A LABORATORY STUDY OF THE EFFECTIVENESS OF VARIOUS CHEMICALS AS SOIL STABILIZING AGENTS

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CAA INFORMATION AND STATISTICS

A LABORATORY STUDY OF THE EFFECTIVENESS OF VARIOUS CHEMICALS AS SOIL STABILIZING AGENTS

SUMMARY

This report describes the laboratory studies made to develop chemicals which, when mixed with natural soils, form an integral material suitable for light paving Since the War Department had expressed interest in the possible military value of such work, the main effort of this study was directed toward the development of materials that could be made readily available in the combat areas, either by their geographic location or by their being effective in such small quantities that the transportation of the material could be reasonably effected

In the earlier phases of this work, the most promising chemical appeared to be a 40 percent solution of sodium silicate to which had been added a solution of sodium aluminate This combination, especially when used with the more sandy soils, gave very high compressive strengths and readily withstood the action of water However, although a large part of this study was devoted to this highly effective combination, no practical means was found whereby the material could be added to the soil in a manner suited to normal construction methods, inasmuch as the two chemicals interacted and "set" immediately upon contact and consequently made the control of mixing and compaction very difficult.

Other chemicals, although yielding lower strength values than the above method, indicated very promising results The best of these were raw tung oil, linseed oil, and a synthetic resin formed by a mixture of furfuryl alcohol and acid The practical use of these materials seemed entirely feasible Other materials, including cottonseed oil, rubber latex and aluminum stearate, were tried with varying success, but were not fully evaluated in this study

Although some of the results obtained from this particular work have not been conclusive, much valuable data have been amassed and are presented here for the purpose of record and as a guide to possible future investigations As several of the materials show definite stabilizing possibilities, it is believed that their further development might result in useful agents, either when employed alone or in combination with other chemicals

For a proper evaluation of this work, it must be understood that this form of chemical stabilization is not meant for use where heavy paving is required, but is merely to be used for light construction or as a temporary expedient for military use until such time as more permanent construction can be undertaken

INTRODUCTION

Shortly after the outbreak of the present war, the Technical Development Division of the Civil Aeronautics Administration initiated a project entitled "The Development of Chemicals to Effect Soil Stabilization," for the purpose of investigating the soil stabilizing effectiveness of various chemical substances and the determination of their applicability to the construction of secondary or temporary roads and airfields Because of the possible military value of such rapid mixed-in-place methods of paving, the interest of the War Department was expressed in this project and the work was recommended for completion by the Secretary of War, in a letter to the Secretary of Commerce, dated April 21, 1942

Since the texture and chemical composition of soils vary over such a wide range, and, since even slight changes in these properties greatly influence the response of soils to the weathering forces of nature and to the various conditions of traffic, the problem of stabilizing soils by chemical means is extremely complex and one unlikely to be solved by a single simple method The investigation conducted by the Technical Development Division on this subject has been comprehensive and fundamental, and to date several promising chemical agents have been developed. This report describes but one phase of the over-all development work, other results, in addition to brief summaries forwarded to the War Department as the work progressed, having been reported in separate publications [1]

In the specifications for this investigation it was stipulated that the chemicals developed should be effective when applied by the usual construction methods, with emphasis on the liquid form, in case it were found feasible to apply the materials to the soil by pressure injection, and further that they should

1. Be relatively insoluble by the action of water after final placement
2. If a liquid, possess low viscosity at the time of application within a temperature range of 40°-140° F
3. Be effective with soil types ranging from sands to silty clay loams

In order to facilitate transportation of the materials to remote areas - a necessary consideration for the military - it was stated that the materials should be effective in small quantities and, if possible, should be obtainable in concentrate form requiring only water for activation prior to use at the construction site. With these points in mind, the laboratory work was undertaken by the Armour Research Foundation, Chicago, Illinois, under contract to the Civil Aeronautics Administration

A thorough search of previous works on the subject of chemical soil stabilization indicated the possible use of several materials as effective stabilizing agents. The most promising of these appeared to be calcium chloride, sodium silicate, silica gel, and other gelatinous substances such as the hydroxides of aluminum, iron, magnesium, and calcium. In addition, it was decided to investigate the possibility of preparing synthetic tricalcium silicate and tricalcium aluminate from aqueous solutions. These compounds are responsible for the strong binding action of portland cement. This procedure was extended to include also the preparation of such substances as plaster of Paris, magnesium oxychloride cement, and other materials. The possibility of stabilizing soils by the chemical preparation of resins also appeared promising

A large number of exploratory tests were made on these and other materials in order to determine their applicability to the problem. The results of these early studies indicated that sodium silicate was the outstanding bonding agent of the group, and it was decided to study this material in detail. Other chemicals investigated at this time are listed in the Appendix

For the purpose of this report, the work has been divided into three general parts: the first describing the preliminary testing to produce a satisfactory method of utilizing the high strength-giving values of sodium silicate by the addition of other chemicals, the second part describing the evaluation of the most effective combination discovered, sodium silicate with sodium aluminate, and the third part describing the evaluation of various promising materials of lesser strength characteristics

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[1] Winterkorn, Hans F., and McAlpin, George W., "Soil Stabilization by the Use of Rosin," CAA Technical Development Note No. 34, June 1943
McAlpin, George W., Mainfort, Robert C., and Winterkorn, Hans F.
"A Laboratory Study of the Soil Stabilizing Effectiveness of a Complex Salt of Abietic Acid," CAA Technical Development Note No. 35, July 1944

LABORATORY TESTING PROCEDURES

In this study, the properties of the treated soils were evaluated by determining the load-sustaining ability of both dry and soaked specimens Two types of loading tests were employed, the unconfined compression, and the load-plunger tests In addition, tests were also conducted to determine the resistance of the treated soil to the action of water

To prepare the test cylinders the soil, chemicals, and necessary water were thoroughly mixed into a uniform blend and the resultant mass compacted by the standard Proctor method (A.A.S H O Designation T99-38) with the exception that the mold used in this case was larger than that normally employed, having an inside diameter of 4 inches and a height of 6 inches [2] For some of the preliminary tests a smaller mold, 3 3/8 inches in diameter by 3 5/8 inches high, was used for ease in working and handling

After proper compaction the cylinders were either air-dried for a definite period or oven-dired to constant weight at a temperature of 140° F , after which period of curing the strength properties of the specimens were determined by either the compression or the load-plunger tests In the latter procedure the compression machine was equipped with a metal plunger, 2 inches long and having a circular end contact area of 0 75 square inch, for applying the load This plunger was placed concentrically on the test specimens and, after a snug bearing had been obtained, load was applied at a constant rate of 400 pounds per minute The maximum load values at failure, or at a plunger penetration of 0 1 inch, were indicative of the relative value of the stabilizing agents either as added to identical soils in varying amounts, or as added to different soils in equal amounts

To determine the effect of moisture on the treated soils, the compacted specimens were dried back a definite amount, either in the air or in the oven, and then immersed in water for varying periods of time during which the amount and effect of the water action were observed For this test the water level was maintained about 1/8 inch below the top of the cylinders and the water changed daily The weights of the specimens were determined each day and by comparison with the known dry weight the percent moisture was determined From these data the moisture absorption curves for the various conditions of treatment were plotted At the end of the soaking period the usual load-plunger or compression tests were made

THE EFFECTIVENESS OF SODIUM SILICATE

Sodium silicate, commonly known as "waterglass," is a colorless, highly alkaline substance, readily soluble in water and available commercially either in solution or in concentrated crystal form The material is available in sizeable quantities and is easy to handle Commercial forms of sodium silicate vary to a certain degree in chemical composition and the viscosity of the solution increases with the amount of sodium present in the compound Laboratory tests indicated that a 40 percent solution (40 grams of sodium silicate per 100 c.c of water) of the formula Na_2O 3.2 SiO_2 would be most suitable for the present studies

From the start of this investigation some very firmly bonded masses were obtained by treatment with sodium silicate, especially with soils high in sand content However, the resulting mixtures were unable to withstand the action of water and, therefore, it became necessary to develop a waterproofing agent which, when added to the soil either with the sodium silicate or by a separate application, would form a water insoluble bond Before investigating this phase of the work, however, a thorough study of the bonding action of the sodium silicate was made

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[2] Standard Proctor mold is 4 inches in diameter and 4.59 inches high.

Bonding Action of Sodium Silicate

It was clearly indicated by early testing that the sodium silicate method of treatment was far more effective with sandy soils than with those in which silt and clay predominated. Preliminary tests also showed that with an increase in the amount of silt and clay present in the soil, the percentage of treatment required for optimum strength increased and the maximum obtainable strength decreased The sandy soils seem to be well suited for bonding by the action of sodium silicate and, in addition, because of their friable character, it is possible to obtain thorough dispersion of the solution during mixing, resulting in uniformly treated specimens. As the clay and silt content of the soil is increased, however, the dispersion of the admixture became difficult and small pockets of the heavier materials remained untreated, resulting in weak, honeycombed specimens Attempts to overcome this defect by the use of commercial wetting agents were unsuccessful.

Figure 1 shows the comparative effect of the sodium silicate on different soil types when each had been treated with a pre-determined optimum amount of the solution For this test six different soil types, ranging in texture from fine sand to clay, were mixed with enough sodium silicate solution to give optimum strength value for each type tested The specimens were compacted in the 3 3/8-inch by 3 5/8-inch mold, oven-dried to constant weight at 140°F , and broken in direct compression

Under these tests the stabilized sand cylinders withstood loads of well over 20,000 pounds, whereas the treated clay samples were crushed at less than 5,000 pounds A variation was also indicated in the optimum amount of sodium silicate required for maximum strengths, the values ranging from 8 percent for the sand to 14 percent for the heavier soils (dry sodium silicate expressed as a percentage of dry weight of soil). The difficulty of obtaining a uniform dispersion of the solution throughout the finer texture soils was again very apparent during these tests, resulting in very erratic data for these type soils The addition of higher percentages of solution failed to improve the results to a significant degree.

From these and other tests it was indicated that for the sandy soil a treatment of 8 percent sodium silicate, based on the dry weight of the soil, when applied as a 40 percent solution, gave excellent results Further study indicated that this percentage could also be used with the heavier soils with satisfactory results Therefore, in order to keep the percentages of treatment low it was decided to use 8 percent treatment as a maximum throughout the remainder of this investigation

Figure 2 shows the results of tests conducted on the sandy soil treated with 8 percent sodium silicate, to determine the relationship between the load sustaining power and the amount of moisture in the sample after a period of curing These results indicate that the range of moisture content between 35 and 30 percent of that at which the specimens were compacted is critical, with maximum strength being reached when the samples have dried back to about 31 percent of their molded moisture content

Although the sodium silicate gave excellent binding qualities, especially with the sandy soils, none of the specimens, when treated with this chemical alone, would retain their original strength for more than 7 hours of immersion in water After this period they weakened rapidly and at the end of 24 hours of soaking had practically disintegrated Therefore, in an effort to make use of the high strength giving values of the sodium silicate, it was decided to conduct systematic tests for the purpose of finding a waterproofing agent which, when added in conjunction with the sodium silicate, would result in both a water resistant and high load sustaining material

The Effect of Waterproofing Agents with Sodium Silicate

Exploratory investigations were made on several materials to determine their usefulness as waterproofing agents Among those showing some success were fatty acids, such as oleic acid and cottonseed pitch, liquid asphalt and pitches, pickle liquor, a waste product of the steel industry, consisting of 7 percent ferrous sulfate and 3 percent sulfuric acid; and lignin sulfonic acid, a waste product of the paper industry

The most promising materials, however, and those offering the least transportation difficulty, were the aqueous solutions of the following salts: calcium chloride, magnesium chloride, barium chloride, aluminum chloride, magnesium sulfate, magnesium oxychloride, zinc silicofluoride and magnesium silicofluoride

For the purpose of investigating these materials more fully, a series of tests were undertaken using three representative soil types; beach sand, fine sandy loam, and silt These soils were mixed with 8 percent sodium silicate, molded, and oven-dried The resultant cylinders were then immersed in an aqueous solution of the various chemicals for 15 minutes, air-dried for 5 days, and tested for their load sustaining power

Figure 3 indicates the result of these tests, showing the effect of the added chemicals on the dry strength of the sodium silicate treated specimens When the broken specimens were examined at the end of this testing, it was found that the chemical solution had only partially penetrated the sandy loam and silt during the 15-minute immersion period Since this introduced a variable in the test results it was decided, for the purpose of comparison, to use only the data obtained from the uniformly penetrated sand specimens

With the exception of calcium chloride, all of the agents employed in this test resulted in lower dry strength values than were obtained for the "control" specimens which were treated with sodium silicate only Therefore, from this group of chemicals the calcium chloride was selected for more detailed study

Early in the tests with the sodium silicate-calcium chloride specimens it was found that the waterproofing value was improved by further treatment of the specimens with a 10 percent solution of sulfuric acid A series of tests were conducted wherein the sodium silicate treated cylinders were immersed for 15 minutes in calcium chloride solutions of varying concentrations (10%, 20%, and 30%), air-dried at room temperature for different periods of time, after which one series was broken in compression while the other was further immersed for a 15-minute period in a 10 percent solution of sulfuric acid before breaking.

From these tests it was found that the dry strength of the treated specimens varied with the concentration of the calcium chloride solution employed. Use of the 30 percent concentration resulted in load sustaining values as high as those obtained with sodium silicate alone, while the 20 percent solutions were only slightly less effective The addition of the surfuric acid, although increasing the water resistance of the samples, lowered the dry strength The addition of a 2 percent sodium chloride solution to the calcium chloride improved the strength values somewhat

Although this method of treatment had at first appeared promising it was subsequently noted that after air drying for several days the treated specimens exhibited a fine network of fractures throughout their structure In this condition the cylinders offered little resistance to compression and when immersed the small openings allowed the rapid penetration of water, resulting in the leaching of the sodium silicate and calcium chloride from the soil Rapid disintegration of the test specimens followed

Since this detrimental effect was more pronounced with the specimens that had been treated with the 10 percent sulfuric acid solution, numerous tests were made to improve the treatment by reducing the concentration of the acid These tests proved ineffective even when 1 percent solutions were employed

Attention was directed at this time to a new, highly promising material, sodium aluminate Early tests indicated that this material was far superior to any yet investigated for combination with the sodium silicate, so all work was concentrated on this form of treatment

THE SODIUM SILICATE-SODIUM ALUMINATE METHOD OF TREATMENT

Sodium aluminate ($NaAlO_2$) is readily available commercially either in solution or in powder form. Preliminary tests using this material with sandy soils that had been treated with sodium silicate produced cylinders capable of withstanding loads of over 18,000 pounds, even after 7 days immersion in water. A detailed study was therefore begun to completely evaluate this combination.

Separate Application of the Chemicals

The method of applying the chemicals for the first investigation was the same as that used in the previous tests. The soil was mixed with the sodium silicate, compacted, and allowed to dry. The resulting specimens were then immersed in a solution of sodium aluminate for 15 minutes, dried, and broken in compression. In this method of treatment the sodium aluminate tends to prevent the further hardening of the sodium silicate within the soil, so that it is advantageous to dry the treated specimens back to maximum strength before adding the waterproofing chemical. When this is done there is no apparent decrease in the dry cylinder strength by this treatment.

It was found that a dilute solution of sodium aluminate would readily penetrate the sodium silicate treated sandy soils during the 15-minute immersion period, but that as the concentration of the solution was increased the penetration into the soil was retarded due to the resulting high viscosity of the solution. The heavier soils were as usual more difficult to treat even with dilute solutions, so for the first tests only the sandy soil was employed.

Figure 4 shows the relative effectiveness of four different concentrations of sodium aluminate solution (8%, 16%, 24%, and 32%) on the strength and water resistance of sand that had been treated with 8 percent sodium silicate. From these results it can be seen that although a considerable degree of protection is obtained with an 8 percent solution, the optimum value is about 24 percent, a concentration which is also very satisfactory from the standpoint of penetration into the specimens. The specimens treated with sodium silicate alone, it will be recalled, failed in less than 1 day of immersion.

Thorough testing was made to determine the effect of aging on the specimens. Treated samples were air-dried for a period of 126 days, at the end of which time they were carefully examined and tested. From this study it was found that the addition of sodium aluminate to the sodium silicate treated soil does not produce deterioration of the cylinder during the aging process.

Figure 5 shows the strength and moisture absorption curves for 4-inch by 6-inch specimens treated with 8 percent sodium silicate and waterproofed with different percentages of sodium aluminate.

The sodium aluminate was added by immersing the oven-dried sodium silicate specimens in the 24 percent sodium aluminate solution for varying periods of time depending on the percent treatment required. The specimens were then air-dried for 7 days before testing. Even after 5 days immersion these cylinders sustained an average load on the plunger of over 7,000 pounds per square inch.

Other tests were conducted by mixing the sodium aluminate with calcium chloride, but only slight improvement was noted. After further experiment and study it was decided that the sodium silicate specimens treated with the sodium aluminate alone gave the optimum results.

Summary data showing the effectiveness of the separate or "two step" method of application are presented in figure 6. These data include average results obtained from cylinders treated with different percentages of chemicals. Twelve specimens were used for each case. Although some inconsistencies exist between the results, a clear indication can be seen of the relative effectiveness of the treatment on the various soil types. Very high strength values were obtained when using 8 percent sodium silicate with sand, and even the 2 and 4 percent treatments with the sand and fine sandy loam, respectively, when waterproofed with the sodium aluminate solution, withstood a plunger load of 400 pounds per square inch after 5 days' immersion This method of treatment was not successful with the silty clay

In order to simplify the application of the materials, an investigation was undertaken to develop a successful means of applying the chemicals to the soil in a single process

Combined Application of the Chemicals

The principle difficulty in mixing the sodium silicate and sodium aluminate together in a combined method of treatment is the extremely rapid chemical reaction between these two materials When mixed together with the soil a white gelatinous precipitate is formed and the specimens harden so rapidly that proper molding is impossible Several methods were tried to improve this condition but none were very successful All experiments were made with sand and consisted of the following processes

1 The two chemicals were mixed in solution before addition to the soil This, however, resulted in a gelatinous precipitate which could not be mixed uniformly with the soil

2 The sodium silicate was first added to the soil, then the sodium aluminate, and the cylinder quickly molded This resulted in the formation of a white precipitate which rapidly hardened making it very difficult to compact and remove the cylinders from the mold

3 The soil was halved, the sodium silicate being mixed with one part and the sodium aluminate with the other The two portions were then mixed together and molded This also resulted in the formation of a gel while the cylinder was being molded resulting in poor compaction

4 Acids were used to reduce the high alkalinity of the chemicals, thereby retarding the rate of reaction However, unless a very small amount was used, the acid itself caused the formation of a precipitate when mixed with the solutions The small amount that could be used was ineffective in reducing the rate of reaction between the sodium silicate and the sodium aluminate

All cylinders molded by the above methods were very low in compressive strength and all failed completely after a short immersion in water

However, when these tests were extended to include fine sandy loam much better results were obtained, especially when using low concentrations of solutions, although the specimens were still very difficult to mold Figure 7 shows the results of treating fine sandy loam with 4 percent sodium silicate and varied amounts of sodium aluminate These results are very promising, indicating a load sustaining power on the plunger of over 1,000 pounds per square inch for oven-dried specimens after immersion in water for 5 days The optimum ratio of the chemicals appears to be 4 percent sodium silicate to 2 percent sodium aluminate, based on the dry weight of the soil No data were obtained in the moisture absorption as the specimens scaled considerably while soaking, resulting in erroneous weights for the cylinders The load resistance of the specimens at the end of the soaking period, however, indicates that substantial waterproofing was obtained However, unless some method of controlling the rate of "set" can be developed, this method would be unsuited for practical field application

EFFECTIVENESS OF VARIOUS ADMIXTURES

In addition to the study of sodium silicate, the soil stabilizing effectiveness of other chemicals was investigated For these series of tests standard procedures were set up using a single soil type, a fine sandy loam, so that a better means of comparison could be made of the chemicals investigated The soil was analyzed and the moisture density relationships determined by the standard Proctor method

The specimens were prepared and tested, as previously described, using the 4-inch by 6-inch mold All specimens were broken with the plunger, and detailed moisture absorption data obtained for each condition of treatment Several promising chemicals were found

Synthetic Resin (Formed by the Interaction of Furfuryl Alcohol and Sulfuric Acid)

Early experiments in this study indicated that a synthetic resin, formed by the interaction of furfuryl alcohol and sulfuric acid, showed definite promise as a soil stabilizing agent These tests were performed with sand and a detailed study was now begun to evaluate this material using the fine sandy loam

Preliminary studies showed that the rate of resin formation was proportional to the concentration of the acid employed Since it was desired that this formation should not be too rapid, a series of tests were made to determine the optimum concentrations of acid to be used with various percentages of furfuryl alcohol Numerous specimens were molded using different mixing formulas throughout the range of proposed treatments Tests on these specimens indicated that optimum results were obtained by using 1.25 percent of concentrated sulfuric acid, based on the dry weight of the soil, diluted with the water required for optimum moisture of the soil When this dilute solution of acid was added to the furfuryl alcohol treated soil there resulted a slow forming resin which was quite firm in about an hour By this method the amount of sulfuric acid remained constant for all percentages of furfuryl alcohol but the concentration of the solution increased slightly as more furfuryl alcohol was used Throughout the range of treatment investigated (1-10 percent furfuryl alcohol) the variation in the ratio of sulfuric acid to furfuryl alcohol produced no apparent effect on the test results, and since the rate of reaction between the chemicals was considered satisfactory the method was employed throughout this study

In preparing the specimens for testing, part of the mixing water was added to the furfuryl alcohol and the solution mixed with the soil The sulfuric acid was added to the remaining water and the solution worked into the soil mix The plastic mass was then molded into cylinders and tested Different amounts of furfuryl alcohol were used ranging from 1 to 10 percent, based on the dry weight of the soil The load-penetration strengths and moisture absorption data are shown in figure 8 These curves indicate that both the strength and water resistance are proportional to the amount of treatment used In the immersion tests bits of soil flaked from the 1, 2 and 3 percent treated specimens after the first day in water, thereby giving erroneous values to the wet weights after this time However, from other tests on these and similar waterproofing agents, it was possible to estimate the probable trend of the curves and these are shown by the dotted lines

The strength of the specimens that had been oven-dried prior to immersion was much greater than those that were only air-dried Between 3 and 5 percent treatment there was a great increase in the oven-dried strengths This also appeared to be the optimum percentage of treatment for the air-dried specimens, although the increase was more gradual in this case The greatest strengths were obtained with 10 percent treatment but since this study was concerned only with materials effective in small quantities this value was believed to be too high. Five percent was therefore taken as the optimum amount of admixture to be used, and this form of treatment gave very good results

Tung Oil

The value of raw tung oil as a stabilizing agent was investigated because of the reported availability of this material in the China theatre of war Preliminary results indicated that the material was sufficiently promising to justify further investigation.

The mixing process for this method of treatment is very simple The required percentage of tung oil was added to the required amount of water and the solution mixed directly with the soil.

The cylinders were molded in the usual manner, allowed to dry in the air or oven, and immersed Various percentages of tung oil were used, and, in addition, tests were made to study the effect of treating the tung oil in various ways These consisted of

1 Emulsifying the tung oil and water by mechanical agitation, and by mechanical agitation plus the addition of a small amount of triethyanolamine, an emulsifying agent

2 The addition of a drier to the tung oil

3 Thickening the tung oil by heating to 300°F for 4 hours, followed by the addition of a drier (thermolyzed tung oil)

With the exception of the mechanical emulsifying, which increased the air-dried strength of the 3 percent treatment, these special treatments did not appear to effect the normal test results to an appreciable degree

Figure 9 presents the results of the various treatments and shows that the stabilizing effectiveness of the tung oil is proportional to the percentage employed During the soaking period, no scaling of the specimens was noted, all remaining in excellent condition at the end of the 5-day immersion period However, it was found that all specimens failed during the soaking test unless allowed to air-dry for at least 4 days prior to immersion

The plotted data indicates that 5 percent raw tung oil is a very satisfactory treatment for this soil type

Linseed Oil

Since linseed oil is available in many parts of the world, including the combat areas, it was decided to investigate this oil as a possible stabilizing agent

In preparing the samples, the linseed oil was mixed with the required amount of water for compaction and the solution added to the soil The molding and testing were conducted as in the previous tests Four amounts of raw linseed oil were used, 1, 3, 5, and 10 percent In addition, boiled linseed oil and raw linseed oil plus a drier were used, but these treatments did not substantially effect the test results The addition of the drier did, however, increase the oven-dried strength The test results, shown in figure 10, indicate substantially the same trend as does the data for tung oil, although in a lesser degree of effectiveness.

Other Admixtures

The chemicals listed in this section were not as promising as those described above, but with further study might prove effective All gave some degree of stabilization The materials consisted of non-drying and semi-drying oils, rubber latex, and petroleum oil thickened by the addition of an alkaline earth soap, aluminum stearate The summary data for these materials is shown in figure 11

Cottonseed Oil This material, a semi-drying oil, was mixed with the soil in the usual manner. Three amounts of treatment, 3, 5, and 10 percent were used All of the load sustaining values were low, and an increase in the amount of treatment seemed to offer little improvement

Rubber Latex For these tests a 30 percent solution of rubber latex with a 1 percent solution of ammonium hydroxide was mixed with the soil Tests were made on fine sandy loam, sand, and silty clay soils, but the best results were obtained with the fine sandy loam and these values were used as a basis for comparison with the other materials The best results were obtained by using a 7 percent treatment of the 30 percent emulsion It was believed by the investigators that the use of a cold vulcanizing agent with the rubber latex would greatly improve the stabilization properties

Aluminum Stearate Added to Petroleum Oil When petroleum oil, SAE 30, was mixed with the soil in amounts of 3 percent the cylinders withstood a plunger load of 300 pounds per square inch when dry, but completely fell apart after 5 hours in water With the addition of 6 percent aluminum stearate, a water-insoluble soap, the oil was thickened and when mixed with the soil increased the dry strength to 500 pounds per square inch and imparted a certain degree of load sustaining power even after immersion of the cylinder for five days

Castor Oil This non-drying oil proved unsuccessful as a stabilizer when used alone in quantities of 4 percent All cylinders failed in less than 24 hours soaking

DISCUSSION OF RESULTS

For the purpose of comparing the different admixtures, as applied to the fine sandy loam, figure 12 shows the summary data of the optimum percentages of the more promising methods of treatment In all of these tests the specimens were 4 inches in diameter by 6 inches high and the admixtures were applied in solution form

The use of specimens larger than those normally specified for the standard Proctor method of compaction resulted in lower densities than would have been obtained by using the usual mold size. Laboratory tests have shown that both the strength and water resistance of soil specimens are greatly increased by an increase in the density of the specimen This indicates that the test results obtained in this study are lower than would have been obtained had the standard Proctor densities been used

It was clearly shown by the detailed data that the effectiveness of the admixtures increased with the percentage employed, so that it was necessary to select an optimum treatment to be considered in the scope of this work Therefore, the exceptionally good results obtained with the higher percentages of treatment were disregarded and only the lower percentages are included in this summary

From these data it can be seen that all the methods of treatment gave a certain degree of waterproofness to the specimens, thereby increasing the load resistance of the soaked samples. Raw tung oil seems to offer the greatest load resistance after a 5-day immersion period both with the air-dried and oven-dried specimens, whereas the sodium silicate specimens, that were waterproofed by the application of sodium aluminate, and the synthetic resin appear to offer the best resistance to water absorption These results can best be appreciated when it is realized that all untreated specimens of the same type soil failed in less than one day of immersion Even the least effective of these agents withstood not only the 5-day soaking but also a definite amount of load application at the end of this time However, it was necessary to air-dry, or cure-back, all specimens at least one day before immersion, otherwise they failed during the first day of soaking For the lower percentages of treatment, (under 5 percent), a 3-day or 4-day drying period was necessary

The moisture absorption curves all follow a definite pattern in this work similar to that observed in other soil waterproofing studies The curves rise abruptly during the first day of immersion to near maximum after which they level off, gradually approaching a horizontal line as the soaking continues Since the destructive forces of absorbed water on the soil specimens is dependent upon the rate of absorption, it would appear that the greatest disintegrating effect occurs during the first day of soaking when the rate of absorption is high This seems to be true in this study, as all specimens that failed in immersion usually did so during the first day The slow rate of absorption after this time, although reducing the load resistance, left the specimens intact

Of the different treatments investigated, however, the sodium silicate-sodium aluminate method, using two separate applications to the soil, gave by far the highest strength values, when applied to sandy type soil Best results were obtained by using 8 percent sodium silicate with 2 to 3 percent sodium aluminate Lower, but very satisfactory results were shown by using as little as 4 percent sodium silicate with sand and 6 percent with fine sandy loam Silty clays were not successfully treated by this method When mixing the sodium silicate and sodium aluminate together before molding with the soil, very poor results were obtained with sandy soil However, with fine sandy loam a 4 percent treatment of sodium silicate with 2 percent sodium aluminate gave very good values which compare favorably with the other admixtures tested with this type soil The principle difficulty with this method of treatment was the rapid formation of a precipitate upon contact of the sodium silicate and sodium aluminate solutions which prevented the thorough mixing and compaction of the soil. Likewise, difficulty was experienced when mixing the sodium silicate solution with the heavier soils because of the poor dispersion obtained Both of these conditions could probably be improved by using the dry, or powder form, of the chemicals and mixing them with the dry soil before the addition of water

In this study all of the materials investigated were tested in the solution form since it was desired that they could be applied to the soil by spraying or injection Tests on other stabilizing materials have shown that the dry forms of the admixtures are often more effective than the solutions in treating soils. In addition, the ease of mixing, the control of moisture, and the dispersal of the chemical throughout the soil, can generally be facilitated by use of the powder or crystal form of admixture It is, therefore, believed that an investigation of the effectiveness of many of these chemicals in dry form would be of value, especially the sodium silicate-sodium aluminate combination and the synthetic resin. Some of the chemicals, however, such as the tung oil, linseed oil, and cottonseed oil, are ideally suited for direct application to the soil as liquids

It is believed that the more promising of these materials should be investigated, using other and more varied soil types Since the effectiveness of the various stabilizing agents is dependent on both the chemical and physical composition of the soil to be treated, such a study would give a clearer picture of the overall value of each admixture Due to the inherent complexities of each soil, however, it is doubtful if one method of treatment could be developed suitable to all types.

CONCLUSIONS

From the results of the laboratory tests described in this report it can be concluded that the following materials show definite promise as soil stabilizing agents

1 <u>Sodium silicate-sodium aluminate</u> The most successful form of this treatment requires the addition of the sodium silicate to the soil, time for drying, and then the addition of the sodium aluminate Sandy soils can best be treated in this manner It is believed that by using the powdered form of these chemicals instead of the solutions better results and simplified methods of application could be obtained.

2 <u>Raw Tung Oil</u> This method of treatment can be easily applied to the soil in solution form and shows very good stabilizing properties when mixed with fine sandy loams This material should be of particular interest in the China area of operations where the material is reported to be readily available

3. Synthetic Resin This material, formed by the interaction of furfuryl alcohol and sulfuric acid, gave very promising results In addition, the method of application seemed to be well suited to field construction

4 Raw Linseed Oil. While not as effective as the above methods, this treatment does offer some stabilization and should prove of value for certain purposes

Other chemicals, less effective, but offering definite improvement over untreated soil are cottonseed oil, petroleum thickened with aluminum stearate, and rubber latex

As the laboratory tests during this work were limited in scope, being confined principally to moisture absorption, it is believed that further, more systematic studies of the more promising of these materials might be advisable, especially by the use of the alternate wetting and drying and alternate freezing and thawing tests By concentrating on the powder or crystal forms, other of the tested chemicals might well be reviewed.

It is realized that the test values obtained from this study are not comparable to those required for heavy type paving, nor were they meant to be Furthermore, it is possible that some of these methods may not be economically suited to ordinary peace time construction However, the fact that some of these methods, using very low percentages of admixture, resulted in specimens capable of withstanding loads of 500 to 1500 pounds per square inch, as applied by the 0 75 square inch area plunger, would indicate that these methods should be of value in light paving construction, especially in the combat areas where temporary or emergency runways and roads are often necessary

Apart from the possible utilization of the more promising of the materials resulting from this investigation, it is believed that the study has produced much valuable data concerning the over-all subject of chemical soil stabilization

APPENDIX

In this appendix are listed the various chemicals investigated that were not included in the body of the report The list is divided into two parts the first consisting of the materials used in seeking an effective bonding agent, and the second, indicating the various chemicals added to the most promising bonding agent in order to secure water resistance

It will be noted that in a number of cases no percentages of the chemicals used are given These refer to preliminary work in which a large number of materials were subjected to rapid tests in order to determine, with a minimum expenditure of time, their applicability to the problem Therefore, due to the purely qualitative nature of this work, no particular emphasis was placed upon the percentages of materials used In most cases, however, this amount was approximately 8 percent

BONDING AGENTS (without treatment for waterproofing)

Bonding Agent	Soil Type	Binding Properties
aqueous sodium sulfide	silt loam	poor
saturated potassium alum	sand	poor
calcium chloride and magnesium hydroxide suspension	sand	poor
magnesium chloride and ammonia suspension	sand	poor
copper sulfate, ammonia, and sodium silicate solution	sand	poor
sodium silicate and calcium hydroxide	sand	poor
sodium silicate and calcium chloride	sand	good
sodium silicate solution with lime in suspension	sand	poor
sodium silicate with portland cement in suspension	sand	poor
sodium silicate solution containing sodium acid sulfate	sand	poor
various mixtures of ethyl silicate, water and ethyl alcohol	sand	poor
pickle liquor	sand	poor
lignin sulfonic acid	sand	poor
sodium aluminate solution	sand	poor
20% solution zinc silicofluoride with magnesium oxide	sand	poor

WATERPROOFING AGENTS FOR SODIUM SILICATE TREATED SPECIMENS

Waterproofing Agent	Soil Type	Effectiveness
saturated sodium acetate	sand	poor
5% boric acid wash	sand	good
sodium silicofluoride wash	sand	good
equal volumes of calcium chloride and zinc silicofluoride	sand	fair
wash of an aqueous solution of portland cement	sand	poor
magnesium oxychloride cement treatment	sand	poor

Waterproofing Agent	Soil Type	Effectiveness
calcium carbonate solution	sand	poor
magnesium oxide in suspension	sand	poor
sodium acid sulphate	sand	poor
coating of melted sulfur	sand	fair
coating of cottonseed pitch	sand	fair
coating of coal tar pitch	sand	fair
suspension of magnesium oxide in sodium silicate solution followed by a wash of 20% zinc silicofluoride	sand	poor
zinc silicofluoride solution	silty clay	good
copper chloride solution	sand	good
	fine sandy loam	good
	silty clay	good
potassium alum solution	sand	fair
	fine sandy loam	fair
	silty clay	fair
ammonium alum solution	sand	good
	fine sandy loam	poor
	silty clay	poor
equal volumes of calcium chloride and magnesium silicofluoride solution	sand	fair
calcium chloride solution containing calcium oxide in suspension	sand	poor
zinc sulfate solution	sand	good
sodium bisulfate solution	sand	poor
acid cupric chloride solution	sand	poor
acid zinc sulfate solution	sand	poor
dilute sulfuric acid	sand	poor
	fine sandy loam	poor
	silty clay	poor
dilute sulfuric acid followed by a wash with lead acetate solution	sand	fair
calsium chloride solution containing magnesium oxide in suspension followed by a wash with acid magnesium sulfate	sand	very good
sodium acid sulfate followed by a wash with dilute sulfuric acid	sand	good
	fine sandy loam	good
acid cupric chloride followed by a wash with dilute sulfuric acid	sand	good
	fine sandy loam	good
acid zinc sulfate solution followed by a wash with dilute sulfuric acid	sand	good
	fine sandy loam	good
lead acetate solution followed by a wash with dilute sulfuric acid	sand	good
	fine sandy loam	good
aqueous ferric chloride solution followed by a wash with dilute sulfuric acid	sand	good
	fine sandy loam	good
50% magnesium chloride solution followed by a wash with 10% sulfuric acid	sand	fair
	fine sandy loam	very good
	silty clay	fair

Waterproofing Agent	Soil Type	Effectiveness
29% barium chloride solution followed by a wash with 10% sulfuric acid	sand	good
	fine sandy loam	very good
	silty clay	fair
50% magnesium sulfate solution followed by a wash with 10% sulfuric acid	sand	fair
	fine sandy loam	good
	silty clay	fair
50% aluminum chloride solution followed by a wash with 10% sulfuric acid	sand	fair
	fine sandy loam	very good
	silty clay	fair
20% zinc silicofluoride solution followed by a wash with 10% sulfuric acid	sand	fair
	fine sandy loam	very good
	silty clay	fair
20% silicofluoride solution followed by a wash with 10% sulfuric acid	sand	fair
20% magnesium silicofluoride solution followed by a wash with 10% sulfuric acid	fine sandy loam	very good
	silty clay	fair

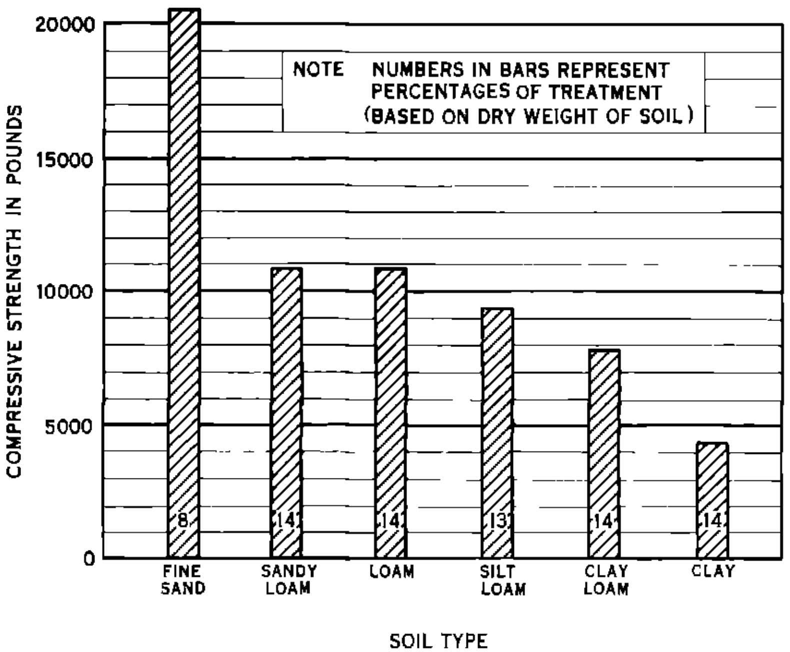

Figure 1 Effect of Sodium Silicate on the Compressive Strength of Oven Dried Sample of Different Soil Types

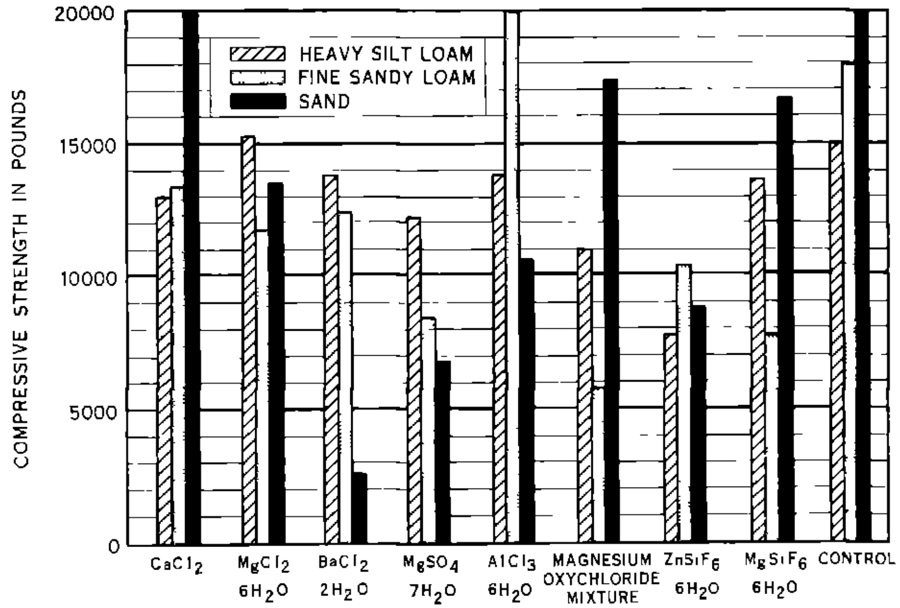

Figure 3 Effect of Various Waterproofing Agents on the Compressive Strengths of Dry Sodium Silicate Treated Specimens Using Three Soil Types

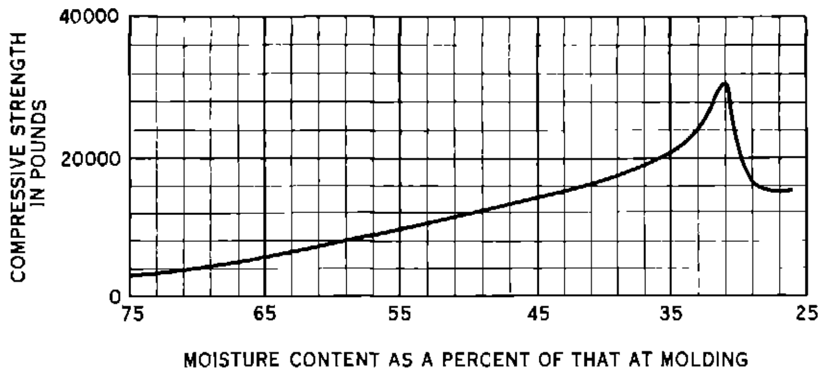

Figure 2 Load-Moisture Relationship for Sand Specimens Treated with 8% Sodium Silicate

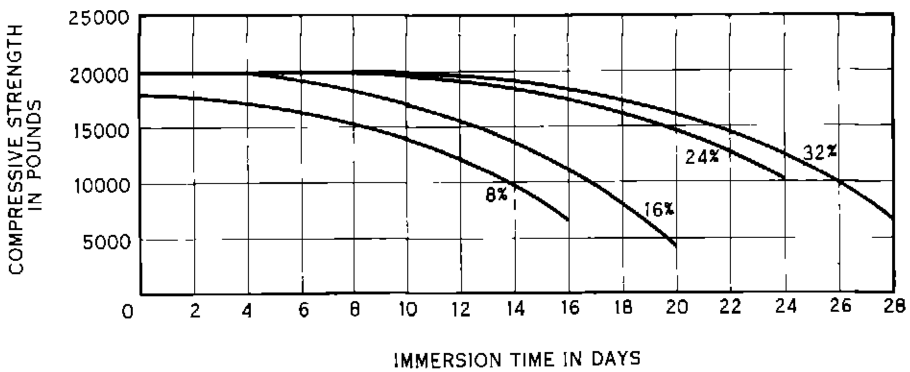

Figure 4 Effect of Varying the Concentration of Sodium Aluminate Solutions on the Strength and Water Resistance of Sodium Silicate Treated Sand Specimens

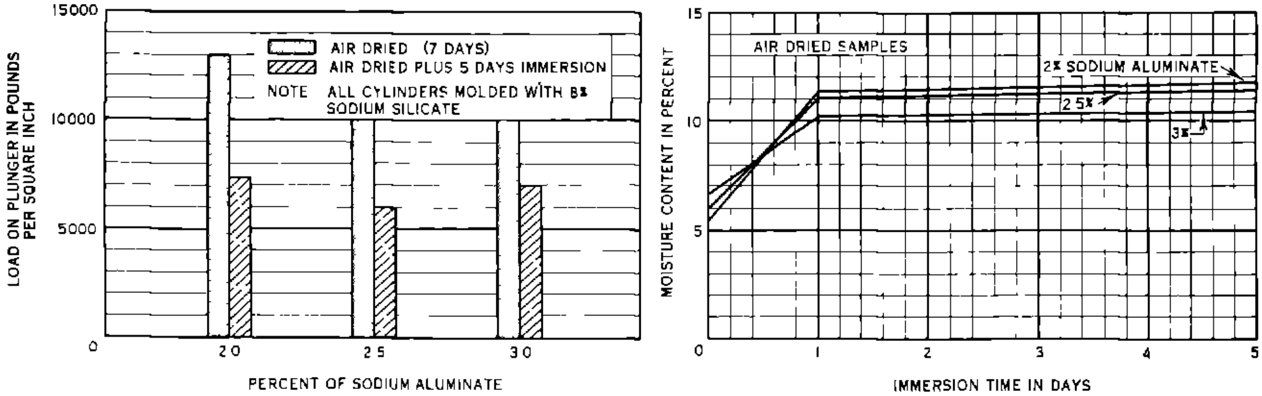

Figure 5 Test Data on the Sodium Silicate-Sodium Aluminate "Two Step" Method of treatment Using Sand

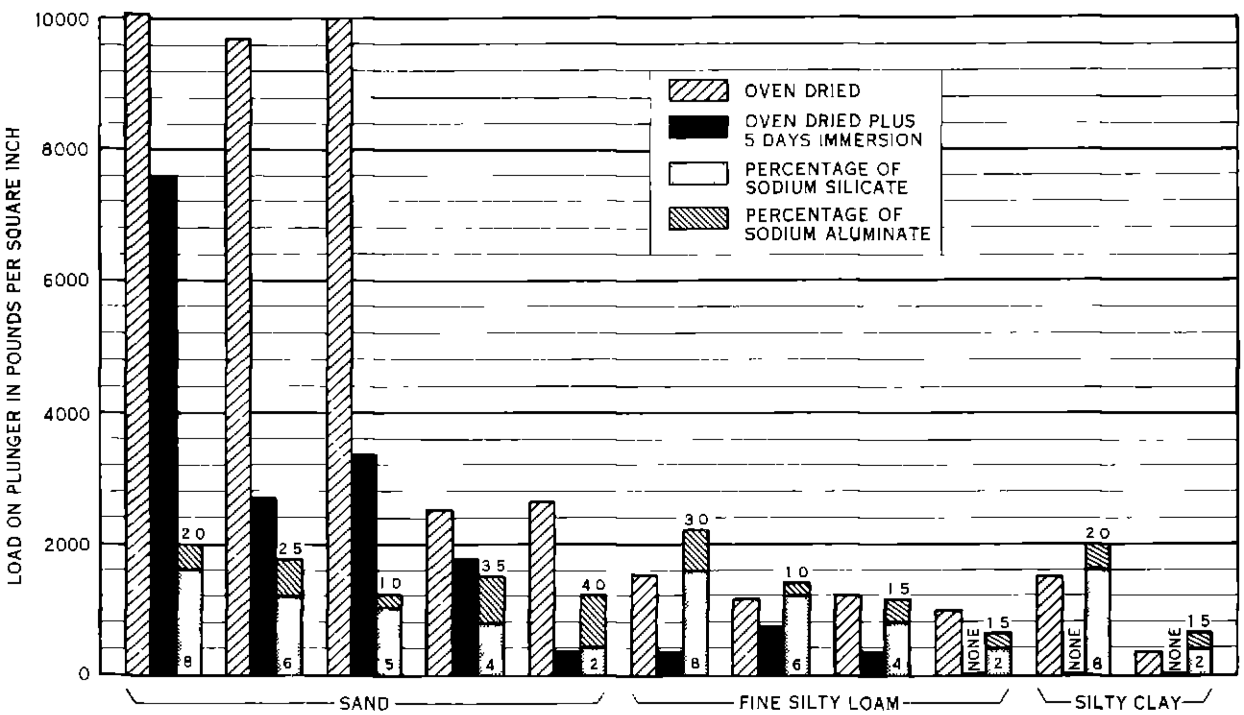

Figure 6 Summary Data of the Sodium Silicate Sodium Aluminate "Two Step" Method of Treatment Using Different Soil Types

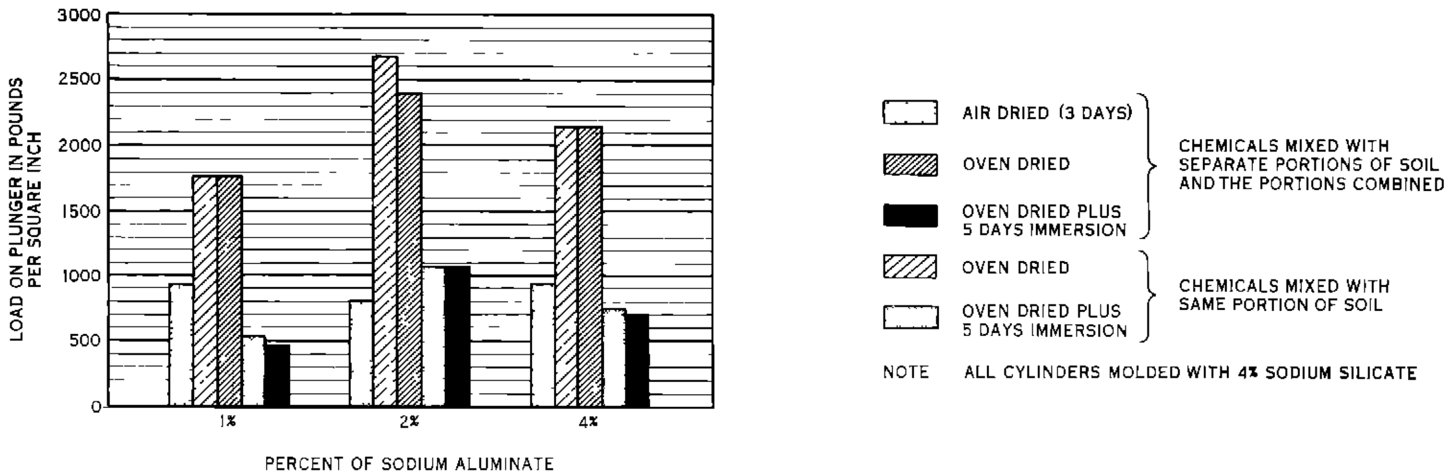

Figure 7 Test Data on the Sodium Silicate Sodium Aluminate "One Step" Method of Treatment Using Fine Sandy Loam

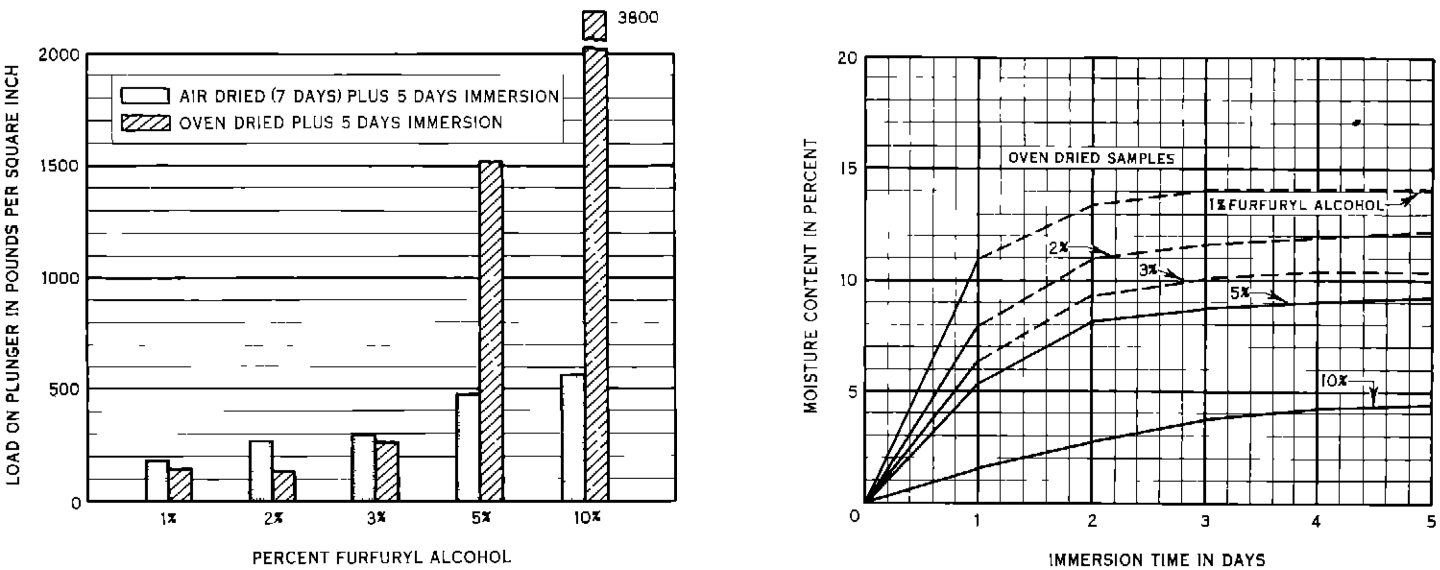

Figure 8 Test Data on a Synthetic Resin (formed by the interaction of furfuryl alcohol and sulfuric acid) as Applied to a Fine Sandy Loam

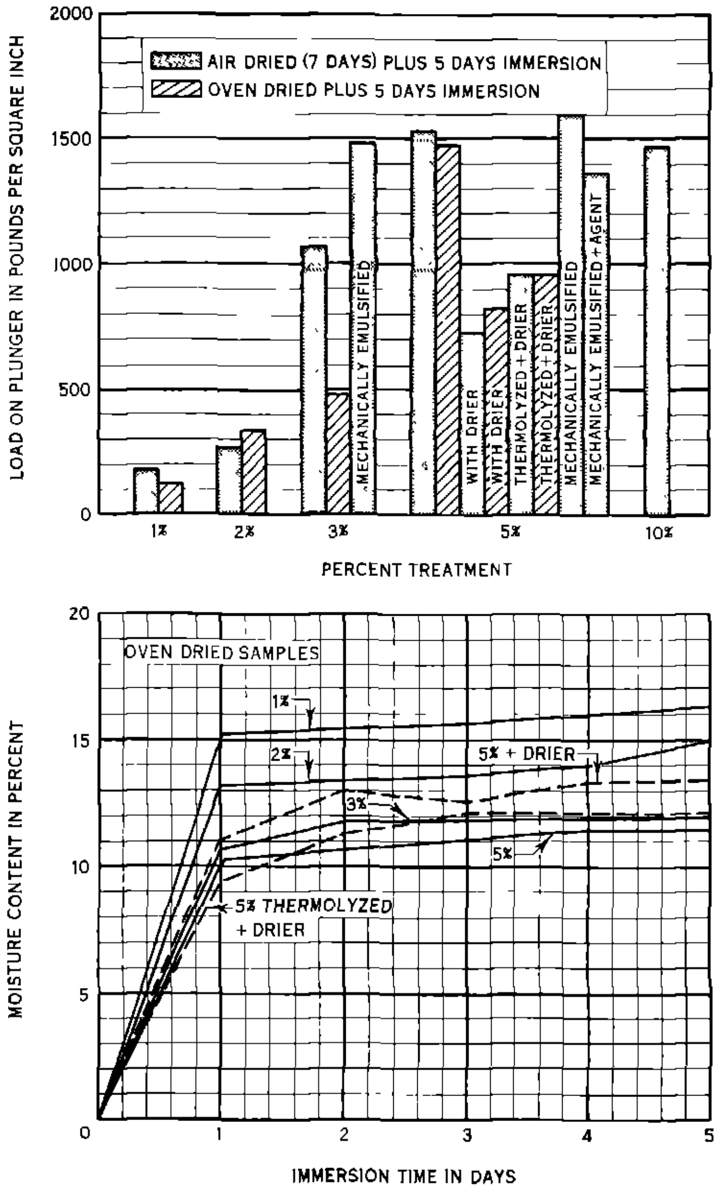

Figure 9 Test Data on Tung Oil as Applied to a Fine Sandy Loam

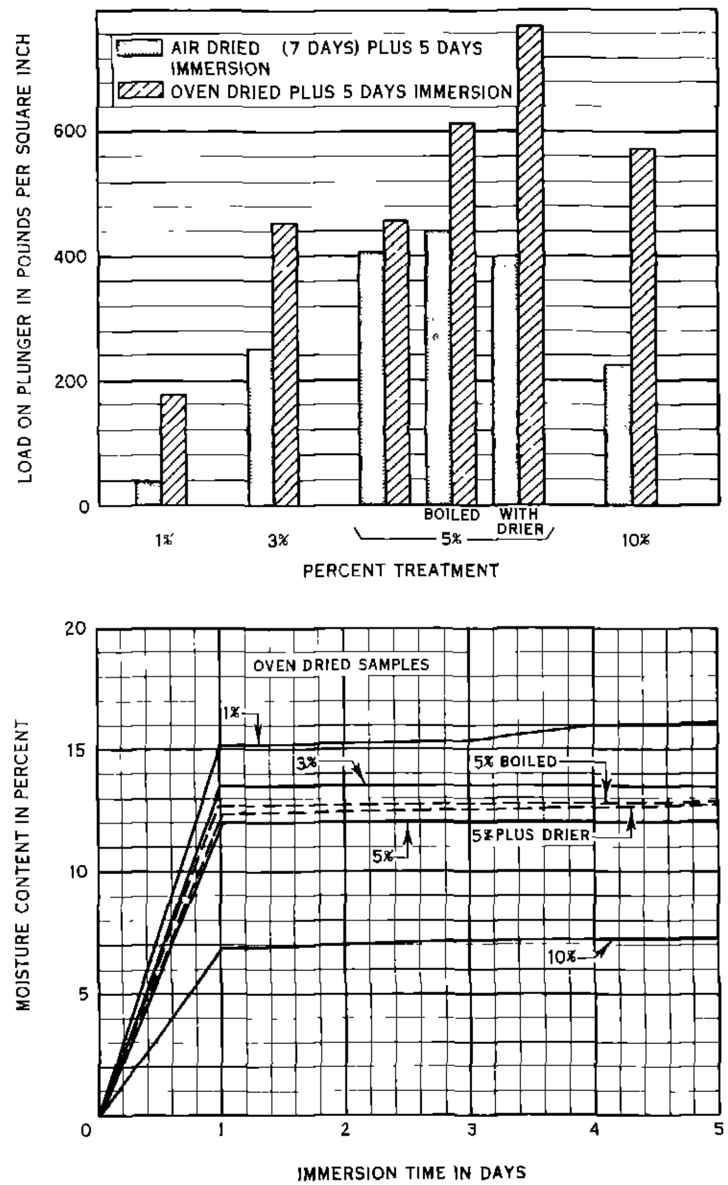

Figure 10 Test Data on Linseed Oil as applied to Fine Sandy Loam

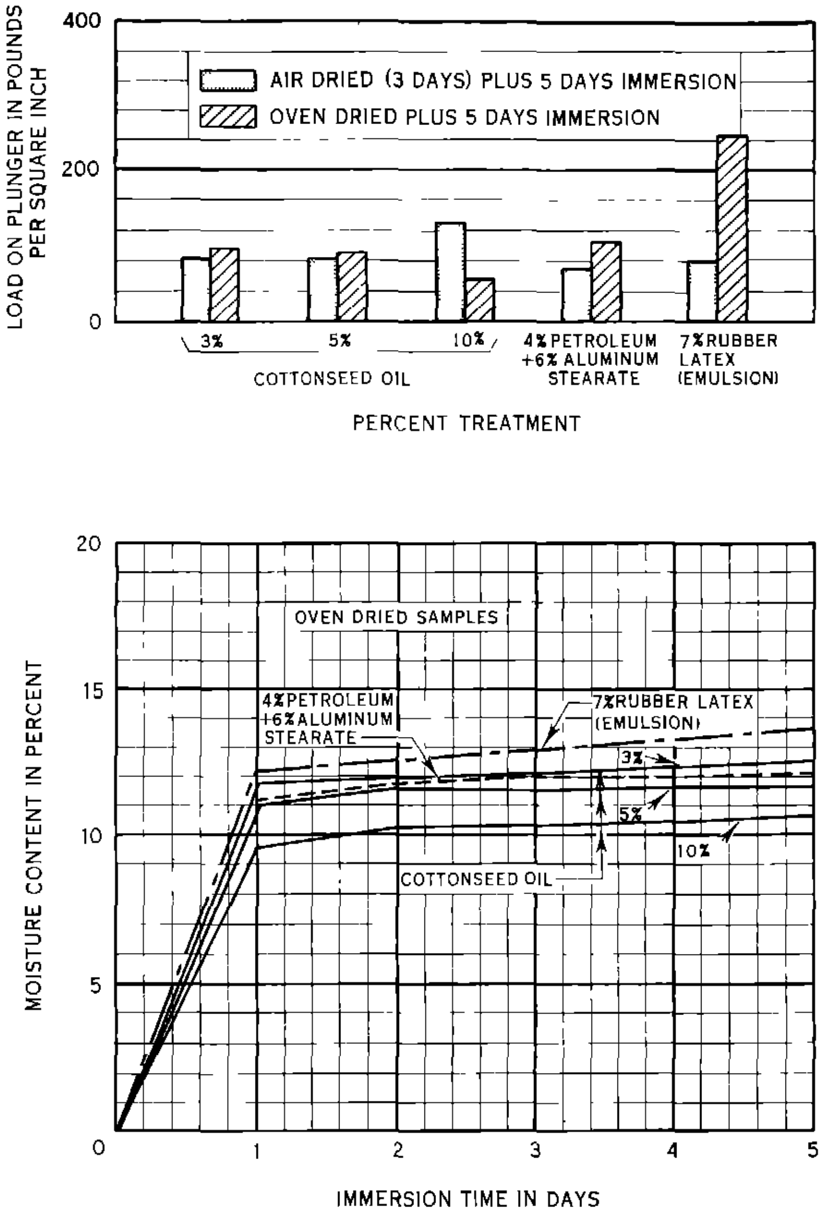

Figure 11 Test Data on Other Admixtures as applied to a Fine Sandy Loam

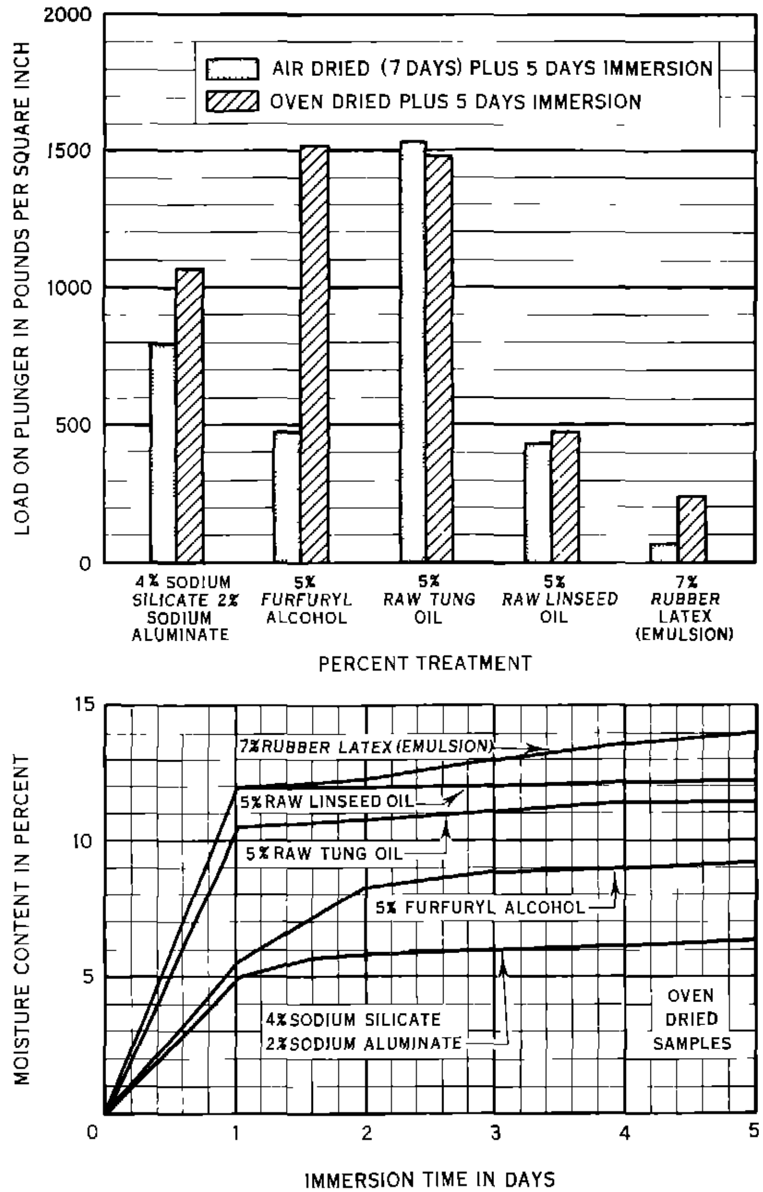

Figure 12 Comparative Data of the Various Admixtures as Applied to a Fine Sandy Loam