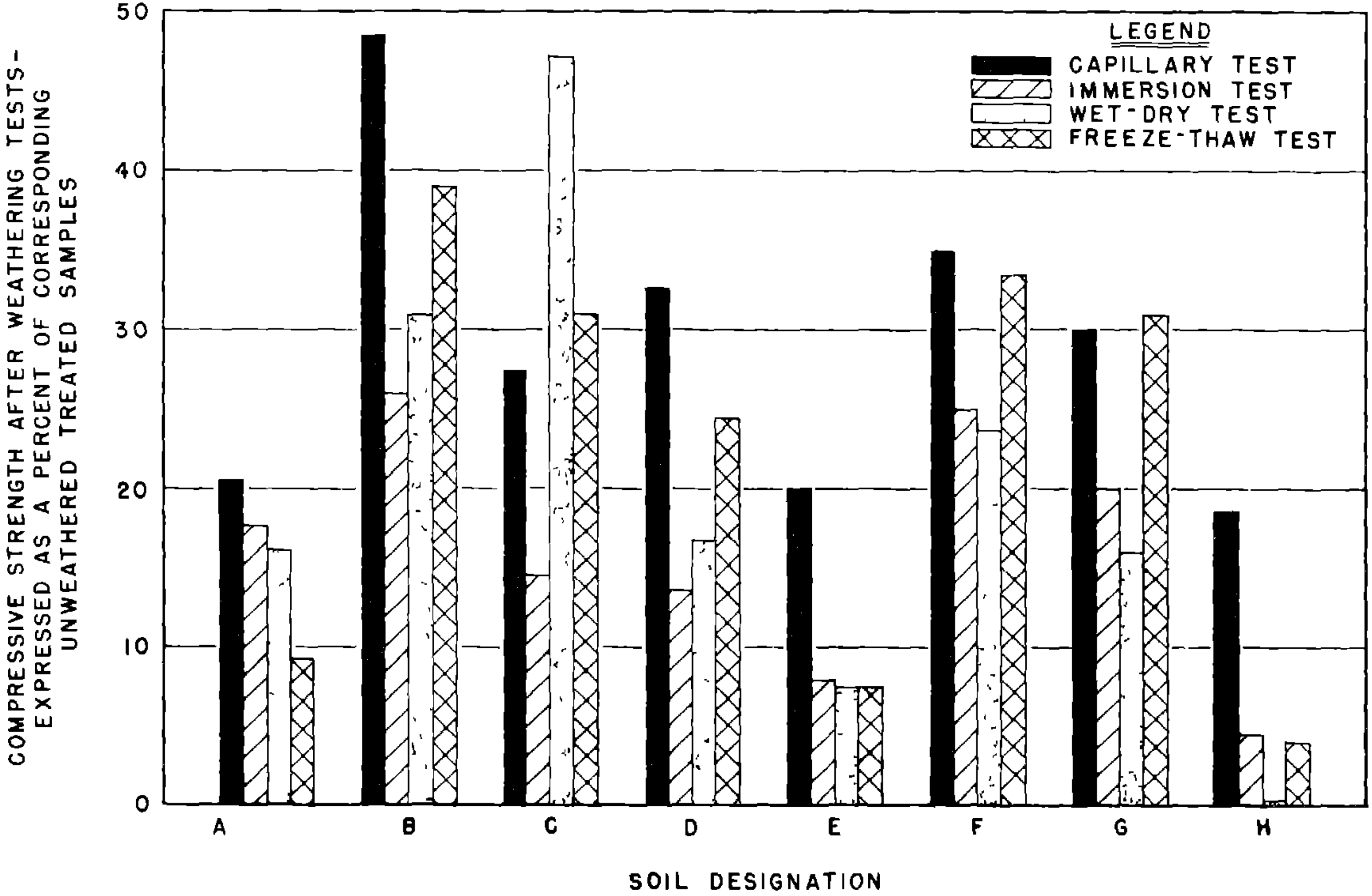


FIGURE 24 RELATIVE SUSCEPTIBILITY OF THE AIR DRIED SOILS TO TREATMENT - EXPRESSED AS A RATIO OF THE COMPRESSIVE STRENGTHS OF TREATED SOILS BEFORE AND AFTER EXPOSURE