A LABORATORY STUDY OF THE SOIL STABILIZING EFFECTIVENESS OF ARTIFICIAL RESINS WITH SPECIAL EMPHASIS ON THE ANILINE - FURFURAL RESINS

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A LABORATORY STUDY OF THE SOIL STABILIZING EFFECTIVENESS OF ARTIFICIAL RESINS WITH SPECIAL EMPHASIS ON THE ANILINE-FURFURAL RESINS

SUMMARY

This report presents the data obtained from a laboratory investigation of the soil stabilizing properties of numerous artificial resins Because of their outstanding effectiveness, the resins formed by the reaction of aniline and furfural were given special attention

For practically all of the exploratory work proper, the compressive strength of 2" x 2" compacted soil cylinders, after exposure to different types of laboratory weathering, were used as a criterion of the effectiveness of the various resin treatments In the evaluation of the effectiveness of one aniline-furfural resin with ten different soils, load-plunger tests were performed on 4" x 6" cylinders in addition to the compression tests on the small specimens

Experiments in which the ratio of aniline to furfural was varied indicated that the resin formed by the reaction of 70 parts of aniline and 30 parts of furfural was the most effective stabilizer This resin gave best results when formed in a neutral or slightly acid medium and was improved by the addition of iron or aluminum salts

Quantities of aniline-furfural resin (ratio 70 30) as small as 2 percent on the basis of the dry weight of soil treated were effective in stabilizing most of the 10 different soils tested It was found that this material acted both as a binding and as a waterproofing agent for the compacted soils That these properties are of significant magnitude is demonstrated by comparing data from tests on various types of stabilizers

Urea-furfural, phenol-furfural, and phenol-formaldehyde mixtures were found ineffective as soil stabilizing agents. Urea-formaldehyde and calcium sulfamate treated specimens showed some promise but the experiments performed were not conclusive

A discussion of the history and structure of aniline-furfural resins and the results of a series of experiments concerning the catalyzation of these materials are given in the Appendixes

INTRODUCTION

The war-time investigations in soil stabilization sponsored by the Technical Development Division, Civil Aeronautics Administration, have emphasized the use of local materials available in combat areas, and the development of superactive stabilizers that would achieve with small quantities the same results as the relatively large quantities employed in the case of conventional methods The stabilizing effectiveness of rosin and its derivatives has been studied and the results have been previously reported [1] Another group of materials that appeared to be of sufficient promise to merit investigation was that of artificial resins

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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, 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

The possible usefulness of artificial resins for highway construction was realized in the early thirties and exploratory investigations were made concerning the following possible applications of such materials [2]

1 The possible use for high-type pavements of plastics made of artificial resins and natural soil as filler,

2 The stabilization of soils by means of artificial resins to serve as base courses for highway and airport pavements,

3 The activation of conventional soil stabilizing materials, such as bitumen, by means of artificial resins, to improve the quality and economic life of stabilized base courses;

4 The improvement of the stripping resistance of bitumen coated mineral aggregate by means of artificial resins

Each of these studies disclosed interesting and pertinent data concerning the applicability of these materials. The last of these subjects was pushed to practical application with satisfactory results [3] Those data resulting from this previous work which deal most directly with the treatment of soils may be summarized as follows

1 Of the lower priced artificial resins such as urea-formaldehyde, urea-furfural, aniline-furfural, and aniline-formaldehyde, the resin made of about 2 parts of aniline and 1 part of furfural was the most effective for soil stabilization and as a precoating for aggregate to increase its affinity for bitumen,[4]

2 About two percent of this resin on the basis of the weight of the dry soil was required for effective soil stabilization at the relatively low densities employed before the advent of even the Proctor method The use of smaller amounts, however, considerably improved the physical properties of the soil investigated. The effectiveness of the aniline-furfural resin did not appear to be lessened in alkaline soils, which usually react badly with bitumen;

3 If used as an activator for bitumen in soil stabilization only about 2 percent of the material, on the basis of the weight of the bitumen were required The latter amount usually ranges between 5 and 8 percent of the dry weight of the soil

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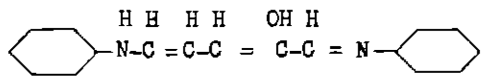
[2]Winterkorn, Hans F , unpublished notes

[3]Winterkorn, Hans F. "Affinity of Hydrophilic Aggregate for Asphaltic Bitumen, Use of Furfural and Its Resinous Derivatives for Improving Affinity," Ind. and Eng Chem , 30, pp 1362-68, 1938 (U S Patent No. 2,314,181 Granted March 16, 1943)

[4]The probable molecular structure of this resin according to the literature and our own experiments is



; This formula well indicates the polar nature of this substance which makes it easily adsorbed by the soil particles, and also explains its dark red color

With the results of these earlier studies as a background, the Civil Aeronautics Administration inaugurated an investigation of the soil stabilizing effectiveness of artificial resins This study, the results of which are presented herein, was conducted under the direction of Dr Hans F Winterkorn in the Soil Mechanics Laboratory of the University of Missouri and in the Soil Science Laboratory of Princeton University, assisted by Rollie G Fehrman, I George Morrison, and Henry Walter The work was supervised for the Airport Development Section of the Civil Aeronautics Administration by George W McAlpin

DESCRIPTION OF MATERIALS

Ten soils, representing textural differences from sand to silty clay, were employed for this investigation Their physical and chemical characteristics are given in table 1 Figure 1 shows the grain-size distribution curves of the soils Only the material passing the No 10 sieve was used in making the test specimens

The chemicals used were of C P quality except the aniline and furfural which were of commercial grades Distilled water was used in all laboratory experiments

PROCEDURES FOR PREPARING AND TESTING OF SPECIMENS

Two sizes of specimens were used during the investigation, viz , 2" x 2" and 4" x 6" compacted soil cylinders Practically all of the exploratory and research work proper was done with the small cylinders The moisture content-density relationship of the soils was determined by the standard Proctor compaction procedure (A A S H O T99-38) with the exception that the size of specimens employed was 4 inches in diameter and 6 inches high (standard specimen is 4" x 4 59") The consequence of this modification was, of course, a lowered maximum density The density of these specimens must therefore be kept in mind in evaluating the test data Work with other stabilizing agents has shown that specimens compacted to the higher static-load density (2000 psi) may be as much as four times as stable as specimens of the same materials compacted to the Proctor density

In molding the larger test specimens, the optimum moisture content of the soils, as found by the modified compaction procedure given above, was employed Because of the low compactive effort used and the low densities obtained, difficulty was encountered in forming specimens with the desired properties These difficulties were magnified in the case of the smaller test specimens because of the small volume of soil employed Fortunately, these variations do not seem to affect disadvantageously the conclusions which can be drawn from the respective experiments

The design values for dry densities and moisture content of compaction as well as the average of the actual values obtained for the 4" x 6" and 2" x 2" specimens, are given in the following table

Planned Properties			Obtained Properties			
			4"x 6" Specimens		2"x 2" Specimens	
Soil	Moisture %	Dry Density Lb/Cu Ft	Moisture %	Dry Density Lb/Cu Ft	Moisture %	Dry Density Lb/Cu Ft
H	12	103	10	103	9 8	96
P	14	109	15	110	12	107
B	14 5	113 5	14 5	115 5	13.5	116
E	14	115	15	114 5	16	106
L	14	116	15	115	16	106
G	15	110	16	112	12	114
U	16	110	17	109	12 5	102
M	17	104	17	104	16	103
N	22	96	21	98	18 5	106
V	28	90	28	96	28 5	96

2" by 2" Specimens

Enough air-dried soil to make twelve 2-inch specimens was weighed out into the mixing pan The soil was divided into two equal portions; one of the resin forming ingredients together with the amount of water to give one-half of the optimum moisture content was thoroughly mixed into each portion Just before the compaction the two portions were combined and thoroughly mixed

The specimens were made by means of a compaction apparatus adopted from the testing of foundry sands and first used for soil stabilization testing by the Portland Cement Association The apparatus permits uniform densification from both top and bottom, the specimen being compacted in a floating ring.

All compacted specimens were air-dried for 7 days Duplicate specimens were then subjected to each of the following variations in exposure, after which their compressive strength was determined

1. No further exposure
2. Two-hours immersion in water
3. One-cycle of wetting and drying[5]
4. Four-cycles of wetting and drying
5. One-cycle of freezing and thawing[6]
6. Four-cycles of freezing and thawing

4" by 6" Specimens

The soil plus the required percentage of water to produce the desired density, together with the stabilizer to be employed, were combined and compacted The resulting wet soil cylinders were extruded from the mold, carefully weighed, air-dried for 3 days, and then dried in an oven at 70° C to constant weight Three identical specimens were then subjected to each of the following variations of exposure

1. No further exposure
2. 10 days capillary absorption[7]
3. 10 days capillary absorption and re-drying in an oven to constant weight
4. 12 cycles freezing and thawing[8]
5. 12 cycles freezing and thawing and re-drying in an oven to constant weight
6. 12 cycles wetting and drying[9]
7. 12 cycles wetting and drying and re-drying in an oven to constant weight

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[5]One wet-dry cycle consisted of 5 hours immersion in water followed by 43 hours oven-drying at 70° C For both the 1 and 4 cycle exposures, the specimens were immersed in water for 2 hours just before being tested for compressive strength

[6]One freeze-thaw cycle consisted of 2 hours immersion in water followed by 24 hours freezing at -10° F and 24 hours thawing in a moist room For both the 1 and 4 cycle exposures, the specimens were immersed in water for 2 hours just before being tested for compressive strength

[7]Specimens were placed on a bed of moist sand

[8]Specimens were first subjected to 10 days capillary absorption. One cycle of freezing and thawing consisted of placing the specimens in a cold room (-10° F) for a period of 8 hours with subsequent thawing in a moist room (70° F - relative humidity 95-100 percent) for 16 hours. Twelve such cycles constituted a freezing and thawing test

[9]Specimens were first subjected to 10 days capillary absorption One cycle of wetting and drying consisted of placing the specimens for 12 hours in a water bath at room temperature, so that the water level of the bath was ¼ inch below the top of the cylinder, with subsequent re-drying in an oven (70° C) for 36 hours. Twelve such cycles constituted a wetting and drying test

After each of these types of exposure, the unconfined specimens were placed upright under the head of a testing machine to which was fastened a metal plunger 2 inches long, machined so as to have a circular head with an area of 0 75 square inches This plunger was placed concentrically on the specimen After seating of the plunger, load was applied at the rate of 400 pounds per minute until the specimen failed or a penetration of 0 1 inch was obtained The load and penetration values for 3 identical specimens were averaged and reported for each combination and treatment

TEST RESULTS I -- ANILINE-FURFURAL RESINS

For the general study of the basic factors influencing the soil stabilizing properties of aniline-furfural resins the previously described compressive strength test on 2 inch by 2 inch specimens was used One soil, Nimitz fine sand - designated as "soil H" in this report - was used for most of these tests

For the specific evaluation of the effectiveness of the 70 30 aniline-furfural resin with 10 different soils, both the compressive strength test on the small specimens and the plunger test on the 4 inch by 6 inch specimens were employed The complete data obtained in these tests are presented in tabular form For the purpose of simplifying this presentation, the effect of the different types of treatment upon the compressive strength of the air-dried specimens and of those that had been immersed in water for 2 hours has been shown graphically Observations based upon the strength values of the air-dried specimens may be open to question inasmuch as the air temperature and humidity during the curing period varied considerably They do, however, indicate general trends that are of value in analyzing the data The results obtained from the wetting-drying and freezing-thawing tests have not been plotted since they, in general, give the same picture as the "wet" data.

The Effect of the Aniline-Furfural Ratio on the Quality of the Resinous Cement in Acid, Alkaline and Neutral Media

The strength data obtained in these tests are shown in figure 2 and in tables 2, 3, 4 and 5. It will be noted that a definite maximum of compressive strength is obtained, which, in all cases except that in which 3 cc of concentrated HCl (hydrochloric acid) were used as a catalyst, comes at a composition of about 70 parts of aniline to 30 parts of furfural In the case of the addition of 3 cc of concentrated HCl the curve shows a maximum at a composition of 1 part of aniline to 1 part of furfural The dry strength curves point to the possible existence of three resin compounds corresponding to compositions of 50 50, 70 30, and 35 65 parts of aniline and of furfural, respectively This impression, however, must be corrected on the basis of the showing in the "wet" test It will be observed that the curve of the neutral specimens shows the highest value for compressive strength and that this value comes at a ratio of 70.30 However, upon the addition of 1 5 cc HCl (0 08% by weight of the dry soil per batch - 12 specimens) the maximum is moved to a ratio of about 2 1 and the best compressive strength obtained is considerably less than that obtained in a neutral medium If more HCl is added (3 cc or 0 16%), the compressive strength further decreases, and the peak of the curve is moved to a ratio of about 1 1 It will also be noticed that though the peak of the curve is lower, the strength of the specimens is less affected by changes in the ratio of the aniline-furfural mixture than in either of the less acid mixtures The alkaline specimens turned out very badly However, the best mixture was around the ratio of 70 30 parts of aniline and furfural, respectively

It is interesting to note that the tests in which specimens were soaked in water gave no indication of a strength maximum at a ratio of 35 parts of aniline to 65 parts of furfural as was found in the specimens tested dry This would indicate that, if a resin might be formed at this ratio, it definitely does not stand weathering

The Effect of Hydrogen and Hydroxyl Ions on Three Aniline-Furfural Resins

The results of tests to determine the effect of hydrogen and hydroxyl ions on the properties of aniline-furfural resins are given in figure 3 and in tables 6, 7, and 8 The data and curves marked dry represent the specimens tested directly after curing without weathering treatment, while the data and curves marked wet are for specimens subjected to two hours' immersion in water It should be noticed that none of the resin binders did as well in alkaline specimens as in neutral or acid specimens The wet test curve for the 70 30 resin shows a sharp rise in strength in the most alkaline specimens indicating the possible catalytic effect of strong alkali

The 50 50 resin turned out to be very weak and unable to withstand weathering conditions

The 70 30 and 35 65 resins both showed a maximum strength slightly on the acid side with the 35.65 resin being by far the weaker of the two and the most favorably affected by the acid treatment

The Effectiveness of Low Percentages of Aniline-Furfural Resins

The results of the respective tests are given in figure 4 and in tables 9 and 10. At the specimen densities employed no appreciable weathering resistance was obtained with the 70 30 resin binder unless two percent or greater were used Weathering resistance of specimens containing two percent of the 35 65 resin was quite low

The Effect of Various Ions on the Quality of Two Aniline-Furfural Resins

Different Anions

The respective data are given in figure 6 and in tables 11 and 12 The dotted line gives the strength after two hours' immersion - no catalyst added Addition of H_2SO_4 (sulfuric acid) gave best results on the 70 30 resin binder while addition of H_3PO_4 (phosphoric acid) gave best results on the 35 65 resin binder None of the admixtures resulted in great improvement, the acetic acid (CH_3COOH) seemed to have even a detrimental effect on the 70 30 resin

Various Amounts of H_2SO_4

Since it appeared to be the non-volatile acids (see the paragraph above) that produced the best results in the anion tests, specimens were prepared using various amounts of H_2SO_4 as catalyst (tables 13 and 14) Figure 5 shows the results of these tests It should be noticed that the curves on this figure for the wet strengths are very similar to those in figure 3 -- the peak of the curves coming slightly on the acid side, then declining again with increasing acidity of the medium This fact might indicate that the values obtained in both the H_2SO_4 test and the anion tests are functions of the acidity rather than of the specific character of the anion added However, in all cases of inorganic admixtures the water affinity of the resulting reaction products must be considered

Different Cations

The respective data are given in figure 8 and in tables 11 and 12 None of the cation treatments produced strengths nearly as good as those of the control specimens in which aniline-furfural alone was used This result is more than likely due to the fact that the cationic compounds were added in the form of hydroxides, it has already been noted (figure 3) that none of the aniline-furfural resins developed its greatest effectiveness in alkaline mixtures

Different Salts

In the case of the salt admixtures, it is difficult to estimate how much of the effect is due to the resulting acidity or alkalinity caused by the reaction of the salt with the system as a whole. Figure 7 shows the results of experiments with salt admixtures illustrating the data given in tables 15 and 16 The specimens containing 70 30 aniline-furfural resin appear favorably affected by several admixtures However, this may in part be due to the fact that the control specimen for the respective batch had a strength of less than 100 lbs per sq in , whereas, for the majority of tests, the strength of the control specimens was about 200 lbs per sq in Such check or control specimens were considered necessary for each batch because of the variation in the temperature and humidity at the time of preparation and curing, and of other known or unknown conditioning factors

Sodium Silicate

Sodium silicate was investigated because of its possible cementing action and its possible catalyzing effect on the resin formation Tables 11 and 12 give the results of these experiments and show that the effect of the sodium silicate is detrimental rather than beneficial

The Effect of Foaming Agents on the Quality of Two Aniline-Furfural Resins

Tables 17 and 18 show the effect of the addition of a combination of various foaming and gas producing agents The proportion of gas-forming materials used for each specimen was calculated on the basis of a desirable pore pressure of 20 lbs per sq in This appeared to be a suitable pressure, however, there is no way of predicting the optimum pressure for the purpose of concentrating the cementing resins on the points of contact of the soil particles.

None of the specimens showed any appreciable improvement, in fact some of them showed a decrease in strength from that of the control However, a beneficial effect could be observed from heating during the wet-dry tests

The Effectiveness of Two Percent Aniline-Furfural Resin (70 30) in the Stabilization of 10 Soils

The determination of the relative effectiveness of a stabilizing agent with widely different soils is a difficult task No testing procedure has been developed that fully evaluates the properties of stabilized mixes employing resinous material, consequently, an analysis of laboratory results requires considerable knowledge of the general behavior of soils and an understanding of the forces of nature to which stabilized soils are subjected in the field

In this part of the investigation, the response of 10 different soils to stabilization with 2 percent aniline-furfural resin (70 30) was determined by two mechanical test procedures. first, by compressive strength tests on 2" x 2" specimens and, second, by plunger-penetration tests on 4" x 6" specimens The data obtained from each of these tests are discussed separately

Compressive Strength - 2" x 2" Specimens

The results obtained from these tests are given in tables 19 to 28, inclusive Figure 9 shows the effectiveness of treatment as a function of the acidity or alkalinity of the media. Figure 10 is a plot of the strength of the treated soils after the different types of weathering In this figure the soils are arranged from left to right in order of increasing plasticity The discussion is divided according to the type of exposure to which the specimens were subjected.

Two-Hours Immersion Referring to figure 10, it is seen that immersing the specimens in water for 2 hours was not a sufficiently severe exposure to greatly affect the heavier soils N and V Inasmuch as the specimens were air-dried before immersion and consequently were not all dried to an equal degree, and because unconfined tests show low stability for low-cohesive soils, the relative response of soils H, P, B, E, and L is difficult to determine The comparatively high strength of soil G may or may not be an indication of success of treatment This soil is probably better than soils U and M, however No definite rating of the soils can be made from these data alone

Alternate Wetting and Drying The graph showing the results of these tests presents an interesting factor about the reaction of the different treated soils to this type of weathering It should be kept in mind that one wetting and drying cycle consisted of 5 hours immersion in water and 43 hours drying at an elevated temperature Because of the great water resistance of aniline-furfural treated specimens, little water was taken in during the wetting period As a consequence, these tests are more heating and cooling than wetting and drying tests

In will be noted that the strength of specimens of soils P, B, E, L and M was greater after 4-cycles than after 1-cycle, while that of soils H, G, U, N and V was less. The increase of strength of the first group of soils probably results from either or both the benefits of repeated drying during the cycling and/or the additional "set" of the resin at the elevated temperature used in drying In the second group, the destructive forces exceeded any benefit that may have been gained On the basis of this difference in performance and the relative strengths of the treated soils after 4 cycles of wetting and drying, it appears that soils P, B, E, L, G and U may be considered to have been satisfactorily treated. Although the latter two of these soils decreased in strength during cycling, they are included in this group because of their high strength after 4 cycles

The effectiveness of treatment with soil H relative to the other soils is not shown by these tests since unconfined compression tests do not give a true comparison of the relative stability of cohesionless and plastic soils The fact that this sand was held together during the exposure shows that aniline-furfural resin has considerable binding power It would seem, however, that a greater amount of treatment is required to satisfactorily stabilize this soil.

The data on soil M seem erratic The only obvious peculiarity of this soil that might explain the large increase in strength during cycling is the activity of the clay fraction The magnitude of this activity is shown by a high base exchange capacity

Soil N would be judged successfully stabilized soil if the specimen strength after 4 cycles were taken as the sole criterion of acceptability The decrease in strength of this soil during cycling indicates, however, that permanent stability has not been attained An increase in the amount of resin admixture would undoubtedly be advantageous

The low strength of soil V after 4 cycles and the considerable reduction in strength during the cycle tests indicate that this soil was not satisfactorily treated with the 2 percent admixture used

Alternate Freezing and Thawing Figure 10 shows that the freezing and thawing tests were considerably more severe on the specimens than the wetting and drying tests, especially in the case of the more plastic soils. This is an interesting item since plastic soils usually suffer less from freezing than non-plastic soils

While the strength of all specimens was quite low, a comparison of the response of the different soils to treatment is possible Considering both the strength after 4 cycles and the reduction in strength during cycling, it seems that soil E should be judged the most susceptible to stabilization Soil L, which on the basis of physical characteristics should perform quite similar to soil E, was much more affected by the weathering As in the wetting and drying test, the strength of soil G was reduced considerably during cycling but was still comparatively high at the completion of the test. Specimens of the sandy soils H and P were very resistant to freezing and thawing well. The action of soil V indicates that it was not sufficiently stabilized

Plunger-Penetration -- 4" x 6" Specimens

The main difference between a plunger-penetration type of test and a compressive strength test is the tendency of the former to measure the properties of a surface or outer crust of the specimens, proportional to the dimensions of the plunger, while the latter method tests the entire specimen The relative merits of the two procedures are controversial, but, as far as this investigation is concerned, both provided pertinent data, and, in general, supported the same conclusions The results obtained from the tests on the 4" x 6" specimens are given in table 29 and in figure 11

Capillary Absorption The original drying of the soils to a constant weight in an oven at 70° C reduced their moisture content from a range of 10-30 percent to a range of 1-3 percent, depending upon the soil type

After capillary absorption for 10 days the soils contained the following amounts of moisture, based upon the weight of the soil after drying in an oven at 70° C

H = 0.9%	G = 2.4%
P = 1 6%	U = 3.6%
B = 2.7%	M = 4.8%
E = 1.6%	N = 4 9%
L = 2.3%	V = •5 4%

These moisture contents are very low; therefore the load-penetration tests on these capillary absorption specimens was a measure of the properties of relative dry specimens The low moisture contents indicate that the aniline-furfural resin was a very good waterproofing agent

It is seen that the plunger-load sustained by all treated specimens after subjection to 10-days capillary absorption was considerable The relative stability of the sandy specimens (soil H) is probably not truly reflected inasmuch as this test procedure provides no confinement for the specimen The soils M and N were the most unstable

Alternate Wetting and Drying The results of the alternate wetting and drying tests are given in the bar graph of figure 11. Besides showing the load sustained by the different soils after the cycling, the ratio of this load to that sustained after the capillary absorption test is given Since the specimens used in these tests were exposed to the 10 days capillary absorption prior to cycling, the plot of this ratio of strengths provides an index of the effect of wetting and drying on the stability of the different soils

It may be seen that the strength of soils P, B, E, L, G and U was increased by the wetting and drying cycles, while that of soils H, M N, and V was decreased (ratio of the former is greater than one,- that of the latter is less than one) While, on the basis of load carried after cycling, soils L, U, and G appear the most stable, it will be noted that they were more greatly affected by wetting and drying than were soils P and B A similar reversal of relationship is noted for soils M and V The fact that soil N had, after the cycling, only 9 percent of the stability measured after the 10 days absorption period indicates that at least the surface of this soil was very detrimentally affected by the weathering cycles

The data obtained by the plunger and by the compressive strength test give the same general indications The treated specimens of soils P, B, E, and L withstood wetting and drying exceptionally well Soils G and U performed well but were not quite as well as the aforementioned group Soils N and V were most affected by wetting and drying The behavior of soil M is erratic, but it should be considered better than N and V though not as good as U Judging from the test procedures employed, soil H requires more binder to withstand the cycling

Alternate Freezing and Thawing. During the freezing and thawing cycles the specimens lost a small amount of moisture; consequently they were relatively dry at the time of the load-penetration test

Approximate moisture contents for the different soils after the freezing and thawing cycles are given below

H = 0 4%	G = 2 2%
P = 0.5%	U = 4 0%
B = 2 8%	M = 4 1%
E = 1.5%	N = 6 7%
L = 2 5%	V = 5 0%

The results of the plunger tests performed after 12 cycles of freezing and thawing are given in figure 11, comparison being made between the load carried after exposure to freeze-thaw and the load after 10 days of capillary absorption As in the case of the compressive strength tests, this type of exposure was the most severe employed The general trends shown by both test procedures were the same The less plastic soils resisted the exposure well while the heavier soils were considerably affected The fact that soil L had, after the freeze-thaw exposures, only 44 percent of the load carrying capacity determined after capillary absorption shows that this soil differs greatly from soil E The good resistance of soil H to freezing and thawing is of outstanding theoretical and practical significance

The load-penetration values after 12 cycles of freezing and thawing were lower than those after 10 days capillary absorption on all soils except E and M This seems to indicate that the freezing and thawing cycles were destructive on most of the soils tested even though, at the low moisture contents prevailing in the specimens, there could be no question of a destructive action by ice formation

It appears that the effect of both the so-called wet-dry and freeze-thaw cycles was a result of the mechanical stresses caused by the temperature changes involved, and of the additional stresses caused by the differences in water affinity of the soils and the differences in the physical state of the absorbed water at the different temperatures involved in the cycle tests.[10]

Summary

The test procedures employed in this study have not yet been correlated with observations on actual field installations using aniline-furfural resin as a stabilizer, therefore, no definite design criteria may be set at the present time. However, the tests do give a relative comparison of the response of the different soils to treatment with 2 percent of aniline-furfural On the basis of the test results presented, the following summarizing comments may be made

1 The fact that untreated specimens of all soils failed when immersed in water and treated specimens withstood even the most severe of the weathering tests indicates that aniline-furfural resin was beneficial in all cases

2 The treated specimens of the medium plastic soils B, E, L, G, and U were very resistant to the alternate wetting and drying test Inasmuch as the destructive forces in these tests are due to the shrinkage and expansion of the specimens during changing moisture and thermal conditions, the successful treatment of these soils is probably due to their good gradation and low plasticity - qualities that have been demonstrated as advantageous for all types of stabilization

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[10]For greater detail concerning these phenomena see Winterkorn, Hans F , "Climate and Highways," Trans Am Geoph Union, June 1944.

3 A comparison of the stability of soil N as measured by the compression tests and by the plunger test is of interest In the former, this soil showed a relatively high strength while in the latter it made the poorest showing of all the soils This may be explained by the fact that, in the first procedure of test, the properties of the entire specimens are measured while in the second, the properties of the outer crust or surface are evaluated The presence of aniline-furfural in this specimen so reduced the water absorption that only the outer crust was affected during the period of exposure The waterproofing of such a plastic soil demonstrates the effectiveness of this agent

4 The fact that all soils showed greater resistance to the wetting and drying exposure than to the freezing and thawing is quite significant especially since the destructive action involved could not be a consequence of ice formation, because of the low moisture content of the specimens In general, stabilizing admixtures that owe their effectiveness to a binding or cementing property are more affected by the freeze-thaw test than by the wet-dry test, for waterproofing admixtures, the reverse is true. This, of course, is a consequence of the use of cementing agents for noncohesive and of waterproofing agents for cohesive soils

5 From the results obtained in this study it may be concluded that the effectiveness of aniline-furfural in the amounts employed is due mainly to its waterproofing properties

6 That aniline-furfural resin acts as a binding as well as a waterproofing agent is demonstrated in the resistance of the soil H specimen to freezing and thawing Inasmuch as the test procedure employed is usually quite destructive on sandy soils, the relatively high strength of soil H is very significant

7. The unexpected poor showing of soil L should serve as a warning of the danger involved in attempting to predict the response of a soil to treatment on the sole basis of its physical characteristics

Comparison of the Soil Stabilizing Effectiveness of Aniline-Furfural Resin (70 30) with that of Other Stabilizers

In order to compare the stabilizing effectiveness of aniline-furfural resin with that of other types of stabilizers, the results from a series of tests performed in another study are presented in tables 30 and 32 Because of the limited scope of these tests and the fact that laboratory tests do not always reflect the relative effectiveness in the field of different types of admixtures, the conclusions drawn are necessarily of a quantitative character However, the results do demonstrate some interesting properties of aniline-furfural resin

Table 32 shows the results obtained from a series of tests employing portland cement, a liquid asphalt, and aniline-furfural resin with six different soils [11] The characteristics of these soils are given in table 31 The plunger test, as previously described, was used in this study

[11] These tests were performed by the Joint Highway Research Project, Purdue University, as part of a project on soil stabilization sponsored by the Civil Aeronautics Administration

Since the effectiveness of portland cement with soils is due to its binding properties and that of liquid asphalt to its waterproofing properties (excluding granular mixes and asphaltic cements), the effectiveness of aniline-furfural resin can perhaps best be seen by comparing the strength of the specimens containing this agent with those made with portland cement, and the moisture absorption with those containing the liquid asphalt. Following this procedure, it may be seen that the aniline-furfural resin compares favorably with cement in binding properties and, at the same time, performs as well as liquid asphalt in waterproofing the soils.

Table 30 presents a comparison of the effectiveness of aniline-furfural resin, a purely waterproofing type of agent designated as Resin Stabilizer 321, and portland cement. It may be seen that by the procedure of test employed (compressive strength of 2" x 2" specimens), aniline-furfural resin appears to be a very effective stabilizer. Inasmuch as Resin 321 has been shown to be very effective in waterproofing the soils in question,[12] the binding properties of the aniline-furfural resin probably account for the differences in strength obtained. It is interesting to note that soils treated with Resin 321 showed practically no stability after the freezing and thawing test - an indication that Resin 321 has no binding effect. A comparison of the strengths of the aniline-furfural specimens and the cement specimens after wetting and drying again demonstrates the excellent waterproofing properties of this resin.

TEST RESULTS II - OTHER ARTIFICIAL RESINS

The Effectiveness of Urea-Furfural and Phenol-Furfural Resins[13]

The results of the experiments on urea-furfural and phenol-furfural resin binders are given in tables 34 and 36, respectively. The phenol-furfural resins did very poorly even with aniline-furfural admixtures. The urea-furfural results were more encouraging but still not nearly as good as those achieved with aniline-furfural. In later experiments urea-furfural was used in combination with natural resin stabilizers. Table 35 shows the effectiveness of urea-furfural with Belro Rosin in the stabilization of soil G. Experiments using Belro Rosin as a stabilizing agent and urea (from urine) and furfural as dispersing agents were performed with soil N. The results of these tests, however, were very poor. Evidently, as in the case of many other resins, urea-furfural resins cannot be used effectively in heavy clay soils at the low densities employed in this test series.

The Effectiveness of Phenol-Formaldehyde Combinations

Combinations of phenol and formaldehyde were tried on Nimitz fine sand (soil H). The specimens failed upon contact with water, showing that the material did not set at the low temperature employed.

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[12] 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.

[13] The effectiveness of these and of other artificial resins depends, of course, to a great extent upon the method of preparation of the resins and of the soil-resin specimens. In this study, such methods of preparation were selected as could be easily adapted to prevailing construction methods. It follows that the conclusions drawn here hold only for the stated experimental conditions and for comparable field methods and conditions.

The Effectiveness of Urea-Formaldehyde Resins

Tables 37 to 39 show the results of experiments using urea-formaldehyde resins including a commercial brand named "Weldwood glue " Though several salt catalysts were used, nowhere in these experiments was a direct acid-base catalysis attempted In those experiments in which acid forming salt were used the PH value of the treated soil was not recorded It should also be noted that for the experiments recorded in table 38 amounts of resin only slightly greater than 1 percent were employed, even the very effective aniline-furfural resins showed poor strength at the prevailing low soil densities until quantities of 2 percent or greater were used.

Olmstead and Klipp[14] found greater percentages (4 percent) of dimethylol urea effective in soil stabilization; however, they used a DuPont preparation, while our stabilizer was prepared in the laboratory from urea and formaldehyde They also made use of acid catalysts just before the addition of the resin to the soil

The field for the development of this resin is still open Better results could, possibly, be achieved by adding the acid catalyst to the soil just previous to the addition of the dimethylolurea Also some of the difficulties encountered by Olmstead and Klipp might be overcome by keeping the resin solution alkaline until it is added to the acidified soil

The effectiveness of Calcium Sulfamate-Formaldehyde Resins

Table 40 gives the results obtained by the use of calcium sulfamate-formaldehyde resins. These results do not appear to be very good However, very little work has been done on this material and it might well bear further investigation especially since the water insoluble resin is easily formed by an exothermic reaction

The Effectiveness of Aniline-Furfural Resins in Conjunction with Vinsol, Congo Resins, and Semi-Solid Amines

Table 41 shows the effectiveness of aniline-furfural resin in conjunction with Congo resins and Vinsol Two percent of resinous material were used in each batch one percent of Vinsol or of the particular Congo resin and one percent of 70 30 aniline-furfural resin The resin mixture was prepared by dissolving the Congo resin or Vinsol in the furfural, then adding the mixing water and aniline to the furfural solution and emulsifying the mixture in a milk shaker before adding it to the soil The results, given in table 41, show that none of the resin mixtures proved to give as good results as the 2 percent aniline-furfural resin control sample on any of the 4 soils tested

Specimens were made using a 2 percent of aniline-furfural resin (25 75) in conjunction with two semi-solid amines Four and one-half percent of amine (on the basis of resin added) was combined with the aniline-furfural solution, and the resulting solution mixed with the soil The results showed no improvement over the control of 2 percent aniline-furfural resin and are not recorded in this report

CONCLUSIONS

On the basis of the experiments performed in this investigation, the following conclusions may be stated

1. Two aniline-furfural combinations were found which gave reasonably good resin binders. These represented ratios of 70 30 and 35·65 of aniline and furfural, respectively The 70 30 resin was much stronger and withstood weathering tests far better than the 35 65 resin

[14] Olmstead, Lewis B and Klipp, L W "Chemical Soil Stabilization of Soils for Military Uses," Research Report No 22

2 Both resins mentioned above were found to give poor results in alkaline mixes Maximum strengths were obtained when the mixes were slightly on the acid side

3 A minimum of approximately 2 percent of the best aniline-furfural resin (70 30) was required to obtain appreciable resistance to weathering for the low specimen densities employed

4 The addition of iron or aluminum salts was found to improve slightly the strength of the resin while the addition of alkaline reacting materials was found to be detrimental

5 Foaming agents combined with gas producing materials were found unsuccessful in improving the strength of the specimens

6 Aniline-furfural resin (70 30) is most effective with medium plastic soils Cohesionless soils and heavy clays probably require greater amounts of admixture for successful treatment, however, the amount required also depends upon the compacted densities of the soil

7 Aniline-furfural resin is both a binding and a waterproofing agent -- both properties are of considerable significance with quantities of admixtures as small as 2 percent

8 Urea-furfural, phenol-furfural, and phenol-formaldehyde resins were found ineffective as soil stabilizing agents in the amounts and form used

9 Urea-formaldehyde and calcium sulfamate-formaldehyde specimens showed some promise but the experiments performed were not conclusive

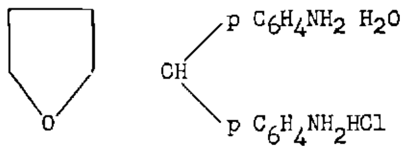
APPENDIX I

THE HISTORY AND STRUCTURE OF ANILINE-FURFURAL RESINS

The formation of resinous masses by reaction of furfural with various substances has been known for a long time Such materials were produced by Persoz[15] in 1860 and Stenhouse[16] in 1870 from furfural and aromatic amines or phenols However, no concise report was made at that time on either the reaction mechanism or the reaction products

Schiff[17] in 1870 assigned the formula

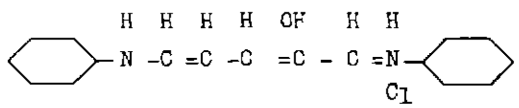
I



to the product obtained by the reaction of 1 mole of furfural with 1 mole of aniline and 1 mole of aniline hydrochloride He considered the compound to be a derivative of furyl diphenyl methane possessing a structure analogous to the dye stuffs of the tri phenyl methane class

Zincke and Mulhausen[18] in 1905 concluded that the furfural ring opened up in the reaction giving the open chain compound

II



Riegel and Hathaway[19] (1941) titrated the product with nitrous acid and found that it reacted quantitatively From this formation of the diazonium salt they concluded that the structure must be as shown in Formula I in order to permit the free NH_2 groups fo be diazotized

However, Williams and Wilson[20] discovered (1942) that in the formation of the diazonium salt of Riegel and Hathaway aniline is liberated They also found that treatment with $NaHSO_3$ liberated aniline from the aniline-furfural product Though the fate of the remainder of the molecule is unknown because of the ease of splitting off aniline from the open chain compound compared to the difficulty that supposedly would be encountered in aplitting off aniline from the dianilinofuryl methane structure, the authors concluded that the correct structure is that proposed by Zincke and Muhlhausen, Formula II. They also indicated that the dianilinofuryl methane structure could not give the

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15 Persoz, Wagner's Jahres Berichts, p.487, (1860)

16 Stenhouse, Proc Roy Soc., Vol 18, p. 537 (1870)
Ann , pp 156, 199, (1870)

17 Schiff, Ann , pp. 201, 355, (1880)
Ann , pp 239, 349, (1887)

18 Zincke and Mulhausen, Ber., Vol 38, pp 382-1, (1905)

19 Riegel and Hathaway, J Am Chem Soc , Vol 63, p 1835 (1941)

20 Williams and Wilson, J. Chem Soc , pp 506-7, (1942)

deep reddish blue color found in the aniline-furfural product which the open chain structure very easily explains

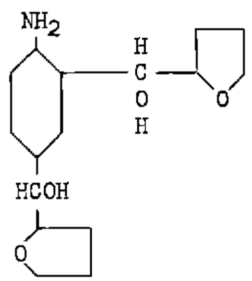
Compounds of the Formula II type are known to crystallize easily, while the free bases generally appear as resinous masses Since the investigation described in this report was concerned with a resin stabilizer, the work was done using 2 moles of aniline to combine with 1 mole of furfural instead of the usual combination using 1 mole of aniline and 1 mole of aniline hydrochloride

For the purpose of checking the proposed structural formulas, two sets of experiments were performed using p-toluidine and dimethyl aniline respectively, instead of aniline In the case of p-toluidine the p position of the benzene ring is full and the reaction should not go if Formula I is the structural formula Structural formula II requires the amino group to be free and theoretically p-toluidine would make a resin under this proposed structure The case of dimethyl aniline is just the reverse. A resin would not be formed if II is the correct formula, while, since the p position is open the resin would be formed according to I

Specimens 2 inches high and 2 inches in diameter were compacted from Nimitz fine sand (soil H) containing 2 percent aniline-furfural in the first 3 batches, 2 percent dimethyl aniline furfural in the next 3 and 2 percent p-toluidine furfural in the last batches These samples were then subjected to the regular freeze-thaw and wet-dry tests The results are shown in table 33

It can easily be seen that the dimethyl aniline furfural specimens did not stand up at all, indicating there was no resin formed On the other hand, while the p-toluidine furfural specimens did not stand up as well as the aniline-furfural specimens, they did far better than the dimethyl aniline furfural. These results lend support to Formula II

The series of tests made to find the best proportions of aniline and furfural for resin formation brought out two maxima in the curve (figure 2) The first and most pronounced coincided with the ratio of 1 mole of furfural to 2 moles of aniline The corresponding molecular structure has already been discussed The second maximum coincides with the ratio of 2 moles of furfural to 1 mole of aniline The structure of this reaction product is probably



This formula is analogous to that for the condensation product of phenols and aldehydes However, at present, the data available are too scarce to permit a definite decision whether the material obtained is a chemical compound or a mixture of 2 1 aniline-furfural resin with furfural and spontaneously formed furfural resins

The resinous material thus formed is not as effective a stabilizer as the 2.1 aniline-furfural compound

APPENDIX II

ANILINE-FURFURAL RESIN CATALYZATION

Recent work with aniline-furfural has shown a retardation of the condensation reaction which with the technical grades of these materials available 10 years ago, started spontaneously and instantaneously, immediately upon combination This fact represents an advantage insofar as it permits a better control of the reaction However, for the latter purpose it is important to have the right catalyst available The tests described in the following were made in an attempt to discover and evaluate an effective and adjustable catalyst for the aniline-furfural reaction These tests were concerned with

1 The Effectiveness of Powdered Chemicals as Catalysts
2 The Catalytic Effectiveness of Aqueous Salt Solutions
3 The Effect of Increasing Amounts of Water on Resin Formation
4 Aniline-Furfural Emulsions

The Catalytic Effectiveness of Powdered Chemicals

Batches containing 2 parts, by weight, of aniline to 1 part of furfural, making a total of about 21 cc of the mixture, were prepared with small amounts of potential catalysts A duplicate was made for each test with the addition of 2 cc of water

One sample containing only aniline and furfural was set aside as a control This sample was still soft after standing 3 days The sample containing 2 cc of water (no catalyst) behaved the same way

The addition of a slight amount of ferric chloride produced solidification both with and without water, but produced better results without water. Possibly a little more of the ferric salt was added to the sample without water

Ferric sulphate produced a solidification, but to a very much lesser degree than the chloride, and the solidification was not noticeable until several days after adding the catalyst

The addition of aluminum chloride caused thickening in the sample containing water in about 30 minutes In the sample without water the reaction was slower, but still definite

Barium chloride, sodium chloride, lead chloride, and calcium sulphate were tried but produced no thickening or hardening effect on the mixture The addition of small amounts of phosphoric acid produced a precipitate which appeared to be an aniline phosphate instead of the resin desired

This group of tests (table 42) pointed at the iron and aluminum chlorides as the best catalysts for the purpose As a check test, two samples were prepared in the same manner as above, one with water and one without water, adding a very small amount of aluminum chloride to each. In one additional sample with the aluminum chloride, 1 drop of phosphoric acid was added causing a slight precipitate as noticed in the earlier tests All samples showed thickening, but not very good solidification

The Catalytic Effectiveness of Aqueous Salt Solutions

From these preliminary tests, the question arose as to the amount and form in which the iron or aluminum chloride would be most effective Therefore, tests were made using different amounts of these salts in aqueous solution The resins were made as formerly Ten grams of aluminum chloride (6 H_2O) were dissolved in 25 cc of water;

and 10 grams of ferric chloride (6 H_2O) were dissolved in 20 cc of water. All tests were made on the pure aniline-furfural mixture without any water except that contained in the catalyzing solution.

To identical samples of the aniline-furfural mixture were added 1/2 cc, 1 cc, 2 cc, 3 cc, 4 cc, and 5 drops (1/4 cc) of catalytic solutions (table 43) All samples became hard after a day and a half. In general it was observed that the greater the amount of the catalyst added, the more rapid the reaction When 3 or 4 cc were added, the mixture hardened before the catalyst could be thoroughly stirred into the batch. The samples containing 1 cc of the catalyst became thick fairly soon after the addition of the catalyst, but did not harden for 4 or 5 hours The samples in which 5 drops of catalyzing material were added took over night to harden. The aluminum chloride produced a better effect for the amount added than the ferric chloride. Much better results were shown when the catalyst was added in solution than when it was added in the crystal form

The Effect of Increasing Amounts of Water on Resin Formation

In order to determine whether or not the action of these catalysts was appreciably affected by the presence of larger quantities of water, batches of the resin were made in the same manner as before, adding increasing amounts of water Six samples were used with each catalyst, a control, in which no water was added, and 5 other samples, to which increasing amounts of water were added. To the first six samples 5 drops of ferric chloride solution were added to each batch, to the second six, 5 drops of aluminum chloride solution (table 44). The samples were stirred well in an attempt to disperse the water into the aniline-furfural mixture However, these attempts were not very successful With one sample an attempt was made to emulsify the aniline-furfural solution and the water However, the emulsifier became clogged, and this process had to be discontinued, however, such emulsification was carried out at a later date in other experiments In these experiments the water remained in a separate phase from the aniline-furfural solution, and had no effect on the solidification of the resin

Aniline-Furfural Emulsions

Batches of aniline and furfural were made using 13 7 cc of aniline and 6 7 cc of furfural in each batch Five drops of ferric-chloride solution (10 grams of ferric chloride in 20 cc of water) were added to each batch (table 46). The first batch was used as a control To succeeding batches, increasing amounts of water were added. All samples were emulsified with ferric chloride added at the time of emulsification. Probably the catalyst was not well dispersed in the control sample, a large dark red spot remained in the emulsifier after the emulsification had been completed

After 1 hour the control sample had developed into a soft resin, the sample containing 5 cc of water had become a viscous liquid; the sample containing 10 cc of water seemed to have a surface scum thicker than the main body The other samples appeared unchanged

After 2 hours apparently all the emulsions held except the sample containing 25 cc of water The emulsion had been broken in that case, and the aniline-furfural mixture had settled to the bottom.

The next observation was made after 3-1/2 hours The control was still soft resin The samples containing 15, 20 and 25 cc of water had broken from the emulsion, and, instead of forming a brittle-like resin, as is usually the case with aniline-furfural, they formed a more or less flocculent precipitate This tendency to form a flocculent precipitate appeared to be more prevalent as more water was added The sample containing 10 cc of water was gummy and showed tendencies to be flocculent In the 5 cc sample, after the soft resin formed, the water collected in the center and there was a tendency to show a fluffy nature in this aqueous portion

In a second group of experiments, batches of aniline-furfural were made in the same manner, except that aluminum chloride solution (10 g in 25 cc water) was added in place of ferric chloride.

The control formed quite a hard resin immediately upon emulsification with the catalyst. The second sample, having 5 cc of water, formed a viscous resin from which water could be squeezed showing that the emulsion was not badly broken before the resin set. However, the resin formed was very soft The sample containing 10 cc of water formed a flocculent precipitate on the bottom of the cup with a gummy resin on top. The emulsion in all samples having more than 5 cc of water were not stable, but broke before or during the reaction; the aniline-furfural settling to the bottom of the cup and the water standing over it

It was found difficult to emulsify the mixture when the catalyst was added at the time of emulsification because chunks of resin would stop up the emulsifier. Therefore a series of experiments was made in which the aniline-furfural and water were emulsified and the catalyst added later It was also desired to see the effect of larger amounts of water; therefore, to 400 cc of water were added 13 7 cc of aniline, 6.7 cc of furfural and 5 drops of respective catalytic solutions Samples were prepared in which the catalyst was added both before and after emulsification (table 45).

After 5 hours, in the case of those samples to which the catalyst was added before emulsification, the samples containing aluminum chloride seemed to remain as a stable emulsion with a slight coating on the bottom of the cup In the case of the sample containing ferric chloride, the emulsion broke and formed a scum that floated on top of the water.

In the cases where the catalyst was not added until after emulsification, the emulsified liquid came out white and milky in color. Upon the addition of 5 drops of the catalyst, the aluminum chloride sample turned pink, and a thick flocculent precipitate was formed Upon the addition of the ferric chloride catalyst to another sample of the same emulsion, the solution turned a dark brown, and a small precipitate was formed. A check test turned out the same as the original

Samples of the emulsion were taken and the amount of the catalyst was tripled The effect was that a thicker and more strongly colored precipitate was formed more quickly in both cases with the aluminum chloride showing the best over-all flocculent effect. The brown color when the iron catalyst was used, and the red color when the aluminum catalyst was used, may indicate that the flocculent precipitates which were obtained were not true aniline-furfural resins, but aluminum and iron complex compounds.

It was found that the emulsification of the aniline-furfural and water in an aluminum emulsifier caused the reaction to be catalyzed sometimes to the extent that a flocculent precipitate was formed However, it was found that a stable emulsion could be obtained by adding a small amount of soap to keep the mixture on the alkaline side until the catalyst was added.

Conclusions

1. The best catalyst found for the aniline-furfural reaction was $AlCl_3$ It was most effective when added as a saturated, or nearly saturated, aqueous solution
2. $FeCl_3$ was not quite as effective as $AlCl_3$ It was more effective when added as a saturated, or nearly saturated, solution than when added in powder form
3. The greater the amount of either of these catalysts used, the greater was the acceleration of the reaction (5 percent $AlCl_3$ added as a saturated aqueous solution produced solidification before the catalyst could be thoroughly mixed with the 21 cc of aniline-furfural used)
4. $BaCl_2$, $FeSO_4$, NaCl, PbO, and H_3PO_4 were tried as catalytic agents, but did not produce good results
5. $FeSO_4$ catalyzed the reaction, but much more slowly than either $FeCl_3$ or $AlCl_3$
6. H_3PO_4 produced an aniline phosphate precipitate.
7. The presence of large quantities of water was found to decrease the effectiveness of the catalysts A soft, gummy resin was formed which tended to settle out at the bottom in tests in which the water was just stirred into the aniline-furfural mixture However, if the water was emulsified with the aniline-furfural mixture, the resin formed as a flocculent precipitate
8. In cases where the samples were emulsified, it was found to be more practical to add the catalyst after the material had been emulsified.
9. The addition of a small amount of soap was effective in keeping the reaction from taking place in the aluminum emulsifier

TABLE 1

PHYSICAL CHEMICAL CHARACTERISTICS OF THE TEN SOILS
EMPLOYED IN THE INVESTIGATION

Soil	Gradation Colloid %	Clay %	Silt %	Sand %	Atterburg Limits L L	P L	P I	S L	Organic Matter %	Base Ex Capacity (1)	Optimum Max Moisture % (2)	Dry Density Lbs/Cu Ft (3)
H	4	5	5	90	Non Plastic				0.42	2.17	12	103
P	9	11	12	77	19.0	17.0	2.0		1.00	5.62	14	109
B	14	22	11	67	22.1	18.1	4.0	14.4	1.36	9.28	14.5	113.5
E	14	18	32	50	22.5	18.3	4.2	15.3	2.47	8.84	14	115
L	9	17	28	55	23.0	18.0	5.0	16.3	1.47	8.71	14.0	101.3
G	7	17	53	30	25.0	18.6	6.4	15.6	1.38	12.86	15	110
U (3)	12	20	41	39	31.8	20.1	11.7	14.9	1.32	10.15	16	110
M	12	25	30	45	32.1	18.4	13.7	15.6	1.79	16.24	17	104
N	19	40	27	33	45.0	19.0	26.0	12.6	1.95	13.59	22	96
V	20	45	21	34	53.5	22.4	31.1	12.7	3.02	18.48	28	90

(1) Mili-equivalents per 100 g (2) By modified procedure described in text (3) This soil contains free $CaCO_3$

TABLE 2

THE EFFECT OF THE ANILINE-FURFURAL RATIO ON THE QUALITY
OF THE RESINOUS CEMENT (NO CATALYST)

Aniline – Furfural Ratio		Compressive Strength in Lbs/Sq In					
Aniline %	Furfural %	Dry	Wet	Dry 1 W-D	Wet 4 W-D	Moist 1 F-T	Wet 4 F-T
10	90	84	26	85	34	25	10
20	80	79	33	59	29	25	27
30	70	125	39	92	32	35	30
40	60	167	40	121	38	40	33
50	50	134	50	158	31	34	35
60	40	262	148	153	49	67	72
70	30	450	239	271	70	144	132
80	20	221	150	108	26	50	21
90	10	98	25	69	29	23	8
0	100	58	6	70	6	12	*

* Mechanical defect
Batch Composition   Soil H, 2% Aniline-Furfural Mixture, no catalyst

TABLE 3

THE EFFECT OF THE ANILINE-FURFURAL RATIO ON THE QUALITY OF THE RESINOUS CEMENT IN THE PRESENCE OF 0 08% HCl AS CATALYST

Aniline – Furfural Ratio		Compressive Strength in Lbs/Sq In					
Aniline %	Furfural %	Dry	Wet	Dry 1 W-D	Wet 4 W-D	Moist 1 F-T	Wet 4 F-T
10	90	40	10	**	10	5	4
20	80	46	14	**	13	8	9
30	70	60	16	11	12	9	8
40	60	43	8	19	10	**	4
50	50	58	62	29	14	3	10
60	40	289	147	80	40	55	52
70	30	207	128	67	11	75	46
80	20	225	40	41	28	11	13
90	10	16	5	8	7	5	5
0	100	67	8	7	2	**	**

** Failed
<u>Batch Composition</u> Soil H, 2% Aniline-Furfural Mixture, 0 08% (1 1/2 cc) HCl

TABLE 4

THE EFFECT OF THE ANILINE-FURFURAL RATIO ON THE QUALITY OF THE RESINOUS CEMENT IN THE PRESENCE OF 0 16% HCl AS CATALYST

Aniline – Furfural Ratio		Compressive Strength in Lbs/Sq In					
Aniline %	Furfural %	Dry	Wet	Dry 1 W-D	Wet 4 W-D	Moist 1 F-T	Wet 4 F-T
10	90	37	24	38	7	21	9
20	80	78	45	88	17	33	26
30	70	137	95	131	29	61	38
40	60	188	109	182	41	73	37
50	50	136	123	137	34	61	29
60	40	116	99	110	31	58	35
70	30	136	75	80	23	41	31
80	20	81	26	45	16	26	12
90	10	48	42	35	9	17	8
0	100	57	11	88	8	6	**

** Failed
<u>Batch Composition</u> Soil H, 2% Aniline-Furfural Mixture, 0 16% (3 cc) HCl

TABLE 5

THE EFFECT OF THE ANILINE-FURFURAL RATIO ON THE QUALITY OF THE RESINOUS CEMENT IN THE PRESENCE OF 0 05% NaOH AS CATALYST

Aniline – Furfural Ratio		Compressive Strength in Lbs/Sq In					
Aniline %	Furfural %	Dry	Wet	Dry 1 W-D	Wet 4 W-D	Moist 1 F-T	Wet 4 F-T
10	90	83	**	**	**	**	**
20	80	84	**	**	**	**	**
30	70	130	**	**	**	**	**
40	60	122	**	**	**	**	**
50	50	86	**	**	**	**	**
60	40	177	9	**	**	7	**
70	30	217	22	212	24	13	5
80	20	201	18	154	25	10	5
90	10	94	12	96	17	4	8
0	100	92	**	**	**	**	**

** Failed
<u>Batch Composition</u> Soil H, 2% Aniline-Furfural Mixture, 10% (10 cc) NaOH

TABLE 6

THE EFFECT OF HYDROGEN AND
HYDROXYL IONS (FROM HCl AND NaOH)
ON A 50 50 ANILINE-FURFURAL RESIN

Catalyst cc	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Dry 1 W-D	Wet 4 W-D	Moist 1 F-T	Wet 4 F-T
Conc HCl						
0 5	98	10	33	28	23	4
1 0	81	7	40	22	21	13
1 5	147	13	31	16	18	15
2 0	74	14	44	18	10	12
3.0	119	37	29	20	7	23
None	39	**	29	15	**	2
10% NaOH						
1	38	2	74	28	**	1
2	51	**	68	19	**	**
4	85	**	45	24	**	**
6	84	**	**	**	**	**
8	106	**	**	**	**	**
10	105	**	**	**	**	**

** Failed
Batch Composition Soil H, 2% Aniline-Furfural Resin (50 50) Amounts of catalyst shown were added to 2200 g of soil

TABLE 7

THE EFFECT OF HYDROGEN AND
HYDROXYL IONS (FROM HCl AND NaOH)
ON A 35 65 ANILINE-FURFURAL RESIN

Catalyst cc	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Dry 1 W-D	Wet 4 W-D	Moist 1 F-T	Wet 4 F-T
Conc HCl						
0 5	66	43	37	26	26	31
1 0	67	67	47	23	51	34
2 0	62	32	26	26	35	14
3 0	64	20	34	26	17	13
None	43	11	20	22	9	9
10% NaOH						
1.0	63	13	63	36	13	10
2 0	88	16	54	19	13	11
4.0	89	5	71	25	5	6
6.0	82	**	**	**	**	**
8 0	118	**	**	**	**	**
10 0	88	**	**	**	**	**

** Failed
Batch Composition Soil H, 2% Aniline-Furfural Resin (35 65). Amounts of catalyst shown were added to 2200 g of soil

TABLE 8

THE EFFECT OF HYDROGEN AND HYDROXYL IONS (FROM HCl AND NaOH) ON A 70 30 ANILINE-FURFURAL RESIN

Catalyst cc	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Dry 1 W-D	Wet 4 W-D	Moist 1 F-T	Wet 4 F-T
Conc HCl						
0 5	481	230	96	65	92	62
1 0	317	113	62	51	51	31
2 0	119	89	28	31	32	37
3 0	118	78	95	20	31	19
None	395	207	95	71	90	82
10% NaOH						
1 0	321	86	66	29	50	40
2 0	209	100	44	38	32	17
4 0	286	32	62	55	15	10
6 0	272	19	75	63	13	6
8 0	341	14	49	54	11	9
10 0	401	62	52	44	23	16

** Failed

Batch Composition Soil H, 2% Aniline-Furfural Resin (70 30) Amounts of catalyst shown were added to 2200 g of soil

TABLE 9

THE EFFECTIVENESS OF LOW PERCENTAGES OF 70 30 ANILINE-FURFURAL RESIN IN ACID, ALKALINE, AND NEUTRAL MEDIA

Percent Resin	Catalyst cc	Compressive Strength in Lbs/Sq In					
		Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
0 5	None	72	33	17	14	17	10
1.0	None	157	96	30	26	30	23
1 5	None	291	161	64	17	76	52
2 0	None	420	303	76	64	121	104
	HCl						
0.5	0 75	53	22	10	14	7	6
1 0	1 50	56	26	11	12	9	8
1 5	2 30	54	36	11	14	15	13
2 0	3.00	124	57	20	37	32	28
	10% NaOH						
0 5	2 5	149	56	19	38	19	16
1.0	5 0	232	25	30	55	13	9
1 5	7 5	304	22	15	60	10	6
2 0	10 0	393	12	44	63	9	6

Batch Composition Soil H, Aniline-Furfural Resin (70 30) Amounts of catalyst shown were added to 2200 g of soil

TABLE 10

THE EFFECTIVENESS OF LOW PERCENTAGES OF 35 65 ANILINE-FURFURAL RESIN IN NEUTRAL MEDIA

Percent Resin	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
1	93	9	18	8	14	12
2	64	10	14	5	15	7
4	32	14	55	24	16	12

Batch Composition Soil H, Aniline-Furfural Resin (35 65)

TABLE 11

THE EFFECT OF VARIOUS IONS ON THE QUALITY
OF 35 65 ANILINE-FURFURAL RESIN

Catalyst	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None (Control)	200	135	71	34	88	57
	Cation Effect					
1 1 g NaOH	155	**	22	25	**	**
1 15 g KCH	71	9	26	22	2	5
2 2 g BaOH	67	12	28	14	9	7
0 7 g $Ca(OH)_2$	76	13	28	16	8	8
	Anion Effect					
1 3 g H_2SO_4	160	106	70	38	50	51
1 7 g HAc	186	135	55	51	53	63
2 25 g HNO_3	173	104	95	36	74	66
0 8 g H_3PO_4	162	171	88	25	87	65
	Effect of Sodium Silicate					
10 cc 50% $Na_2Si_4O_9$	86	14	27	22	10	7
20 cc 50% $Na_2Si_4O_9$	123	45	61	33	28	20

** Failed
Batch Composition Soil H, 2% Aniline-Furfural Resin (35 65) Amounts of catalyst shown were added to 2200 g of soil

TABLE 12

THE EFFECT OF VARIOUS IONS ON THE QUALITY
OF 70 30 ANILINE-FURFURAL RESIN

Catalyst	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
	Cation Effect					
1 1 g NaOH	117	8	32	26	**	**
1 15 g KOH	232	19	135	53	12	6
4 3 g $Ba(OH)_2$	38	7	60	41	8	5
2 2 g $Ba(OH)_2$	124	13	29	28	11	8
1 4 g $Ca(OH)_2$	148	20	27	37	14	12
0 7 g $Ca(OH)_2$	131	16	36	38	14	5
	Anion Effect					
1 1 g H_2SO_4	544	271	98	67	121	66
1 7 g HAC	272	78	52	55	61	32
2 25 g HNO_3	255	139	58	43	70	71
0 8 g H_3PO_4	446	199	84	69	101	55
	Effect of Sodium Silicate					
10cc 50% $Na_2Si_4O_9$	192	21	41	51	16	6
20cc 50% $Na_2Si_4O_9$	108	10	**	**	7	**

** Failed
Batch Composition Soil H, 2% Aniline-Furfural Resin (70 30) Amounts of catalyst shown were added to 2200 g of soil

TABLE 13

THE EFFECT OF INCREASING AMOUNTS OF SULFURIC ACID ON THE QUALITY OF 35 65 ANILINE-FURFURAL RESIN

H_2SO_4 g	Dry	Compressive Strength in Lbs/Sq In					
		Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
1 4	127	138	77	30	57	35
2.8	204	162	75	**	61	43
5 6	162	160	72	**	46	44
8 4	219	163	94	32	49	64
11 2	120	78	80	27	48	30
14 0	131	106	65	39	59	44

** Failed

Batch Composition Soil H, 2% Aniline-Furfural Resin (35 65) Amounts of catalyst shown were added to 2200 g of soil

TABLE 14

THE EFFECT OF INCREASING AMOUNTS OF SULFURIC ACID ON THE QUALITY OF 70 30 ANILINE-FURFURAL RESIN

H_2SO_4 g	Dry	Compressive Strength in Lbs/Sq In				
		Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
1 4	418	168	85	44	106	85
2.8	314	204	77	37	95	60
5 6	402	229	96	55	116	109
8 4	246	172	68	33	84	95
11 2	340	145	77	40	82	73
14 0	250	131	85	37	71	63

Batch Composition Soil H, 2% Aniline-Furfural Resin (70 30) Amounts of catalyst shown were added to 2200 g of soil

TABLE 15

THE EFFECT OF VARIOUS SALTS ON THE QUALITY OF 35 65 ANILINE-FURFURAL RESIN

Catalyst	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	158	131	25	21	12	7
6 3 g $Fe_2(SO_4)_3$ 6 H_2O	109	113	74	35	25	27
3 2 g $Fe_2(SO_4)$ 6 H_2O	124	93	66	26	27	10
2 3 g $FeCl_3$. 6 H_2O	143	76	57	21	34	29
2 0 g $AlCl_3$ 6 H_2O	206	118	22	35	49	59
2 0 g $ZnSO_4$ 7 H_2O	168	97	81	22	29	26
3 0 g $MgSO_4$ H_2O	132	49	33	13	21	7
5 4 g $Al_2(SO_4)_3$ 18 H_2O	129	149	68	38	66	40
5 7 g $Al_2(SO_4)_3(NH_4)_2SO_4$ 24 H_2O	128	109	47	41	56	45
3 5 g Na_2HPO_4	134	10	23	10	**	**

Batch Composition Soil H, 2% Aniline-Furfural Resin (35 65) Approximately 1/40 mole of salt shown

TABLE 16

THE EFFECT OF VARIOUS SALTS ON THE QUALITY OF 70 30 ANILINE-FURFURAL RESIN

Salt g	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	221	67	58	43	119	20
6 3 g $Fe_2(SO_4)_3$ 6 H_2O	37	21	15	15	14	18
3 2 g $Fe_2(SO_4)_3$ 6 H_2O	33	21	18	17	18	5
2 3 g $FeCl_3$ 6 H_2O	109	81	23	26	56	24
2.0 g $AlCl_3$ 6 H_2O	273	205	96	41	95	60
2.0 g $ZnSO_4$ 7 H_2O	320	198	102	48	55	54
3 0 g $MgSO_4$ 7 H_2O	337	166	48	27	62	23
5 4 g $Al_2(SO_4)_3$ 18 H_2O	106	95	16	33	118	74
5 7 g $Al_2(SO_4)_3(NH_4)_2SO_4$ 24 H_2O	138	77	60	21	60	65
3 5 g Na_2HPO_4	410	184	202	38	116	11

Batch Composition Soil H, 2% Aniline-Furfural Resin (70 30) Approximately 1/40 mole of salt as shown.

TABLE 17

THE EFFECT OF FOAMING AGENTS ON THE QUALITY OF 1 3 ANILINE-FURFURAL RESIN

Foaming Agent	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	163	35	55	59	25	12
A	43	10	38	14	10	6
A(1)	55	21	24	10	16	12
B	55	6	12	11	6	**
C	61	9	20	13	8	3
D	89	14	17	50	11	8
E	80	13	11	17	7	6
F	39	7	23	13	8	3

** Failed (1) Heat treated 16 hours at 75 C
Batch Composition Soil F, 2% Aniline-Furfural Resin (1 3) Foaming agent as shown

Composition of Foaming Agents

A = 4g $NaHCO_3$ + 2g NH_4Cl

B = 3g CaC_2 with Vinsol

C = 2 3g $NaNO_2$

D = 2 3g $NaNO_2$ + 2g urea + 1 8g NH_4Cl + Formalin

E = 2 3g $NaNO_2$ + 2g urea + 1.8g NH_4Cl + Furfural

F = 2 3g $NaNO_2$ + 2g urea + 1 8g NH_4Cl

TABLE 18

THE EFFECT OF FOAMING AGENTS ON THE QUALITY
OF 70 30 ANILINE-FURFURAL RESIN

Foaming Agent	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	331	201	80	119	133	83
A	311	122	71	75	70	52
A(1)	150	230	77	82	60	45
B	147	35	24	21	16	15
C	510	186	139	53	53	36
D	535	111	103	58	62	34
E	581	85	88	69	33	19

(1) Heat treated 16 hours at 75°C
Batch Composition Soil H, 2% Aniline-Furfural Resin (70 30) Foaming agent as shown

Composition of Foaming Agents

A = 4g $NaHCO_3$ + 2g NH_4 Cl

B = 3g CaC_2 with Vinsol

C = 2 3g $NaNO_2$

D = 2 3g $NaNO_2$ + 2g urea + 1 8 NH_4Cl + 4g Formalin

E = 2 3g $NaNO_2$ + 2g urea + 1.8g NH_4Cl + 3g Furfural

TABLE 19

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN
(70 30) IN THE STABILIZATION OF SOIL B AS A FUNCTION
OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	556	460	359	521	248	93
3 cc Conc HCl	540	403	441	425	243	89
1 5 cc Conc HCl	547	282	384	383	278	67
2 cc 10% NaOH Sol	592	434	315	316	200	80
6 cc 10% NaOH Sol	600	362	140	496	79	41
10 cc 10% NaOH Sol	672	350	263	488	188	67

Batch Composition Soil B, 2% Aniline-Furfural Resin (70 30) Amounts of catalyst shown were added to 2500 g of soil

TABLE 20

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70:30) IN THE STABILIZATION OF SOIL E AS A FUNCTION OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In.					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	702	528	203	518	282	137
3 cc Conc. HCl	280	220	77	162	173	86
1.5 cc Conc. HCl	208	313	184	328	204	146
2 cc 10% NaOH	561	441	181	213	261	161
6 cc 10% NaOH	803	418	172	770	133	85
10 cc 10% NaOH	743	406	219	626	223	77

Batch Composition: Soil E, 2% Aniline-Furfural Resin (70:30). Amounts of catalyst shown were added to 2200 g of soil.

TABLE 21

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70:30) IN THE STABILIZATION OF SOIL G AS A FUNCTION OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In.					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	884	681	642	477	395	132
3 cc Conc. HCl	834	685	704	512	402	206
1.5 cc Conc. HCl	1325	1044	1174	555	563	259
2 cc 10% NaOH Sol.	944	445	979	679	401	209
6 cc 10% NaOH Sol.	1395	657	613	1087	451	170

Batch Composition: Soil G, 2% Aniline-Furfural Resin (70:30). Amounts of catalyst shown were added to 2520 g of soil.

TABLE 22

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70:30) IN THE STABILIZATION OF SOIL H AS A FUNCTION OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In.					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	396	211	96	54	91	83
3 cc Conc. HCl	132	79	65	20	32	19
1.5 cc Conc. HCl	207	128	67	11	76	46
2 cc 10% NaOH Sol.	210	106	44	39	32	17
6 cc 10% NaOH Sol.	272	20	75	63	14	6
10 cc 10% HaOH Sol.	452	62	77	45	23	16

Batch Composition: Soil H, 2% Aniline-Furfural Resin (70:30). Amounts of catalyst shown were added to 2100 g of soil.

TABLE 23

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70:30) IN THE STABILIZATION OF SOIL L AS A FUNCTION OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In.					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	478	377	172	513	162	51
3 cc Conc. HCl	221	348	117	398	93	85
1.5 cc Conc. HCl	453	372	75	350	196	82
2 cc 10% NaOH Sol.	562	411	78	353	143	43
6 cc 10% NaOH Sol.	611	269	69	299	99	48
10 cc 10% NaOH Sol.	506	157	112	316	149	49

Batch Composition: Soil L, 2% Aniline-Furfural Resin (70:30). Amounts of catalyst shown were added to 2200 g of soil.

TABLE 24

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70:30) IN THE STABILIZATION OF SOIL M AS A FUNCTION OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In.					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	1124	249	515	1196	175	35
3 cc Conc. HCl	907	589	560	948	182	78
1.5 cc Conc. HCl	820	139	109	499	17	5
2 cc 10% NaOH Sol.	956	405	189	702	83	22
6 cc 10% NaOH Sol.	827	184	75	445	82	15
10 cc 10% NaOH Sol.	815	214	221	198	135	26

Batch Composition: Soil M, 2% Aniline-Furfural Resin (70:30). Amounts of catalyst shown were added to 2200 g of soil.

TABLE 25

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70:30) IN THE STABILIZATION OF SOIL N AS A FUNCTION OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In.					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	1273	981	1263	884	99	105
3 cc Conc. HCl	947	797	808	722	448	90
1.5 cc Conc. HCl	1003	771	835	247	178	54
2 cc 10% NaOH Sol.	1060	643	782	436	419	96
6 cc 10% NaOH Sol.	1208	638	942	713	178	22
10 cc 10% NaOH Sol.	1019	443	804	210	248	25

Batch Composition: Soil N, 2% Aniline-Furfural Resin (70:30). Amounts of catalyst shown were added to 2200 g of soil.

TABLE 26

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70 30) IN THE STABILIZATION OF SOIL P AS A FUNCTION OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	494	173	252	284	135	59
3 cc Conc HCl	414	283	158	188	149	99
1 5 cc Conc HCl	412	318	356	256	165	130
2 cc 10% NaOH Sol	496	298	298	198	140	78
6 cc 10% NaOh Sol	503	31	99	198	83	17
10 cc 10% NaOH Sol	561	181	45	167	92	45

Batch Composition Soil P, 2% Aniline-Furfural Resin (70 30) Amounts of catalyst shown were added to 2360 g of soil

TABLE 27

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70 30) IN THE STABILIZATION OF SOIL U AS A FUNCTION OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	622	310	536	466	185	43
3 cc Conc. HCl	482	200	370	222	96	25
1 5 cc Conc HCl	436	48	309	314	121	28
2 cc 10% NaOH Sol	277	**	38	29	10	5
6 cc 10% NaOH Sol	406	68	134	201	45	**
10 cc 10% NaOH Sol	553	**	191	137	13	12

**Failed

Batch Composition Soil U, 2% Aniline-Furfural Resin (70 30) Amounts of catalyst shown were added to 2270 g of soil

TABLE 28

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70 30) IN THE STABILIZATION OF SOIL V AS A FUNCTION OF THE ACIDITY OR ALKALINITY OF THE MEDIA

Catalyst	Compressive Strength in Lbs/Sq In					
	Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
None	749	468	664	223	72	12
3 cc Conc HCl	935	530	386	**	86	19
1 5 cc Conc HCl	1147	512	242	**	40	13
2 cc 10% NaOH Sol	1143	276	51	**	18	9
6 cc 10% NaOH Sol	915	500	222	25	24	16
10 cc 10% NaOH Sol	1089	528	127	**	45	10

**Failed

Batch Composition Soil V, 2% Aniline-Furfural Resin (70 30) Amounts of catalyst shown were added to 2310 g of soil

TABLE 29

THE EFFECTIVENESS OF TWO PERCENT OF ANILINE-FURFURAL RESIN (70 30) IN THE STABILIZATION OF 10 SOILS - 4" x 6" SPECIMENS

Soil	Plunger Load in Lbs After Different Conditions of Treatment							
	1a	1	2	3	4	5	6	7
H	360	767	358	669	329	852	175	442
P	2041	1327	554	1102	493	1144	941	1136
B	2039	1588	584	1488	565	1515	987	1549
E	2446	1339	613	1313	638	1527	991	1591
L	2812	2442	820	1911	360	942	1376	1648
G	2216	1991	727	2083	539	1681	1098	1987
U	2364	1880	602	1784	429	1568	1240	1665
M	2065	1201	367	1025	397	685	298	860
N	1552	1286	350	1516	160	623	31	476
V	1701	1936	688	2348	351	2024	311	1164

Batch Composition 2% Aniline-Furfural Resin (70 30)

Conditions of Treatment

All specimens were air-dried for three days, dried to constant weight in an oven and then subjected to the different conditions of treatment described below

1a Untreated specimen - No further exposure - tested dry
1 No further exposure - tested dry
2 10 days capillary absorption - tested wet
3 10 days capillary absorption, and re-drying in oven-tested dry
4 10 days capillary absorption and 12 cycles of freezing and thawing - tested wet
5 10 days capillary absorption, 12 cycles of freezing and thawing, and re-drying in oven-tested dry
6 10 days capillary absorption, and 12 cycles of wetting and drying - tested wet
7 10 days capillary absorption, 12 cycles of wetting and drying, and re-drying in oven-tested dry

TABLE 30

COMPARISON OF THE SOIL STABILIZING EFFECTIVENESS OF ANILINE-FURFURAL (70 30), RESIN STABILIZER 321, AND PORTLAND CEMENT

Soil	Type of Admixture	Compressive Strength in Lbs/Sq In					
		Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
H	Aniline-Furfural	396	211	96	54	91	83
	Resin 321	17	3	**	**	**	**
	Portland Cement	106	61	59	54	47	37
P	Aniline-Furfural	494	173	252	284	135	59
	Resin 321	95	41	91	29	8	1
	Portland Cement	185	98	73	97	80	92
B	Aniline-Furfural	556	460	359	521	248	93
	Resin 321	255	157	163	156	53	7
	Portland Cement	420	269	178	397	225	198
E	Aniline-Furfural	702	528	203	518	282	137
	Resin 321	341	187	210	141	89	34
	Portland Cement	307	171	146	141	119	83
L	Aniline-Furfural	478	377	172	513	162	51
	Resin 321	413	142	178 (1)	258	48	7
	Portland Cement	350	227	153	185	154	148
G	Aniline Furfural	884	681	642	477	395	132
	Resin 321	390	57	121	195	39	2
	Portland Cement	291	131	47	75	85	75
U	Aniline-Furfural	622	310	536	466	185	43
	Resin 321	264	67	176	134	3	1
	Portland Cement	317	153	102	120	115	90
M	Aniline-Furfural	1124	249	515	1196	175	35
	Resin 321	425	234	233	308	73	4
	Portland Cement	367	181	112	97	103	111
N	Aniline-Furfural	1273	981	1263	884	99	105
	Resin 321	645	195	306	20	86	2
	Portland Cement	470	206	95	118	142	96
V	Aniline-Furfural	749	468	664	223	72	12
	Resin 321	384	110	142 (1)	67	20	1
	Portland Cement	370	177	127	130	128	117

(1) One test only **Failed

Batch composition Specimens treated with 2% Aniline-Furfural Resin (70 30), 1% Resin 321, and 6% Portland Cement respectively

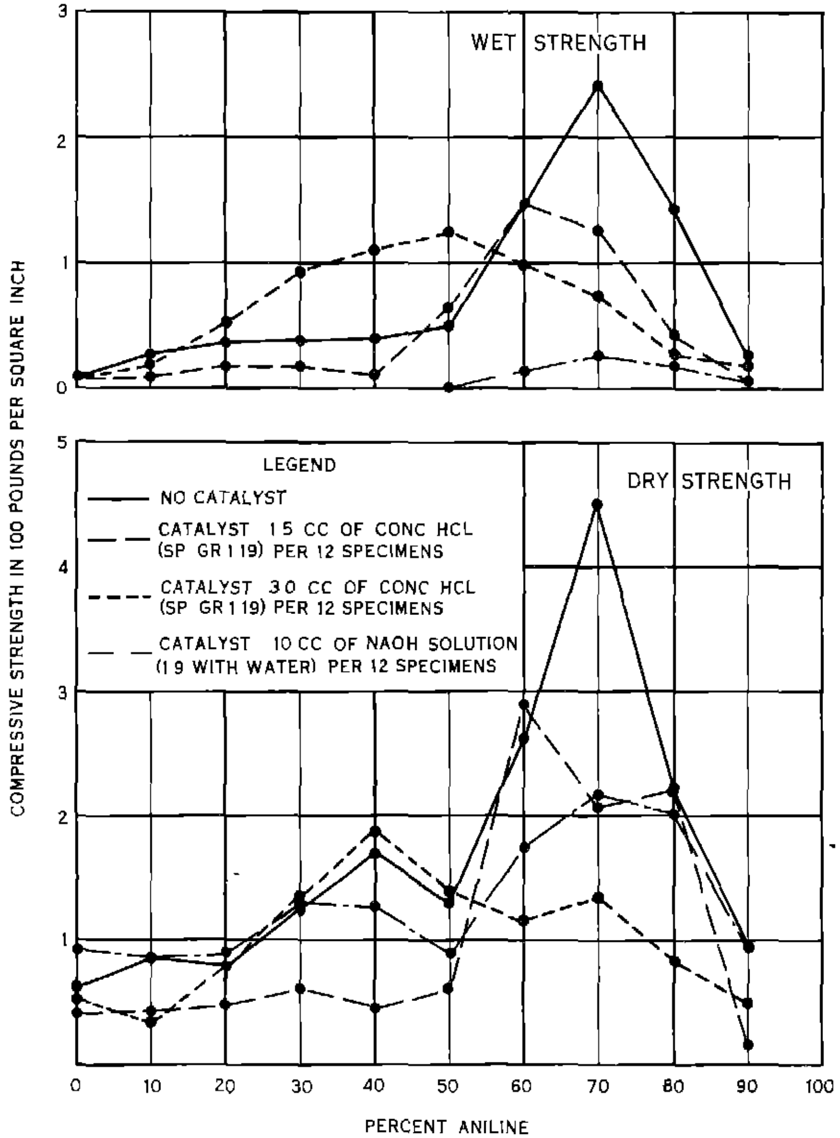


Figure 2 The Effect of the Aniline Furfural Ratio on the Quality of the Resinous Cement in Acid, Basic and Neutral Media

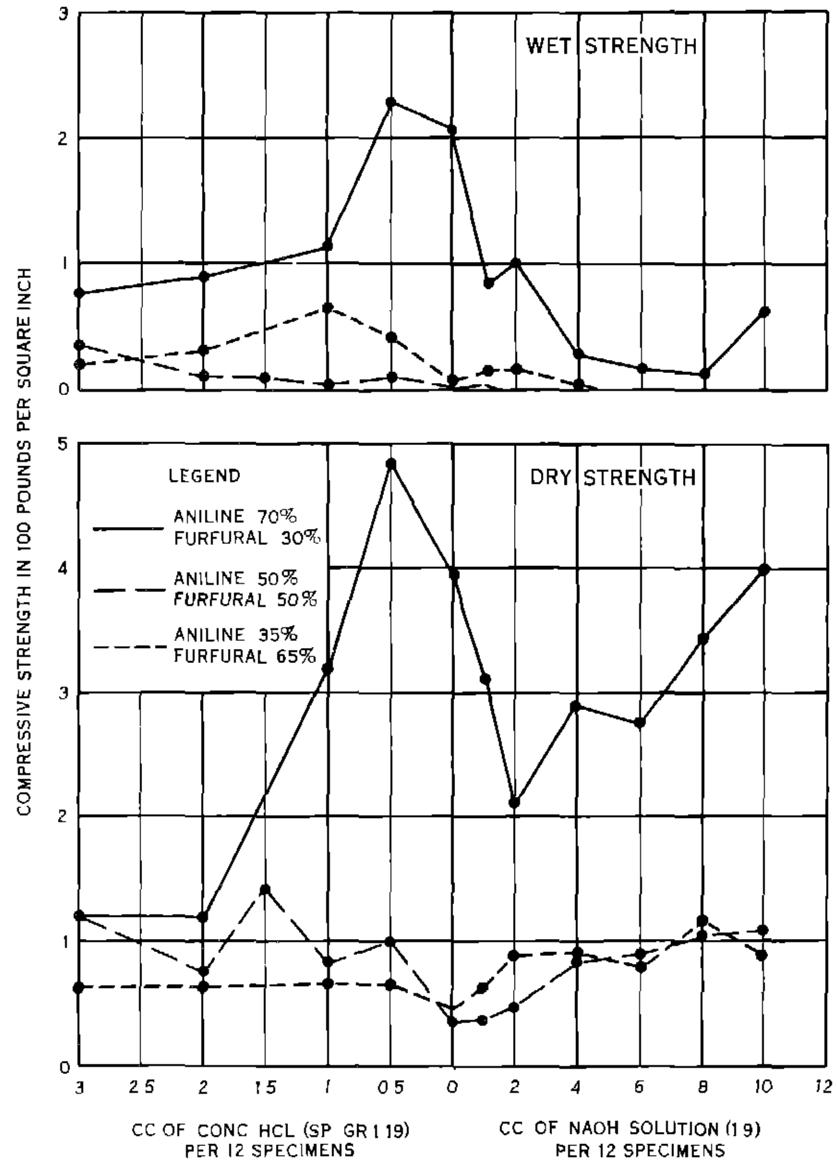


Figure 3 The Effect of Hydrogen and Hydroxyl Ions (from HCl and NaOH) on Three Aniline Furfural Resins

TABLE 33

STRUCTURE STUDIES ON ANILINE-FURFURAL RESINS
THROUGH THE USE OF DIMETHYLANILINE AND
P-TOLUIDINE IN REACTION WITH FURFURAL

Resin Material	Catalyst	Compressive Strength in Lbs/Sq In					
		Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
2 1 Aniline-Furfural	None	393	276	101	21	124	82
2 1 Aniline-Furfural	3 cc HCl Conc	132	64	34	17	43	31
2 1 Aniline-Furfural	10 cc 10% NaOH	103	8	19	--	8	**
2 1 Dimethylaniline-Furfural	None	31	--	**	**	**	**
2 1 Dimethylaniline-Furfural	3 cc HCl Conc	18	**	**	**	**	**
2 1 Dimethylaniline-Furfural	10 cc 10% NaOH	60	**	**	**	**	**
70 30 p-Toluidine-Furfural	None	19	5	31	16	7	4
35 65 p-Toluidine-Furfural	None	18	6	38	16	2	**
50 50 p-Toluidine-Furfural	None	94	47	37	31	33	28
70 30 p-Toluidine-Furfural	3 cc HCl Conc	108	74	31	29	52	40

**Failed
<u>Batch Composition</u> Soil H, 2% Resinous Material
Amounts of catalyst shown were added to 2100 g of soil

TABLE 34

THE EFFECTIVENESS OF UREA-FURFURAL RESINS

Resin Material	Catalyst	Compressive Strength in Lbs/Sq In					
		Dry	Wet	Dry 1 W-D	Dry 4 W-D	Wet 1 F-T	Wet 4 F-T
1 1 Urea-Furfural	3 cc HCl Conc	46	6	80	30	22	2
1 2 Urea-Furfural) 1 3 Aniline-Furfural)	3 cc HCl Conc	118	73	100	44	26	24

<u>Batch Composition</u> Soil H, 2% Resinous Material
Amounts of catalyst shown were added to 2100 g of soil

TABLE 35

THE EFFECTIVENESS OF DIFFERENT AMOUNTS OF FURFURAL
ADDED TO URINE AND BELRO ROSIN IN THE STABILIZATION OF SOIL G

Urine cc	Furfural g	Dry	Wet	Compressive Strength in Lbs/Sq In			
				Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
260	12 8	878	659	599	407	154	15
260	9 6	972	715	558	415	266	33
260	6 4	936	389	518	305	159	17
260	3 2	1026	615	70	**	189	20
130	6 4	1028	17	7	**	3	**
130	4 8	1156	545	558	494	148	15
130	3 2	1220	631	259	497	212	20
130	1 6	925	175	14	118	33	**

**Failed
<u>Batch Composition</u> 2520 g Soil G, 50 g Belro Rosin
Amount of urine and furfural per batch as shown

TABLE 36

THE EFFECTIVENESS OF PHENOL-FURFURAL RESINS

Resin Material Molar Ratio	Catalyst	Compressive Strength in Lbs/Sq In					
		Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
1 2 Phenol-Furfural	5 cc HCl Conc	12	**	**	**	**	**
1 1 Phenol-Furfural	20 cc 10% NaOH	53	**	**	**	**	**
1 2 Aniline-Furfural) 1 2 Phenol-Furfural)	4 cc HCl Conc	52	24	33	36	20	11
1 2 Aniline-Furfural) 1 2 Phenol-Furfural)	4 cc HCl Conc	79	32	59	49	22	15

** Failed

Batch Composition Soil H, 2% Resinous Material. Amounts of catalyst shown were added to 2100 g of soil

TABLE 37

THE EFFECTIVENESS OF UREA-FORMALDEHYDE RESINS

Percent Resin	Catalysts Added	Compressive Strength in Lbs/Sq In					
		Dry	Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
2	0 5 g NH_4Cl	239	9	90	74	56	16
2 (1)	0 5 g NH_4Cl	140	12	44	31	14	8
2	2 0 g Resorcinol 0 5 g NH_4Cl	255	16	127	84	15	10
1	3 5 g Resorcinol 0 25 g NH_4Cl	199	15	93	116	14	12
1	1 7 g Resorcinol 0 25 g NH_4Cl	96	7	64	35	2	**
1	0 25 g NH_4Cl	65	*	**	**	**	**
1 5	2 5 g Resorcinol 0 4 g NH_4Cl	115	11	92	77	11	7
1 5	0 4 g NH_4Cl	122	15	81	54	6	2
2	0 5 g NH_4Cl 2% Armour Amine 1180 B Lot 601 7	19	10	13	9	11	10
2	0 5 g NH_4Cl 2% Armour Amine Coco B Lot 390 1	26	5	11	11	8	12
2	1 0 g NH_4Cl 3 5 g Resorcinol 1 g $NaHCO_3$	69	16	97	60	14	7

** Failed

(1) The resin was reacted in the usual way (1 part urea to 2 parts formalin reacted at 50-55° C) However, the resin was then dried and added in the powdered form instead of the usual reaction solution

Batch Composition Soil H, percent Resin Solution (1 part of urea to 2 parts of formalin) Amounts of catalyst shown were added to 2100 g of soil

TABLE 38

THE EFFECTIVENESS OF SMALL PERCENTAGES OF UREA-FORMALDEHYDE RESIN IN THE STABILIZATION OF SELECTED SOILS

Soil	Dry	Wet	Compressive Strength in Lbs/Sq In			
			Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
E	474	151	66	40	28	25
H	60	5	17	6	4	2
N	1039	**	**	**	**	**
P	390	9	7	5	3	3
V	735	**	**	**	**	**

** Failed
Batch composition 20g Urea + 60cc 37% Formalin (makes 1 2 to 1 3% Dimethylolurea Resin for each batch)
Soil as shown

TABLE 39

THE EFFECTIVENESS OF WELDWOOD GLUE IN THE STABILIZATION OF SELECTED SOILS

Soil	Dry	Wet	Wet 1 W-D	Compressive Strength in Lbs/Sq In		
				Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
E	169	**	**	**	**	**
H	62	8	16	3	4	3
N	567	**	**	**	**	**
P	133	**	**	**	**	**
V	659	**	**	**	**	**

** Failed
Batch composition 40g of Weldwood glue per batch (approximately 1 8%) Soil as shown

TABLE 40

THE EFFECTIVENESS OF CALCIUM SULFAMATE-FORMALDEHYDE RESIN (1) IN THE STABILIZATION OF SOILS M AND E

Resin Added to Neutralize	Dry	Compressive Strength in Lbs/Sq In				
		Wet	Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
	Soil E					
Total base exchange ions	215	10	8	2	5	3
Total Ca ions	193	8	6	1	3	3
$\frac{1}{2}$ Total base exchange ions	264	4	**	**	3	3
$\frac{1}{2}$ Ca ions	262	3	**	**	1	2
	Soil M					
Total base exchange ions	196	38	3	1	3	2
$\frac{1}{2}$ Total base exchange ions	310	3	**	**	**	2
$\frac{1}{2}$ Ca ions	344	-	**	**	**	**

(1) Sulfamic acid and formaldehyde were added on the basis of the base exchange ions which might be supplied to the resin
**Failed

TABLE 41

THE EFFECTIVENESS OF ANILINE-FURFURAL RESIN IN CONJUNCTION WITH VINSOL AND CONGO RESINS

Soil	Natural Resin Added	Aniline-Furfural Added (1) %	Dry	Wet	Compressive Strength in Lbs/Sq In			
					Wet 1 W-D	Wet 4 W-D	Wet 1 F-T	Wet 4 F-T
H	1% Congo TV2	1	58	10	6	9	2	*
	1% Congo No. 28	1	82	11	7	14	7	5
	1% Congo PC1	1	126	63	48	31	29	6
	1% Vinsol	1	77	39	12	13	6	2
	None	2	283	265	116	67	60	92
E	1% Congo TV2	1	804	618	425	505	191	132
	1% Congo PC1	1	741	699	650	691	298	136
	1% Congo No 28	1	720	536	248	510	249	59
	1% Vinsol	1	820	561	380	407	231	51
	None	2	970	789	702	434	413	256
M	1% Congo TV2	1	909	679	703	621	229	32
	1% Congo No 28	1	902	623	734	568	238	27
	1% Congo PC1	1	1095	819	800	785	321	10
	1% Vinsol	1	1061	833	979	796	303	62
	None	2	911	779	802	650	330	106
L	1% Congo TV2	1	934	660	938	288	223	57
	1% Congo No 28	1	766	134	52	296	16	7
	1% Congo PC1	1	874	570	283	692	230	90
	1% Vinsol	1	783	489	31	398	165	53
	None	2	788	578	675	666	283	182

**Failed
(1) V ratio of aniline-furfural Percentage added is based on the dry weight of soil used

TABLE 42

ANILINE-FURFURAL RESIN CATALYZATION

Salt	Result	
	No Water	2 cc Water
None (Control)	Soft, viscous liquid	Soft, viscous liquid
$FeCl_3$	Good hardening over night	Harder than control but still soft
$AlCl_3$	Good hardening over night	Became thick after 30 minutes Good brittle resin
$BaCl_2$	No effect - same as control	No effect - same as control
$FeSO_4$	Very little effect almost same as control	Very little effect, same as control
NaCl	No effect - same as control	No effect - same as control
PbO		No effect - same as control
H_3PO_4	Immediate precipitate of aniline phosphate	
$H_3PO_4 + AlCl_3$		Immediate precipitate of aniline phosphate Rest of mixture remained soft

<u>Batch composition</u> 13 7 cc Aniline and 6 7 cc Furfural in each sample Approximate 0 1 g of the catalyst.

TABLE 43

ANILINE-FURFURAL RESIN CATALYZATION

Catalytic Solution-cc	Effect
	$AlCl_3$
1/4	Very slow hardening Brittle resin after one day
1/2	Faster hardening Good resin formed in 18 hours
1	Good resin formed over night
2	Brittle solid in less than two hours
3	Resin formed immediately
4	Resin formed immediately
	$FeCl_3$
1/4	Slow hardening into brittle resin
1/2	Good resin formed over night
1	Good resin formed overnight Harder resin than given with 1/2 cc of $FeCl_3$
2	Good resin in several hours
3	Rapid resin formation
4	Very rapid solidification
5	Very rapid solidification

Catalytic Solutions
10g $FeCl_3$ 6 H_2O + 20 cc H_2O
10g $AlCl_3$ 6 H_2O + 25 cc H_2O

Batch Composition
13 7 cc Aniline
6 7 cc Furfural

Note Aluminum salt generally did better than iron salt The more salt in either case, the quicker and more brittle the resin formed

TABLE 44

ANILINE-FURFURAL RESIN CATALIZATION

Water cc No Emulsification	Effect: 1/4 cc $FeCl_3$ Solution	Effect: 1/4 cc $AlCl_3$ Solution
None (Control)	Resin formed but remained fairly soft	Brittle resin formed slowly one day
5	Resin formed but was slightly softer than control	Resin formed but remained fairly soft instead of hardening as in the control
10 15 20 25	Resin formed under a layer of water becoming increasingly softer the more water used	Resin formed under a layer of water becoming increasingly softer the more water used

Catalytic Solutions
10g $FeCl_3$ 6 H_2O + 20 cc H_2O
10g $AlCl_3$ 6 H_2O + 25 cc H_2O

Batch Composition
13 7 cc Aniline
6 7 cc Furfural

TABLE 45

ANILINE-FURFURAL RESIN CATALYZATION

Catalyst	H_2O Content	Effect
1/4 cc $AlCl_3$ Sol added before emulsification	400 cc	Remained emulsified and formed slight precipitation on bottom
1/4 cc $FeCl_3$ Sol added before emulsification	400 cc	Emulsion broke and a flocculent precipitate was formed which floated on the top of the aqueous solution
1/4 cc $AlCl_3$ Sol added to portion of sample after emulsification	400 cc	Sample came through in a white milky emulsion which turned pink upon addition of $AlCl_3$ with formation of flocculent precipitate
1/4 cc $FeCl_3$ Sol added to portion of sample after emulsification	400 cc	Sample was milky when emulsified (as above) but turned brown upon addition of $FeCl_3$ with formation of brown flocculent precipitate

Catalytic Solutions
10g $FeCl_3$ 6 H_2O + 20 cc H_2O
10g $AlCl_3$ 6 H_2O + 25 cc H_2O

Batch Composition
13 7 cc Aniline
6 7 cc Furfural
Varied water content (Emulsified)

Note 1. The addition of larger amounts of catalyst in duplicate of the last two tests yielded a faster reaction with a brighter color
Note 2 It was found that the addition of a small amount of soap prevented the emulsion from reacting while in the emulsifier

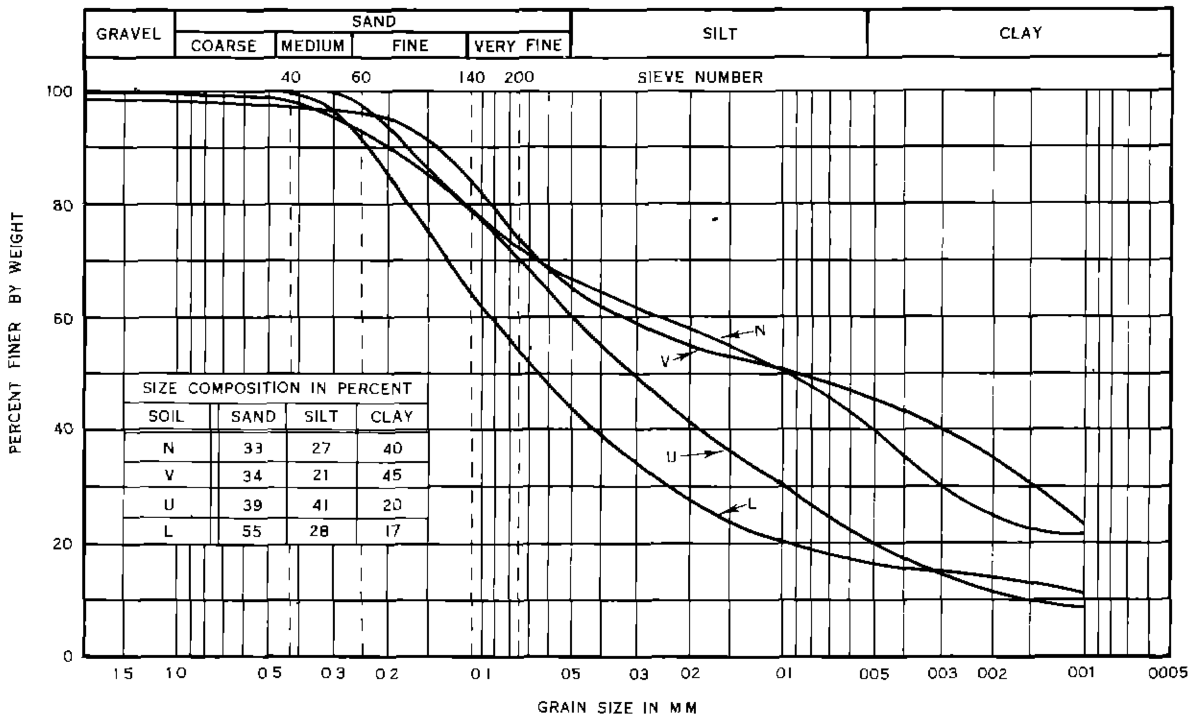
TABLE 46

ANILINE-FURFURAL RESIN CATALYZATION

Water Content-cc	Effect
	Catalyst 1/4 cc of $FeCl_3$ Solution
None (Control)	Soft resin formed in one hour (catalyst may not have been thoroughly mixed)
5	Viscous liquid, later developed into a soft resin water collecting at the center
10	Liquid, thicker scum on top later became gummy with small spots of floccules
15	Emulsion broken after about 2 hours, flocculent precipitate
20	Emulsion broken after about 2 hours, flocculent precipitate
25	Emulsion broken after about 1 hour, flocculent precipitate
	Catalyst 1/4 cc of $AlCl_3$ Solution
None (Control)	Immediate formation of a fairly hard brittle resin
5	Very viscous resin from which water could be squeezed, showing emulsion had not been broken
10	All had broken from emulsion in 2 hours These samples showed much less tendency to be flocculated than those treated with $FeCl_3$ A resin of somewhat gummy texture was formed at the bottom of the cup becoming increasingly softer and lighter in color with samples having increasing water contents.

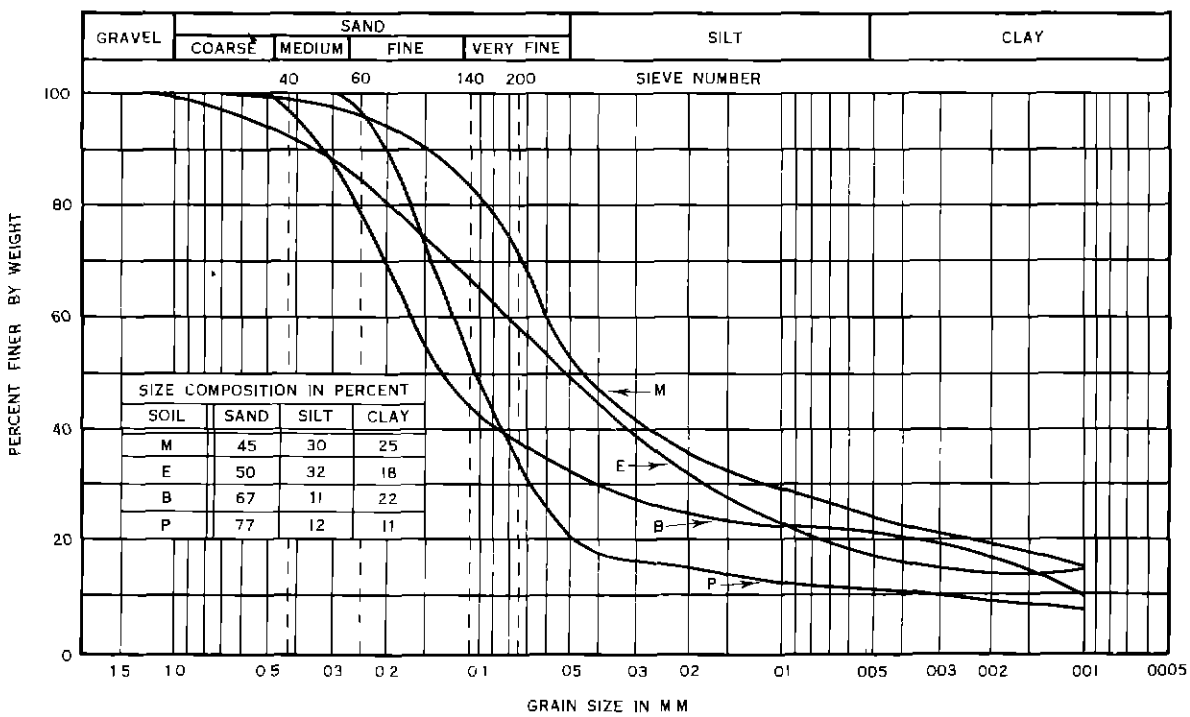
Catalytic Solution
10g $FeCl_3$ 6 H_2O + 20 cc H_2O
10g $AlCl_3$ 6 H_2O + 25 cc H_2O

Batch Composition
13 7 cc Aniline + 6.7 cc Furfural
Varied water content (emulsified)



SIZE COMPOSITION IN PERCENT

SOIL	SAND	SILT	CLAY
N	33	27	40
V	34	21	45
U	39	41	20
L	55	28	17



SIZE COMPOSITION IN PERCENT

SOIL	SAND	SILT	CLAY
M	45	30	25
E	50	32	18
B	67	11	22
P	77	12	11

Figure 1 Grain Size Distribution of the Different soils

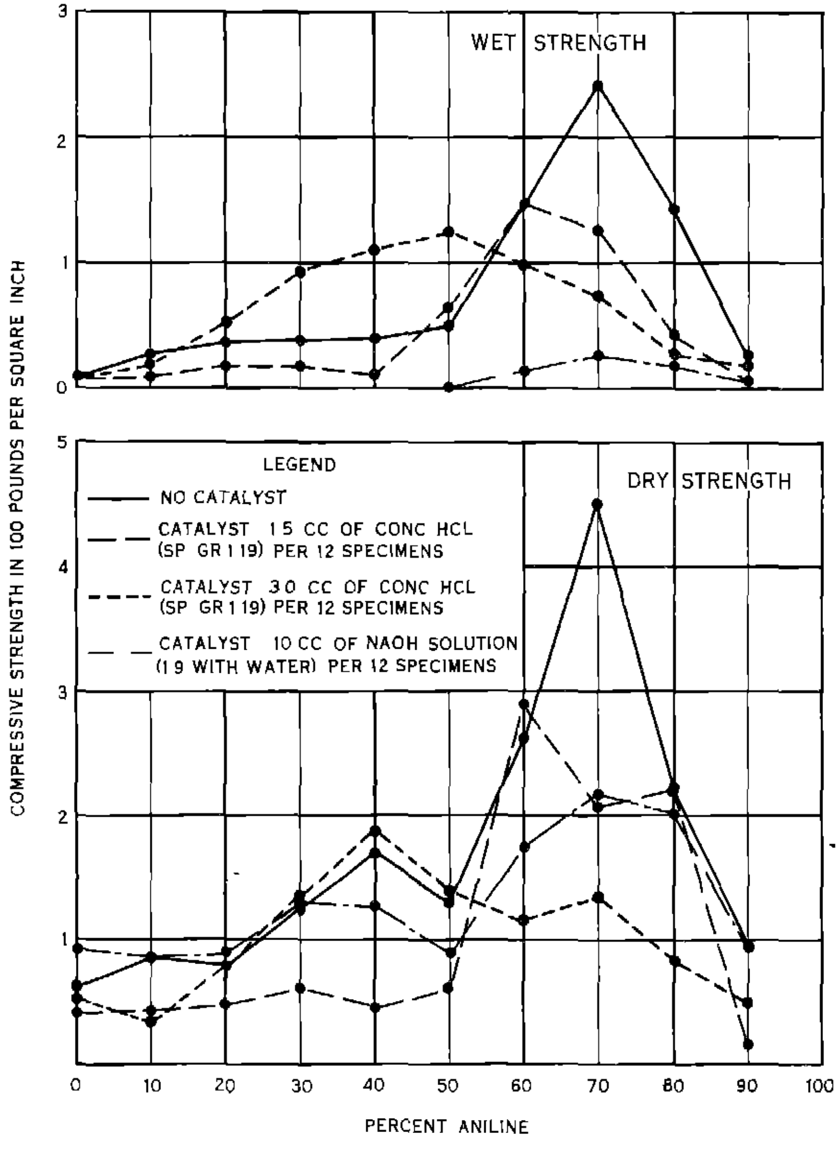


Figure 2 The Effect of the Aniline Furfural Ratio on the Quality of the Resinous Cement in Acid, Basic and Neutral Media

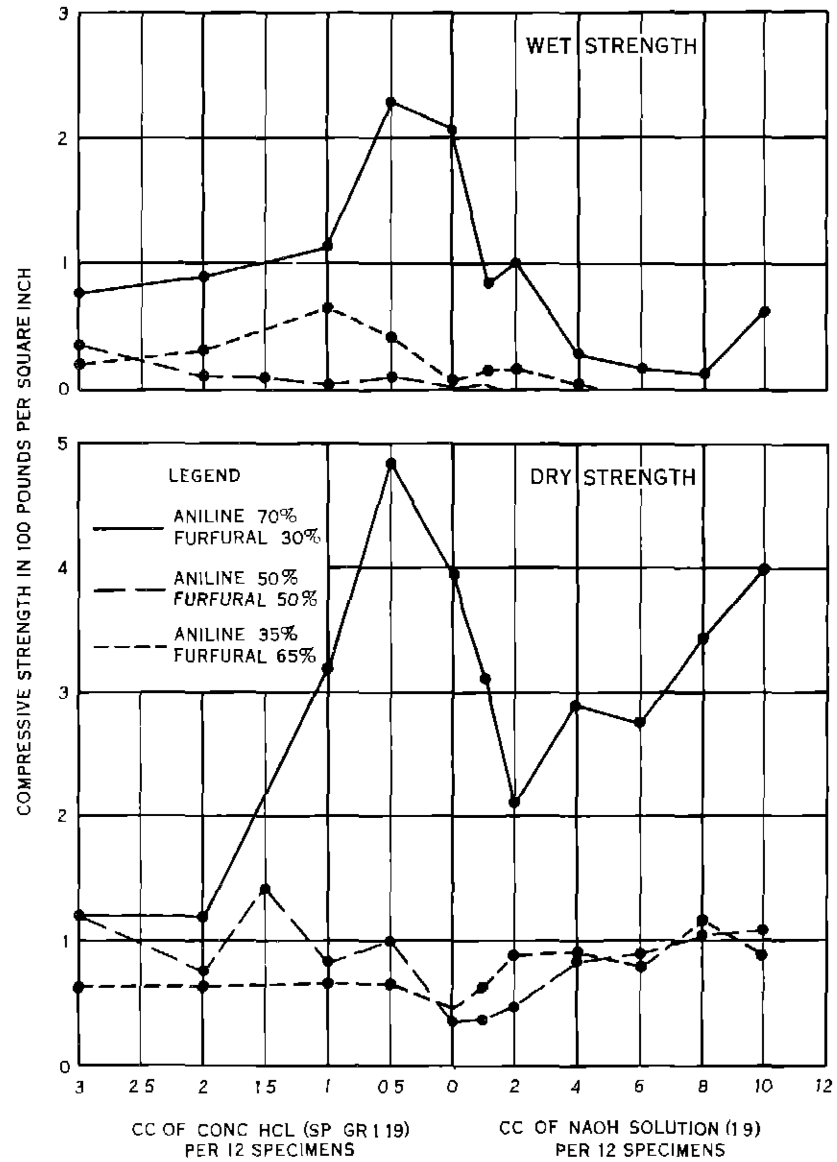


Figure 3 The Effect of Hydrogen and Hydroxyl Ions (from HCl and NaOH) on Three Aniline Furfural Resins

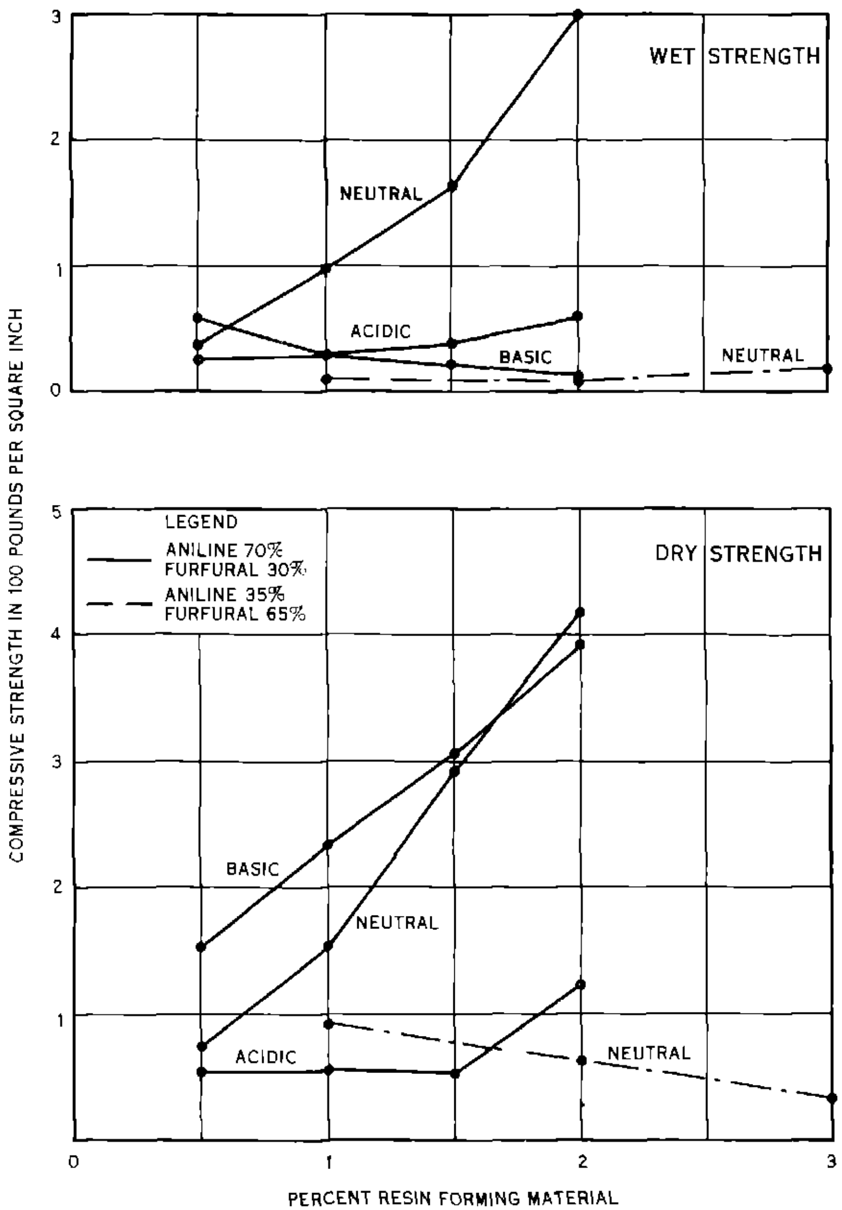


Figure 4 The Effectiveness of Low Percentages of Aniline Furfural Resins

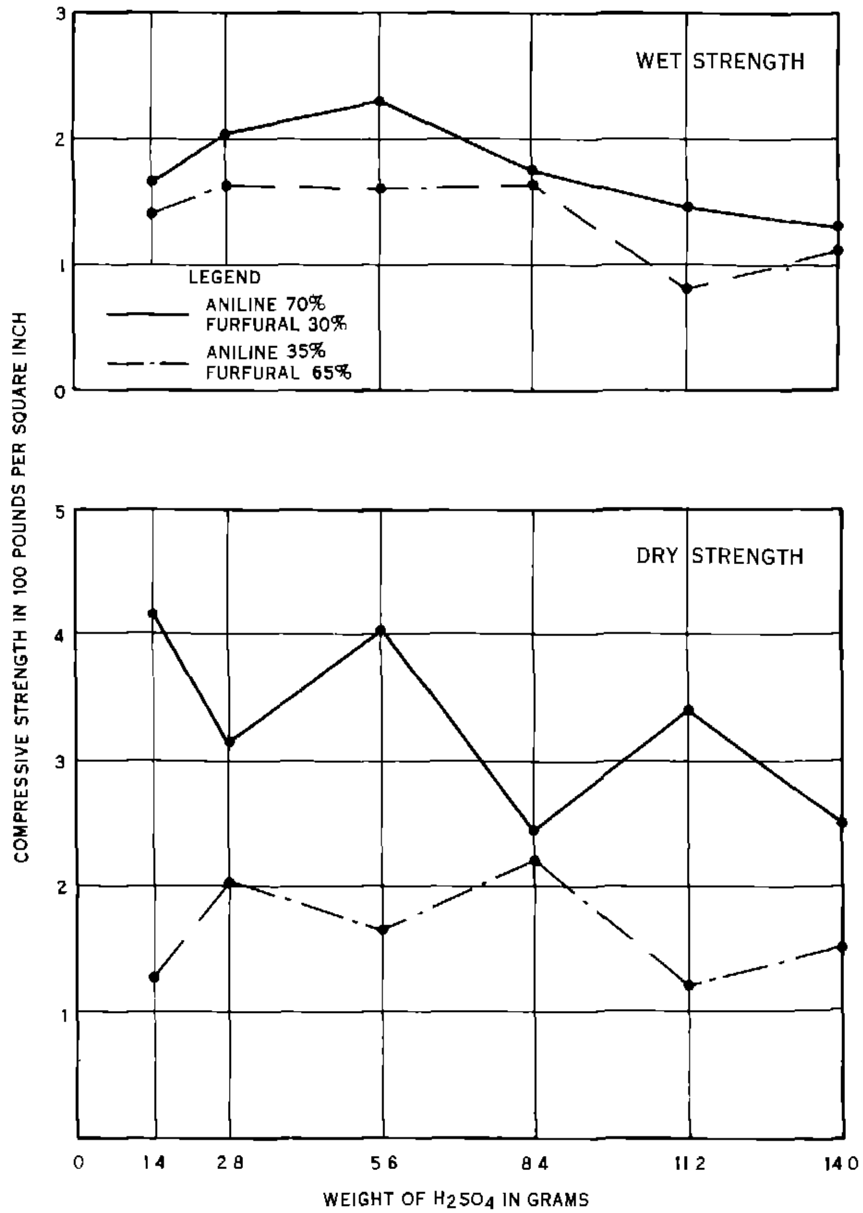


Figure 5 The Effect of Different Amounts of Sulfuric Acid on Two Aniline Furfural Resins

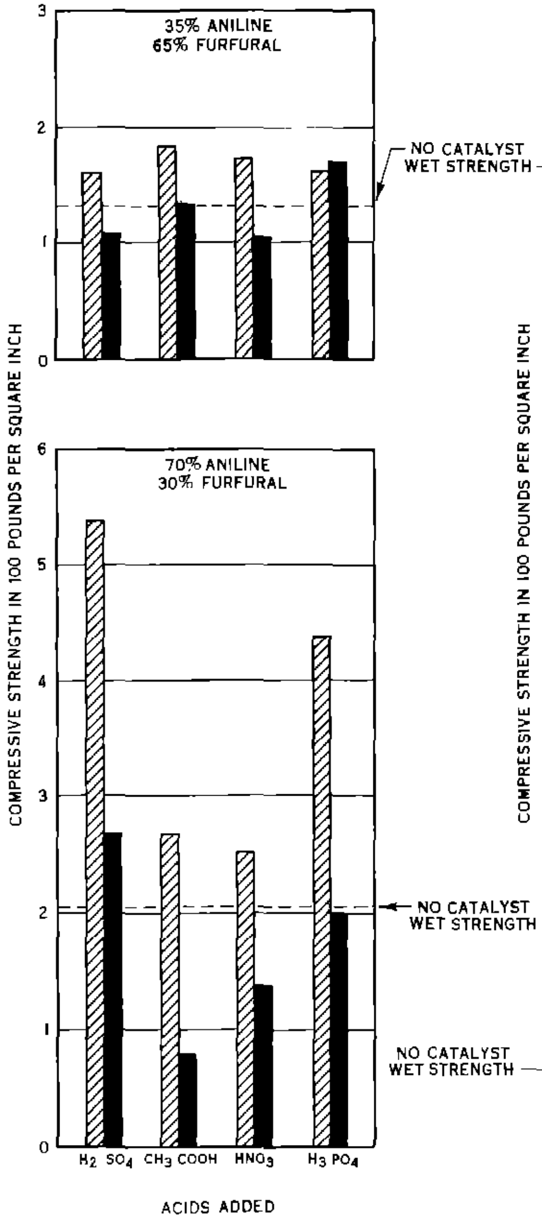


Figure 6 The Effect of Different Anions on the Quality of Two Aniline Furfural Resins

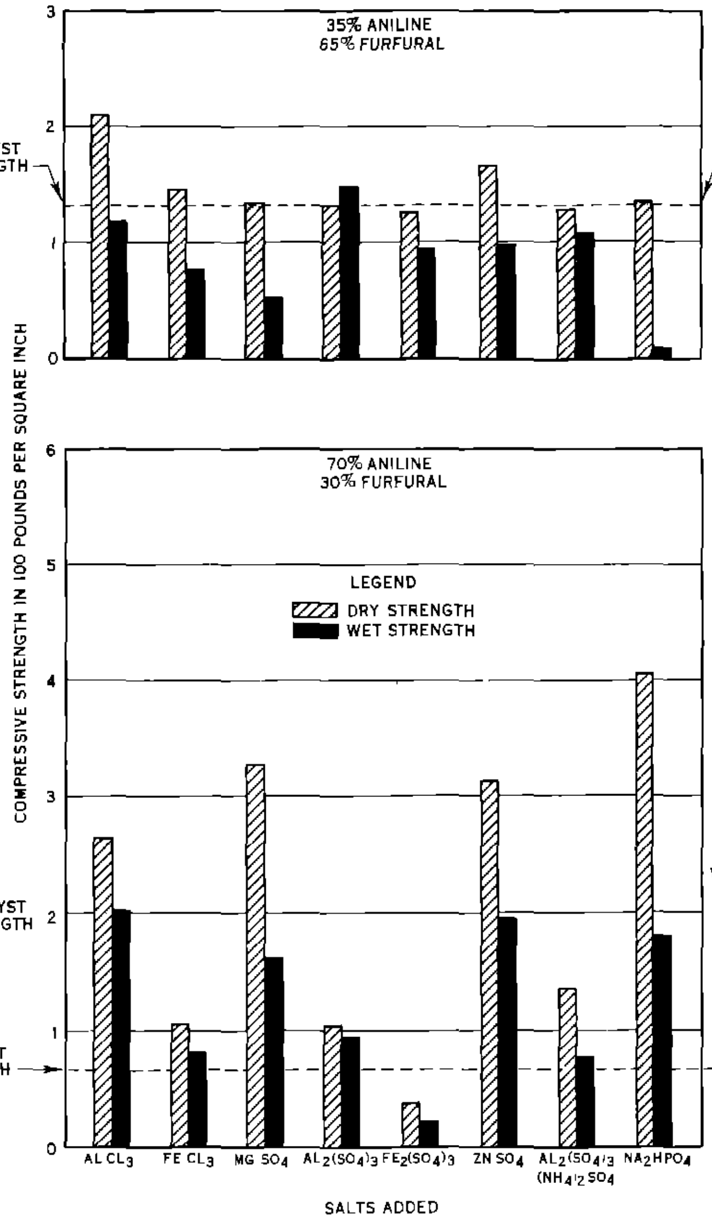


Figure 7 The Effect of Different Salts on the Quality of Two Aniline Furfural Resins

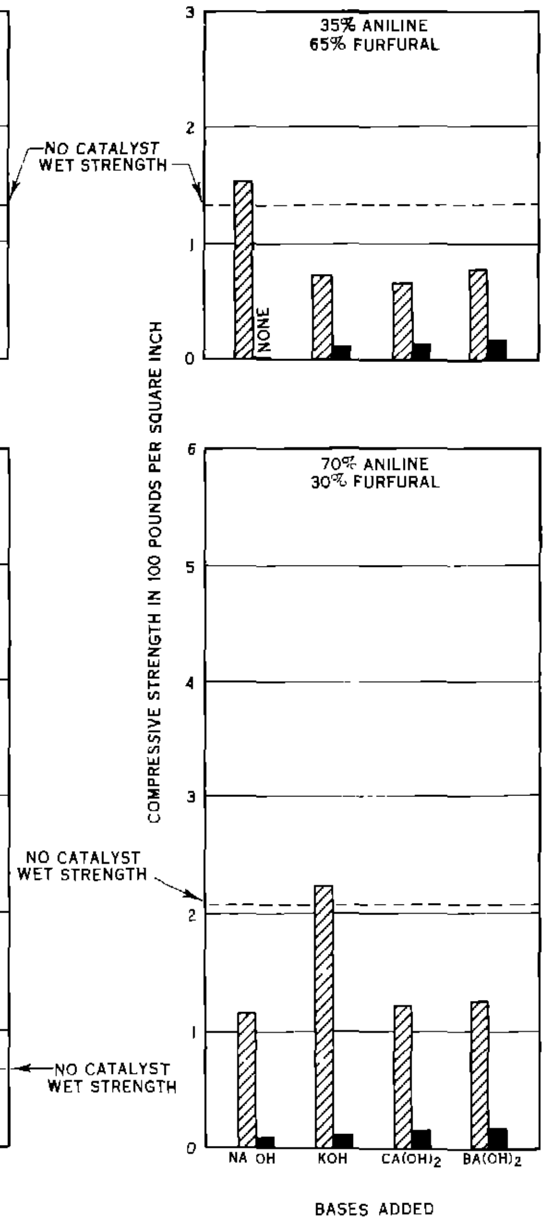


Figure 8 The Effect of Different Cations on the Quality of Two Aniline Furfural Resins

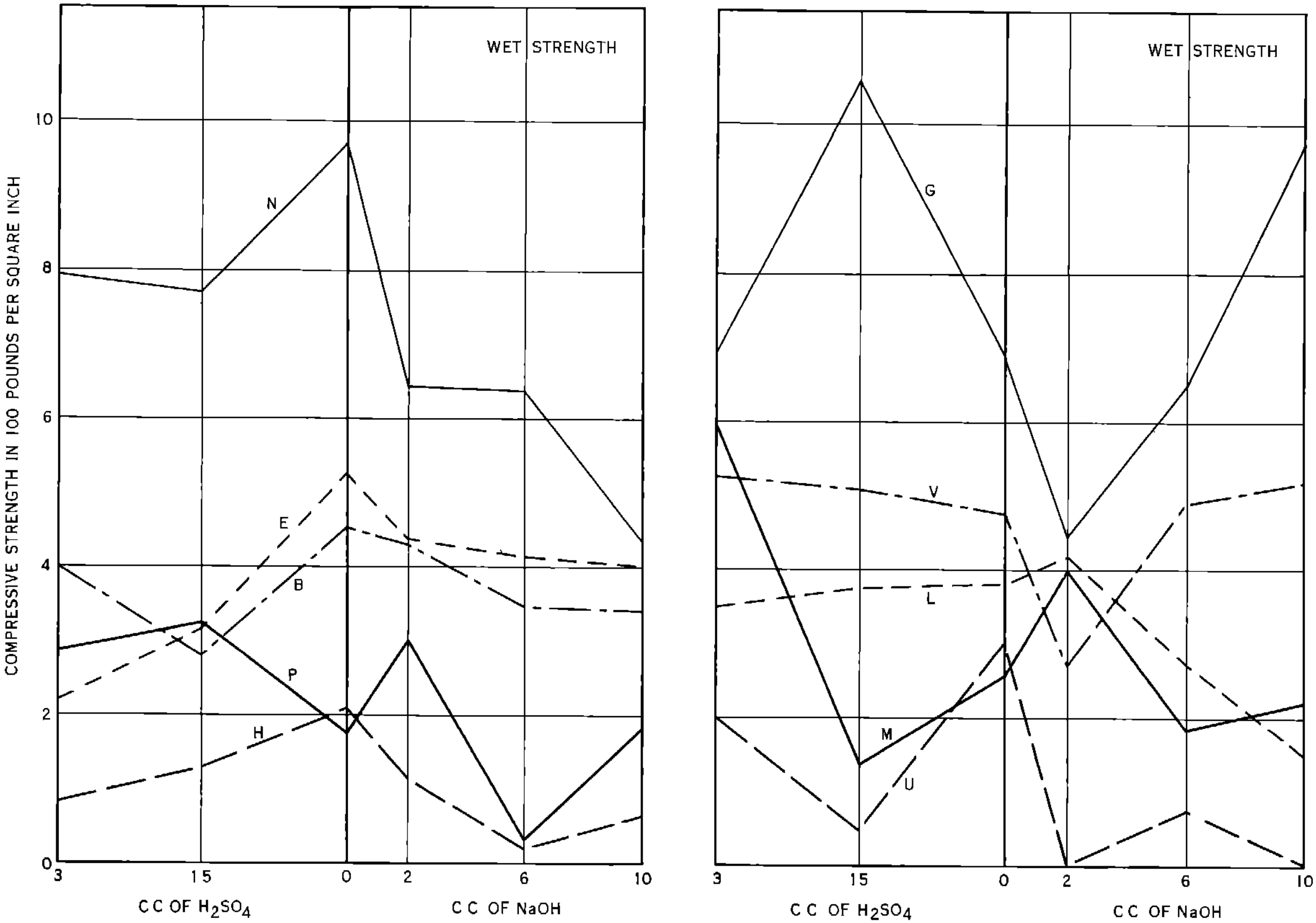


Figure 9 The Effectiveness of Two Percent Aniline Furfural Resin (70 30) in the Stabilization of Ten Soils as a Function of the Acidity or Alkalinity of the Media 2″ x 2″ Specimens

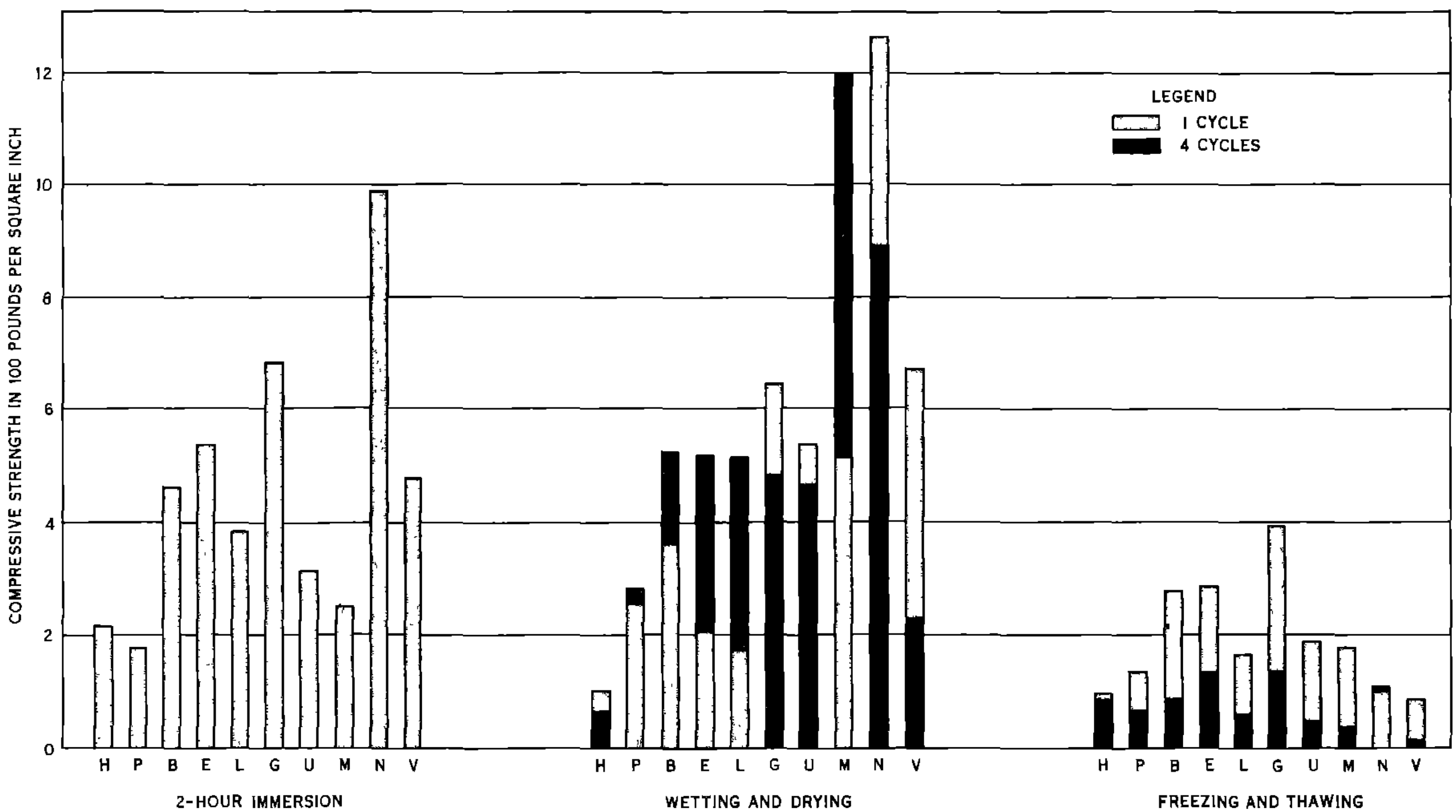


Figure 10 The Effectiveness of Two Percent Aniline Furfural Resin (2 1) in the Stabilization of Ten Soils (No Catalyst) 2″ x 2″ Specimens

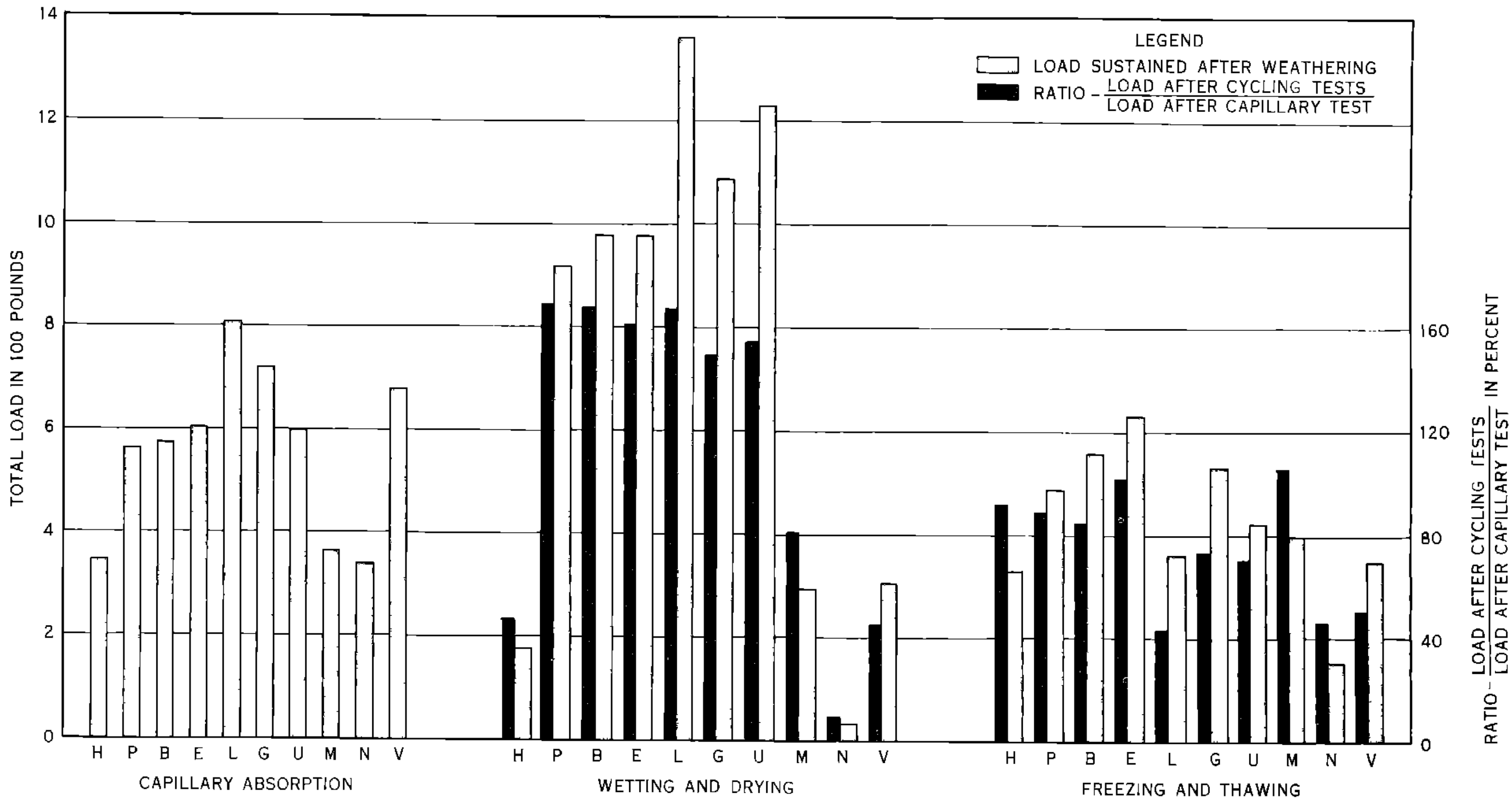


Figure 11 The Effectiveness of Two Percent Aniline Furfural Resin (2 1) in the Stabilization of Ten Soils (No Catalyst) 4" x 6" Specimens