A SUMMARY REPORT ON SOIL STABILIZATION BY THE USE OF CHEMICAL ADMIXTURES

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SUMMARY

This report presents the results obtained from laboratory and field investigations of the soil stabilizing properties of numerous chemicals with respect to their applicability for road and airport construction. Laboratory testing procedures are described which were developed for evaluating the various chemical soil treatments studied.

Although no entirely successful material was found during these investigations, several have shown good soil stabilizing properties. The most effective of these are:

1. Portland cement plus certain resin admixtures.
2. Aniline-furfural resin plus certain additives.
3. Resorcinal-formaldehyde resin (Amberlite PR-115) plus hardener.
4. Phenol-formaldehyde resin (Resinox 9673) plus catalyst.

Bituminous materials were not effective when applied alone to any of the soils used in these tests. MC-2, RC-2 and asphalt emulsion, however, were considerably improved by the addition of small quantities of artificial resins, particularly aniline-furfural, Amberlite PR-115 and Resinox 9673. Hydrated lime also proved beneficial to bituminous materials. Sodium silicate, hydrated lime, powdered slag, calcium chloride and resinous water-repellents (materials which have been advocated for soil stabilization purposes) were not effective when subjected to severe laboratory and field exposure.

Due to the relatively high cost of synthetic resins, their use in normal paving construction as primary soil stabilizing agents is not practical at the present time. Their use in small quantities as activators and modifiers for the lower priced, traditional paving materials appears to be economically feasible. In such application several of the admixtures have been quite promising.

As a result of this study it has become apparent that a more basic understanding of fundamental soil properties is required before the complex reaction between soils and chemical treatments can be fully evaluated. The composition of natural soils, and their consequent reactivity to chemical modification, has been the greatest variable encountered during this study. Until these variables can be more fully understood and controlled, the future development of soil stabilization cannot be directed with optimum efficiency.

INTRODUCTION

For the past several years the Technical Development and Evaluation Center has conducted studies to develop, improve and evaluate the techniques of chemical soil stabilization for use in airport paving construction. In this report the term "chemical soil stabilization" is used to describe any method whereby the engineering properties of natural soils are improved by the chemical or physico-chemical interaction between an admixture and a soil and includes the use of such general materials as Portland cement, bitumens, lime, etc. The desired stabilizing effect may be obtained by bonding, waterproofing or otherwise modifying the natural soil in such manner that the resulting mixture will withstand the detrimental forces of weather, moisture and traffic. The successful application of these techniques to road and airfield construction should permit the economical and efficient utilization of natural soils for the construction of durable wearing surfaces and base courses.

The early phases of this work, begun in 1939, were concerned with:

1. Development of laboratory testing procedures for determining the acceptability of soil stabilizing agents - primarily Portland cement and bituminous materials.
2. Investigation of the relative efficiency of field equipment as used in processing soil-cement.
3. Laboratory and field testing of available stabilizing materials.

Part of the work performed under Item 1 was conducted under the direction of Professor W. S. Housel through contract between the Technical Development and Evaluation Center and the University of Michigan. All of the work performed under Item 3 was conducted under the direction of Professor K. B. Woods through contract between the TDEC and Purdue University.

Although not conclusive, this initial work was fundamental and comprehensive and has served as a foundation for subsequent work in this field.

Shortly after the outbreak of World War II, additional studies were undertaken; to develop new, more highly active types of chemical soil stabilizers which would be effective in small quantities, and to develop methods of successfully utilizing the possible soil stabilizing potential of materials available in the different combat areas. Most of this work was conducted through development contracts with the University of Missouri, Purdue University, Armour Research Foundation and Princeton University.

The most significant results obtained from this contractual work and from that performed earlier in the soils laboratory of the TDEC have been summarized and reported in Technical Development publications.[1,2,3,4,5]

Although the development of new chemicals for soil stabilization was initially considered to be of primary interest to the armed forces, the test results indicated that some of these materials might be of value in normal civilian construction. The evaluation of newly developed materials and combinations has continued, therefore, in the soils laboratories of the TDEC. Summarized in this report is the more significant work completed to date in the field of chemical soil stabilization, both as performed under contract and in the TDEC laboratories. Emphasis has been given to work performed since World War II, but previously unreported work conducted during the war years, especially that performed under contract at Purdue University, also is included.

Throughout this project, close cooperation was maintained with organizations engaged in similar work. At the present time, the Army Engineers Research and Development Laboratories at Fort Belvoir and the Navy Bureau of Yards and Docks are conducting extensive and valuable investigations in the field of soil stabilization. Although their ultimate objectives differ somewhat from those of non-military groups, the fundamental concepts involved are similar. Considerable assistance in this work has been received from the chemical industry and is reflected in the materials sent to us for investigation by various commercial organizations.

MATERIALS TESTED

Soils

In order to test the effectiveness of prospective chemical stabilizing agents upon a wide range of soils, samples were obtained from different locations throughout the United States, with textures varying from sand to clay. The characteristics of the soils used in the TDEC laboratories are shown in Table I and the grain size analysis curves are presented in Fig. 1. The primary physical characteristics of the more important soils used in the testing at Purdue University are shown in Table II. For most of the testing described in this report the -10 fraction of the soil was used. For special work, however, both the -4 and -3/8-inch fractions sometimes were employed. The TDEC soils are designated by letter in order of ascending values of their liquid limit.

Chemical Admixtures

The chemical admixtures used were either commercially available or were sup-

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

[2] George W. McAlpin, R. C. Mainfort and Hans F. Winterkorn, "A Laboratory Study of the Soil Stabilizing Effectiveness of a Complex Salt of Abietic Acid," Technical Development Note No. 35, July 1944.

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

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

[5] R. C. Mainfort, "A Study of the Soil Stabilizing Properties of Tung Oil," Technical Development Report No. 80, April 1948.

plied from laboratory or pilot plant productions. Table III lists the admixtures investigated and their sources of supply. For convenience in presentation these materials have been placed under general headings, although in certain cases there is some overlapping of characteristics. The bulk materials used, such as Portland cement, bitumens and resins were the normally available commercial grades. Reagent chemicals were generally of C. P. grade or higher.

TESTING PROCEDURES

Preparation of Samples

The natural soil as obtained from the field was air-dried, screened and classified according to standard soil testing procedures. Maximum density and optimum moisture were determined by the standard or modified Proctor procedures or both. The selection of either of these compaction efforts for use in exploratory testing appears to be entirely a matter of choice since no change in relative effectiveness of the tested admixtures was noted by the use of either method. With silty clay soils, however, more clearly defined curves were obtained by using the modified compaction effort. In many tests the density as determined for the natural soil was used also for molding treated samples of the same soil. In order to secure properly molded samples when using higher percentages of certain admixtures it was found necessary, however, to use the maximum density as determined with the admixture in the soil. Fig. 2 shows the effect that certain admixtures have on the maximum density and optimum moisture content of different soils as compared with those obtained on identical natural soils. For these determinations the admixture was added to the soil prior to the incremental addition of water and the compaction test conducted in the usual manner. For all of the more significant evaluation tests the moisture-density relationships were determined with the admixture included in the soil and such procedure is recommended where the addition of a chemical materially affects the moisture-density relationship of the soil.

After determining the amounts of soil, admixture and water required to form a specified sample, the proportioned materials were thoroughly mixed, the order and method depending upon the nature of the treatment used. If in a powdered form, the chemical usually was applied to the dry soil prior to the addition of water; if water soluble, it sometimes was added in solution with the mix water. If in liquid form, the material usually was added directly to the previously moistened soil, or if miscible, was added to the mix water. Small batches of materials were mixed by a Hobart paddle type dough mixer, the larger by a Simpson laboratory mixer. For particularly large batches, as used in field test panels, a Lancaster SKG mixer was used. A minimum mixing period of five minutes was used for all tests performed in the laboratory. A better dispersion of the more viscous liquid admixtures usually was obtained if the moistened soil was slaked for several hours prior to the addition of the chemical.

After mixing, the quantity of material required to produce a sample of specified density and size was weighed and placed in a compaction mold. For all the exploratory work and most of the more detailed laboratory studies 2- by 2-inch cylindrical samples were used, molded with the special tamping device shown in Fig. 3. This apparatus permits dynamic compaction of a sample by double piston action, the load being applied to both the top and bottom of the sample. For special laboratory and field tests, where larger samples appeared advisable, 2 1/2- by 4-inch cylinders were used. These were molded in a single layer to predetermined density by the static load method, using a laboratory press for applying the load.

Uniform densities throughout the molded samples usually were obtained by both static and dynamic compaction when the samples did not exceed a height of 2 1/2 inches. Attempts to construct higher samples resulted in a considerable variation in density from the top to the bottom of the sample. Dynamic tamping in several small layers, as used in Proctor molding, produced uniform density but resulted in samples that were particularly susceptible to failure at the compaction planes during weathering.

As both the 2- by 2-inch and the 2 1/2- by 4-inch samples were satisfactory, the smaller sized sample was selected for most of the routine testing in order to conserve labor, materials and storage space.

Where test panels were constructed

for comparing field and laboratory weathering tests, the treated soil was molded to required density by tamping a weighed amount of proportioned material into a form of known volume, using 1 1/2-inch layers. The compactive effort was furnished by a small vibratory compactor, which is shown in operation in Fig. 4.

Curing of Samples

From studies in chemical soil stabilization, it was found that the type and amount of curing allowed a sample, prior to its subjection to exposure, is of considerable importance, and that different types of admixtures react to curing in different ways. The usual methods recommended for curing treated soil samples are: (a) moist-curing, (b) oven-drying to constant weight at temperatures not exceeding 140°F, (c) air-drying to constant weight, or (d) partially drying to a predetermined moisture content. Although all of these methods have been used to some extent during this study it is believed that moist-curing and air-drying more nearly fit conditions likely to be attained in the field. Oven-drying at 140°F is advantageous for obtaining a uniform rate of drying and for attaining a well-defined moisture content from which absorption tests could begin, and to which weathered samples could be returned after testing. For natural soil and certain admixtures oven-drying is suitable, but for other materials, particularly bitumens and resins, the application of heat at 140°F over the period necessary to completely dry a sample results in an improvement to the treatment that cannot be duplicated under normal field construction procedures. For this reason, curing the samples at higher than normal room temperatures was, with the exception of earlier tests, eliminated from consideration in evaluating chemical admixtures.

A partial drying back of the sample, either by moist- or air-cure, is probably nearer to the field conditions likely to be attained but is very difficult to control and duplicate in the laboratory. It should be realized, in this connection, that actual curing conditions to be expected in the field are extremely variable depending upon general and specific weather conditions, soil types, drainage and other factors. For the purpose of studying the waterproofing as well as the bonding characteristics of the chemical treatments, emphasis was placed on air-drying the samples in most of this work. The effects of both moist- and air-curing, however, were investigated for all treatments. Materials which were known to require moist-curing for proper hardening, such as Portland cement, were moist-cured prior to air-drying.

Evaluation of Unweathered Samples

Immediately after curing and prior to laboratory or field exposure, control samples of both treated and untreated soil were broken in compression, at a uniform rate of loading, by an electrically operated hydraulic testing machine. The usual method for obtaining unconfined compression strength of the samples is shown in Fig. 5. A close-up view of the special equipment used for obtaining the partially confined compressive strength of the 2 1/2- by 4-inch samples, loading normal to the edge, is shown in Fig. 6. The device used for confining the sample is part of the equipment provided with the Marshall stability apparatus[6] as used for testing the stability of bituminous mixtures.

The compressive strengths of the unweathered samples were used to determine the relative bonding action of different treatments, to compare treated soils with identical non-treated soils, and to determine the deterioration of the samples due to exposure by comparison of their weathered and non-weathered strengths.

Laboratory Weathering Tests

Other than the procedures used for evaluating the effectiveness of soil-cement, there are no recognized standard procedures for testing the durability of chemically treated soil samples at the present time. A Bituminous Producers Co-operative Research Committee has recommended certain procedures for testing soil-bituminous combinations, but the proposed test methods vary for the particular type of admixture used and are concerned with only one form of laboratory exposure, moisture absorption.[7]

In many of the earlier investigations of

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[6] This apparatus is designed and distributed by the Marshall Consulting and Testing Laboratories, Jackson, Miss.

[7] A. S. T. M. Designation: D915-47T.

soil stabilizing materials very mild exposure tests were used, the treated samples in some cases being subjected to only a few hours of capillary absorption or immersion. Certain materials tested in this manner appeared to have stabilizing properties which, under more severe laboratory or field exposure, proved to be merely temporary.

As additional test data became available the trend was toward more severe laboratory testing procedures. Observation of field results indicated that a properly stabilized soil should be able to withstand not only moisture absorption but also freezing and thawing, wetting and drying or other temperature variations in the presence of moisture. In earlier test work, it was considered unnecessary to design stabilized mixes to resist freezing and thawing if they were to be used in non-freezing areas. Laboratory tests conducted during this investigation have shown, however, that a cooling and warming test conducted in a manner similar to the usual freezing and thawing test, but using a minimum temperature of +35°F rather than -10°F, is almost as destructive as the freezing and thawing test, and is much more severe than an absorption test.

As a result of comparative laboratory and field studies described in this report a laboratory procedure for evaluating chemically stabilized soil samples was developed. After the samples are molded to a selected density and allowed to cure either in air or in a moist cabinet they are subjected to the following successive exposures:

1. Three-day capillary absorption in a moist cabinet.
2. Four-day immersion.
3. Twelve cycles of alternate freezing at -10°F for 8 hours and thawing in immersion at room temperature for 16 hours.
4. Twelve cycles of alternate wetting by immersion for 8 hours and oven-drying at 140°F for 16 hours.
5. Seven-day immersion.

The selection of the sequence used in this testing procedure was made in an effort to closely approach the most detrimental field weathering conditions to be expected. Thus, the samples were thoroughly soaked prior to the freezing and thawing test, a condition which is likely to occur in the field. The wetting and drying test followed the destructive action of freezing and thawing in order to minimize the possible beneficial effects imparted to some chemical treatments by the heating required during the drying cycle of this exposure. When used in this manner the wetting and drying test proved to be progressively destructive even to those samples which benefit from the application of heat at the beginning of exposure. Immersion, subsequent to the wetting and drying test, was found to be necessary in order that test samples might be rewetted to a degree comparable to that existing before application of the drying cycle of the wetting and drying test. Although capillary absorption by itself is not a sufficiently severe test for accelerated laboratory exposure, it is believed to be a natural method for beginning the moisture absorption portion of the exposure test, particularly when air-dried samples are used. The severity of the immersion test on a dry sample is clearly shown in the alternate wetting and drying cycles of the exposure test.

The combined form of exposure test has been used during this study for all of the severe laboratory testing, unless specifically described otherwise. The various operational procedures for this test are shown in Figs. 7A, B, C and D.

Field Weathering Tests

The chemical stabilizers which the laboratory test results indicated to be the most promising were subjected to field weathering exposure. In this way not only were the more promising treatments evaluated under field conditions, but the applicability of the laboratory test procedures could be partially determined. For the field weathering tests, samples duplicating those tested in the laboratory, both in construction and curing, were buried flush with the ground with no cover and allowed to weather for certain specified periods of time, usually for one, two or three years. Fig. 8A shows a section of the buried samples as placed in a field test plot. The samples were examined, and in some instances weighed, periodically during exposure.

In addition to the buried cylindrical samples, small test panels of treated soil were constructed for auxiliary weathering tests. Fig. 8B shows a general view of some of the areas, 2 by 2 feet by 4 inches deep, which were compacted as shown in Fig. 4.

Similar field tests were made at Purdue University for evaluating different chemical admixtures. In that case, however, two test areas were used, one a well-drained location in which the samples were buried in sand, and the other a poorly drained location in which the samples were buried in a plastic soil. In our work only one test plot was used, a level graded area of natural, silty clay soil.

Evaluation of Weathered Samples

At the conclusion of the laboratory and field exposure tests the surviving samples were broken in compression as described previously. The compressive strengths of the weathered samples were compared with those obtained for similarly treated and untreated unweathered samples. These values were used as a relative index of the effectiveness of the different treatments. The samples were weighed after molding, after curing, periodically throughout their exposure and at the end of the testing. Dry weights were obtained for all samples either after breaking or at their point of failure during exposure. From these data the moisture content of the samples during the testing could be studied. The appearance of the sample during the testing, the moisture absorption characteristics, and the breaking load were used to evaluate the relative merits of the different admixtures.

In the tests performed at Purdue unconfined samples also were broken in compression at a constant rate of loading, but the load was applied through a 3/4-inch circular plunger placed concentrically on the top of the sample.

Field test panels were evaluated by visual inspection and simple penetration measurement.

TEST RESULTS

The over-all testing of prospective soil stabilizing agents as described in this report has covered a considerable period of time and, with some of the materials, has been the work of different investigators. For this reason, and because of the fact that uniform test procedures were not always employed, much of the exploratory and earlier work is presented in qualitative form.

Specific test results which demonstrate the typical effectiveness of different admixtures with various soils are presented in a series of tables and photographic reproductions. These data include the results of comprehensive laboratory and field tests in which the more promising admixtures were tested with representative soil types or with those soils that offered particular stabilization problems. No specific data concerning weathered untreated samples are shown because all of these failed early during exposure.

Some of the admixtures have been previously evaluated and reported in detail but are reviewed here in the light of more severe and controlled exposure tests and for the purpose of comparison with newer materials under identical test conditions.

In studying the test results it should be realized that many of the commercial materials investigated were not developed primarily for soil stabilization use and that the results obtained in this connection do not necessarily reflect the effectiveness of these materials when used for other purposes.

Exploratory Tests

All of the materials investigated as possible soil stabilizing agents were subjected to preliminary testing prior to large scale evaluations in order to determine their promise in this field. In some cases the preliminary testing was conducted in considerable detail, while in others a material was eliminated from further consideration after brief indicator tests.

The proposed admixtures were tested with at least two soils using quantities normally ranging from one to five per cent of the dry weight of the treated soil or quantities specifically recommended by the producer. Both moist- and air-cured samples were used. All of the exploratory testing included some form of absorption, freezing and thawing, wetting and drying or a combination of these tests.

A summary of the qualitative results obtained from the exploratory testing is included as part of Table IV. The degree of effectiveness as expressed in this table is based on average results obtained from all soils tested. For specific soils the classification could be modified in certain cases.

Experimental work also was conducted

in an attempt to improve the stabilizing effectiveness of the more promising or more available admixtures by the addition of small quantities of a second chemical. These additives were usually applied in quantities ranging between two and ten per cent of the weight of the basic stabilizer. Table V shows the qualitative effectiveness of several additives as used with five primary admixtures. These data are based upon average test results obtained with several soils.

Severe Laboratory and Field Tests

In addition to the exploratory tests discussed previously, Table IV also includes a summary of the qualitative results obtained from the more severe laboratory and field testing. These tests included the more promising materials as indicated by the preliminary tests as well as those conventionally used for soil stabilization such as Portland cement and various bitumens.

Table VI summarizes in a more quantitative form the test results obtained when 2- by 2-inch air-dried samples of six treated soils were subjected to progressive laboratory exposure. The unconfined compressive strength and moisture content, after a complete series of exposures, are listed in the table. When complete deterioration occurred before completion of the test, the table shows the point at which it occurred. The exposure of soils B, F and H was less severe than that to which the other soils were subjected, the freeze-thaw and wet-dry portion of the test in these cases having been reduced from 12 to 6 cycles each.

Figs. 9 through 11 are photographic reproductions which illustrate the progressive deterioration of treated 2- by 2-inch air-dried samples of soils C, D and I, due to the laboratory exposure. The blank spaces in some of the illustrations indicate that the samples failed during exposure.

The three soils used were obtained from widely scattered sites in the United States and a considerable variation can be seen in the reaction of these soils to treatment. This is particularly true of soils C and D which reacted differently to a basic grouping of admixtures. Soil C, for example, was very susceptible to cement treatment but was benefited only slightly by most resins. Soil D, on the other hand, was particularly benefited by resin treatment but could not be stabilized with cement. Soil I was intermediate in its reaction to the stabilizers.

Table VII and Fig. 12 show the results of initial testing to determine the effectiveness of certain soil treatments under both laboratory and field exposure and to compare the relative severity of field and accelerated laboratory weathering. Eight representative soil treatments were used with two soil types, a sandy clay loam (soil B), and a clay loam (soil F). All samples were 2 1/2 by 4 inches and were oven-dried to constant weight at a temperature of 140°F prior to testing. The laboratory portion of this test, conducted prior to the development of the progressive exposure test used in most of this study, consisted of two individual exposures. A portion of the samples was tested in unconfined compression after 10 and 30 days of capillary absorption only, the remainder after 10 days of capillary absorption plus 10 and 30 cycles of alternate freezing and thawing.

Cement plus Montar No. 3, cement plus Aroclor 4065, aniline-furfural, and to a lesser degree, cement alone, were the only treatments able to successfully withstand both laboratory and field exposure in this test. Aniline-furfural was particularly effective with soil F under field exposure. In this test, however, it should be mentioned that although the cement-treated samples failed by splitting into sections, each portion in itself was firm and capable of withstanding considerable load application. The compressive strengths shown for these samples were obtained using the largest portion of the split sample.

Although the laboratory and field exposure results shown in Table VII were both indicative of the general effectiveness of the different admixtures tested, no quantitative correlation between the two was obtained.

Table VIII presents the results of continued laboratory and field comparative tests in which a clay loam (soil C) was treated with 14 admixture combinations. The progressive exposure test, adopted for use in this study, was used for the laboratory portion of this test. Both 2 1/2- by 4-inch and 2- by 2-inch samples were used, and 2- by 2-foot test panels were weathered concurrently in the test plot with the buried cylindrical samples. These data, in addition to showing the relative merit of the admixtures tested, also show good correlation between the results obtained with the 2- by 2-inch and the 2 1/2-

by 4-inch samples. Also, with the exception of the aniline-furfural samples, a good coordination was obtained between laboratory and field results for similar samples. The appearance of the 2 1/2- by 4-inch samples before testing and after laboratory and field exposure can be seen in Fig. 13. For all treatments with the exception of asphalt emulsion and MC-2, where the laboratory tests were more severe than the field exposure, (due primarily to their particular susceptibility to the detrimental effects of immersion) the appearance of the samples indicates equal severity between the laboratory and field tests. The same comparison holds true for the 2- by 2-inch samples.

Fig. 14 shows the condition of the 2- by 2-foot by 4-inch deep field test panels of soil C, treated with eight admixture combinations, after one winter of field exposure. Due to a limited quantity of admixtures some of the treatments were placed two in a panel. The rough and broken edges of the treated sections are due to removing the wooden forms. The test panel, treated with five per cent aniline-furfural, Fig. 14A, had a hard crust on the top which, although quite firm, could easily be penetrated by scraping with a spoon. Beneath this surface, the soil was dry but quite loose. The dark area visible on this section was due to moisture trapped on the surface during a rain which fell 24 hours prior to taking the photograph and which was unable to penetrate the treated soil during that time. This is an indication of the excellent water-repellency of the aniline-furfural treatment. Fig. 14B shows a section treated with five per cent Resinox plus hexamethylenetetramine. The top 1 1/2 inches of this panel were very loose and could easily be scraped away. Below this point, however, the treated soil was quite firm. Figs. 14C and D show the panels treated with five per cent asphalt emulsion and MC-2 respectively. Both of these panels were further treated with 0.2 per cent of Aggrecote 600 added to the soil prior to the addition of the bitumen. These sections were very poor and the entire depth of the panel could easily be penetrated with a ruler and scraped away with a spoon. The section treated with five per cent Amberlite PR-115 plus hardener, shown in Fig. 14F, was the most uniformly stable of the resinous treated panels. Although the surface could be removed by hand scraping to a depth of one-half inch, it could not be penetrated by the ruler and the rest of the section was quite firm. The sections containing cement and cement treated with 0.6 per cent Piccolyte S-125 and Piccoumaron XX-100 all were very hard and by far the best of the treated panels. No difference between the plain cement and the treated cement panels was apparent.

The weathering of these test panels was similar, in general, to that of the concurrent weathering of the buried cylindrical samples.

Table IX gives a summary of the more significant field and laboratory results obtained at Purdue University during its TDEC contract investigation of various soil stabilizing agents. Standard Proctor and 6-inch high and 4-inch diameter test samples, using the -4 fraction of the soils, were used for this work. All samples were oven-dried to constant weight at a temperature of 140°F prior to testing.

The results indicate that six per cent treatment of aniline-furfural was the best admixture used in this group. Field exposure of the samples was conducted for 1-, 2- and 3-year periods. Only the 3-year results are presented in the table, however, as these, in general, reflect or amplify the failure trends noted for the shorter periods. The field test panels used at Purdue were five feet square and six inches deep, constructed of gravelly, sandy loam soil. Five different treatments were used: Six per cent SC-3, six per cent aniline-furfural, six per cent asphalt emulsion, ten per cent Portland cement and ten per cent Portland cement plus five per cent Vinsol. The section treated with aniline-furfural was outstanding, showing very little deterioration during the three years of weathering. The cement panel remained firm except for scaling of the top inch or so, but the cement plus Vinsol was poor. All panels of the other treatments failed completely. In general, the results obtained with the test panels were in agreement with those obtained for similarly treated buried samples.

Effect of Sample Size on Resistance to Exposure

Several sizes of samples have been used in the TDEC soil stabilization studies and those conducted by other investigators. In order to determine the effect of this variable on resistance to weathering, tests were conducted in which different sizes of similarly treated samples of the same soil were subjected to identical laboratory and field exposure. For this purpose, 15 batches of soil C were prepared, each treated with a different admixture combination. From each batch three different sizes of cylindrical samples were molded to equal densities: (1) 2-inch height and 2-inch diameter; (2) 3 1/2-inch height and 2 1/4-inch diameter; and (3) 2 1/2-inch height and 4-inch diameter. The 2- by 2-inch samples were molded dynamically, the two larger sizes by the static method. Three samples of each size and treatment were subjected to identical curing and laboratory and field exposure. Figs. 15 and 16 show the appearance of a representative group of treatments for the three different sized samples after laboratory and field exposure. These photographic reproductions clearly indicate that the resistance of the samples to weathering was not affected by their size. These results are further confirmed by the data shown in Table VIII in which the breaking loads of two sizes of samples of soil C, treated with similar admixtures, show the same relative values when compared with the loads resisted by comparable unweathered samples. These results indicate that the 2- by 2-inch samples are as satisfactory for comparative testing as are larger samples, or those having a greater height-to-diameter ratio. Evaluation of the smaller samples requires a severity of exposure equal to that required for testing larger samples.

DISCUSSION OF INORGANIC CEMENTING MATERIALS

Several inorganic cementing materials studied in this work were capable of hardening or bonding soil but none imparted appreciable waterproofing characteristics to the resultant structure. Although a soil that has been successfully bonded will absorb considerably less moisture than the same untreated soil, this is usually due to the inability of the bonded sample to swell rather than to any waterproofing action of the treatment.

A relatively high percentage of an inorganic cementing agent (ten per cent or more) is normally required for properly bonding a soil. Smaller quantities of materials of this type, however, are sometimes effective in improving the usefulness of a soil by modifying its physical and chemical characteristics. Portland cement, lime, sodium silicate and crushed slag are particularly effective in reducing the plasticity of fine-grained soils.

All soil samples treated with inorganic cementing materials were susceptible to moisture attack, especially under freezing and thawing conditions.

Portland Cement

Portland cement probably has been used more widely and with greater success than any other soil stabilizing material, and its properties in this respect have been reported by numerous investigators. Although an excellent bonding agent for many soils, Portland cement does not impart water-repellent characteristics to the treated soil, and under certain climatic conditions, especially where wide temperature variations prevail, has not always proved to be a durable admixture. In addition to the highly plastic soils, which are not recommended for cement treatment, there exist certain soils of good physical characteristics which cannot be successfully stabilized with cement.[8, 9] Soil D used in this study, is a "problem soil" of this type with which no reasonable amount of cement was effective.

The prime reason for including cement in this study was not to further evaluate soil-cement mixtures, but to attempt their improvement by the addition of other admixtures which might result in a more generally applicable and durable treatment. A treatment whereby the excellent bonding properties of cement could be augmented by water-repellent characteristics would be desirable.

All of the cement used was obtained from fresh supplies and was screened to pass a No. 200 sieve prior to mixing with the soil. Some variations in the stabilizing effectiveness of cement obtained from different sources

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[8] Miles D. Catton and E. S. Felt, "Effect of Soil and Calcium Chloride Admixtures on Soil-Cement Mixtures." Proc. Highway Research Board, Vol. 23, pp. 497-529.

[9] Soil-Cement Mixtures - Laboratory Handbook, Portland Cement Association (1950).

were noted, the causes of which are not known. For tests in which special additives were applied to the soil-cement mixture the moist-curing time was varied from 7 to 28 days in order to determine the actual permanent stabilizing effect of the additional admixtures rather than their possible high-early strength-producing value.

The qualitative results of exploratory tests to determine the effectiveness of different admixtures with soil-cement are given in Table V. Some of the promising combinations were later subjected to more thorough testing while others remain to be investigated further. Many of the additives, although promising in the exploratory work, were not effective when subjected to more severe laboratory and field exposure. The effectiveness of the admixtures applied to soil-cement varied with the type of soil used. The most beneficial, expressed in terms of their effectiveness over a wide range of soils, were Resin 321, Aroclor 4065, Montar No. 3, Piccolyte S-125, Piccoumaron XX-100, Monsanto CRD 108-133-155 and Santo Resin. Some of these treatments are included in the severe exposure test data presented in Tables VI through IX and Figs. 12 through 13. As can be noted, none of the improvements were large and their effectiveness varied with different soils and test conditions. Considerably more data are required before the results can be considered conclusive.

Although the results at Purdue showed the effect of Resin 321 to be detrimental rather than beneficial, this has not been borne out so far in our investigations. The poor showing at Purdue may have been due to the large quantity of resin used (20 per cent by weight of cement) or to the oven-drying of the samples prior to testing.

Stabinol, containing 80 per cent cement, was beneficial only to the extent of the added cement. An extensive field test, using soil G, in which Stabinol was mixed with cement in varying ratios, clearly indicated that no benefit was obtained from the resinous portion of Stabinol. Vinsol, NVX, a commercial powdered rosin, natural resins and partially neutralized Vinsol and natural resins, proved to be detrimental to the stability of soil-cement mixtures.

Considerable attention was given to the use of oleic and stearic acid and the salts of these organic acids for waterproofing soil-cement but, although temporary water-repellency was obtained, none were significantly effective when subjected to severe exposure. In some cases the use of stearates reduced the strength of the soil-cement mixture. Calcium and magnesium stearate were the most effective of these materials.

Slight improvement to soil-cement was obtained by the addition of several inorganic chemicals including sodium silicate and potassium permanganate. Calcium and sodium chloride were detrimental under severe exposure, and the addition of bituminous materials to soil-cement was detrimental in all cases.

A considerable number of admixtures were used in an effort to improve the reaction of soil D to cement treatment. Sterox LF-87 was particularly effective in this respect. Resinox 9672, Resin 321, and, to a lesser degree Piccoumaron XX-100 and Montar No. 3, also were beneficial. Resinox 9672 was very detrimental when added to cement-treated samples of soils other than D. Studies of the reaction of cement with soil D are being continued.

The Purdue laboratory and field results and those of the TDEC with soils B and F (Tables VII and IX and Fig. 12) indicate a need for improving soil-cement treatments. The poor results obtained in these tests, however, with the exception of the Purdue test plot, appear to be due to the oven-drying of the samples (after 7-day moist-curing) prior to exposure. Other tests conducted during this study have indicated that moist- or air-cured samples of cement-treated soils are superior to oven-dried samples.

Most of the admixtures used with soil-cement, when added in quantities ranging from one to ten per cent of the weight of cement, showed no well-defined optimum effective ratio of additive to cement. For comparative purposes an arbitrary value of five per cent, by weight of cement, was selected for all treatments unless otherwise shown. With or without additional admixtures cement proved to be the most generally satisfactory stabilizing agent investigated. Additional study that might extend its usefulness appears fully warranted.

Lime

A considerable amount of work has been conducted by various investigators to determine the suitability of lime (slaked) as a soil stabilizing agent. All of the results of tests performed with lime during this study were negative. Some bonding of the soil was obtained with treatments of six per cent and higher, but the samples were particularly susceptible to the disintegrating action of alternate freezing and thawing. The addition of lime considerably modified all of the soils tested. Plastic soils, in particular, when treated with lime, were much easier to mix uniformly, and mold to required density than were the same soils when untreated. Numerous admixtures were used in an effort to improve the soil stabilizing characteristics of lime but none proved to be particularly effective under prolonged exposure. Salicylic acid and zinc stearate were the most effective. Field samples treated with lime failed completely during one winter of exposure. Tables VI and VII, and Figs. 9, 10 and 11 show specific test data for soil-lime mixtures.

Sodium Silicate

The use of sodium silicate is another method for solidifying soils which has received considerable attention. Good bonding of sandy soils has been attained with treatments of six per cent or more of sodium silicate, but such treatments will not withstand attack by moisture. Very little effectiveness was obtained by the application of sodium silicate to fine-grained soils. Earlier studies[10] indicated that the addition of sodium aluminate greatly increased the resistance of the sodium-silicate sample to moisture attack but later tests, using a variety of soils and more severe exposure tests, have clearly shown this combination to be unsuitable as a soil stabilizing agent. Some improvement was obtained by adding small percentages of magnesium stearate, Aroclor 1271, stearic acid and triethanolamine individually to the sodium-silicate-treated soil but none of these were significantly effective under severe exposure conditions.

The most suitable form of sodium silicate for soil stabilization purposes found in these studies was a 40 per cent solution, 40-42° Be , with a $Na_2O:SiO_2$ ratio of 1:3.25. Table VI and Figs. 9, 10 and 11 show the effectiveness of a 14 per cent treatment of this solution.

Unless a very successful additive should be found, sodium silicate cannot be considered a suitable soil stabilizing agent for paving purposes.

Combinations of sodium silicate and a strong inorganic salt such as calcium chloride have been used successfully for stabilizing medium and fine sand masses in deep foundation construction. In this method the two chemicals (usually applied separately by pressure injection) react within the sand pores to form an impervious gel which upon hardening binds the sand particles into a solid mass. Sodium silicate alone, and in combination with other chemicals, has also been used to temporarily harden sandy soils to such an extent that excavation work could proceed without the use of shoring.

Powdered Slag

Two samples of powdered slag were furnished for testing by the National Slag Assoc. This material is similar in appearance to Portland cement, but it provided only slight bonding when mixed with soils in quantities up to 20 per cent. Combinations of crushed slag and various resins also were ineffective. The addition of small quantities of crushed slag considerably modified the characteristics of the more plastic soils. In this respect the admixture reacted with the soil in a manner similar to cement and lime, reducing the plasticity and allowing the soils to be more uniformly and easily mixed.

Other Additives

Inorganic soluble salts such as sodium, calcium and barium chloride, and copper and barium sulfate, were ineffective for soil stabilizing purposes as required in this study. Calcium chloride and sodium chloride have been used successfully, however, to enable granular stabilized roads to retain a moisture content beneficial to stability and to facilitate further densification of the road under the action of traffic. Oxychloride cement, zinc oxide and plaster of Paris did not set up well when mixed with soils in the quantity allowed in this study. Natural and air-entrained cements were not as effective as Portland cement.

[10] See footnote 3.

DISCUSSION OF BITUMINOUS MATERIALS

Bituminous materials have been used extensively for soil stabilization, and their properties in this respect have been thoroughly investigated in the laboratory and field by numerous agencies. A brief summary of the methods used for testing and applying these materials has been compiled by the Highway Research Board.[11]

None of the bituminous materials used in the TDEC study were particularly effective. It was very difficult to obtain a thorough mixture of the bitumens and the finer grained soils, even though mixing methods recommended by the individual producers were followed closely. In an effort to determine the most effective procedure the bitumens were added to the prepared soil under the following conditions: (a) air-dried soil, (b) soil at optimum moisture, (c) soil above optimum moisture (near liquid limit) and (d) soil at different intermediate moisture contents.

In all cases the moistened soil was allowed to slake for a period of 24 hours prior to adding the bitumen. None of these variations in mixing procedure appeared to improve the resulting stability of the samples, although visual inspection indicated that more nearly uniform dispersion was obtained when the bituminous materials were added to the soil at a moisture content well above optimum and mixed in slurry form. In this case, the mixtures were dried back to near optimum moisture before molding. All of the bitumens provided a certain degree of water-repellency to the treated soil but the test samples were particularly susceptible to the destructive action of alternate freezing and thawing. Some treatments began failure early in the absorption portion of the laboratory exposure test.

The emphasis in this study was placed on attempts to improve the effectiveness of the different bitumens and to extend their stabilizing usefulness to cover a wider range of soils - particularly the fine-grained soils.

Cut-Back Asphalts

The cut-back asphalts used in this study were MC-1, MC-2, RC-2 and SC-3. MC-2 and RC-2 were the most suitable, although not very effective. MC-2, in quantities of eight per cent, was able to withstand the severe laboratory exposure test with soils D and I. MC-2 and RC-2 significantly improved soil B, when used in quantities of five per cent. The effectiveness of the asphalt was increased by the addition of Amberlite PR-115 plus hardener, Resinox 9673 plus "hexa", slaked lime, aniline-furfural, Lauxite RF-901, Aggrecote 600 or zinc stearate. The additives were applied individually to the bitumen-treated soil in quantities of 20 per cent by weight of bitumen. Slaked lime, Lauxite RF-901, Amberlite PR-115, Resinox 9673 and aniline-furfural were the most promising combinations and these will be investigated further.

SC-3 (road oil) was tested at Purdue and gave promising results when used with granular soil, but was not effective with finer grained soils. Tables VI, VIII and IX and Figs. 9, 10, 11, 13 and 14 show the relatively poor laboratory and field results obtained with soil-asphalt combinations.

Asphalt Emulsion

With the exception of soil B, none of the soils tested by Purdue or the TDEC could be successfully stabilized with asphalt emulsion, even when quantities as high as 25 per cent were used. Although the emulsion was easy to apply and mixed well with the soils, very few treated samples could withstand even the less severe form of exposure test.

Considerable effort was made to improve the asphalt emulsion treatment by the addition of other admixtures, the most promising of which were Amberlite PR-115 plus hardener, Resinox 9673 plus "hexa", aniline-furfural and slaked lime. All of these treatments were added in quantities of 20 per cent or less of the weight of the emulsion. Tables V, VI, VIII, IX and Figs. 9, 10, 11, 13 and 14 show specific laboratory and field test results obtained with different quantities of treated and untreated asphalt emulsion. Of particular interest is the excellent effectiveness of Amberlite PR-115 plus hardener with five per cent asphalt emulsion applied to soil B, a sandy clay loam, as indicated in Table VI. This treatment was not as effective, however, with the finer grained soils.

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[11] Soil Bituminous Roads, Current Road Problems, No. 12, Highway Research Board Publication (Sept. 1946).

Powdered Asphalt

The test work performed at Purdue indicated that some stability was imparted to a granular soil by the use of equal quantities of powdered asphalt and kerosene. This combination was not effective, however, with the more plastic soils tested.

Road Tar

None of the road tars used in this study proved to be generally suitable as soil stabilizing agents, although TM-2 (Federal specification corresponding closely to RT-6) was effective with one granular soil. RT-3, RT-5 and RT-8 were not effective with the soils studied. Two forms of tar emulsion furnished by the Reilly Tar and Chemical Co. also were ineffective for stabilizing soils. No admixtures were found which would increase the effectiveness of tar as a soil stabilizing agent.

DISCUSSION OF RESINOUS WATERPROOFING MATERIALS

For the purpose of soil stabilization, resinous waterproofing materials are considered to be those natural or synthetic resins whose chief function is to maintain the moisture content of a soil at or below optimum moisture by preventing entry of water into the treated and compacted mixture. Very slight or no cementing action is obtained from these materials. Unlike the bonding agents, whose effectiveness increases with the quantity used, waterproofing agents usually attain maximum effectiveness when used in small quantities - two per cent or less by weight of the treated soil.

Although imparting desirable characteristics to the soil, and providing considerable waterproofing effect under mild exposure, none of the water-repellent resins appears to be a suitable soil stabilizing agent at the present time. Tables VI and IX and Figs. 9, 10 and 11, show the relative effectiveness of the most important of these materials. It has been suggested that soil bacterial activity may have a detrimental effect on the permanency of organic soil stabilizers such as bituminous and resinous materials.[12]

A considerable amount of laboratory and field testing of resinous waterproofing materials has been conducted by the Corps of Engineers.[13]

Stabinol

Stabinol is composed of 75 per cent Portland cement and 25 per cent of a complex resinous compound. When used in the small quantities recommended by the producer, the cement fraction cannot impart appreciable bonding to the treated soil and acts only as a carrier for the resinous material and as a possible modifier for the soil to allow more effective use of the resin. A maximum of two per cent treatment usually has been recommended for water-repellent purposes.

A considerable amount of laboratory testing of Stabinol was conducted in the TDEC laboratories and at Princeton and several small test roads, treated with Stabinol, were constructed by the CAA regional offices.

Initial laboratory tests were quite promising. In further studies, however, involving field testing, more severe laboratory exposure and the use of a wider range of soils, Stabinol was not effective unless applied in sufficient quantities to enable the cement fraction to become active as a bonding material. Used in larger quantities, however, Stabinol cannot be considered as strictly a waterproofing material. Soils A, B, E and G were the most susceptible to Stabinol treatment. Later tests indicated that the effectiveness of Stabinol was considerably reduced by long storage.

Stabinol is no longer produced as a soil stabilizing agent.

Resin 321

The effectiveness of Resin 321 as a soil stabilizing material has been previously reported by the TDEC,[14] and also by the Corps of Engineers.[15] Tests conducted by the TDEC subsequent to the publishing of these reports continued to show that Resin 321 is the best of the waterproofing agents studied and that its water-repellent characteristics can be utilized for improving the

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[12] Hans F. Winterkorn, "A Fundamental Approach to the Stabilization of Cohesive Soils." Proc. Highway Research Board, Vol. 28, pp. 415-422. 1948

[13] "Resinous Water Repellents for Soils" Technical Memorandum No. 217-1, U. S. Waterways Experiment Station, May 1946.

[14] See footnotes 1 and 2.

[15] See footnote 13.

effectiveness of other stabilizing materials. However, the beneficial qualities of Resin 321 are reduced considerably under severe laboratory and field exposure. The soils most susceptible to treatment (A, B, D and E) could not be stabilized successfully with Resin 321 under field exposure.

Like Stabinol, Resin 321 is no longer produced for soil stabilization purposes.

Vinsol and NVX

Vinsol and NVX (a neutralized form of Vinsol) are powdered resins which, like Stabinol and Resin 321, function to impart water-repellent characteristics when mixed with soils. With the soils used in this study, Vinsol was superior to NVX but far inferior to both Stabinol and Resin 321.

Vinsol resin completely and partially neutralized by potassium hydroxide and by sodium hydroxide was prepared by Dr. Winterkorn at Princeton but none of the resins were particularly effective. Vinsol and NVX were tested in powder and slurry form and with various additives including caustic soda, alcohol, acetone and other organic solvents but no appreciable improvement in their effectiveness was noted.

Laboratory and field testing of Vinsol and NVX also has been reported by the Corps of Engineers.[16]

Others

A considerable number of natural and partially neutralized natural resins were investigated at Princeton, including Belro, Congo and Manila Copals, Kauri, Batavia Damar and Elemi resins. All of these were slightly beneficial as soil waterproofing agents but are recommended only for temporary emergency use in areas where they are locally available.

Other resinous materials tested, none of which were particularly effective, were Soilpak (approximately seven parts of lime to one resin), Valite (a sugar resin), commercial powdered rosin, lignin sulfate and partially neutralized Tall oil.

DISCUSSION OF RESINOUS BONDING MATERIALS

Resinous bonding materials, as applied to soil stabilization, are considered to be those synthetic resins which cement or bond the particles of soils with which they are mixed. Some of these resins also are good water-repellent materials. Approximately five per cent of the resin was arbitrarily selected as a maximum treatment in most of these studies but testing of higher percentages indicated that the effectiveness of the resin treatment increased with the quantity used. Some of these materials showed considerable effectiveness when used in quantities of less than five per cent. Although several of the synthetic resins have shown considerable promise as soil stabilizing agents this form of treatment is still in experimental stages. The present high cost of such materials, as compared to conventional methods of soil treatment, is an important factor to be considered in their possible use as soil stabilizing agents. Initial phases of the work with synthetic resins have been reported by the CAA and other agencies.[17, 18, 19]

Aniline-Furfural Resin

The soil stabilizing properties of the resin formed by the interaction in the soil of two parts of aniline and one part of furfural has been thoroughly investigated and reported.[20] Since the publication of the original data considerable work has been performed in the TDEC laboratories to study further methods of utilizing this treatment; to evaluate its effectiveness by means of severe laboratory and field exposure; and to determine the influence of various catalysts[21] on the effectiveness of the basic admixture.

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[16] See footnote 13.

[17] See footnote 4.

[18] Lewis B. Olmstead and L. W. Klipp, "Chemical Stabilization of Soils for Military Uses" U. S. Department of Agriculture Research Report No. 22, May 10, 1944.

[19] Vincent B. Smith, "Army, Navy Release New Data on Chemical Soil Stabilization." Engineering News Record Vol. 144, No. 11, pp. 23-24, March 16, 1950.

[20] See footnote 4.

[21] In this report the term "catalyst" is used, as it is in the plastics industry, to describe materials which harden or accelerate the setting of resinous materials. In this case the catalyst actually takes part in the resin-forming reaction.

Since aniline and furfural begin reaction upon contact it is necessary to add the chemicals to the soil separately. The maximum stability of treated samples was attained when either of two methods of application was used: (a) the two chemicals added separately to the soil after the required mix water had been incorporated and (b) the two chemicals added to the dry soil in separate portions of the required mix water.

Unless special catalysts were used, the reaction between aniline and furfural in moist soil was slow, treated samples being easily molded within at least eight hours after mixing, indicating that little "set" of the mixture had taken place. Samples which were moist-cured prior to testing were always greatly inferior to those permitted to air- or oven-dry, indicating that complete resinification of aniline and furfural does not take place under moist-cure conditions.

The laboratory and field testing results shown in Tables VI through IX, and Figs. 9 through 14, corroborate earlier findings which showed that aniline-furfural, under air-dry conditions, is one of the best soil stabilizing agents. In tests where aniline-furfural treated soil samples were oven-dried prior to exposure they proved superior to those treated with even higher percentages of cement. This was particularly true in the Purdue tests, where not only the oven-dried samples of aniline-furfural but also the undried test panel of aniline-furfural weathered far better than the corresponding samples and test panel treated with higher percentages of cement.

Aniline-furfural proved to be an effective bonding and waterproofing agent over a wide range of soils but the degree of effectiveness varied with the particular soil treated. Soil D was very susceptible of this form of stabilization, while soil C was difficult to treat successfully. The laboratory exposure tests were more detrimental to aniline-furfural treated samples of soil C than was field weathering. This was the only soil and treatment that reacted in this manner.

Numerous catalysts were added to the aniline-furfural treatment and studied in an effort to improve the effectiveness of the resin treatment. The preliminary results obtained with some of these are included in Table V. Under more severe laboratory exposure and over a wide range of soils, several additives applied in quantities of ten per cent by weight of resin, were effective, particularly CRD 155 (a resin emulsion) potassium dichromate, copper sulfate, ammonium chloride, Santo Resin, NVX and Valite. Magnesium and calcium stearate, ferric chloride, Aroclor 1271, zinc sulfate, Montar No. 3 and chlorosulfonic acid were effective but to a lesser degree. The more promising of these additives are being investigated further.

Furfural plus aniline sulfate and furfural plus aniline chloride were very effective, but to a lesser degree than furfural plus aniline. Two parts of aniline sulfate to one part furfural was the most effective of these combinations.

Aniline-furfural mixture at the present time costs about 15 cents per pound and is the cheapest of the synthetic bonding resins studied. Aniline, being toxic, must be handled with considerable care.

Resorcinol-Formaldehyde Resin

A resorcinol-formaldehyde resin, designated Amberlite PR-115, furnished by the Resinous Products Division of the Rohm and Haas Co. was found to be the best synthetic resin for hardening soil under moist-cure conditions at room temperature. Samples treated with this material and stored in a moist cabinet were quite firm within a few hours after mixing. Air-dried samples were equally as stable as those moist-cured. A similar resorcinol resin, Lauxite RF-901, furnished by the Monsanto Chemical Co., was not as effective as Amberlite PR-115.

Amberlite is furnished in liquid form and requires the addition of 15 per cent, by weight of the resin, of an aldehyde hardener to accelerate and complete the resinification. The Amberlite can be readily applied directly to the soil or in the required mix water. The hardener, paraformaldehyde plus filler, can not be readily mixed with water and was added to the dry soil prior to the addition of the Amberlite.

At least five per cent of this treatment is required for effective soil stabilization but higher percentages of treatment produce higher stabilites. Although not an outstanding stabilizing agent, Amberlite showed considerable promise even under severe laboratory exposure.

Buried field samples using soil C treated with five per cent Amberlite were not satisfactory but the similarly treated field test panel was, with the exception of the cement treatments, the best of the panels tested. Results of the Amberlite testing are included in Tables VI and VIII and Figs. 9, 10, 11, 13 and 14, all of which refer to air-dried samples, with the exception of the field test panel.

At the present time Amberlite is far too costly for consideration as a primary soil stabilizing agent. However, its desirable properties appear to be suitable for improving other, more economical admixes, particularly the bituminous materials. Asphalt emulsion with soil B, was greatly benefited by the addition of small quantities of Amberlite.

Phenol-Formaldehyde Resin

Several forms of phenol-formaldehyde resin were furnished for testing by the Central Research Department of the Monsanto Chemical Co. The outstanding material of this group was a "two stage" type resin designated Resinox L-9673, which required the addition of ten per cent of hexamethylenetetramine for obtaining proper set. This material was furnished in lump form which could be easily pulverized in a ball mill. The mixing of these materials with the soil was accomplished by applying the water insoluble powdered Resinox to the dry soil and adding the "hexa" in solution with the mix water. Five per cent treatment was used for most of the tests although higher percentage treatments were more effective. When higher percentages of Resinox were used it was necessary to reduce considerably the normal molding moisture requirements in order to avoid gummy, over-wet mixtures.

Resinox L-9673 reacts with the soil in a manner similar to Amberlite PR-115 although it is not quite as effective. It sets well at room temperature under moist-curing but is equally effective when air- or oven-dried. The results with Resinox were erratic indicating that there may have been variations in the different samples received, or that the samples may have been affected by storage conditions prior to use. In the laboratory tests Resinox L-9673 was quite promising but all samples failed during field exposure. Soils A and B were particularly benefited by this treatment. Numerous catalysts were tried in an effort to improve the effectiveness of the Resinox but none were particularly beneficial. Magnesium and zinc stearate, potassium permanganate and ammonium chloride were of slight benefit. The effectiveness of Resinox L-9673 is shown in Tables VI through VIII and Figs. 9 through 16.

Resinox L-9673 is available only in limited quantities at the present time. Although promising as a soil stabilizing agent and as an additive to soil bituminous mixtures, it is not as effective as less costly and more available stabilizers. For this reason further study of Resinox L-9673 as a primary soil stabilizing material does not appear warranted.

Other Resinoxes, of the single stage type requiring no catalyst, were less effective than Resinox L-9673. Beneficial effect was obtained with Resinox L-9671 and L-9672 but Resinox L-9819, L-9820 and J-489 were detrimental.

Urea-Formaldehyde Resins

Several commercial urea-formaldehyde resins were tested but only two forms of the material were effective with soil. These were furnished by the Resinous Products Division of the Rohm and Haas Co. and designated Uformite CB-552 and CB-553. These resins are produced in powder form and are precatalyzed so that no activator is required to insure complete reaction. The materials are quite similar in their action and both set up with equal effectiveness under moist- and air-cure conditions. The Uformites were particularly effective with soils A and D but were not effective with other soils under severe laboratory and field exposure. Various chemicals were added to the soil-Uformite mixture in an attempt to extend its effectiveness over a wider range of soils but none of these were particularly beneficial. Slight improvement was obtained with zinc stearate, calcium stearate and salicylic acid when added in quantities of 20 per cent by weight of the Uformite. Test results with Uformite CB-552 are shown in Tables VI and VII and Figs. 9 through 12.

The addition of Uformite tends to dry a moist soil and to disperse or "fluff" the particles. This action greatly reduces the density, and increases the optimum moisture obtained by a given compactive effort for Uformite-treated soil as compared with untreated soil. See Fig. 2. The optimum amount of Uformite treatment for effective stabilization was between five and six per cent. Increasing this percentage of treatment resulted in weaker samples. A liquid form of Uformite, designated 430, and a similar liquid urea-formaldehyde resin, requiring the addition of a hardener, produced by the American Cyanamid Co. and designated Urac 185 were not suitable as soil stabilizing agents. Powdered forms of urea-formaldehyde resin produced by the Monsanto Chemical Co. (Lauxite UF-77 and 101) reacted in a similar manner to Uformite CB-552. Several experimental laboratory mixtures of urea and formaldehyde were not effective soil stabilizers.

Furfuryl Alcohol plus Sulfuric Acid

The soil stabilizing effectiveness of the resin formed by the interaction of furfuryl alcohol and sulfuric acid, as indicated by preliminary tests using a sandy soil, has been described in a previous report.[22] In this method of treatment the furfuryl alcohol and the required acid were added to the soil in separate portions of the mix water. Sulfuric acid was used for most of these tests, although other strong inorganic acids were equally effective in forming the resin. The reaction of furfuryl alcohol with strong acid solutions is very rapid, requiring considerable care in handling. As mixed in the soil, however, the reaction is not violent and the rate of resinification can be readily controlled by varying the concentration of the acid. Acid salts were not effective in forming a stable resin with furfuryl alcohol.

Promising results were obtained in the preliminary work with sandy soils by this method of treatment, particularly when the samples were oven-dried prior to testing. However, the treatment was found to be only slightly effective with other types of soil under air-dry or moist-curing conditions. Freeze-thaw and field weathering tests were particularly destructive to furfuryl alcohol-treated samples as shown by the test data included in Tables VI and VII and Fig. 12.

The furfuryl alcohol treatment is much more expensive and far less effective than that using aniline-furfural, hence, of the two, emphasis in this study has been placed on the latter compound.

Others

A considerable number of miscellaneous resins were investigated, none of which were particularly effective when used alone with soils (See Table IV). Some were beneficial for improving the soil stabilizing characteristics of other materials.

Melamine-Formaldehyde Resin

A liquid form of melamine-formaldehyde resin, Resimene M75, as furnished by the Monsanto Chemical Co., was found to be unsuitable as a soil stabilizing agent, and ineffective as an additive with other stabilizing materials. A catalyst is required for activating this resin.

Styrene Resin

Several forms of styrene resins were tested. These were furnished in powder, liquid and in special emulsion form but none were found to be successful soil stabilizers under severe testing. Two of these resins, Stymer Solution (Monsanto) and Goodrite Resin 50 (B. F. Goodrich) were beneficial to both cement and aniline-furfural-treated soils.

Coumarone-Indene and Polyterpene Resins

Coumarone-Indene and Polyterpene resins were quite similar in their action and were slightly beneficial to the soils treated, although they cannot be considered successful soil stabilizing agents. Piccolyte S-125, Piccoumaron XX-100 and Santo Resin were beneficial to soil-cement mixtures.

DISCUSSION OF MISCELLANEOUS MATERIALS

Under the heading of Miscellaneous Materials are included organic and inorganic chemicals and compounds which are not included under specific headings. Except for a few of the more promising materials, no data other than the qualitative results listed in Table IV were obtained.

Tung Oil

The results obtained at the TDEC from the laboratory testing of tung oil-treated soil samples have been presented in two reports.[23, 24] Although the data reported in these publications indicated tung oil to be a promising stabilizer with certain soil types

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[22] See footnote 3.

[23] See footnote 3.

[24] See footnote 5.

when air-dried, its use is not economically feasible for normal construction purposes in this country. The test results shown in Figs. 9, 10 and 11, and Table VI show that tung oil-treated samples were not particularly effective under severe exposure. The tung oil used in these tests, however, had been stored in the laboratory for several years and may have lost some of its effectiveness. Tung oil was superior to all other drying oils studied; which included linseed oil, soya oil and three synthetic drying oils produced by the Monsanto Chemical Co. The addition of Aroclor 1271 and calcium oxide, both improved the effectiveness of tung oil to a small degree.

Silicone Oil

A silicone oil, supplied by the Dow Chemical Co. was found to be unsuitable as a soil stabilizing material. When added in small quantities to some of the resin stabilizers, however, it proved beneficial. The use of silicones in combination with bituminous materials, resins and other stabilizing agents is a promising field yet to be explored.

Stearates

Stearates were investigated for their possible waterproofing effect. Stearic acid, aluminum, calcium, magnesium, sodium and zinc stearates all improved the mixing characteristics of the more plastic soils and imparted a certain degree of water-repellency but none were effective when subjected to freezing and thawing exposure. Calcium and magnesium stearate, particularly, imparted temporary waterproofing characteristics to soil-cement mixtures but their effectiveness was destroyed by severe exposure.

Tall Oil

A whole tall oil, high in rosin acids, was tested with several soils and found to be unsuitable as a stabilizing agent. No catalysts were found that would improve its soil stabilizing properties. Partially neutralized tall oil, in powder form, was tested at Princeton directly with soil and as an additive to bituminous materials. Both methods of application were only slightly beneficial.

Amines

Several commercially available amines were investigated as applied directly to the soil and as added to other soil stabilizing materials. Aggrecote 600, a complex amine produced by the Minnesota Mining and Manufacturing Co. for improving the adhesion of bituminous materials to mineral aggregate, was only slightly effective when added to soil as a primary treatment. Pre-coating the soil and allowing to dry, prior to the addition of bituminous materials, did not appreciably improve the susceptibility of the soils to bituminous treatment.

Armour Amine 1180-B was slightly beneficial to soils under mild exposure conditions. Rosin Amine D (Hercules Powder Co.) was not effective either directly or as an additive to other treatments.

CONCLUSIONS

From the results presented in this report it is apparent that no entirely satisfactory soil stabilizing agent has been found. Although several materials are effective under specific conditions or with certain soils, none has proved to be universally suitable. Based upon the soils and methods employed in this study the following conclusions can be stated concerning the testing procedures and soil stabilizing materials investigated.

Testing Procedures

1. Proposed soil stabilizing materials should be tested in combination with a large number of soils because the effectiveness of a particular treatment varies with the soil used. The characteristics of the natural soils are the greatest variables encountered in soil stabilization.
2. The use of small 2- by 2-inch cylindrical samples appears satisfactory for preliminary laboratory and field evaluation of chemically treated soils. No significant differences in test results were observed when larger samples were used. Unconfined compression tests were as significant as more elaborate test methods for obtaining relative stability of treated samples.
3. The moisture-density relationship of most soils is considerably modified by the addition of certain chemicals and this important soil characteristic should be investigated for each treatment studied.
4. Oven-drying of chemically treated soil samples prior to testing is not recommended. Resinous bonding materials, in particular, are greatly benefited by higher temperatures

and should not be tested under conditions not attainable in normal construction procedure. Certain other chemical treatments are adversely affected by oven-drying. Air-drying and moist-curing were found to be satisfactory.

5. Simple absorption tests were not sufficiently severe for properly evaluating the effectiveness of chemical admixtures. Alternate freezing and thawing or alternate warming and cooling cycles (with minimum temperature of +35°F) should be included in all testing, the samples in each case having ample opportunity to absorb moisture prior to beginning the test and during the thawing or warming portion of the cycle.

6. The progressive laboratory exposure test developed during this study for evaluating the effectiveness of chemical soil treatments produced a weathering effect similar to that attained by 1-year field exposure.

Materials

1. Portland cement, when applied in quantities of ten per cent or more, was the most generally acceptable soil stabilizing material studied. Considerable effort was expended to improve the resistance of soil-cement to moisture attack and to improve its effectiveness over a wide range of soils. The most generally effective additives found were Montar No. 3, Aroclor 4065, Piccolyte S-125, Piccoumaron XX-100, Santo Resin, Resin 321, CRD 108 and CRD 155.

A problem soil (soil D) which could not be stabilized by a treatment of 20 per cent cement alone, reacted normally and was stabilized with ten per cent cement when an additional treatment of five per cent (by weight of cement) of a polyoxyethelene ester, Sterox LF-87, was applied. Resinox 9672 and Resin 321 also were beneficial to the soil D-cement mixture.

2. The resin formed by the interaction of two parts aniline and one part furfural was a very good bonding agent for soil and the most effective waterproofing material investigated in this study. This resin was quite effective when used in quantities as low as two per cent although higher percentages were more beneficial. Under certain test conditions a 4 to 6 per cent treatment of aniline-furfural proved superior to treatments of 10 to 12 per cent cement. Maximum effectiveness, however, could be attained only by drying the aniline-furfural samples prior to testing. Several additives were found for improving the air-dried treatment, the most generally beneficial of which were Resin Emulsion CRD 155, ammonium chloride, Santo Resin, potassium dichromate, Valite and copper sulfate. Chlorosulfonic acid was very effective in improving the susceptibility of soil C to aniline-furfural treatment. This soil, otherwise, was one of the most difficult to treat successfully with aniline-furfural. No admixtures were found which would appreciably improve the moist-cured samples of aniline-furfural.

3. Amberlite PR-115 (plus paraformaldehyde hardener) and Resinox 9673 (plus hexamethylenetetramine catalyst) were the most promising commercial resins studied when used in quantities of five per cent or higher. Both of these materials have the desirable characteristic of being able to harden the soil at room temperature, under moist-cure conditions. The high cost of these resins does not permit their use in normal civil construction at the present time. However, both Amberlite PR-115 and Resinox 9673 were effective in improving bituminous soil treatments when used in small quantities and with further development their use for this purpose may be economically feasible.

4. None of the bituminous materials were effective as soil stabilizing agents. MC-2 and very high percentages of asphalt emulsion were the best. The effectiveness of MC-2, RC-2 and asphalt emulsion were improved by the addition of 20 per cent, by weight of the basic admixture, of aniline-furfural, Amberlite PR-115, Lauxite RF-901, Resinox 9673 and hydrated lime.

5. None of the powdered resinous water-repellents were successful under severe exposure. Resin 321 was the most effective of the strictly waterproofing agents and also was beneficial when added to cement and aniline-furfural.

6. Hydrated lime, sodium silicate, powdered slag and calcium chloride were among the most commonly available materials found to be unsuitable soil stabilizing materials. However, small quantities of lime, sodium silicate and powdered slag were effective in reducing the plasticity of fine-grained soils.

It is emphasized that these conclusions are based entirely upon methods of tests described in this report. Under actual service conditions the performance of any of these materials could differ from their performance as reflected bv their resistance to disintegration when subjected to the laboratory and small-scale field exposure tests. In order to more fully evaluate the effectiveness of soil stabilizing agents, without the immediate construction of expensive field installations, a special circular track has been fabricated at the TDEC laboratories which will permit the comparative testing of different stabilized pavements under controlled traffic application and controlled moisture conditions.

In addition to the conclusions reached concerning testing procedures and the evaluation of specific admixtures, results of this study also indicate that a more basic understanding of the nature and composition of natural soils is necessary before a complete solution of the soil stabilization problem can be attained. This finding has been corroborated by a study of the work of others. The physical and chemical characteristics of soils are extremely complex and variable, and consequently their reactions to a particular chemical treatment cannot be accurately predicted or fully explained by any of the known soil testing procedures. The soil classification tests normally used - grain size distribution, plasticity index, maximum density, pH determination, etc. - are not sufficient for evaluating the susceptibility of a given soil to chemical treatment. In fact, some soils react with chemical admixtures in a manner quite opposite to that expected from a study of these classification tests.

It is apparent that certain soils possess peculiar properties, as yet unevaluated, which determine whether the soil system as a whole will react in a favorable or unfavorable manner to a particular chemical treatment. For the full utilization of present data and as a guide to future developments it is essential that these properties be isolated and understood. In this way beneficial characteristics can be utilized to the maximum and detrimental characteristics eliminated or neutralized. A full and proper understanding of these factors will require a comprehensive study of basic soil composition and of the reactions involved in the combination of the various soil components with chemical admixtures. Such a difficult and detailed study should properly require the combined knowledge and techniques of the chemical and engineering professions.

TABLE I

Characteristics Of TDEC Test Soils

Soil	Texture	Atterberg Limits				Compaction Data				Sp. Gr.	pH
						Standard AASHO		Modified AASHO			
		L.L.	P.L.	P.I.	S.L.	M.D.	O.M.	M.D.	O.M.		
A	Sandy Loam	17.7	14.8	2.9	14.5	119.0	11.0	--	--	2.67	7.4
B	Sandy Clay Loam	21.2	NP	--	--	121.0	10.8	130.5	9.1	2.72	7.9
C	Clay Loam	26.0	14.7	11.3	12.6	121.8	11.4	133.2	8.4	2.73	8.4
D	Sandy Loam	26.8	NP	--	--	110.2	16.0	117.2	14.6	2.73	7.8
E	Loam	28.0	20.0	8.0	15.1	115.1	13.8	122.0	11.6	2.64	6.4
F	Clay Loam	30.2	14.5	15.7	13.0	116.8	13.4	128.6	10.4	2.74	8.0
G	Silt	30.7	25.5	5.2	22.1	106.6	16.9	--	--	2.70	7.6
H	Silty Clay Loam	32.0	16.2	15.8	14.3	111.8	15.8	122.2	12.5	2.68	7.7
I	Clay Loam	33.4	20.0	13.4	15.9	114.6	14.0	--	--	2.69	5.0
J	Clay	49.5	28.0	21.5	21.6	95.1	23.5	--	--	2.70	5.1

TABLE II

Characteristics Of Purdue Test Soils

Texture	Gradation-Percent			Atterberg Limits		Standard AASHO Compaction Data		Sp. Gr.
	Sand	Silt	Clay	L.L.	P.I.	M.D.	O.M.	
Gravelly Sandy Loam	50	34	16	20.5	6.0	122.0	12.0	2.71
Sandy Loam	58	29	13	NP	--	107.0	16.5	2.63
Silty Loam	12	64	24	41.9	16.9	103.3	18.3	2.70
Silty Clay	2	58	40	47.4	18.3	99.8	22.0	2.72
Clay Loam	26	52	22	42.7	23.2	107.5	17.5	2.70
Clay	11	52	37	49.3	27.9	99.8	22.0	2.67

TABLE III

Materials Tested As Soil Stabilizing Agents

Material	Source
Inorganic Cementing Agents	
Portland Cement	Commercial
Natural Cement	Commercial
Powdered Slag	National Slag Assoc.
Hydrated Lime	Commercial
Sodium Silicate	Commercial
Oxychloride Cement	Laboratory
Bituminous Materials	
Asphalt Emulsion	American Bitumals Co.
Tar TM-1, TM-2, RT-3, RT-6, RT-8	Commercial
MC-2, RC-2, MC-1	Standard Oil Co. of N. J.
Emulsified Tar	Reilly Tar & Chemical Co.
Road Oil SC-3	Commercial
Powdered Asphalt	Commercial
Resinous Waterproofing Agents	
Vinsol (Powdered Resin)	Hercules Powder Co.
NVX (Neutralized Vinsol)	Hercules Powder Co.
Stabinol (75% Cement + 25% Resin)	Hercules Powder Co.
Resin 321 (Salt of Abietic Acid)	Hercules Powder Co.
Rosin Powder	Commercial
Soilpak (Resin + Lime)	Service Engineering Co.
Valite-7796 (Thermoplastic Resin)	Valite Corp.
Natural Resins	Commercial
Belro (Partially Neutralized)	H. F. Winterkorn
Vinsol (Partially Neutralized)	H. F. Winterkorn
Lignin Sulfate	H. F. Winterkorn
Synthetic Resin Bonding Agents	
Resinox 9673 + hexa (Phenol-Formaldehyde Resin)	Monsanto Chemical Co.
Resinox 9671, 9672 (Phenol-Formaldehyde Resin)	Monsanto Chemical Co.
Resinox 9820, 9819, 482 (Phenol-Formaldehyde Resin)	Monsanto Chemical Co.
Uformite CB 552, 553 (Urea-Formaldehyde Resin)	Rohm & Haas Co.
Uformite 430 (Urea-Formaldehyde Resin)	Rohm & Haas Co.
Urac 185 + hardener (Urea-Formaldehyde Resin)	American Cyanamid Co.
Lauxite UF 77 (Urea-Formaldehyde Resin)	Monsanto Chemical Co.
Lauxite UF 101 + Hardener (Urea-Formaldehyde Resin)	Monsanto Chemical Co.
Amberlite PR-115 + Hardener (Resorcinol Resin)	Rohm & Haas Co.
Lauxite RF 901 + Hardener (Resorcinol Resin)	Monsanto Chemical Co.
Resimene M75 + Hardener (Melamine-Formaldehyde Resin)	Monsanto Chemical Co.
Resloom M75 + Hardener (Melamine-Formaldehyde Resin)	Monsanto Chemical Co.
Plast-O-Trete (Styrene Resin)	West Atlantic Corp.
Stymer Solution (Styrene Resin)	Monsanto Chemical Co.
CRD 108 (Styrene Resin)	Monsanto Chemical Co.
CRD 119 (Styrene Resin)	Monsanto Chemical Co.
CRD 155 (Resin Emulsion)	Monsanto Chemical Co.
Modified Styrene 480 (Styrene Resin)	Penn. Ind. Chemical Co.
Piccoumaron XX-100 (Coumarone-Indene Resin)	Penn. Ind. Chemical Co.
Piccolyte S-125 (Polyterpene Resin)	Penn. Ind. Chemical Co.
Santo-Resin (Polyterpene Resin)	Monsanto Chemical Co.
Aniline-Furfural	Commercial
Furfuryl Alcohol + H_2SO_4	Commercial
Phenol-Furfural	Laboratory
Urea-Furfural	Laboratory
Mersize (Thermoplastic Resin)	Monsanto Chemical Co.
CRD 134 (Thermoplastic Resin)	Monsanto Chemical Co.

TABLE III (CONTINUED)

Material	Source
Synthetic Resin Bonding Agents (Continued)	
Resproof, WR (Thermosetting Resin)	Monsanto Chemical Co.
Sterox LFA 87 (Polyoxyethylene Ester)	Monsanto Chemical Co.
CRD 136 (Hydrocarbons + Metallic Salts)	Monsanto Chemical Co.
Transphalt 100	Penn. Ind. Chemical Co.
Geon Latex 31 (Vinyl Resin Latex)	B.F. Goodrich Chemical Co.
Goodrite Resin 50 (Styrene-Butadiene)	B.F. Goodrich Chemical Co.
Goodrite Latex 50	B.F. Goodrich Chemical Co.
Methylmethacrylate (Poly)	Commercial
Calcium Methacrylate + Benzoyl Peroxide	U.S. Plastic Products Corp.
Miscellaneous Materials	
Tung Oil	Commercial
Linseed Oil	Commercial
Soya Oil	Monsanto Chemical Co.
Drying Oils - 201423-24-35	Monsanto Chemical Co.
Motor Oil SAE 30, 50	Commercial
Silicone Oil	Dow Chemical Co.
Rosin Oil	Commercial
Tall Oil	Commercial
Castor Oil	Commercial
Crude Oil	Commercial
Rosin Amine D	Hercules Powder Co.
Kelkote (Soya Protein)	Spenser Kellogg & Sons
Aggrecote 600 (Complex Amine)	Minnesota Mining & Mfg. Co.
Aroclor 1168, 1170, 1171, 4065, 5060, 1260, Montar No. 3 (Chlorinated Diphenyl)	Monsanto Chemical Co.
Hevea Latex	Monsanto Chemical Co.
Compound SS-1, SS-2	Dewey & Almy Chemical Co.
Dicalite SA-1 (Diatomaceous Earth)	Dicalite Co.
Volclay (Bentonite)	Commercial
Armour Amine 1180-B	Armour & Co.
Calcium Chloride	Commercial
Sodium Chloride	Commercial
Sodium Alginate	Commercial
Al., Ca., Mg., Na., Zn., Stearates	Commercial
Stearic Acid	Commercial
Oleic Acid	Commercial
Ethyl Silicate	Commercial
Resorcinol	Commercial
Sodium Oleate	Commercial
Tannic Acid + Calcium Chloride	Commercial
Aniline	Commercial
Furfural	Commercial
Sulfur (Powdered)	Commercial
Silicic Acid	Commercial
Barium Chloride	Commercial
Zinc Oxide	Commercial
Tetrahydrofurfuryl Alcohol	Commercial
Barium Hydroxide	Commercial
Calcium Hydroxide	Commercial
Ferric Chloride + Ammonia	Commercial
Aluminum Sulfate	Commercial
Magnesium Sulfate	Commercial
Magnesium Sulfate + Na. Silicofluoride	Commercial
Barium Chloride + Na. Silicofluoride	Commercial
Calcium Chloride + Na. Silicofluoride	Commercial
Abietic Acid	Commercial
Ethyl Silicate + Furfural	Commercial

TABLE IV

Qualitative Results Of Laboratory And Field Testing Of Proposed Soil Stabilizing Agents

Material	Effectiveness of Admixture as Indicated by Different Exposure[1]			
	Laboratory Exposure		Field Exposure	
	Preliminary	Severe	Buried Samples	Test Panels
Inorganic Cementing Materials				
Portland Cement	Very Good	Very Good	Very Good	Good
Natural Cement	Good	--	--	--
Powdered Slag	Slight	Unsuitable	--	--
Hydrated Lime	Fair	Unsuitable	Unsuitable	--
Sodium Silicate	Fair	Unsuitable	Unsuitable	--
Oxychloride Cement	Unsuitable	--	--	--
Bituminous Materials				
Asphalt Emulsion	Fair	Unsuitable	Unsuitable	Unsuitable
Tar (TM-1, TM-2, RT-3, RT-6, RT-8)	Fair	Slight	Slight (TM-2)	--
MC-1, MC-2, RC-2	Fair	Slight	Unsuitable (MC-2)	Unsuitable (MC-2)
Emulsified Tar	Unsuitable	--	--	--
Road Oil SC-3	Fair	Slight	Slight	Unsuitable
Powdered Asphalt + Kerosene	Slight	Slight	Slight	--
Resinous Waterproofing Materials				
Vinsol	Slight	Unsuitable	Unsuitable	--
NVX	Slight	Unsuitable	--	--
Stabinol	Good	Fair	Slight	Unsuitable
Resin 321	Good	Fair	Unsuitable	--
Rosin Powder	Slight	Unsuitable	--	--
Soilpak	Unsuitable	--	--	--
Valite 7796-D	Unsuitable	--	--	--
Natural Resins	Slight	--	--	--
Belro (Partially Neutralized)	Slight	--	--	--
Vinsol (Partially Neutralized)	Unsuitable	--	--	--
Lignin Sulfate	Unsuitable	--	--	--
Synthetic Resin Bonding Materials				
Resinox 9673 + "hexa"	Good	Fair	Unsuitable	Slight
Resinox 9671, 9672	Slight	Unsuitable	--	--
Resinox 9819, 9820, 482	Unsuitable	--	--	--
Uformite CB552, CB553	Fair	Slight	Unsuitable	--
Uformite 430	Unsuitable	--	--	--
Urac 185 + Hardener	Unsuitable	--	--	--

TABLE IV (CONTINUED)

Material	Effectiveness of Admixture as Indicated by Different Exposure [1]			
	Laboratory Exposure		Field Exposure	
	Preliminary	Severe	Buried Samples	Test Panels
Lauxite UF-77	Unsuitable	--	--	--
Lauxite UF-101 + Hardener	Fair	Unsuitable	--	--
Lauxite RF-901 + Hardener	Good	Good	--	--
Amberlite PR115 + Hardener	Good	Slight	Slight	Slight
Resimene M75 + Hardener	Slight	Unsuitable	--	--
Resloom M75 + Hardener	Slight	--	--	--
Plast-O-Trete	Slight	Unsuitable	--	--
Stymer Solution	Slight	Unsuitable	--	--
CRD 108	Slight	Unsuitable	--	--
CRD 119	Unsuitable	--	--	--
CRD 155 (Resin Emulsion)	Slight	Unsuitable	--	--
Modified Styrene 480	Fair	Slight	--	--
Piccoumaron XX-100	Fair	Slight	--	--
Piccolyte S-125	Slight	Slight	--	--
Santo Resin	Unsuitable	--	--	--
Aniline-Furfural (2:1)	Very Good	Good	Very Good	Good
Furfuryl Alcohol + H_2SO_4	Fair	Unsuitable	Unsuitable	--
Phenol-Furfural	Slight	Unsuitable	--	--
Urea-Furfural	Slight	Unsuitable	--	--
Mersize	Unsuitable	--	--	--
CRD 134	Unsuitable	--	--	--
Resproof WR	Slight	--	--	--
Sterox LFA 87	Slight	--	--	--
CRD 136	Unsuitable	--	--	--
Transphalt 100	Fair	Slight	--	--
Geon Latex 31X	Unsuitable	--	--	--
Goodrite Resin 50	Slight	Unsuitable	--	--
Goodrite Latex 50	Slight	Unsuitable	--	--
Methyl Methacrylate (poly)	Unsuitable	--	--	--
Calcium Methacrylate + Benzoyl Peroxide	Unsuitable	--	--	--
Miscellaneous Materials				
Tung Oil	Good	Fair	Slight	--
Linseed Oil	Fair	--	--	--
Soya Oil	Unsuitable	--	--	--
Drying Oils 201423-24-35	Unsuitable	--	--	--
Motor Oil SAE 30, 50	Unsuitable	--	--	--
Silicone Oil	Slight	--	--	--
Rosin Oil	Unsuitable	--	--	--
Tall Oil	Unsuitable	--	--	--
Castor Oil	--	--	--	--

TABLE IV (CONTINUED)

	Effectiveness of Admixture as Indicated by Different Exposure [1]			
Material	Laboratory Exposure		Field Exposure	
	Preliminary	Severe	Buried Samples	Test Panels
Crude Oil	--	--	--	--
Rosin Amine D	Unsuitable	--	--	--
Kelkote	Unsuitable	--	--	--
Aggrecote 600	Slight	Unsuitable	--	--
Aroclor 1168, 1170, 1171, 1260	Unsuitable	--	--	--
Aroclor 4065, 5060, Montar No. 3	Unsuitable	--	--	--
Hevea Latex	Unsuitable	--	--	--
Compound SS-1, SS-2	Unsuitable	--	--	--
Dicalite SA-1	Unsuitable	--	--	--
Volclay	Unsuitable	--	--	--
Armour Amine 1180-B	Slight	--	--	--
Calcium Chloride	Unsuitable	--	--	--
Sodium Chloride	Unsuitable	--	--	--
Sodium Alginate	Unsuitable	--	--	--
Stearates (Al., Ca., Mg., Na., Zn.)	Slight	Unsuitable	--	--
Stearic Acid	Slight	Unsuitable	--	--
Oleic Acid	Slight	--	--	--
Ethyl Silicate	Unsuitable	--	--	--
Resorcinol	Unsuitable	--	--	--
Sodium Oleate	Unsuitable	--	--	--
Tannic Acid + Calcium Chloride	Unsuitable	--	--	--
Aniline	Unsuitable	--	--	--
Furfural	Unsuitable	--	--	--
Sulfur (powdered)	Unsuitable	--	--	--
Silicic Acid	Unsuitable	--	--	--
Barium Chloride	Unsuitable	--	--	--
Zinc Oxide	Unsuitable	--	--	--
Tetrahydrofurfuryl Alcohol	Unsuitable	--	--	--
Barium Hydroxide	Unsuitable	--	--	--
Calcium Hydroxide	Unsuitable	--	--	--
Ferric Chloride + Ammonia	Unsuitable	--	--	--
Aluminum Sulfate	Unsuitable	--	--	--
Magnesium Sulfate	Unsuitable	--	--	--
Magnesium Sulfate + Na. Silicofluoride	Unsuitable	--	--	--
Barium Chloride + Na. Silicofluoride	Unsuitable	--	--	--
Calcium Chloride + Na. Silicofluoride	Unsuitable	--	--	--
Abietic Acid	Unsuitable	--	--	--
Ethyl Silicate + Furfural	Unsuitable	--	--	--

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[1] Based on average results with several soil types.

TABLE V

Qualitative Effectiveness Of Additives As Applied To Soils Treated With Different Basic Admixtures

Additive	Primary Treatment				
	Cement	Lime	Asphalt Emulsion	Aniline-Furfural	Sodium Silicate
Aroclor 1271	+	+	0	+	0
Aroclor 4065	+	0	---	0	---
Aroclor 1171, 5060	0	---	---	---	0
Aroclor 1168, 1170	-	---	---	---	0
Montar No. 3	+	0	0	0	---
Piccolyte 125	+	+	+	0	0
Piccoumaron XX-100	+	-	---	0	0
Transphalt 100	0	-	0	0	---
Modified Styrene 480	0	0	0	---	0
Goodrite Resin 50	+	+	0	+	-
Plast-O-Trete	0	0	0	---	---
Stymer Solution	+	---	+	+	0
CRD 108	+	0	0	+	0
CRD 133	+	+	+	+	---
CRD 119	-	---	---	---	---
CRD 134	---	---	---	-	---
CRD 155	+	+	0	+	0
Resin 321	+	-	0	+	0
Vinsol	-	0	0	0	0
NVX	-	-	0	+	-
Stabinol	+	---	---	---	---
Uformite 552	-	-	0	0	-
Resinox 9672	-	-	0	0	-
Resinox 9673 + hexa	-	-	+	---	-
Resinox 9671, 9819, 482	-	---	-	---	-
Amberlite + hardener	-	---	+	---	---
Resimene M75	-	-	0	0	---
Aniline-Furfural	-	+	+	---	0
Santo Resin	+	---	---	+	---
Valite	-	0	0	+	0
Sterox LF87	+	-	0	-	0
Aggrecote 600	---	---	+	0	---
Hevea Latex	---	---	+	---	---
Stearic Acid	0	---	---	+	+
Calcium Stearate	+	-	0	+	+
Zinc Stearate	-	0	+	0	+
Magnesium Stearate	+	---	---	+	+
Sodium Oleate	-	---	---	-	---
Calcium Chloride	-	+	---	+	0
Potassium Permanganate	0	---	---	-	---
Sodium Silicate	+	0	0	-	---
Copper Sulfate	0	---	---	+	0
Chlorosulfonic Acid	+	---	---	+	0
Potassium Dichromate	0	-	---	+	-
Sodium Silicofluoride	---	-	-	+	0
Triethanolamine	---	---	0	0	0

+ = Beneficial
0 = No important effect
- = Detrimental
--- = Not tested

TABLE VI

Effectiveness Of Different Admixtures With Six Soils As Indicated By Progressive Laboratory Exposure - 2- By 2-Inch Air-Dried Samples

Treatment	Soil B[1]		Soil C		Soil D		Soil F[1]		Soil H[1]		Soil I	
	Breaking Load or Point of Failure	M.C. at Breaking Load or Point of Failure	Breaking Load or Point of Failure	M.C. at Breaking Load or Point of Failure	Breaking Load or Point of Failure	M.C. at Breaking Load or Point of Failure	Breaking Load or Point of Failure	M.C. at Breaking Load or Point of Failure	Breaking Load or Point of Failure	M.C. at Breaking Load or Point of Failure	Breaking Load or Point of Failure	M.C. at Breaking Load or Point of Failure
12% Cement	4215	8.3	6700	10.4	9 F-T	26.0	4790	10.8	4472	9.3	1900	14.9
do + 0.6% Aroclor 4065	5070	7.6	--	--	5 F-T	14.9	4943	10.1	4265	10.4	--	--
do + 0.6% Montar	4960	7.7	6800	10.1	12 F-T	25.5	5475	9.5	3890	10.5	2130	14.9
do + 0.6% Piccoumaron	--	--	7400	10.1	12 F-T	24.5	--	--	--	--	2130	14.8
5% Cement	540	12.3	30	12.9	8 F-T	27.1	4 W-D	14.0	4 W-D	17.0	12 F-T	19.7
5% Lime	2 F-T	18.1	6 F-T	14.7	9 F-T	30.3	2 F-T	23.1	2 Imm	12.8	4 F-T	22.5
14% Sodium Silicate Sol.	115	11.2	2 F-T	33.2	2 F-T	31.6	1 Imm	27.7	1 Imm	34.4	2 W-D	26.4
12% Powdered Slag	2 Imm	16.2	--	--	2 F-T	18.5	3 Imm	24.1	3 F-T	20.1	--	--
8% MC-2	--	--	2 F-T	28.8	475	7.4	--	--	--	--	240	9.4
5% MC-2	80	16.2	1 F-T	26.4	--	--	3 W-D	20.1	3 W-D	26.4	--	--
5% RC-2	110	12.5	Imm	19.1	--	--	3 W-D	16.2	5 W-D	25.4	--	--
20% Asphalt Emulsion	620	6.4	6 F-T	23.8	300	8.5	1 W-D	24.1	--	--	12 F-T	25.8
5% AE + Amberlite	1110	4.6	6 F-T	18.4	30	7.6	110	13.6	6 F-T	14.8	12 F-T	22.0
do + Aniline-Furfural	--	--	12 F-T	18.1	760	7.6	--	--	--	--	12 F-T	17.9
5% Aniline-Furfural	1700	4.3	12 F-T	11.8	2200	5.0	1650	5.9	2950	2.5	750	3.9
5% Amberlite	1330	10.3	330	16.3	1450	17.1	330	15.7	285	18.2	12 W-D	16.8
5% Resinox	1050	11.0	230	13.6	530	19.5	250	15.1	350	16.6	610	15.7
5% Uformite	310	15.8	6 F-T	18.9	680	19.5	20	24.6	1 W-D	24.8	12 F-T	22.8
5% Furfuryl Alcohol[2]	1 F-T	17.5	1 W-D	15.6	--	--	Imm	29.2	1 Imm	23.9	--	--
5% Stabinol	1210	5.9	6 F-T	11.5	30	11.2	6 F-T	14.1	6 F-T	12.0	9 F-T	16.9
2% Resin 321	3 Imm	13.9	1 F-T	21.8	610	4.6	1 F-T	17.2	3 Imm	12.1	30	8.4
2% NVX	3 Imm	18.8	1 F-T	--	30	9.4	3 Imm	20.1	2 Imm	13.0	4 F-T	30.8
2% Vinsol	1 Imm	14.6	1 F-T	27.9	2 F-T	23.2	1 Imm	22.0	1 Imm	13.0	2 F-T	23.2
2% Tung Oil	80	16.5	12 F-T	19.8	30	17.2	6 F-T	19.8	6 F-T	24.5	12 F-T	23.4

[1] Only six cycles of F-T and W-D were used instead of the usual 12 cycles.

[2] Plus 0.4% H_2SO_4.

TABLE VII

Effectiveness Of Different Admixtures With Two Soils As Indicated By Laboratory And Field Exposure - 2 1/2- By 4-Inch Oven-Dried Samples

Treatment	Unweathered Oven-Dried[1]	10-Day Capillary		30-Day Capillary		10 Cycle Freeze-Thaw		30 Cycle Freeze-Thaw		1-Year Field	
	Load	Load	M.C.	Load	M.C.	Load	M.C.	Load	M.C.	Load	M.C.
					Soil B						
12% Cement	16,500	7,000	13.0	6,550	13.6	4,850	13.7	1,550	17.5	3,500[4]	10.7
do + 0.6% Aroclor 4065	19,170	8,840	12.6	7,650	13.5	4,950	14.7	3,200	17.2	8,400	10.0
do + 0.6% Montar	18,850	7,820	12.6	8,600	13.0	5,800	14.7	2,010	19.1	7,200	11.0
4% Aniline-Furfural	9,500	5,550	2.0	4.180	3.0	4,550	3.0	2,400	4.1	8,100	3.1
4% Resinox[2]	16,420	2,800	9.5	2.620	10.4	2,900	10.4	1,150	16.0	115	13.2
4% Uformite[2]	4,650	1,300	4.8	1,300	5.7	0	20.0	0	20.6	0	--
4% Furfuryl Alcohol[3]	11,450	900	13.0	700	15.1	250	19.9	200	21.6	0	--
4% Lime[2]	7,650	2,250	6.5	1,950	10.0	900	15.3	150	20.2	60	15.0
					Soil F						
12% Cement	18,600	5,690	13.8	6,260	13.8	2,213	13.0	0	18.3	4,100[4]	10.1
do + 0.6% Aroclor 4065	18,910	5,460	14.9	6,500	14.5	3,200	13.6	0	16.2	4,250[4]	10.1
do + 0.6% Montar	18,190	5,230	14.7	6,010	14.7	3,130	14.3	0	17.7	4,400[4]	10.3
4% Aniline Furfural	9,780	4,170	2.7	3,480	4.5	3,350	2.9	2,835	5.2	3,050	3.1
4% Resinox[2]	15,950	--	--	1,100	14.6	--	--	0	20.0	0	--
4% Uformite[2]	2,300	--	--	500	19.1	--	--	0	27.8	0	--
4% Furfuryl Alcohol[3]	12,900	--	--	690	15.4	--	--	0	24.5	0	--
4% Lime[2]	5,880	--	--	1,080	14.6	--	--	0	21.6	45	18.1

[1] Less than 1% moisture content

[2] Plus 0.2% zinc stearate

[3] Plus 0.4% H_2SO_4

[4] Sample split in firm sections

TABLE VIII

Effectiveness Of Different Admixtures With Soil C As Indicated By Laboratory And Field Exposure - 2 1/2- By 4-Inch And 2- By 2-Inch Air-Dried Samples

	2 1/2" x 4" Samples						2" x 2" Samples					
Treatment	Unexposed		Laboratory		Field[5]		Unexposed		Laboratory		Field[5]	
	Load	M.C.	Load	M.C.	Load	M.C.	Load	M.C.	Load	M.C.	Load	M.C.
14% Cement	17,527	3.4	11,750	10.1	9,350	11.6	11,900	2.0	8,200	9.8	6,500	9.5
12% Cement[1]	16,850	3.2	10,150	10.8	7,150	11.7	11,400	1.9	6,450	10.4	5,495	11.0
do + 0.6% Montar[1]	15,450	2.9	10,000	11.2	7,875	11.8	10,900	1.8	7,150	10.2	5,040	10.4
do + 0.6% Aroclor 4065	15,750	2.9	10,500	11.1	7,800	11.2	11,000	1.8	6,700	10.0	5,360	10.0
do + 0.6% Piccolyte	14,875	3.5	10,850	10.5	9,300	11.1	9,300	2.1	6,100	10.5	--	--
do + 0.6% Piccoumaron[1]	14,250	3.4	11,700	10.3	8,250	11.5	10,250	2.0	7,700	10.3	--	--
2% Aniline-Furfural	7,550	1.4	30	8.3	610	4.5	5,180	1.1	280	7.5	420	4.3
5% Aniline-Furfural[2]	10,250	1.2	485	6.9	4,095	2.5	7,375	1.0	875	6.9	3,545	2.5
5% Amberlite[2]	11,250	2.6	50	19.8	100	12.8	6,025	2.1	20	18.8	30	12.0
5% Resinox[3]	11,600	2.3	0	15.7	90	11.4	6,460	1.8	20	13.4	20	9.4
5% Asphalt Emulsion	5,495	1.4	0	24.0	0	8.1	3,170	1.2	0	22.1	0	10.9
do + 0.2% Aggrecote[4]	4,705	1.2	0	18.7	0	10.6	3,300	1.2	0	22.0	0	10.6
5% MC-2	1,600	2.1	0	16.1	0	15.6	1,615	1.6	0	20.6	0	11.6
do + 0.2% Aggrecote[4]	1,425	2.1	0	13.8	0	11.6	1,565	1.5	0	20.5	0	11.6

[1] Field Test Panel - Good

[2] Field Test Panel - Fair

[3] Field Test Panel - Top 2" poor - rest firm

[4] Field Test Panel - Poor

[5] One winter of exposure

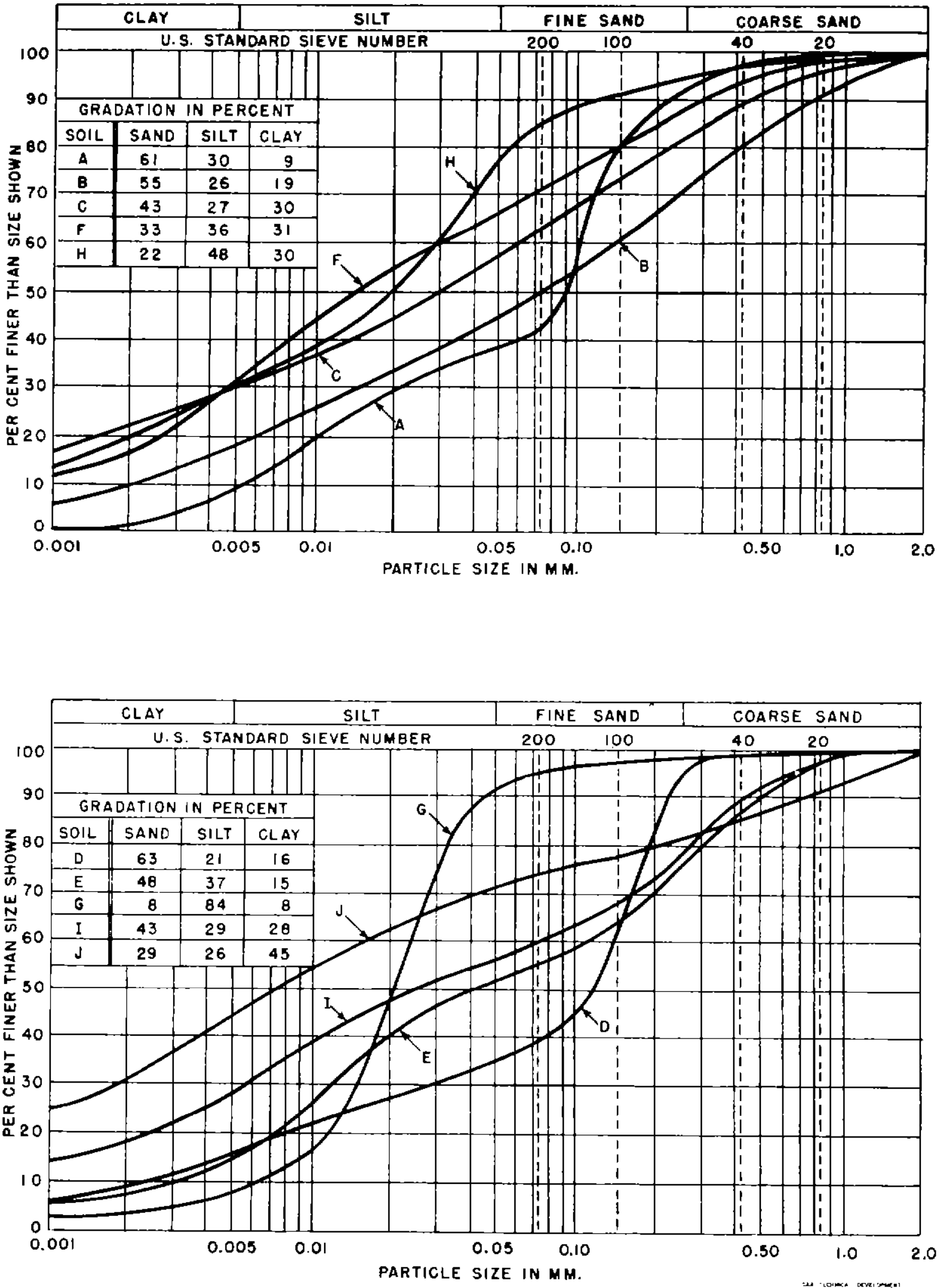
TABLE IX

Effectiveness of Different Admixtures With Six Soils As Indicated By Laboratory And Field Exposure - 6- By 4-Inch Oven-Dried Samples (Purdue)

Treatment	Unweathered (Dry)		10-Day Capillary		12 Cycles Freeze-Thaw		3-Year Field Exposure Well Drained		3-Year Field Exposure Poorly Drained	
	Load	M.C.%	Load	M.C.%	Load	M.C.%	Load	M.C.%	Load	M.C.%
Gravelly Sandy Loam										
10% Cement	3248	2.5	1793	11.6	1900	12.1	5185	6.7	4420	8.3
10% Cement + 2% Resin 321	2780	2.2	2653	1.8	2870	3.6	0	14.1	0	17.3
10% Cement + 5% Vinsol	2310	5.6	2220	6.5	1538	7.9	0	16.0	0	25.2
6% Aniline-Furfural	1630	0.8	1316	1.4	1015	1.5	995	0.6	337	7.4
5% Resin 321	453	3.1	300	4.7	10	15.4	0	9.2	0	13.1
3% Powd. Asphalt + 3% Kerosene	453	1.7	323	0.9	245	4.3	255	2.1	103	8.4
6% TM-2	507	1.2	397	2.6	270	4.2	377	1.1	572	8.6
6% SC-3	452	0.5	328	1.6	185	2.1	127	2.6	0	9.1
6% MC-1	455	2.3	308	3.5	112	3.9	0	5.9	0	14.2
6% Asphalt Emulsion	960	0.2	52	13.8	33	12.0	0	8.8	0	12.7
Sandy Loam										
10% Cement	1443	0.9	552	16.8	122	27.1	0	18.9	0	18.5
6% Aniline-Furfural	1146	0.7	625	1.9	595	1.6	482	1.8	0	12.2
6% SC-3	262	0.5	158	3.1	238	5.5	137	6.9	0	16.5
Silty Loam										
10% Cement	1640	1.3	758	18.3	228	23.0	0	23.7	0	24.1
6% Aniline-Furfural	852	1.2	587	1.6	475	0.9	385	1.7	0	8.5
6% SC-3	413	1.2	277	3.1	0	--	0	13.8	0	19.9

TABLE IX (CONTINUED)

Treatment	Unweathered (Dry)		10-Day Capillary		12 Cycles Freeze-Thaw		3-Year Field Exposure Well Drained		3-Year Field Exposure Poorly Drained	
	Load	M.C.%	Load	M.C.%	Load	M.C.%	Load	M.C.%	Load	M.C.%
Silty Clay										
10% Cement	1942	2.7	488	20.8	202	20.8	0	27.6	0	27.6
10% Cement + 2% Resin 321	1260	6.4	663	3.5	90	13.4	0	30.6	0	43.3
10% Cement + 5% Vinsol	2045	6.0	1292	13.3	105	21.7	0	25.9	0	38.1
6% Aniline-Furfural	625	0.7	327	2.4	0	--	0	7.7	0	18.7
5% Resin 321	964	5.7	590	2.3	0	--	0	23.8	0	33.4
3% Powd. Asphalt + 3% Kerosene	465	0.7	272	6.0	0	--	0	19.9	0	29.4
6% TM-2	560	1.3	113	10.9	--	--	0	8.9	0	22.6
6% SC-3	415	1.0	236	5.8	0	--	0	14.1	0	26.2
6% MC-1	293	1.6	90	7.0	0	--	0	24.8	0	31.1
12% Asphalt Emulsion	770	2.5	307	11.8	15	23.3	0	21.7	0	27.4
Clay Loam										
10% Cement	2052	3.4	760	20.1	168	23.3	0	26.4	0	28.1
6% Aniline-Furfural	745	0.4	1065	2.1	0	--	470	2.2	0	9.9
6% SC-3	362	0.6	235	2.2	--	--	0	9.1	0	16.3
Clay										
10% Cement	2065	3.6	610	20.3	332	24.6	0	29.1	0	28.9
6% Aniline-Furfural	840	2.0	477	3.8	280	4.9	245	4.3	0	21.1
6% SC-3	143	1.6	83	3.0	45	9.0	0	9.3	0	31.8



GRADATION IN PERCENT

SOIL	SAND	SILT	CLAY
A	61	30	9
B	55	26	19
C	43	27	30
F	33	36	31
H	22	48	30

GRADATION IN PERCENT

SOIL	SAND	SILT	CLAY
D	63	21	16
E	48	37	15
G	8	84	8
I	43	29	28
J	29	26	45

Fig. 1 Grain Size - Distribution Curves for the TDEC Test Soils

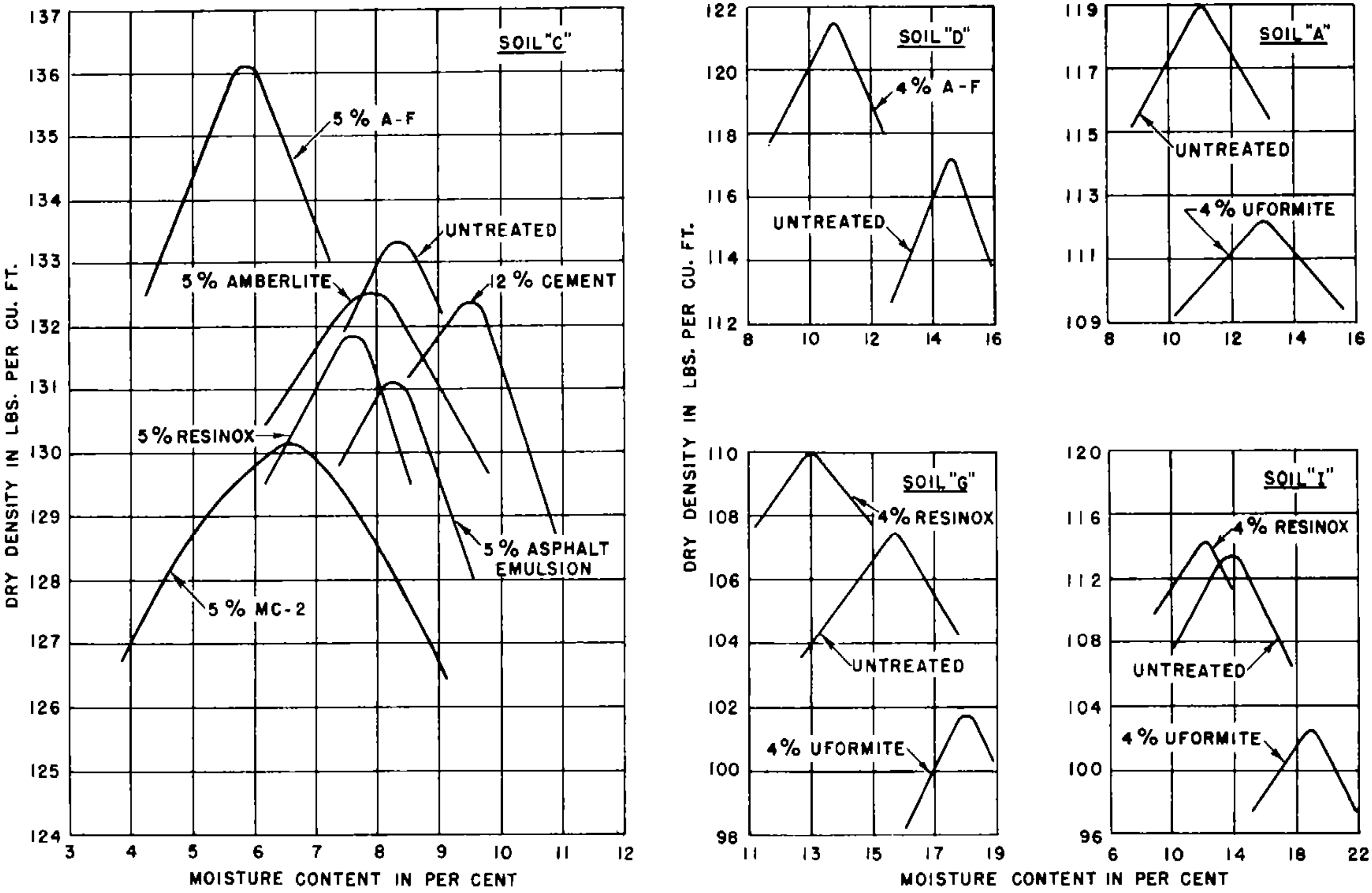


Fig. 2 Effect of Admixtures on the Moisture-Density Relationships for Five Soils

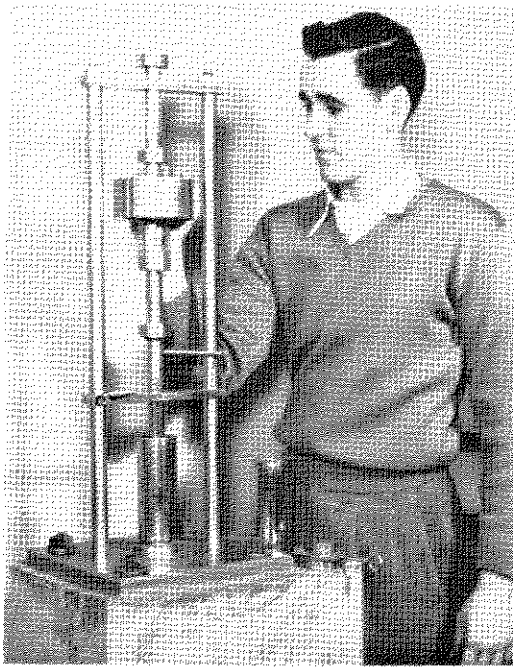


Fig. 3 Equipment Used for Compacting 2-Inch by 2-Inch Soil Samples

Fig. 4 Vibratory Tamper Used for Compacting Test Panels

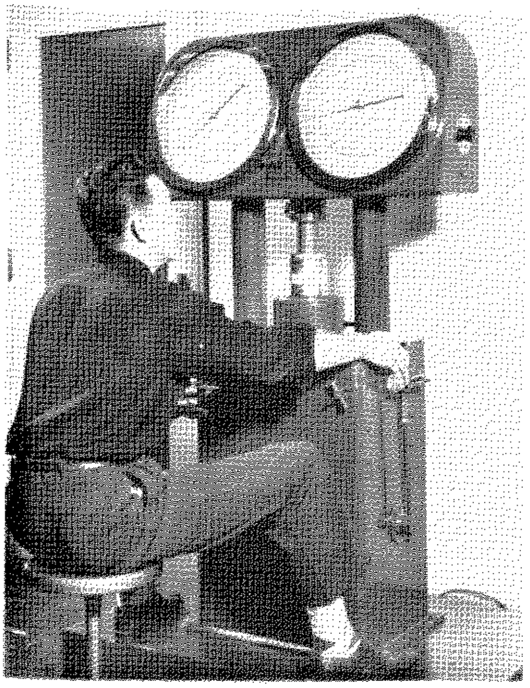


Fig. 5 Testing Machine Used for Obtaining Unconfined Compressive Strength of Soil Samples

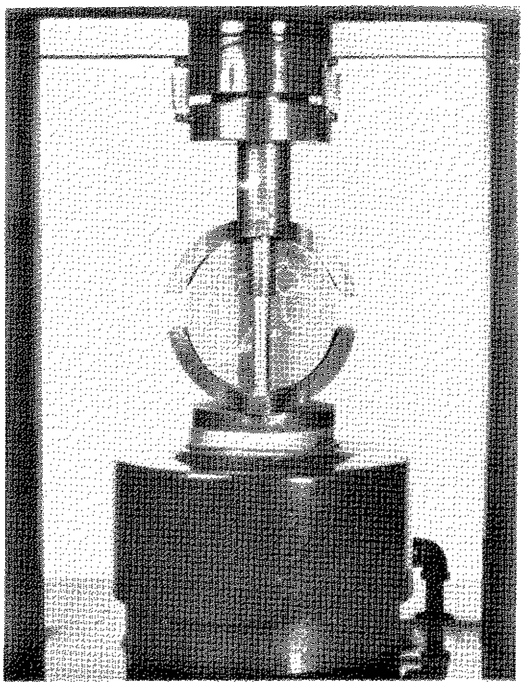
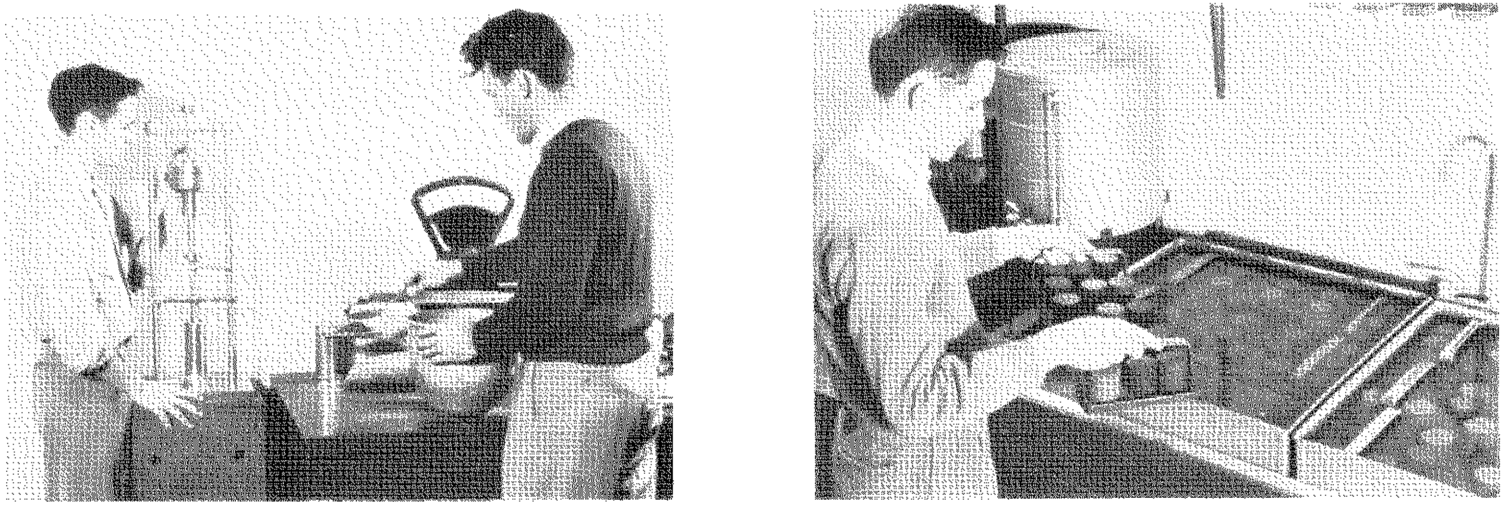
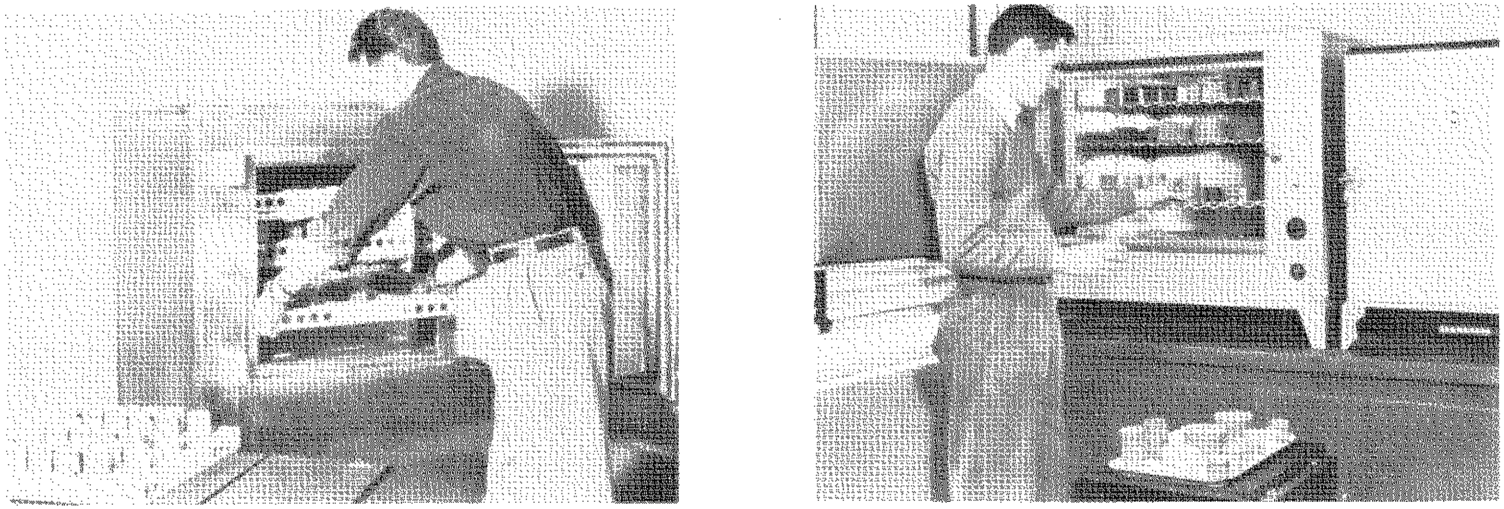


Fig. 6 Device Used for Obtaining Partially Confined Compressive Strength of 2 1/2-Inch by 4-Inch Soil Samples



(A) PREPARATION OF TEST SAMPLES

(B) ABSORPTION: IMMERSION OF SAMPLES



(C) FREEZE-THAW: REMOVAL OF FROZEN SAMPLES

(D) WET-DRY: REMOVAL OF OVEN-DRIED SAMPLES

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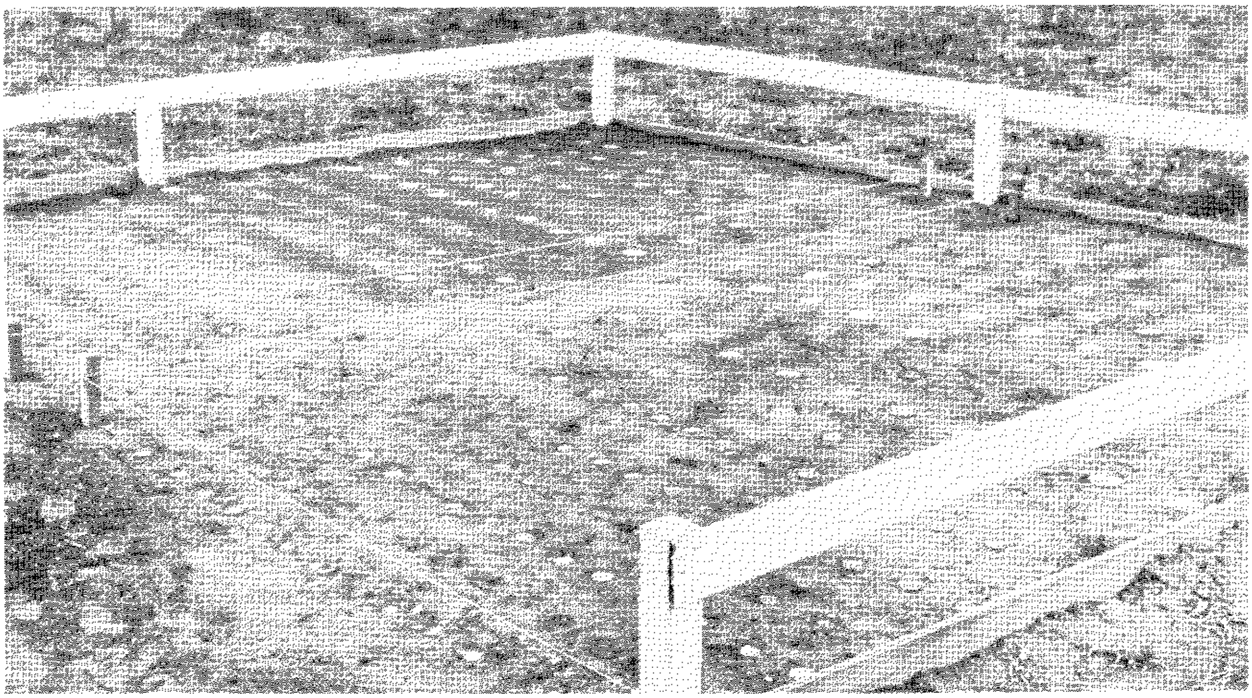
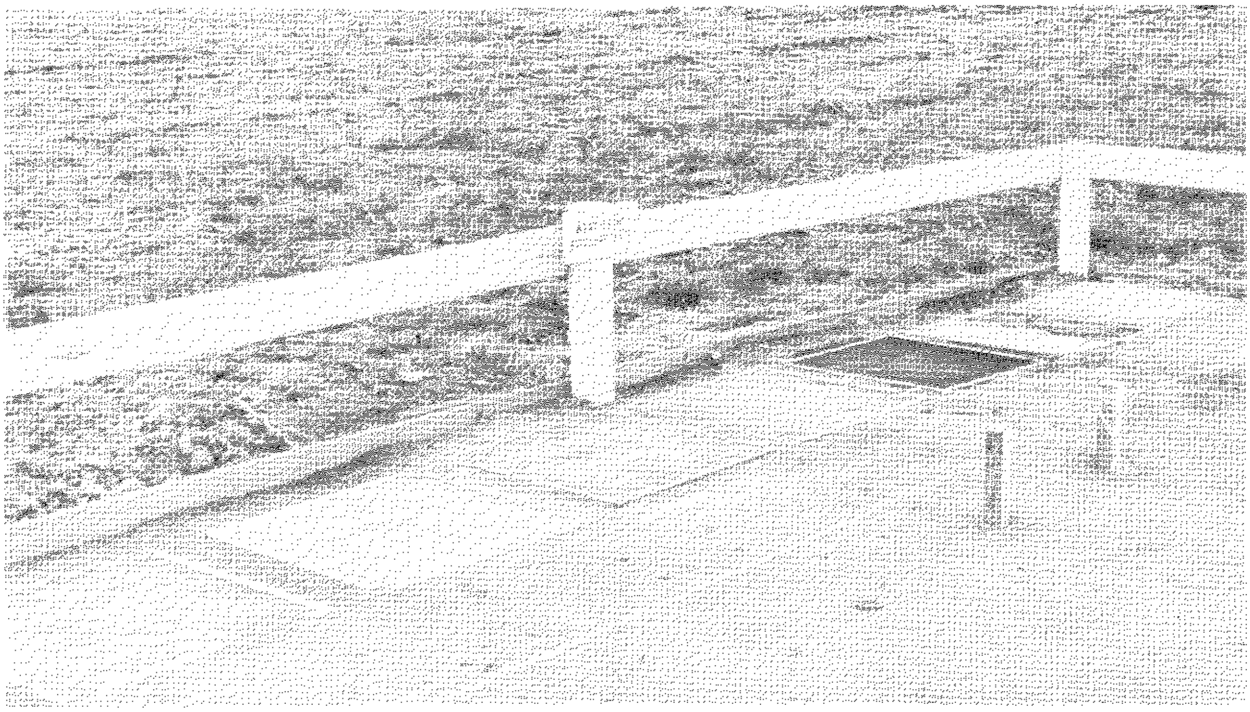
Fig. 7 Operations During Laboratory Exposure Testing



(A) SECTION OF BURIED SAMPLES DURING EXPOSURE



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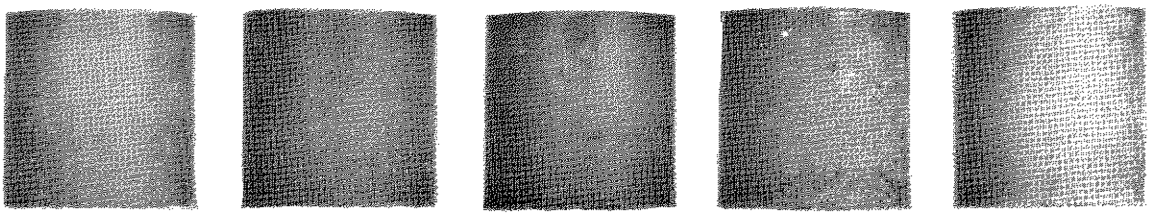
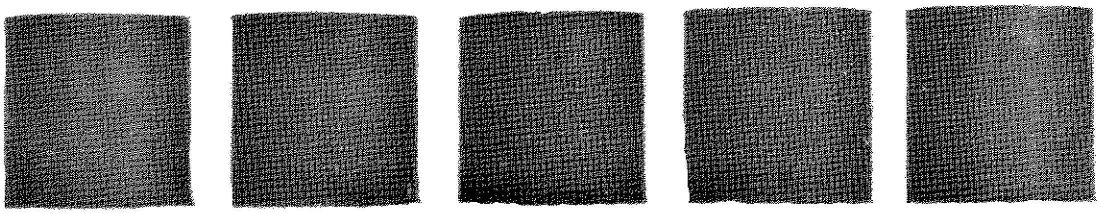
(B) TEST PANELS AT BEGINNING OF EXPOSURE

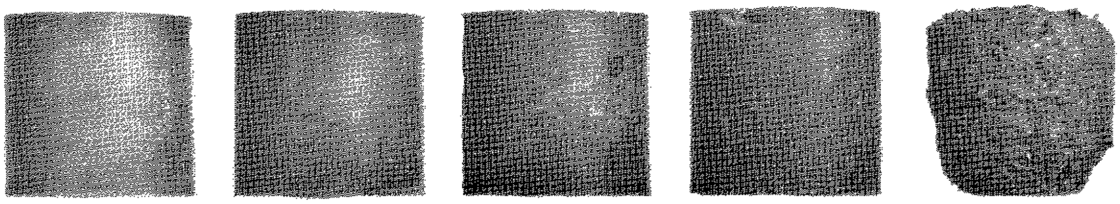
Fig. 8 Field Exposure of Treated Soil Samples



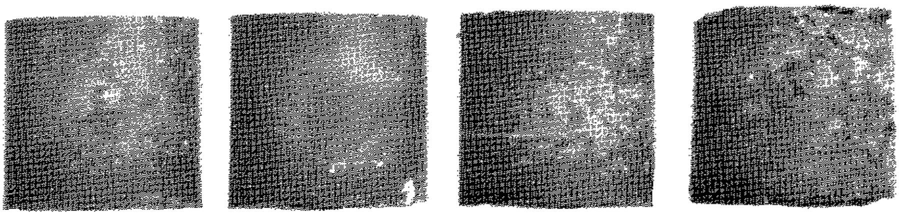
START OF TEST



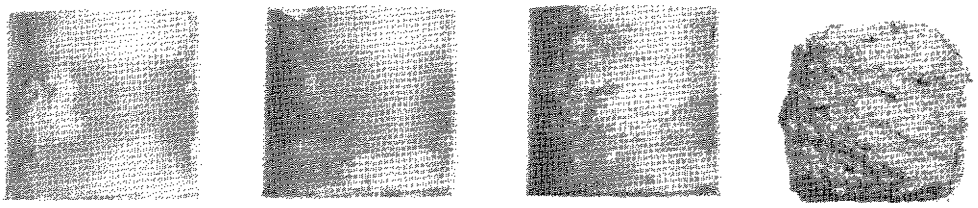
SEVEN DAY ABSORPTION



SIX CYCLES FREEZE-THAW



TWELVE CYCLES FREEZE-THAW



END OF TEST

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Fig. 9 (1) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil C

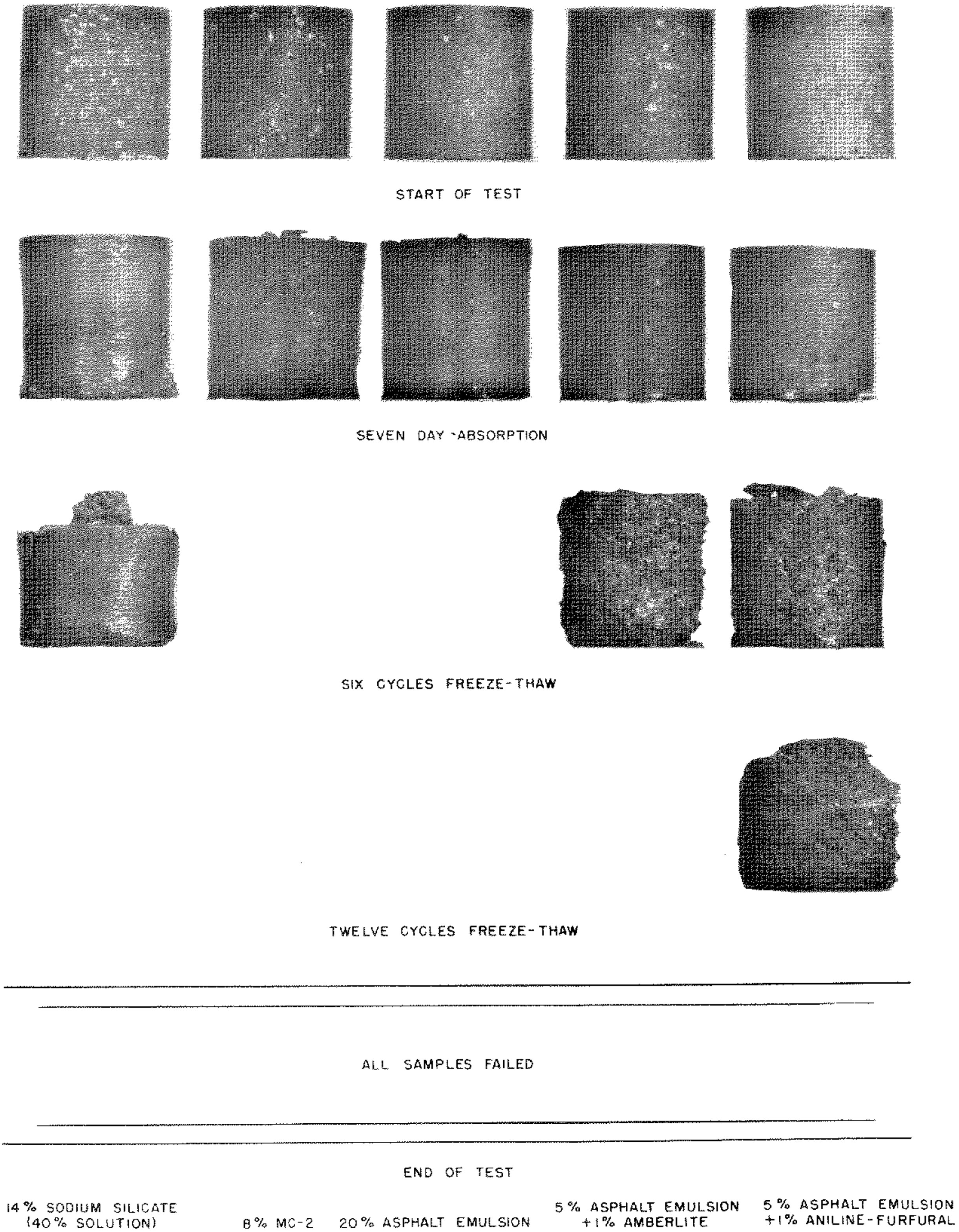

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Fig. 9 (2) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil C

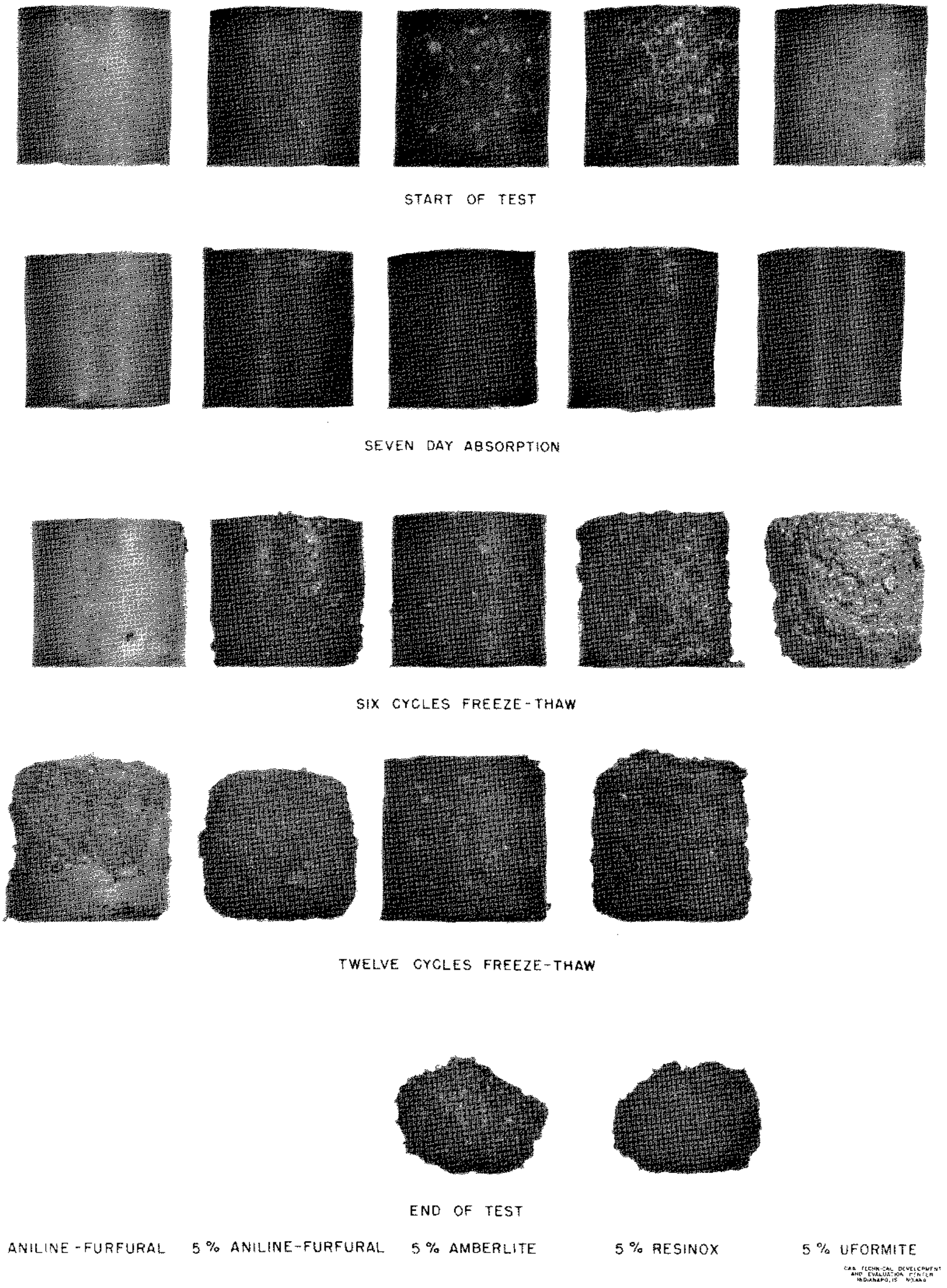


Fig. 9 (3) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil C

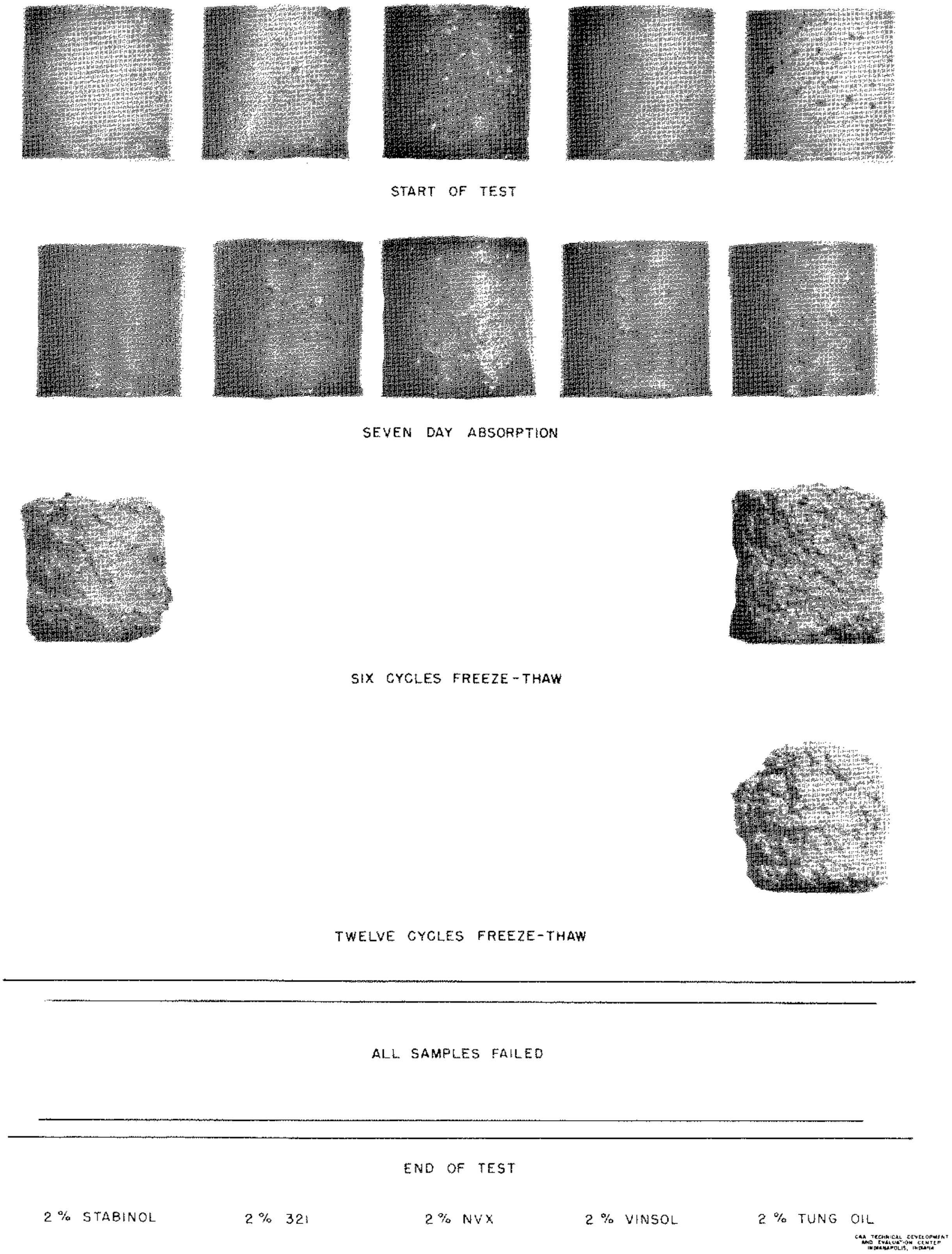


Fig. 9 (4) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil C

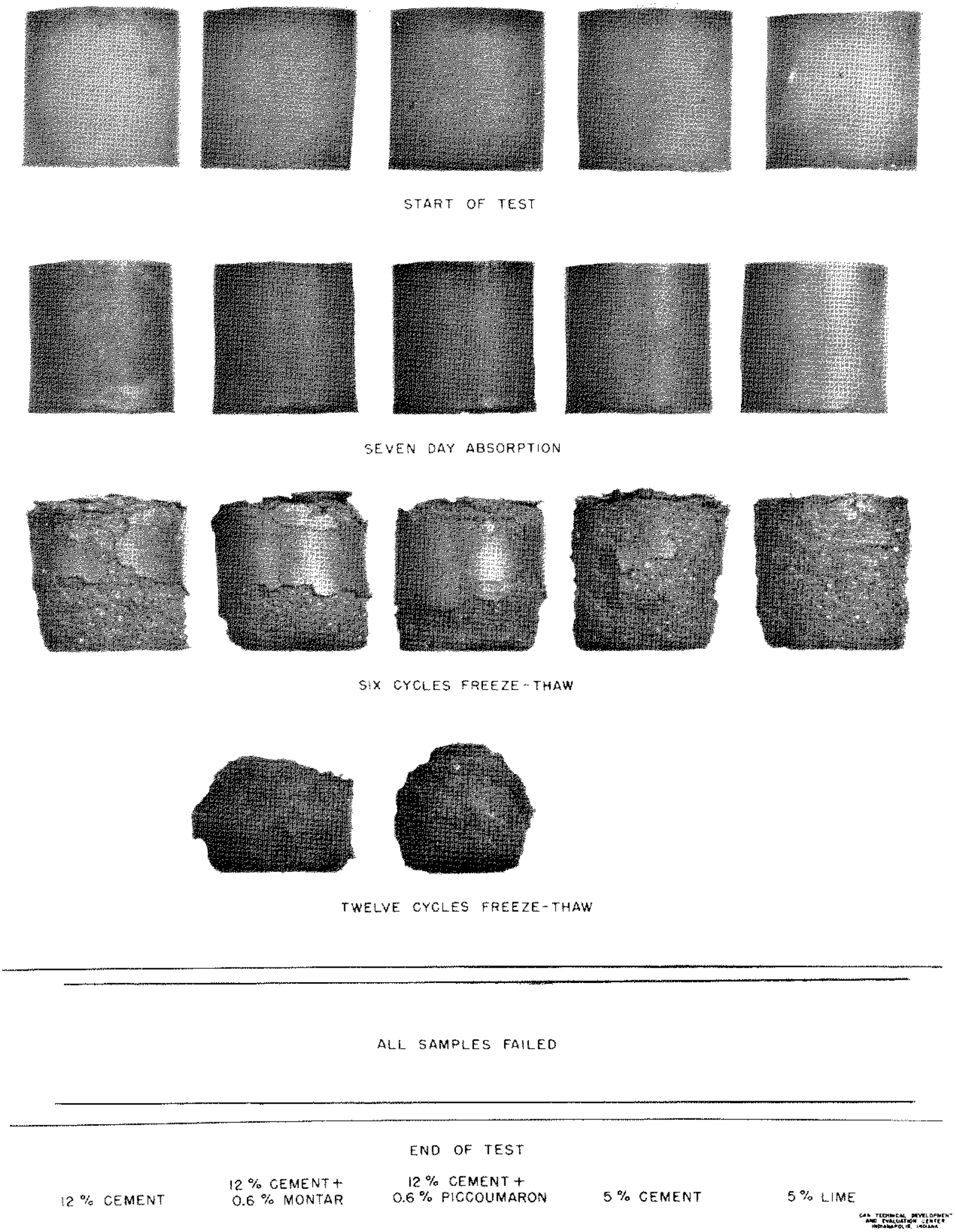
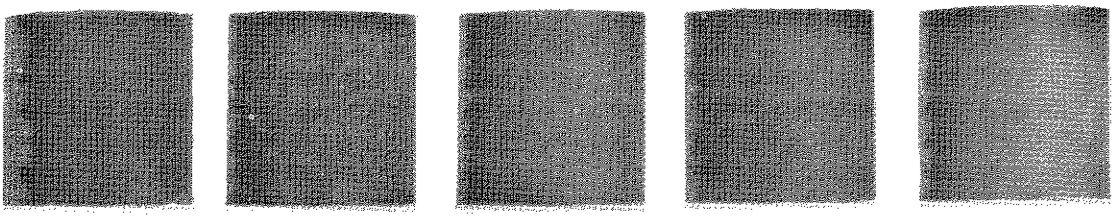
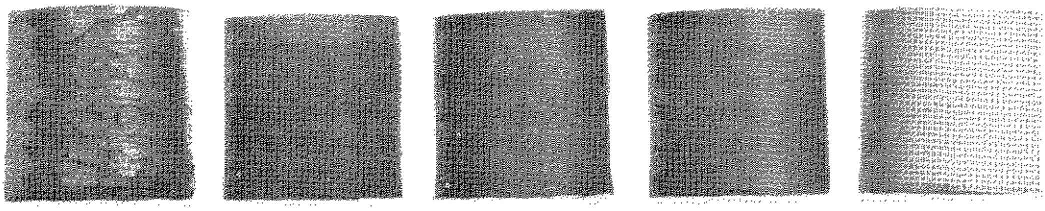


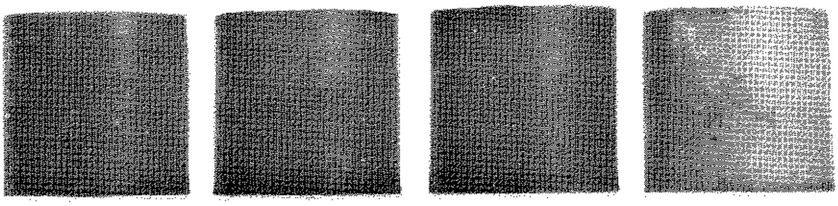
Fig. 10 (1) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil D



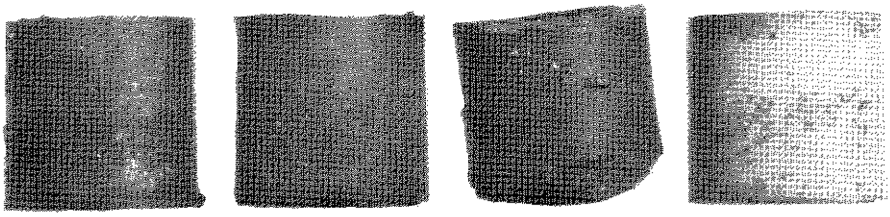
START OF TEST



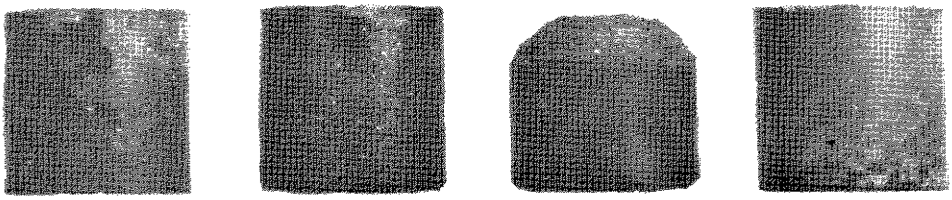
SEVEN DAY ABSORPTION



SIX CYCLES FREEZE-THAW



TWELVE CYCLES FREEZE-THAW



END OF TEST

14 % SODIUM SILICATE
(40 % SOLUTION)

8 % MC-2

20 % ASPHALT EMULSION

5 % ASPHALT EMULSION
+1% AMBERLITE

5 % ASPHALT EMULSION
+1% ANILINE-FURFURAL

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Fig. 10 (2) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil D

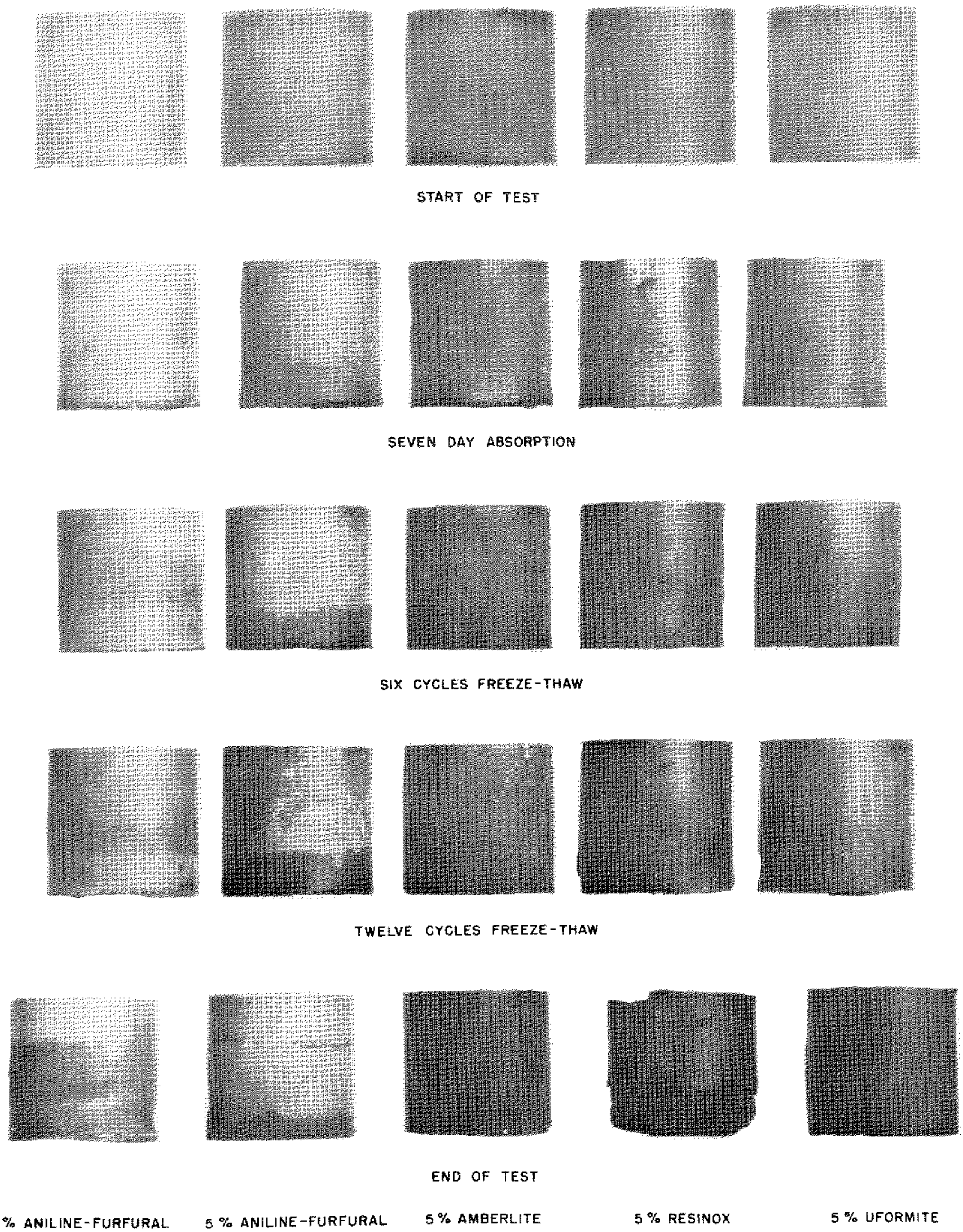

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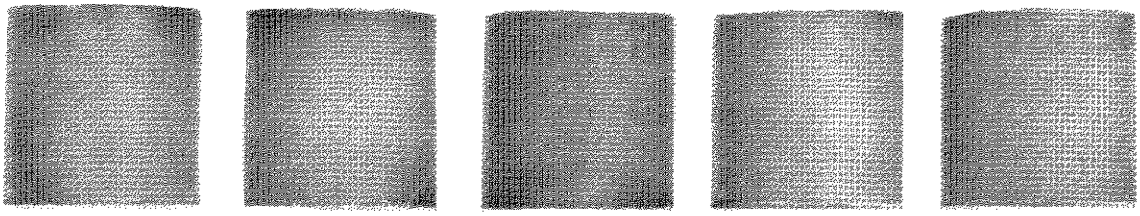
Fig. 10 (3) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil D



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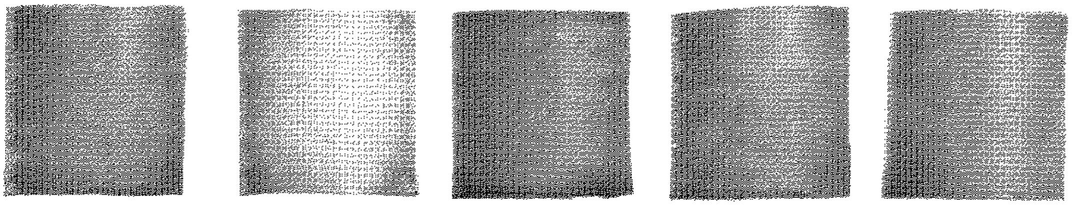
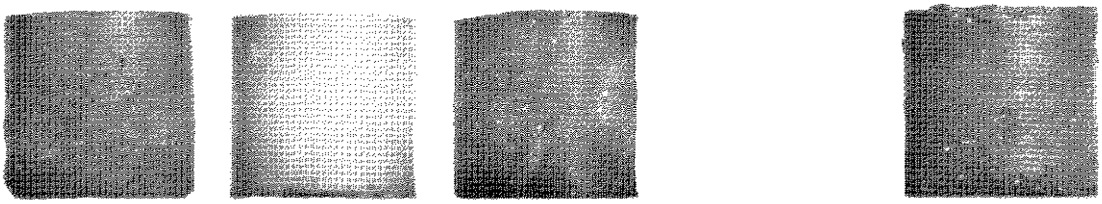
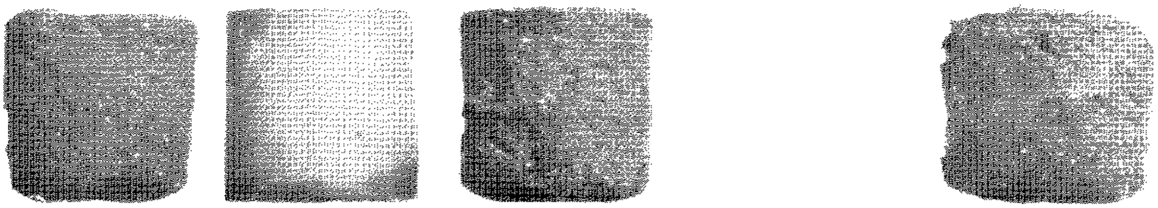


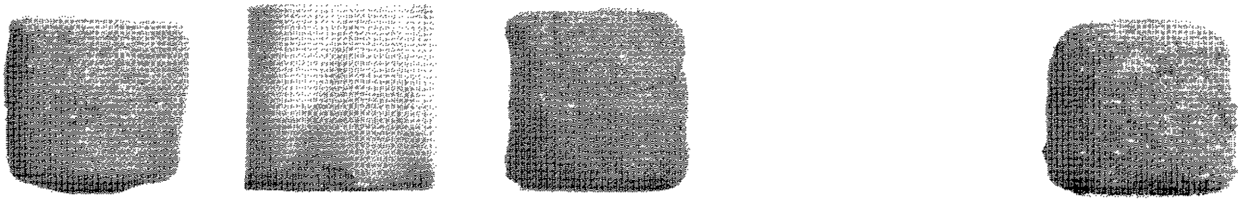
SEVEN DAY ABSORPTION



SIX CYCLES FREEZE-THAW



TWELVE CYCLES FREEZE-THAW



END OF TEST

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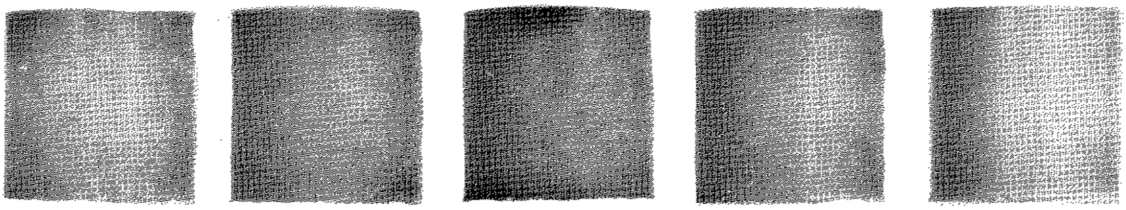
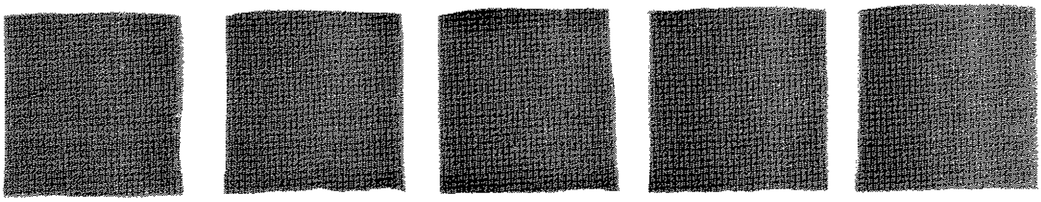
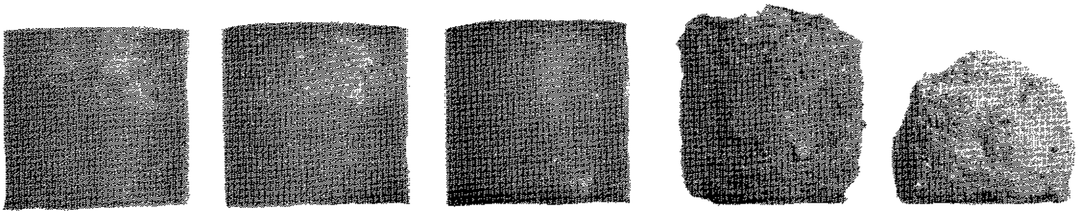
Fig. 10 (4) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil D



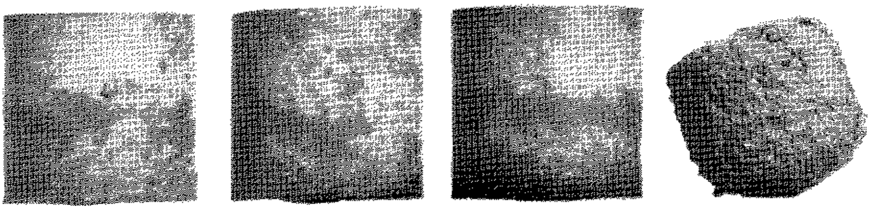
START OF TEST



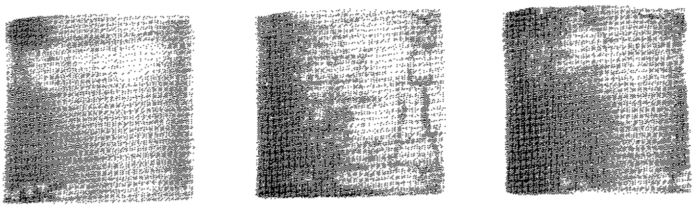
SEVEN DAY ABSORPTION



SIX CYCLES FREEZE-THAW



TWELVE CYCLES FREEZE-THAW



END OF TEST

12 % CEMENT

12 % CEMENT +
0.6 % MONTAR

12 % CEMENT +
0.6 % PICCOUMARON

5 % CEMENT

5 % LIME

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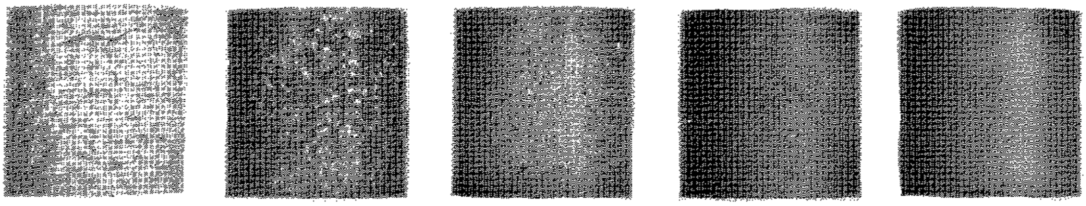
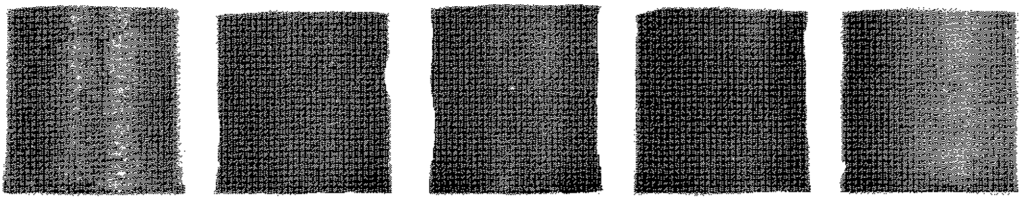
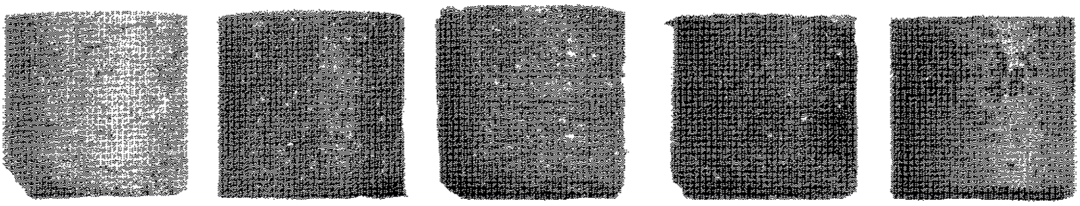
Fig. 11 (1) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil I



START OF TEST

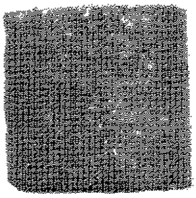


SEVEN DAY ABSORPTION



SIX CYCLES FREEZE-THAW

TWELVE CYCLES FREEZE-THAW



END OF TEST

14 % SODIUM SILICATE (40 % SOLUTION)

8 % MC-2

20 % ASPHALT EMULSION

5 % ASPHALT EMULSION + 1 % AMBERLITE

5 % ASPHALT EMULSION +1 % ANILINE-FURFURAL

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Fig. 11 (2) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil I

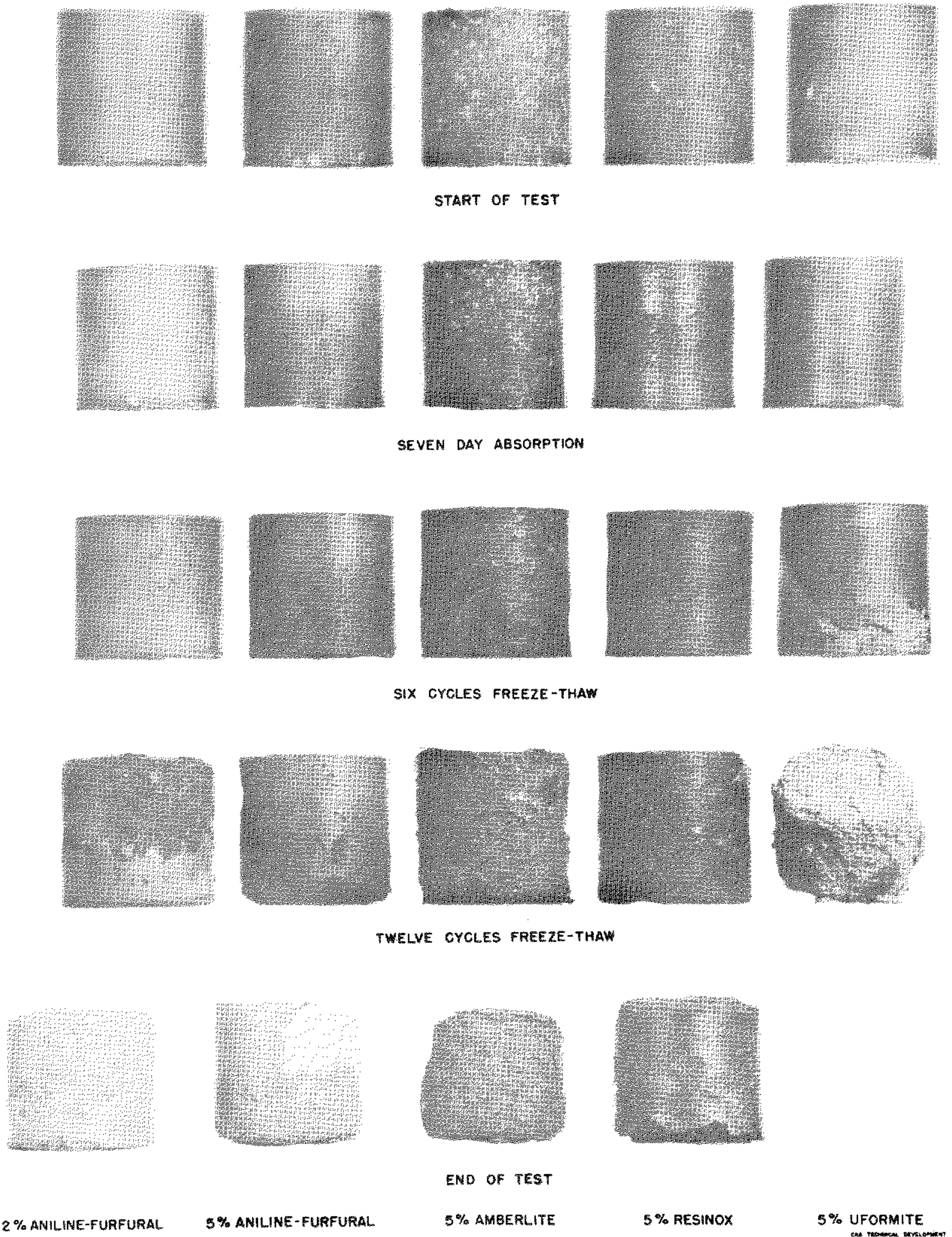

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Fig. 11 (3) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil I

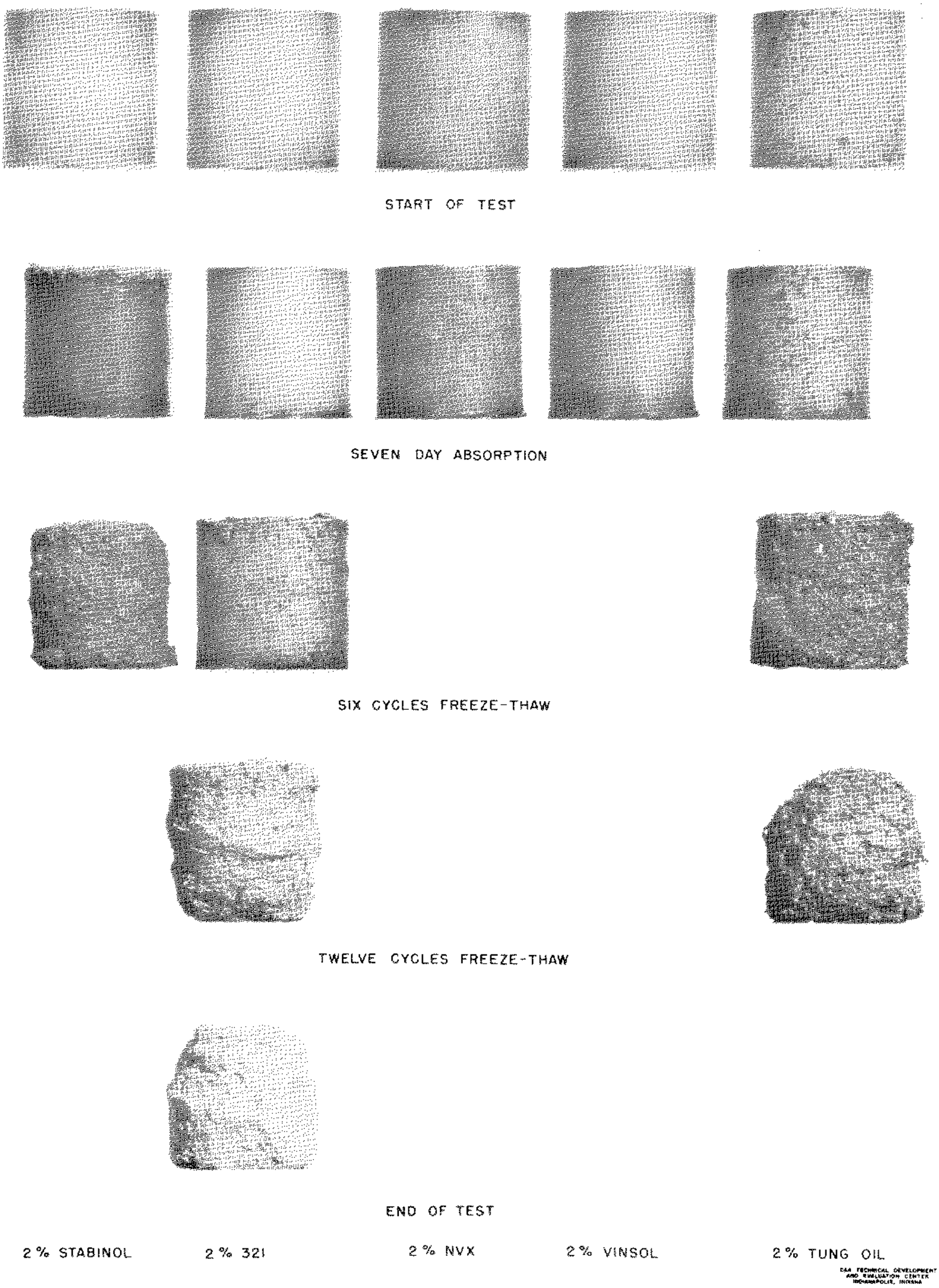
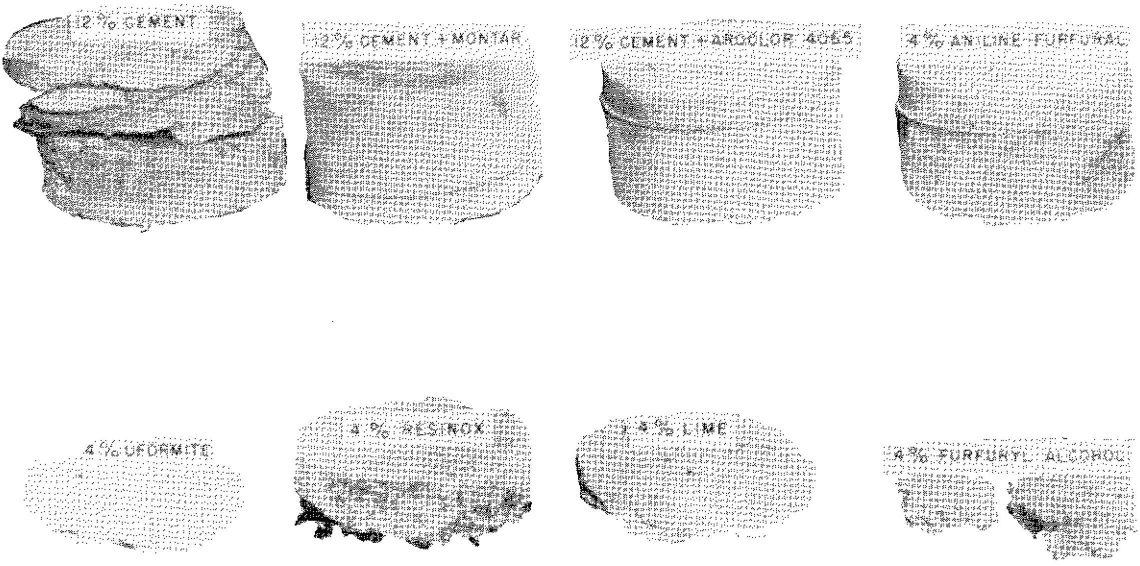
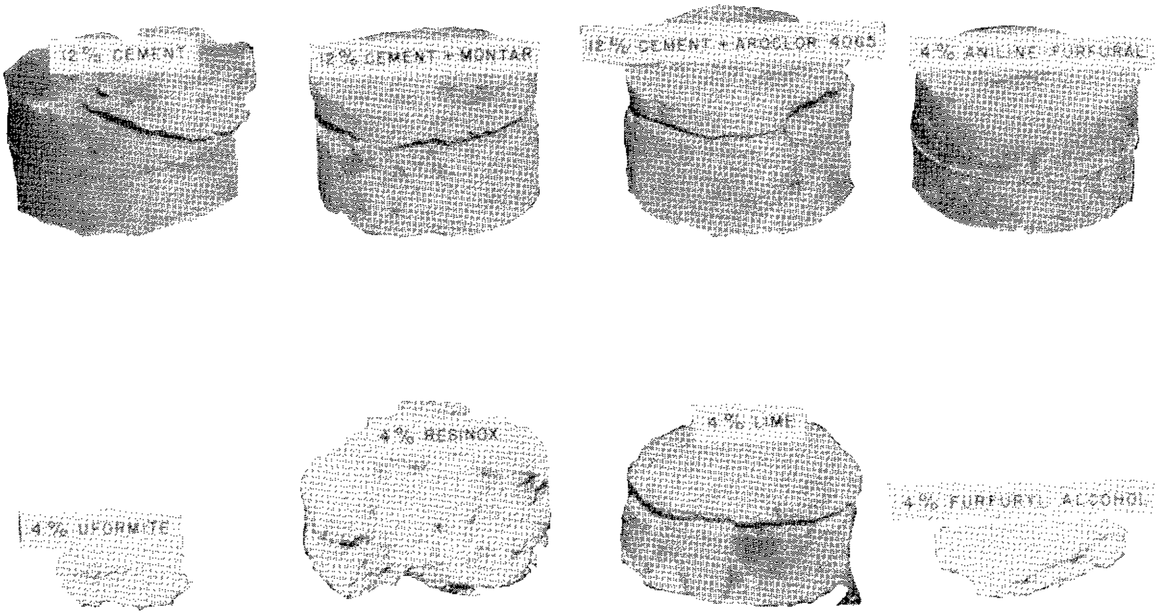


Fig. 11 (4) Effectiveness of Different Admixtures During Progressive Laboratory Exposure - Soil I



SOIL "B"



SOIL "F"

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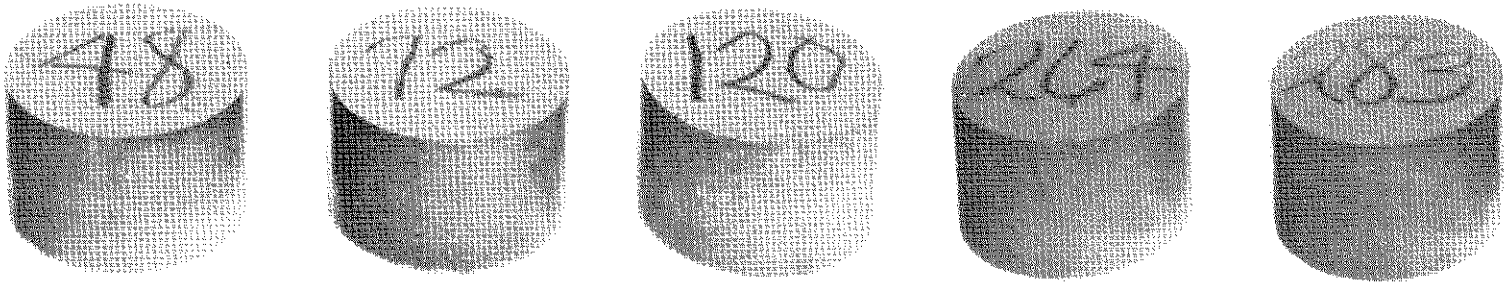
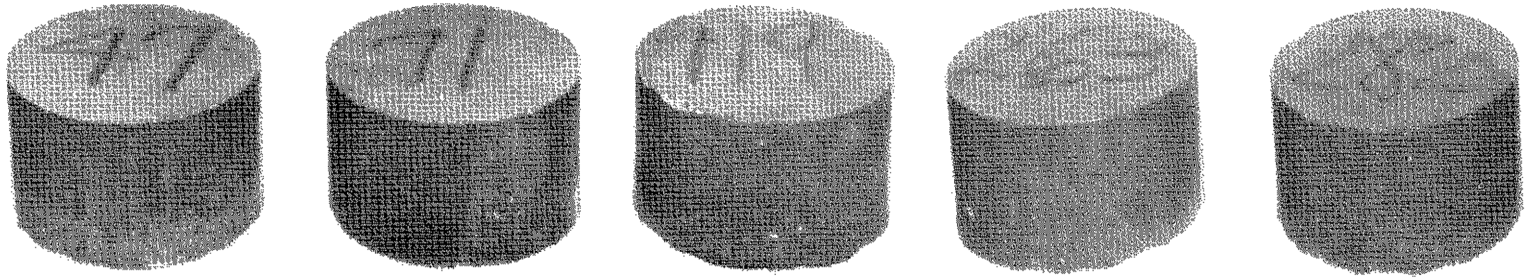
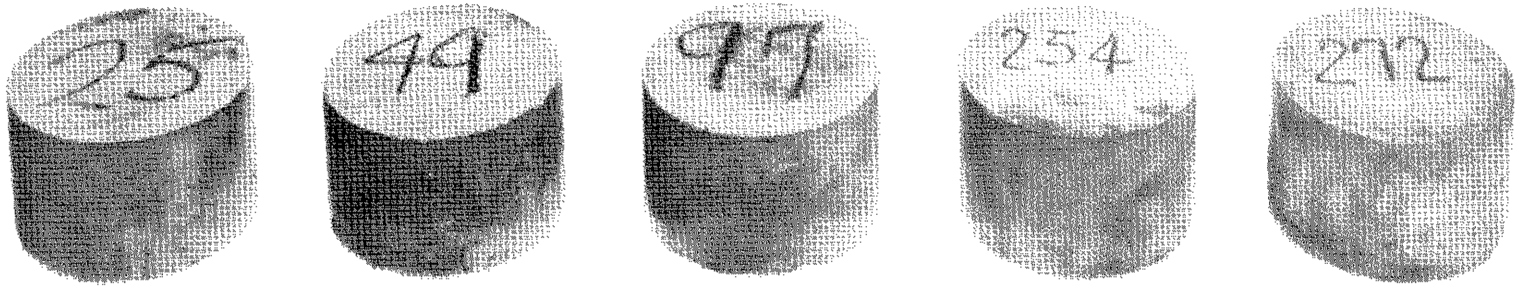
Fig. 12 Chemically Treated Samples After One Year of Field Exposure - Soils B and F



UNWEATHERED



AFTER LABORATORY EXPOSURE



AFTER FIELD EXPOSURE

12 % CEMENT

12 % CEMENT + MONTAR

12 % CEMENT + AROCLOR 4065

12 % CEMENT + PICCOLYTE

12 % CEMENT + PICCOUMARON

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Fig. 13 (1) Comparison of Laboratory and Field Exposure of Chemically Treated Samples - Soil C

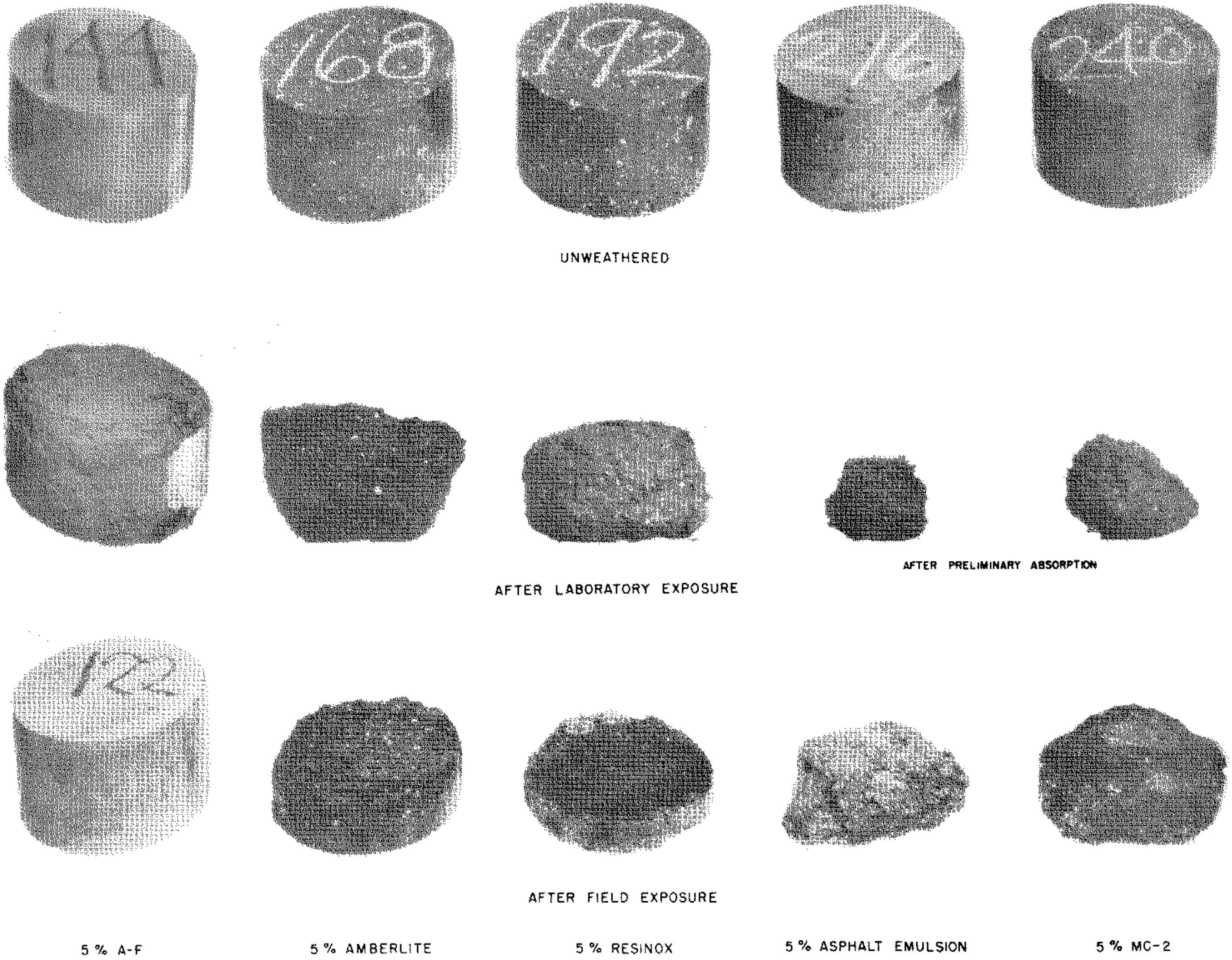

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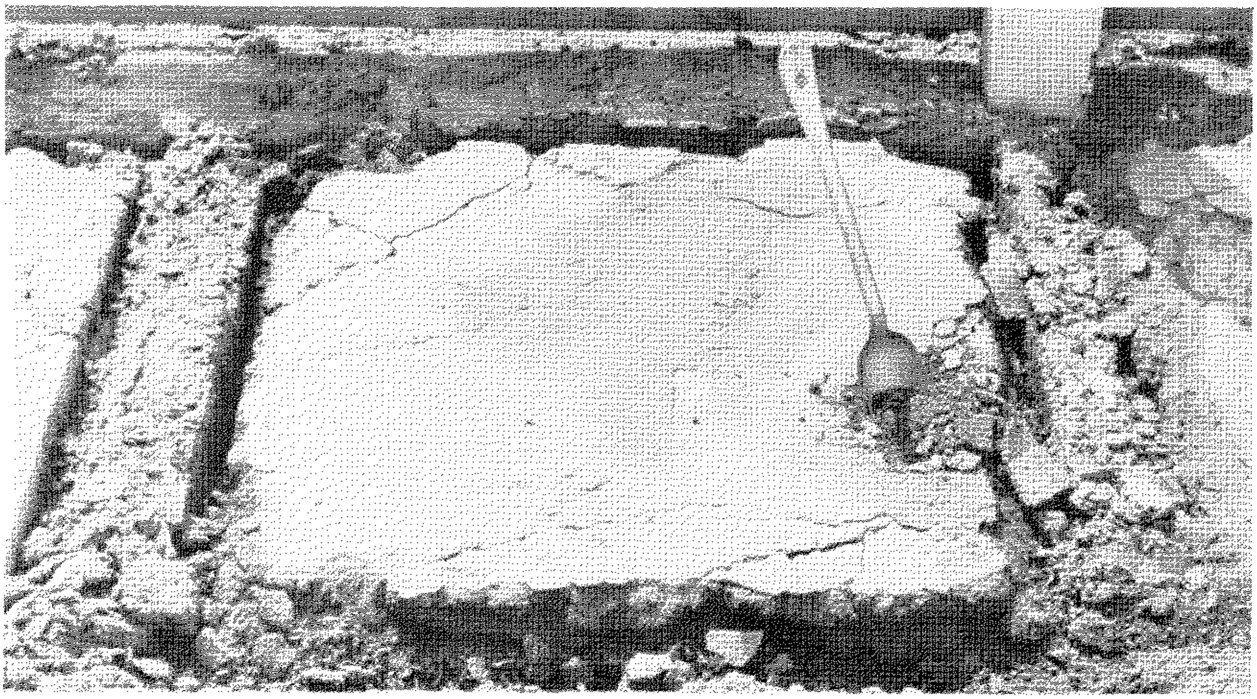
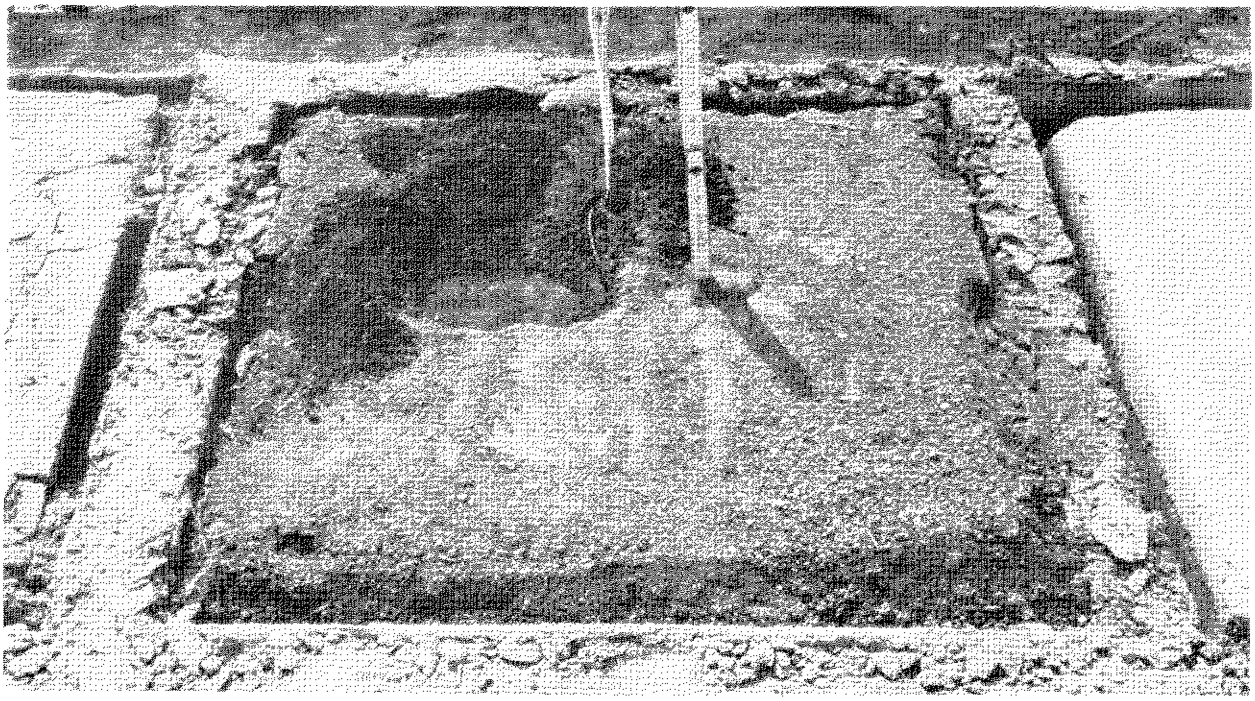
Fig. 13 (2) Comparison of Laboratory and Field Exposure of Chemically Treated Samples - Soil C



(A) 5 % ANILINE - FURFURAL



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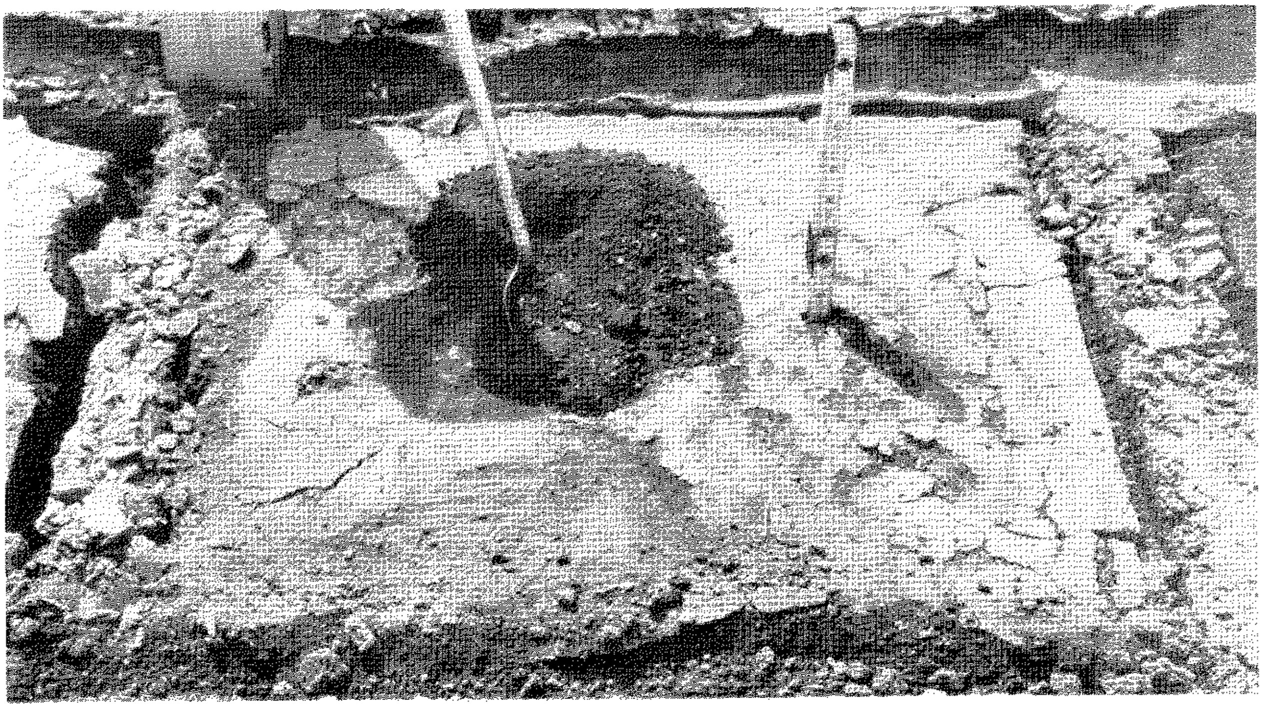
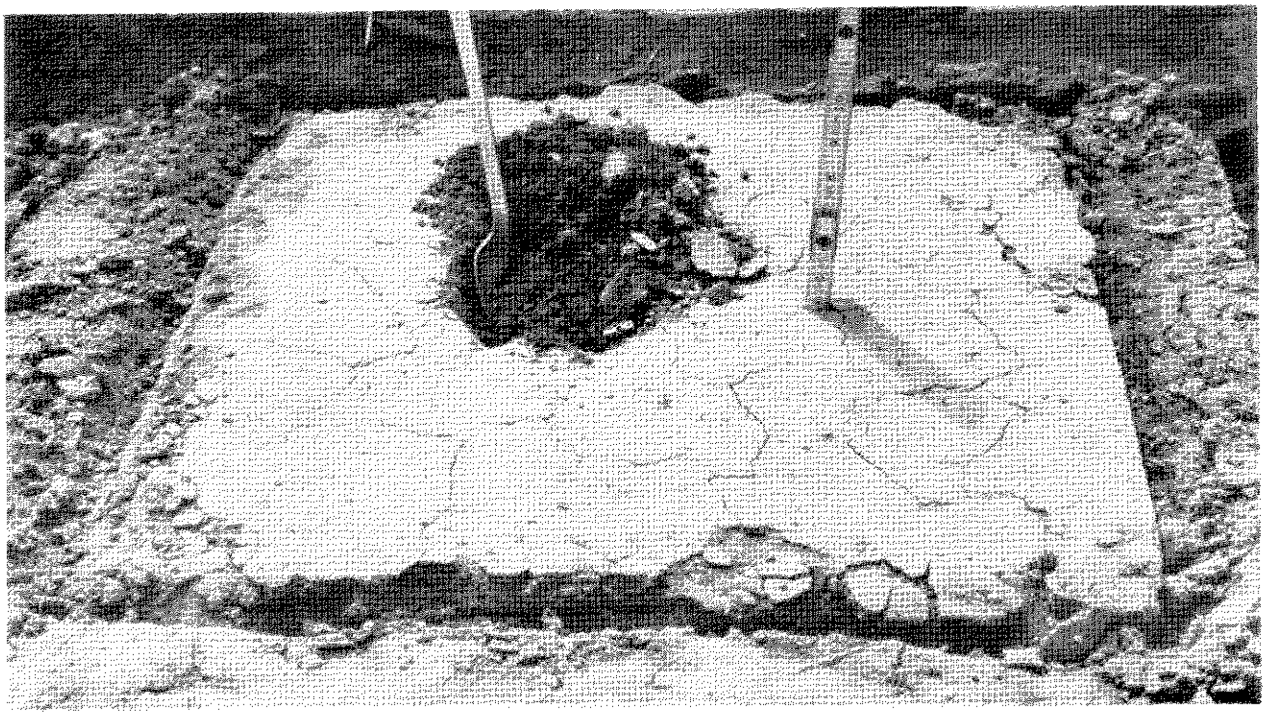
(B) 5 % RESINOX

Fig. 14 (1) 2-Foot by 2-Foot by 4-Inch Test Panels of Treated Soil After One Winter of Field Exposure - Soil C



(C) 5 % MC-2 + AGGRECOTE



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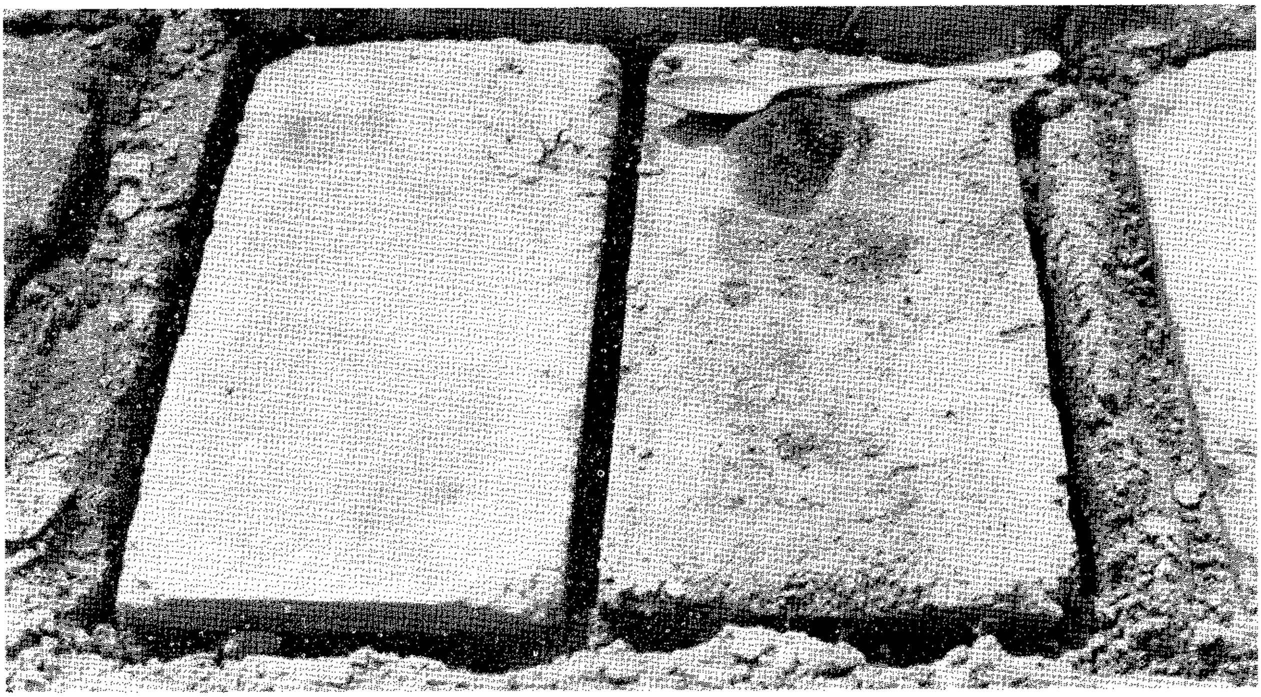
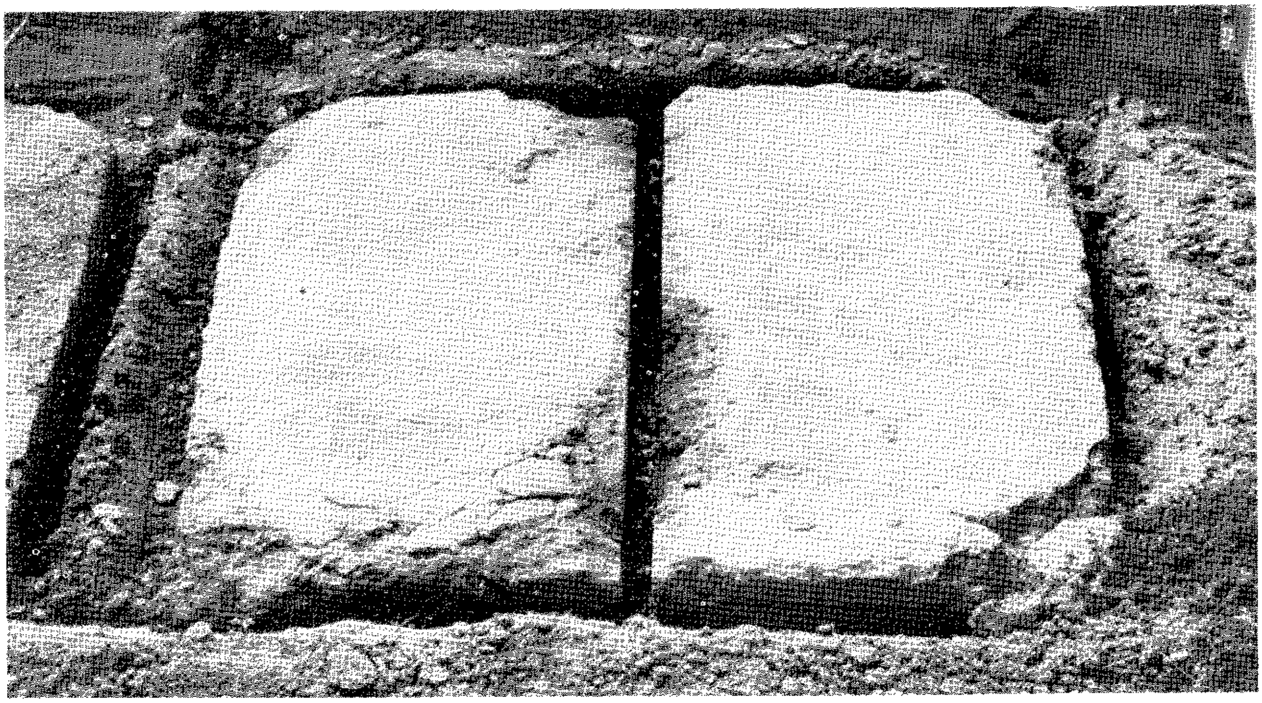
(D) 5 % ASPHALT EMULSION + AGGRECOTE

Fig. 14 (2) 2-Foot by 2-Foot by 4-Inch Test Panels of Treated Soil After One Winter of Field Exposure - Soil C



(E) 12 % CEMENT

(F) 5 % AMBERLITE



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+ PICCOLYTE

+ PICCOUMARON

(G) 12 % CEMENT

Fig. 14 (3) 2-Foot by 2-Foot by 4-Inch Test Panels of Treated Soil After One Winter of Field Exposure - Soil C

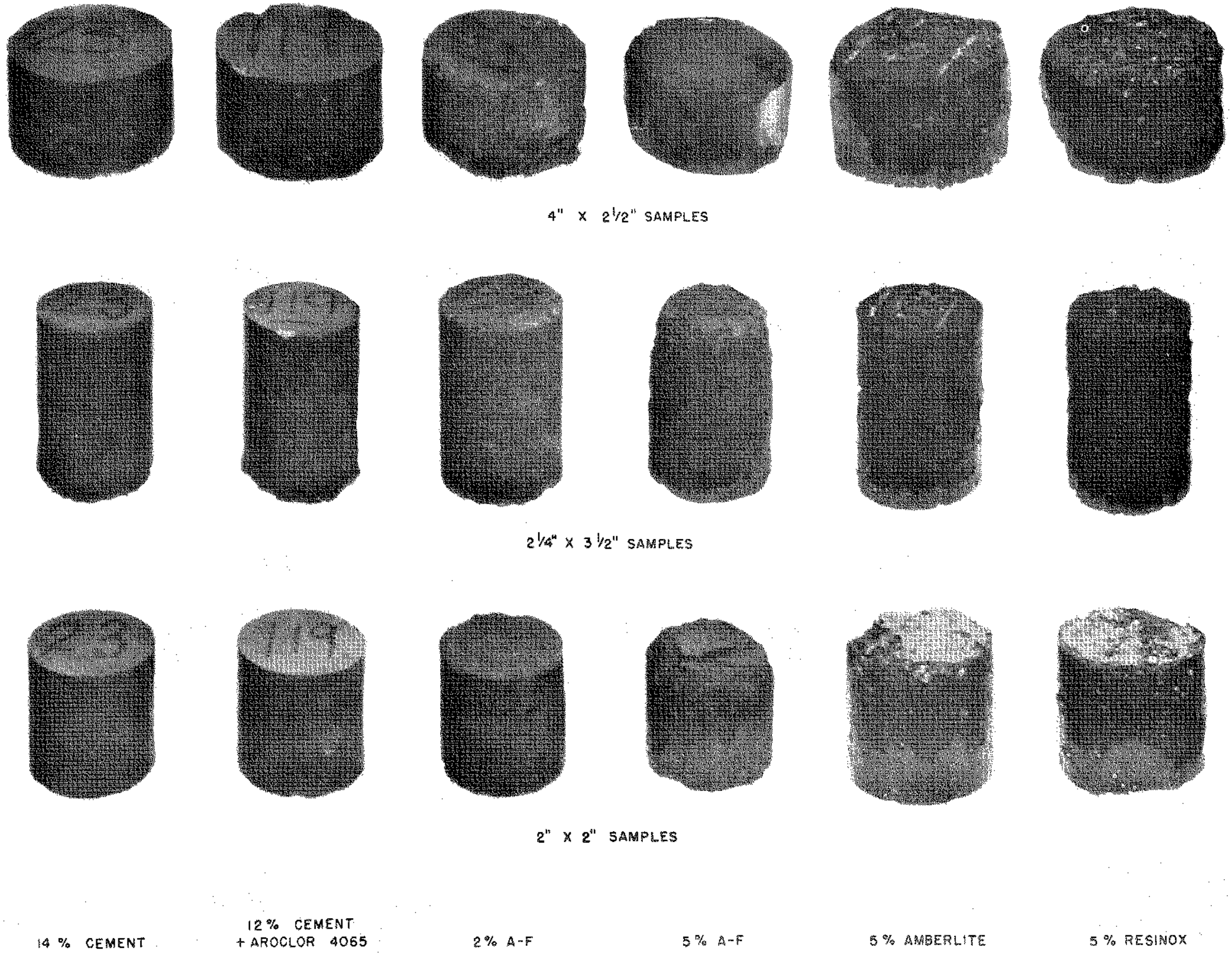

Fig. 15 Effect of Sample Size on the Resistance of Chemically Treated Soil to Laboratory Exposure - Soil C

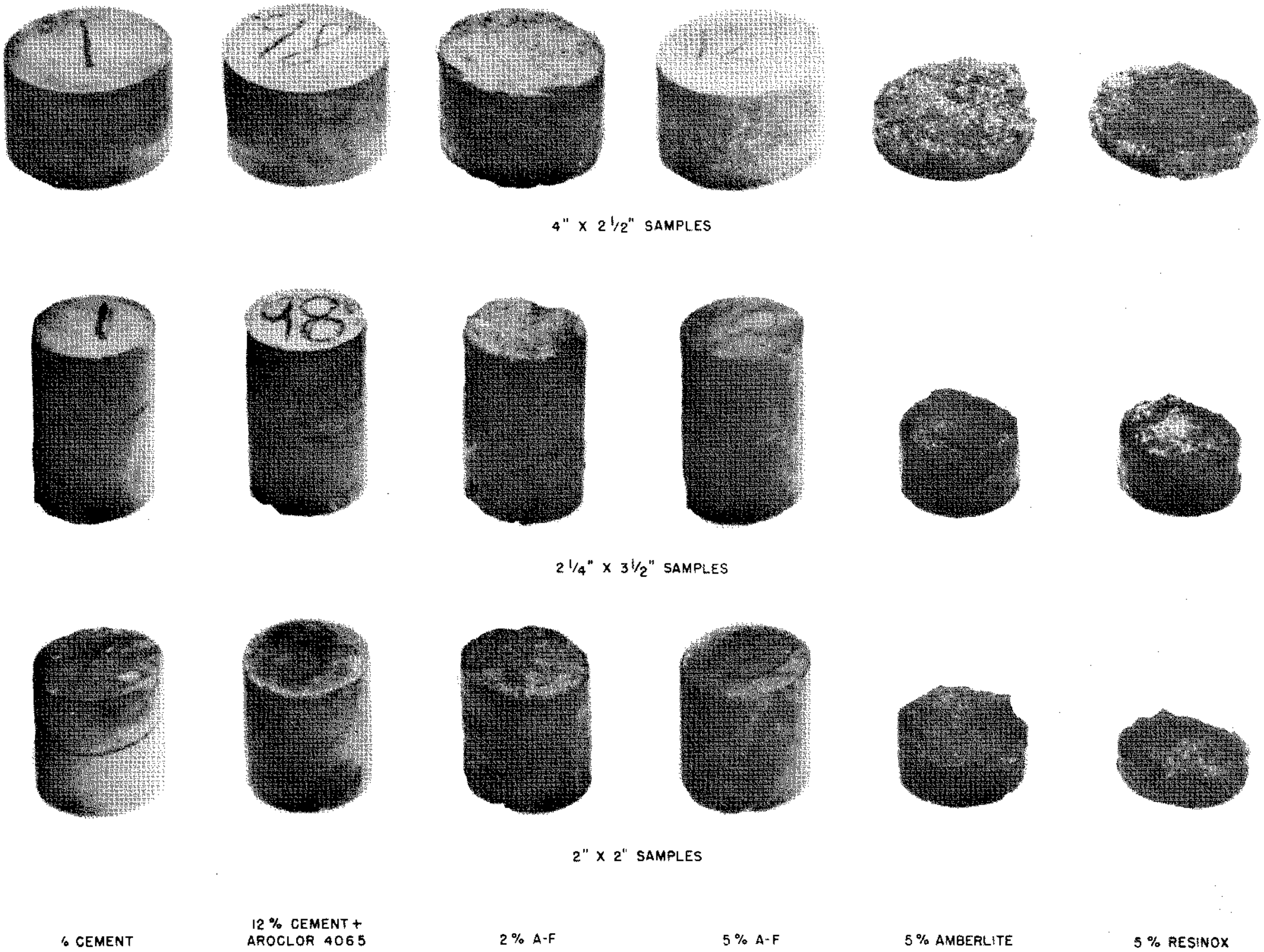

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Fig. 16 Effect of Sample Size on the Resistance of Chemically Treated Soil to Field Exposure - Soil C

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