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EFFECT OF CERTAIN LARGE ORGANIC CATIONS ON PHYSICO-COLLOIDAL PROPERTIES RELATED TO SOIL STABILITY

by

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The Requirements for the Degree of
DOCTOR OF PHILOSOPHY

Major Subject: Highway Engineering

Approved:

In Charge of Major Work

Head of Major Department

Dean of Graduate College

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I. INTRODUCTION

Ever since soil has been used as a construction material, men have searched for methods or materials to make it stable in all kinds of weather. Myers (1) has well expressed the fondest desire of most highway engineers,

> The alchemists of ancient times sought the philosopher's stone, which was believed to have the power to transmute the baser metals into gold. The philosopher's stone that intrigues the imagination of the highway engineer is the thing or method that will have the power to transmute cheaply any kind of soil into a material that will resist abrasion and displacement under traffic in all kinds of weather, and that will retain these properties indefinitely.

Researches during the past decade have shown that the physico-colloidal reactions of soils are controlled for the most part by the clay fraction, and, in particular, by the colloid portion of the clay. It was logical then that the ceramist and soil scientist, and much more recently the engineer, should concentrate their attention on the clay minerals, since it appears that they are the key to the rational control of soil properties by man. Grim (2) has reviewed the work of the last 10 or 15 years and presented modern concepts concerning the composition, structure, and certain properties of the individual clay minerals. The structural relationships of the clay mineral particle and water are also explained. Winterkorn and Moorman (3), working with homoionic Putnam soil, found that its engineering properties could be radically altered through change of the adsorbed inorganic cations. More recently, Johnson and Davidson (4) have presented results which indicate that a range of engineering properties is possible in synthetic graded soil mixtures when any of the following factors are varied: (1) clay mineral;

(2) particle size of clay mineral; or (3) counterion associated with the colloidal properties of the clay mineral.

While the ionic-exchange method of altering the properties of clay has been the subject of much research, most investigators have been principally concerned with the inorganic cations. Very little work has been done using organic cations, and this is especially true in the engineering field.

The purpose of the investigation reported herein was to study the effect of some large organic cations on physico-colloidal properties related to soil stability.

II. REVIEW OF LITERATURE

During an investigation of various cations in base exchange reactions with Putnam clay, Gieseking and Jenny (5) found methylene blue to be very effective in replacing adsorbed inorganic cations.

In working with minerals from soil clays, Van Baren (6) found that immersion liquids containing organic amino compounds gave high indexes of refraction.

Gieseking (7) found that minerals of the montmorillonite-beidellite-nontronite type adsorb large substituted ammonium ions of the NH_3R^+, $NH_2R_2^+$, NHR_3^+, and NR_4^+ types, giving rise to (001) interplanar spacings greater than those of the same minerals saturated with smaller cations such as calcium or hydrogen. The diffracted radiation from the (001) planes of these minerals, treated with the complex organic cations, was much more intense than the same diffraction from the calcium or hydrogen systems. The gradual increase in the amount of complex cation added to montmorillonite systems resulted in increases in (001) spacings and intensity of diffraction from these planes until a maximum was reached. No correlation was found between the (001) interplanar spacing and molecular dimensions of the organic cation. These results were interpreted as showing that a portion of the complex cations were adsorbed within the variable (001) interplanar spacings of the minerals.

The large complex cations used by Gieseking were very strongly adsorbed by montmorillonite. They were found to be exchanged by other cations of approximately the same size, but they were not exchanged by hydrogen, which is very effective in replacing small cations. The substituted ammonium cations were found to be very effective in flocculating the dispersed clays. Montmorillonite saturated with the large cations did not show the water adsorption, swelling, and dispersion characteristic of Ca-, Na-, and H- montmorillonite.

Hauser and Leggett (8) have observed that characteristic colors are produced when reactive types of clay are treated with certain aromatic amines. Bentonite and kaolin clays were reactive; illites reacted only slightly. The benzidenes gave blue, anilines green, and toluidines, pink or yellow colors. The intensity of the color was found to vary with the type of clay, bentonite giving a brighter color than kaolin.

Hendricks (9) investigated a number of organic salts of the clay mineral montmorillonite and found that the organic cation was held to the surface of the silicate layers of the mineral not only by the Coulomb forces between the ions, but also by van der Waals' attraction of the molecules to the surface. It was also demonstrated that the amine salts of montmorillonite adsorb less water than sodium and calcium salts of the same clay. Hendricks offered two reasons for the lower water adsorption by the organic salts of montmorillonite: (1) the large volumes of the cations employed exclude water from large areas of the surfaces concerned, and (2) the structures of the hexagonal network of water molecules on the remainder of the clay surface are destroyed because of the shape of the organic cations adsorbed.

Bradley (10) studied the associations between montmorillonite and organic liquids of two related types: (1) the aliphatic di- and polyamines and (2) the glycols, polyglycols, and polyglycol ethers. Members of the two groups tended to differentiate themselves both in the nature of the clay complexes which they formed and in the fact that the amines were active in base exchange, but the glycols were not. Evidence was found that the amines were held to the montmorillonite by forces in addition to the ionic-exchange forces. Bradley indicated that the nature of the additional attraction was a hydrogen bonding between the aliphatic carbon atoms and the oxygen ions of the silicate sheets.

Grim, Allaway, and Cuthbert (11) found additions of amines or other organic cations to samples of kaolinite, illite, and montmorillonite in amounts less than equivalent to the base exchange capacity of the clay are rather completely adsorbed in base exchange reactions. Amounts of large organic cations added in excess of the base exchange capacity of the clay tended to be adsorbed by a different reaction, thought to be dependent on the action of van der Waals' forces. The ability of clays to absorb water was observed to be greatly reduced by treating the clays with certain compounds that furnish a large organic cation. The decrease in water content as compared with that of untreated clay was relatively greater for montmorillonite than for kaolinite. This was thought to indicate that the adsorbed ions on montmorillonite occupy a greater proportion of the surface of the clay than do the adsorbed cations on kaolinite. No great change in water content was obtained by increasing the dosage of organic electrolyte treatment from one to two times the equivalent of the base exchange capacity.

Recently Grim, Allaway, and Cuthbert (12) have reported on the preparation of porous clay bodies, capable of being fired without losing their porous nature or shape, by mixing air into fluid clay slips that contain compounds which furnish a large organic cation. The compounds effective in producing porous clay bodies by this process were amines, or other organic cations, in which one or more large hydrocarbon groups are attached to the basic nitrogen atom. Dodecylamine acetate was used in most of the development work. An explanation is given for the decreased water adsorption by clays treated with organic cations, namely, the organic cations are taken up by the clay in a base exchange reaction, with the basic nitrogen atom of molecule closely held to the mineral surface, and with the hydrocarbon part of the molecule arrayed on the surface or directed outward from the surface, leading to the formation of considerable areas on the mineral that are not wetted by water. It was noted that increasing the dosage of dodecylamine acetate above one percent by weight of the clay brought about a decrease in air dry strength and at the higher percentages the clay was very weak. This loss of strength was explained on the basis of the work of Grim and Cuthbert (13) who found that the development of bonding strength in clay bodies is contingent upon the formation of films of water on the surfaces of the individual particles. Such films could not be continuous upon clays containing adsorbed dodecylamine.

Clark (14) investigated the water absorption and swelling of a clay loam soil from Harmondsworth treated with a water soluble commercial form of cetyl pyridinium bromide in amounts ranging from 0 to 1.0 percent by dry soil weight. Both absorption and swelling were materially reduced by addition of the chemical. Minimum absorption occurred with 0.5 percent chemical and minimum swelling with 0.6 percent. The absorption studies resulted in the conclusion that addition of chemical to the clay soil did not prevent movement of water through the pore spaces, but did inhibit the adsorption of water to the clay particles. It was concluded from the swelling studies that reduction in swelling was due to adsorption of cetyl pyridinium ions on the surfaces of the clay fraction, which is the component responsible for the swelling properties of a soil, thereby reducing their tendency to hydrate.

As one phase of the investigation reported herein, Whitesell (15) studied the effect of different percentages of two water soluble organic compounds containing large organic cations, on the water-density relationships of Edina subsoil, a plastic silty clay soil from Wayne County, Iowa. The chemicals used were fatty acid amine acetates known commercially as Armac T and Armac 18D. Optimum moisture and maximum dry density were determined for each chemical admixture by means of the Standard Proctor and modified A.A.S.H.O. density tests. Whitesell's results are summarized in Tables 1 and 2 and plotted in Figs. 1 and 2.

Table 1

Effect of Armac T admixtures to Edina subsoil on optimum moisture and maximum dry density*

Armac T admixture		Std. Proctor density		Mod. A.A.S.H.O. density	
% saturation B.E.C.	% dry wt. soil	Opt. moist., %	Max. dry density, p.c.f.	Opt. moist., %	Max. dry density, p.c.f.
0	0.00	29.9	88.2	18.6	104.4
10	1.29	31.2	86.7	18.9	103.2
25	3.22	30.0	84.8	17.5	101.5
50	6.44	28.8	85.6	18.5	99.4
75	9.66	28.6	85.1	18.4	97.5

*After Whitesell (15, p. 19)

Table 2

Effect of Armac 18D admixtures to Edina subsoil on optimum moisture and maximum dry density*

Armac 18D admixture		Std. Proctor density		Mod. A.A.S.H.O. density	
% saturation B.E.C.	% dry wt. soil	Opt. moist., %	Max. dry density, p.c.f.	Opt. moist., %	Max. dry density, p.c.f.
0	0.00	29.9	88.2	18.6	104.4
10	1.50	29.8	89.2	20.5	102.0
25	3.26	27.3	88.7	17.8	101.6
50	6.52	28.2	85.2	20.2	95.8
75	9.78	26.2	85.8	19.9	95.7

*After Whitesell (15, p. 21)

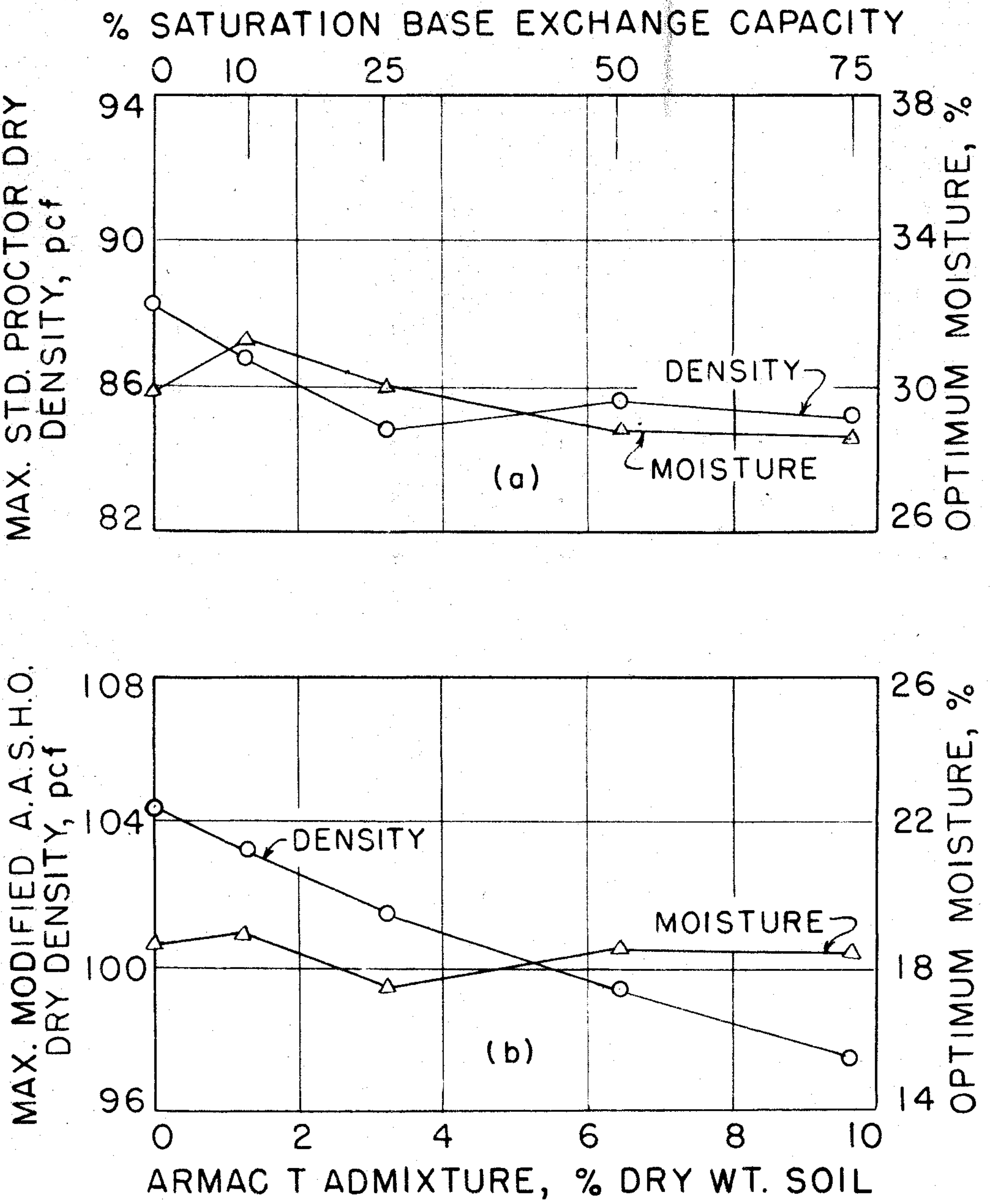

Fig. 1. Effect of Armac T admixtures to Edina subsoil on optimum moisture and maximum dry density, after Whitesell (15, p. 19).

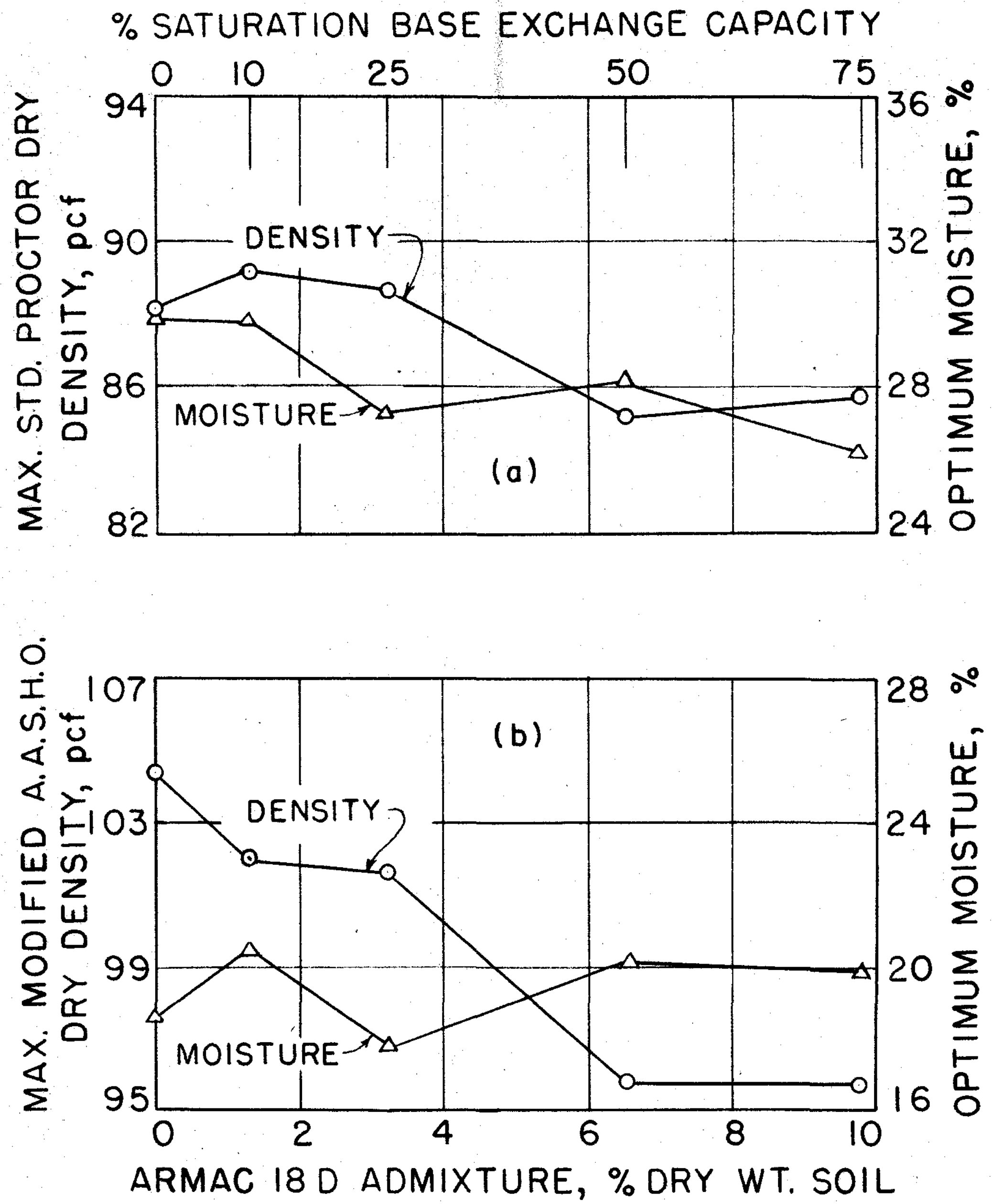

Fig. 2. Effect of Armac 18D admixtures to Edina subsoil on optimum moisture and maximum dry density, after Whitesell (15, p. 21).

III. INVESTIGATION

A. Evaluation of Cationic Chemicals

The main objective in this part of the investigation was to evaluate 6 water soluble cationic chemicals as soil stabilizing agents and to select one of them for further study. A plastic fine grained soil was used with these chemicals because it is the type of soil whose properties are most in need of modification, and it was felt that such a material would best measure the effectiveness of large organic cations as soil stabilizing agents.

1. Materials

a. Soil. The soil used was Edina silt loam, B horizon clay from Wayne County, Iowa. It will be referred to hereafter as Edina subsoil. Approximately 400 pounds of this material were obtained from a test hole located 50 feet west of the southwest quarter of Section 7, T 68 N, R 21 W. The sampling depth was 26 to 34 inches.

Edina silt loam occurs in the Shelby-Seymour-Edina soil association area of southern Iowa. It is a member of a group of soils technically known as Planosols, characterized by compact and heavy-textured claypans and generally occurring on flat positions. The parent material of Edina silt loam is moderately deep to shallow fine loess. The surface soil of the type is very dark grayish-brown in color with a lower surface of white, fine floury rather compact silt loam. The subsoil is dull gray, highly mottled clay that is extremely intractable and hard when dry but sticky and plastic when wet.

Pedologic and classification data for the Edina subsoil sample used in this investigation are summarized in Table 3. The base exchange capacity of this material was 40 milliequivalents per 100 grams of soil[a].

Table 3

Pedologic and classification data for the Edina subsoil sample

Great soil group	Planosol
Series	Edina
Type	Edina silt loam
Horizon	B
Parent material	Moderately deep to shallow fine loess
Natural vegetation	Grass
Slope range, percent	0-2
Textural classification (5 micron clay)	Silty clay
Revised Public Roads Administration classification	A-7-6(20)

b. <u>Cationic chemicals</u>. Six organic compounds containing large organic cations were used, namely: (1) Armac T, (2) Armac 18D, (3) Armac 12D, (4) Rosin Amine-D Acetate, (5) Amine 220, and (6) Ammonyx T. To the writer's knowledge, none of these compounds had been reported on as soil stabilizing agents. Grim, Allaway, and Cuthbert (11, 12), however, had previously used Armac 12D (dodecylamine acetate) in their investigations.

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[a] Determined by the Soils Subsection, Iowa Agricultural Experiment Station, Iowa State College, Ames, Iowa.

(1) Armacs. "Armac" is the Armour[a] trade name for the water soluble amine acetates made from the Armeens by treating them with glacial acetic acid. "Armeen" is the trade name for a series of long chain amines which are obtained from fatty acids. The Armeens are soluble in oils and oil-like materials but are insoluble in water. There is a corresponding Armac for every Armeen. For example, Armeen T becomes Armac T when neutralized with glacial acetic acid. The composition of the Armacs used in this study may be judged from Table 4, which presents the composition of the corresponding Armeens. The Armacs used were light yellowish-brown in color and were solids at room temperature.

Table 4

Composition and constants of Armeen T, Armeen 18D, and Armeen 12D (16)

n-Primary Amine	Carbon chain length	Armeen T	Armeen 18D	Armeen 12D
Dodecyl	12	-	-	90%
Tetradecyl	14	-	-	9%
Hexadecyl	16	30%	6%	-
Octadecyl	18	25%	93%	-
Octadecenyl	18	45%	1%	1%
Mean molecular wt. of primary amine content		263	267	185
Molecular combining weight		310	276	191
% Primary Amine by titration		85	97	97
Approximate melting point, ° C.		46	55	24

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[a] Armour Chemical Division, Armour and Company, 1355 W. 31st St., Chicago 9, Illinois.

somewhat resembling tallow.

The Armacs are cationic in character, as were all the chemicals used in this investigation. Armour and Company (17) describe the cationic nature of the Armacs as follows:

> The chemical structure of an Armeen may be written as RNH_2, wherein the R grouping may be considered as representing the long carbon chain grouping found in the original fatty acids. Upon inspection it becomes apparent that this is an ammonia molecule with a fatty group replacing one of the hydrocarbons. Thus the fatty amine radical in the acetate salt may be expected to be cationic in character, just as is the ammonium radical in ammonium acetate
>
> $$\left[NH_4\right]^+ \left[Ac\right]^- .$$
>
> Similarly, we may write
>
> $$\left[RNH_3\right]^+ \left[Ac\right]^- .$$
>
> The name "cationic", when used in connection with a chemical radical, means that the radical is positively charged and travels to the cathode if electricity is passed through its solution.

The Armacs are used in industry to cause surface change phenomena. Small quantities of these chemicals are sufficient to cause certain types of water-loving surfaces to become water-repelling and oil-loving.

Investigations by Armour and Company have shown the Armacs to be very effective as germicides, fungicides, and algacides. To quote from personal correspondence with Mr. E. W. Segebrecht (18) of the Armour Chemical Division:

> We have carried on considerable investigations on the Armacs as germicides, fungicides and algacides. Results have shown these aliphatic amine acetates to be very effective in this capacity and we have found no organism that would survive treatment with one of these products. It is true, however, that presence of large amounts of organic matter will effect materially the germicidal characteristics of these chemicals, rendering them almost impotent.

(2) Rosin Amine-D Acetate. Rosin Amine-D Acetate is the acetic acid salt of Rosin Amine-D, both being products of the Hercules Powder Company[a]. Rosin Amine-D is a primary amine obtained from a special grade of modified rosin. It is a pale colored, viscous liquid, insoluble in water but soluble in many organic solvents. Rosin Amine-D Acetate is water soluble and is prepared as a pale yellow 70 percent paste in water. A typical analysis and characteristic physical properties of Rosin Amine-D (19) are as follows:

Physical State	Viscous yellow liquid
Color	Pale yellow
Density @ 25° C.	0.997
Refractive Index @ 20° C.	1.5410
Nitrogen Content	4.2 - 4.5%
Bromine number ($KBr-KBrO_3$)	49
Viscosity @ 25° C.	4670 Centistrokes
Boiling Range (5 mm.)	187 - 211° C.
Boiling Range (10 mm.)	270 - 291° C.
Boiling Range (760 mm.)	344° C. (Partial Decomposition)
Flash Point (Cleveland Open Cup)	192° C.
Heat of Vaporization	20,100 calories per mole
Neutralization Equivalent	317

Rosin Amine-D Acetate was not in commercial production at the time of this study but was available in limited quantities for testing purposes. Correspondence with Mr. J. M. Schantz (20), manager of the Technical Service, indicated that Rosin Amine-D and its acetate had been found to possess bactericidal and fungicidal properties which would

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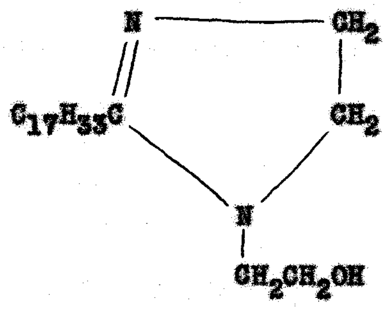
[a] Hercules Powder Company, Naval Stores Dept., Wilmington 99, Delaware.

probably protect it from attack by micro-organisms in soil.

(3) Amine 220. Amine 220 is a product of Carbide and Carbon Chemicals Corporation[a]. It is a deep brown, high-boiling, oil-soluble liquid with an ammoniacal odor. It is soluble in water and has cationic surface-active properties. The chemical structure of Amine 220 may be written (21) as,



Additional physical properties of Amine 220 are;

Molecular Weight	350
Equivalent Weight	175
Boiling Pt. at 1 mm. Hg.	235.0° C.
Flash Point (Open Cup)	465° F.
Solubility in mineral oil, %	10
Specific Gravity at 20/20° C.	0.9300-0.9360
Viscosity at 100° F., centipoises	120-150

(4) Ammonyx T. Ammonyx T is the trade name of a high molecular weight cationic wetting agent produced by the Onyx Oil and Chemical Company[b]. It is a higher molecular aliphatic quarternary ammonium halide and is a slightly greenish-yellow, clear, viscous liquid which is

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[a] Carbide and Carbon Chemicals Corporation, 30 East 42nd Street, New York 17, N. Y.

[b] Onyx Oil and Chemical Co., 15 Exchange Place, Jersey City 2, N. J.

completely soluble in cold or hot water. The molecular weight of Ammonyx T is 436 10. It is a powerful germicide and fungicide.

2. *Method of procedure*

a. *Cationic treatment of soil.* Before chemical treatment, the Edina subsoil was ground with mortar and pestle to pass through the No. 40 sieve (100 percent passed). The finely ground material was then stored in large pans for several days to enable it to reach uniform hygroscopic moisture content.

Initially each chemical was added to three, 1000 gram (dry weight) samples[a] of Edina subsoil in such quantities that the base exchange capacities of the samples were saturated 1, 10, and 75 percent, respectively. Later the investigation was extended to include samples saturated 25 and 50 percent with Armac T and Armac 18D, and 5 percent with Rosin Amine-D Acetate. Table 5 shows the relationship between percent saturation of base exchange capacity and percent by dry weight of soil for the six cationic chemicals used.

The weights of each chemical needed to saturate the base exchange capacity of the soil to the various percentages were calculated by means of the equivalent weight of the chemical and the base exchange capacity of the soil. This can best be explained by a sample calculation for Armac T.

Example. Calculate the weight of Armac T needed to saturate the base exchange capacity of 1000 grams (dry weight) of Edina subsoil 75 percent.

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[a] The term dry weight is used herein to mean oven dry weight. Air dried weight when used will be designated as such.

Table 5

Relationship between percent saturation of base exchange capacity and percent by dry soil weight for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Chemical admixture, percent dry soil weight					
	Armac T	Armac 18D	Armac 12D	Rosin Acetate Amine D	Amine 220	Ammonyx T
0	0.00	0.00	0.00	0.00	0.00	0.00
1	0.13	0.13	0.10	0.22	0.07	0.17
5	--	--	--	1.07	--	--
10	1.29	1.30	0.98	2.15	0.70	1.74
25	3.22	3.26	--	--	--	--
50	6.44	6.52	--	--	--	--
75	9.66	9.78	7.32	16.11	5.25	13.08

Given: Base exchange capacity of soil = 40 milliequivalents per 100 grams, molecular weight of monovalent Armeen T = 263, and molecular weight of acetate radical = 59.

Solution:

Gram-molecular weight of Armeen T = 263 grams
Gram-molecular weight of acetate radical = 59 grams
Gram-molecular weight of Armac T = 322 grams
Equivalent wt. of Armac T = 322   1 = 322 grams
1 milliequivalent of Armac T = 322 milligrams

Therefore, 75 percent saturation of 1000 grams of soil will require 40 X 10 X 0.75 X 322 = 96600 milligrams = 96.6 grams of Armac T.

Before adding to the soil, the chemicals were dissolved in an amount of water equal in weight to the soil to be treated, which amounted to 1000 c.c. in this study. Heating the solution below 100° C. aided in dissolving the chemicals, especially the larger quantities. Some of the chemicals dissolved more readily than others. Armac T proved to be one of the easier to work with from this standpoint.

After preparation, the solutions were immediately added to the soil samples and the mixtures stirred thoroughly in large, flat pans. Drying was carried out at room temperature. When air dry the mixtures were ground with mortar and pestle to pass through the No. 40 sieve and then stored for testing. A definite decrease in the air dry strength of the treated soil was noticeable at this time, especially when the base exchange capacity of the soil was saturated more than 10 percent.

b. Tests to evaluate untreated Edina subsoil. Routine laboratory tests were conducted on representative samples of Edina subsoil for classification purposes and to determine physical and chemical properties of interest to the engineer. The majority of these tests were performed in accordance with specifications set up by the American Association of State Highway Officials (22). Such tests are not described in detail. Where the standard test procedure is altered or where a non-standard test is used, the method is described and readily available references cited.

(1) Mechanical analysis. This test was performed on two separate samples of soil in accordance with A.A.S.H.O. Designation: T88-42. Dispersion method B was used in preparing soil for the hydrometer test. In general this test procedure is satisfactory when the grain size distribution curve is desired only for sizes greater than 1 or 2 microns.

(2) Hydrometer test under multiple gravity. In fine clays a large percentage by weight may be finer than one micron (0.001 mm.), and it is helpful in characterizing the clay to know the grain size distribution of this finer portion. Norton (23) has developed apparatus and a method for doing this with the long-armed centrifuge and Bouyoucos

hydrometer. In this apparatus the jar is suspended at the end of a rotating arm. The centrifugal force caused by rotation introduces an acceleration many times greater than gravity and causes much faster settlement than occurs under gravity alone. Grain size distribution curves which extend to 0.1 micron may be obtained in a few hours by the use of this apparatus. Using the method of Norton (23) and similar apparatus, the grain size distribution for Edina subsoil was determined down to 0.1 micron. Two samples of soil were tested simultaneously using Daxad - 23[a] as the dispersing agent.

(3) Liquid limit. The liquid limit of a soil is that water content, as determined in accordance with A.A.S.H.O. Designation: T89-42, at which the soil passes from a plastic to a liquid state. The standard mechanical method was used in this study with the exception that the soil was thoroughly mixed with distilled water to above the liquid limit and then put in a humidifier for approximately 24 hours before testing. The test was then performed as the soil dried out, with no further additions of soil or water. This modification gave consistent results and seems justified with heavy clay soils because of the more uniform moisture film distribution obtained.

(4) Plastic limit. The plastic limit is the lowest water content, determined in accordance with A.A.S.H.O. Designation: T90-42, at which the soil becomes plastic. The standard procedure was followed.

(5) Plasticity index. The plasticity index of a soil is the numerical difference between its liquid limit and its plastic limit. A.A.S.H.O. Designation: T91-42 covers certain exceptions.

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[a] A cement deflocculent manufactured by Dewey & Almy Co., Cambridge, Mass.

(6) Shrinkage limit. The shrinkage limit is defined as the maximum calculated water content, at which a reduction in water content will not cause a decrease in the volume of the soil mass. This test was performed in accordance with A.A.S.H.O. Designation: T92-42.

(7) Shrinkage ratio. The shrinkage ratio of a soil is the ratio between a given volume change and the corresponding change in water content above the shrinkage limit. The calculation of this ratio is covered in A.A.S.H.O. Designation: T92-42.

(8) Hygroscopic moisture. This moisture content was determined in accordance with A.A.S.H.O. Designation: T88-42.

(9) Centrifuge moisture equivalent. The centrifuge moisture equivalent is the amount of water retained by a soil which has been first saturated with water and then subjected to a force equal to 1000 times the force of gravity for one hour. It was determined according to A.A.S.H.O. Designation: T99-42.

(10) Specific gravity. The specific gravity of the Edina subsoil was determined by the pycnometer method, A.A.S.H.O. Designation: T100-38. Three determinations were made.

(11) Organic matter content. The procedure used is explained in the Soil Engineering laboratory manual (24) used at Iowa State College. The principle involved in this method of determining the organic content of soil is to oxidize the organic matter in one gram of soil by adding 10 c.c. of potassium dichromate. Then, the amount of ferrous ammonium sulphate required to reduce 10 c.c. of clean potassium dichromate gives an indication of the amount of organic matter in the soil.

(12) pH value. Ten grams of soil which had been ground with mortar and pestle to pass through the No. 40 sieve were added to 100 c.c. of distilled water and the mixture allowed to stand for about 24 hours

with occasional stirring. The pH value was then obtained by use of a Beckman pH meter[a].

(13) Differential thermal analysis. This test (25) affords a comparatively easy method for clay mineral identification. The analysis was made on the fraction finer than one micron or, in other words, on the colloid portion of Edina subsoil. The minus one micron material was obtained by a sedimentation method. One hundred grams of the whole soil were thoroughly dispersed in 4000 c.c. of distilled water using Daxad-23 as the dispersing agent. After 24 hours sedimentation time, the portion finer than one micron was syphoned off using Stokes law to calculate the sampling depth. The dispersed colloidal material thus collected was flocculated with a small dosage of 12 N HCl and settled out by means of the long-armed centrifuge. The soil colloids were then washed 3 times with distilled water. The resultant material was oven dried at 100° C., ground with mortar and pestle to pass the No. 60 sieve, and stored for about one month at room temperature before testing.

The differential thermal analysis consists of measuring the difference in temperature between a soil sample and an inert material as they are heated at a constant rate from room temperature up to 1000° C. Endothermic reactions, as the evaporation of water from the sample takes place, cause the temperature of the sample to fall below that of the inert material. Exothermic reactions cause the temperature of the sample to rise above that of the inert material. By comparing the thermal curve of the sample with similar curves of pure clay minerals, it is possible to identify the types of clay minerals present in the sample.

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[a] Manufactured by Central Scientific Company, 1700 Irving Park Blvd., Chicago, Ill.

The thermal curve presented in this report was obtained with apparatus similar to that described by Norton (25). A 0.5 gram soil sample was used, and the intensity of the endothermic and exothermic effects and the temperatures at which they took place were recorded photographically.

c. Tests to evaluate effect of cationic admixtures. Preliminary work with Edina subsoil revealed that too much time was required to air dry large molded test specimens, if they were air dried at a rate slow enough to avoid shrinkage cracks. Accordingly, tests were selected which would furnish the desired comparative information on the chemicals without use of large specimens. The procedures for some of these tests have already been given and are not repeated. However, the physico-colloidal meaning of all tests used in this part of the study is discussed, since an understanding of it is necessary for correct interpretation of the effect of large organic cations on engineering soil properties.

(1) Liquid limit. The procedure for this test has been covered previously. By definition the liquid limit is that amount of water, expressed in percent per dry weight of soil, which must be added to a soil in order that the water layers most distant from the soil particle surface acquire the properties of free water. It is therefore indicative of both the size and the surface activity of the soil components. Soils at the liquid limit can be considered as of equal, though small, shear resistance. At the liquid limit cohesion is practically equal to zero.

(2) Plastic limit. The method of performing this test has already been given. The plastic limit may be considered as that amount of water, expressed in percent per dry weight of soil, which must be added to the soil in order to provide a film around each particle of sufficient thickness to permit the particles to orient themselves and slide over each other, although still possessing cohesion in appreciable

amount. It is indicative of the internal soil surface in a system and the activity of this surface.

(3) Plasticity index. This term, as previously stated, is defined as the difference between the liquid limit and the plastic limit. At the plastic limit the soil particles have a degree of lubrication sufficiently high to permit them to slide over each other when loaded, although still possessing a considerable amount of cohesion. At the liquid limit the soil particles are separated to such an extent that practically no cohesion exists between them. It follows, therefore, that the difference between the 2 values indicates the increase in moisture content required to increase the thickness of the water films separating the soil particles to a degree such that the cohesion existing between them is reduced practically to zero. Thus, the plasticity index may be considered as a measure of the cohesion possessed by soil.

(4) Shrinkage limit. The definition and method of performing this test have already been covered. During the process of drying a cohesive soil, the material will decrease in volume. This phenomenon is a result of capillary forces acting on the soil. The shrinkage will progress to some point after which continued decrease in moisture content will cause no further shrinkage. The moisture content, expressed in percent of the dry soil weight, at which the soil ceases to shrink is called the shrinkage limit. Detrimental shrinkage cannot occur when the shrinkage limit is equal to or greater than the moisture content of a soil mixture.

(5) Shrinkage ratio. The definition and method of calculating this ratio have been previously given. The shrinkage ratio is also the apparent specific gravity of soil shrinkage pats in the oven dried state.

(6) Ratio of shrinkage limit to liquid limit. The ratio of shrinkage limit to liquid limit indicates the shrinkage properties of a soil (26). The smaller the shrinkage limit as compared with the liquid limit, the greater will be the tendency for the soil to shrink.

(7) Ratio of liquid limit to clay content. The ratio of liquid limit to clay content discloses the relative activity of the clay fraction (26). Liquid limits approximately equal to the clay content indicate the presence of inactive fine particles capable of forming pastes with additions of relatively small amounts of water. The more the liquid limit exceeds the clay content, the more the presence of undesirable gluey colloids is indicated. The term clay is herein used to describe the soil fraction having an equivalent spherical diameter smaller than 5 microns.

(8) Relative air dry strength. Air dry compressive strength is a qualitative measure of air dry shearing strength, the latter being a function of the soil's internal friction angle and cohesion. In clay type soils cohesion plays the most important role.

As previously stated, preliminary work with the highly plastic Edina subsoil indicated that too much time would be required to air dry standard type compression test specimens at a rate slow enough to avoid shrinkage cracking. This was especially true for untreated soil samples and for those containing the smaller amounts of cationic chemicals. A test procedure was developed, therefore, to furnish data on the relative air dry strength of untreated and treated soil, utilizing small specimens. These specimens were air dried shrinkage pats prepared in 1 3/4 inch diameter by about 1/2 inch high porcelain milk dishes of the type used in the standard volumetric shrinkage test, A.A.S.H.O. Designation: T92-42. Porter (27) had previously used pats of this type to measure the relative strength of clay soil. The method of preparing the pats was the same as that used in preparing shrinkage pats in the standard test, with the exception that the pats used in the present study were not oven dried. After molding, the pats were allowed to air dry in the porcelain milk dishes until firm enough to be removed, and then were stored in a closed cabinet at room temperature until they reached constant weight. Seven days proved to be an adequate drying period for specimens of this size, but all pats used in this investigation were dried for one month before testing.

The relative strengths of the air dry pats were evaluated by rupturing them with a soil penetrometer of the type used in conjunction with the standard Proctor density test for determining the penetration resistance of compacted soil. The needle tip having an area of 1/20 square inches proved to be best adapted for the soil used in this study. The pat was placed on a machined steel block and the load applied manually at a slow, steady rate until the specimen failed. A sliding ring on the calibrated portion of the penetrometer gave the failure load directly for the size needle used. This reading divided by the area of the needle tip gave the failure load in pounds per square inch. The impact of the needle on the steel block after the pat ruptured did not disturb the sliding ring reading. The maximum load that could be applied with the penetrometer, using the 1/20 square inch needle tip, was 2200 pounds per square inch. Pats that withstood this load without breaking had their air dry strengths recorded as 2200+. Figure 3 shows the penetrometer being used.

Usually the first break of a full size specimen divided it into 2 or more pieces as shown in Figure 4, each of which was large enough to be tested. The relative air dry strength was recorded as the average of several tests on 2 pats.

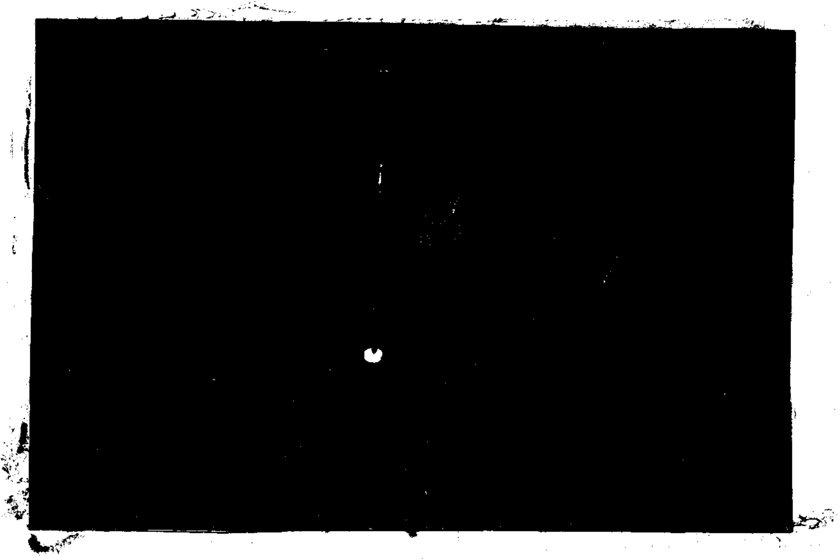

Fig. 3. Soil penetrometer being used to load and rupture air dried shrinkage pat.

Fig. 4. First break of a full size pat.

(9) Rate of slaking. The slaking test is essentially a determination of the rate at which a soil specimen disintegrates when immersed in water. Hogentogler (28, p. 378) describes the significance of this test as follows:

> The rate of disintegration depends upon such factors as the affinity of the soil for water, the amount of expansion of the soil when wetted, the speed with which the water penetrates the soil, and the character of the cracking produced by unequal expansion of the sample. This test gives an indication of the relative resistance of different soils to erosion and may also be used to determine the effect of different admixtures for water-proofing a given soil. Also, tests performed on undried specimens are a measure of the extent to which the capillarity of the soil is satisfied by the moisture present in the sample. The test is more or less qualitative in character, and neither a standard procedure nor definite limiting values have been established.

The slaking specimens used in the present study were air dried shrinkage pats of the type used in the penetrometer strength tests. The pats were placed on copper wire rings (Fig. 5) which were attached to a ring stand, and then completely immersed in distilled water. Figure 6 shows the pats on the rings ready for immersion. The ring diameters were adjusted so that they were always 1/8 of an inch smaller than the bottom diameters of the soil pats on them. The slaking value was the time in minutes for the pat to disintegrate sufficiently to fall through the ring. Pats which did not fall through the rings were kept immersed for seven days, and then removed for photographing. The water was at room temperature (about 78° F.) throughout the tests, and a head of one inch of water was kept on the pats at all times.

3. Presentation and discussion of results

a. Untreated Edina subsoil. The gradation of the Edina subsoil sample is given in Table 6 and the grain size distribution curve shown by Figure 7. It will be noted that 52.3 percent of this soil is 5 micron

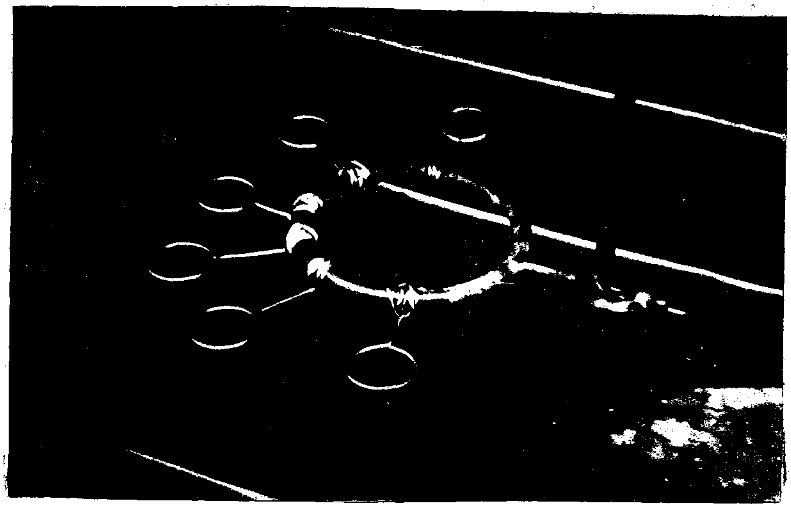

Fig. 5. Copper wire rings used in slaking test.

Fig. 6. Pats on rings ready for immersion.

Table 6

Grain-size distribution* for Edina subsoil sample

Sieve number	Equivalent spherical diameter, mm.	Percent finer, by dry soil wt.
60	0.250	100.0
100	0.147	99.8
150	0.104	99.6
200	0.074	99.3
270	0.050	97.3
	0.005	52.3
	0.002	37.0
	0.001	27.8
	0.0002	10.3
	0.0001	6.5

*Values taken from plotted grain size distribution curve.

clay and that 27.8 percent is in the colloid size range[a]. The fact that 6.5 percent is finer than 0.1 micron probably indicates the presence of montmorillonite type clay minerals.

Some properties of Edina subsoil are shown in Table 7. The high liquid limit is indicative of a large and highly active internal soil surface. The high plasticity index indicates that this soil is extremely cohesive. The very low shrinkage limit and the comparatively high shrinkage ratio are indicative of high shrinkage and swelling characteristics. The high hygroscopic moisture content and centrifuge moisture equivalent furnish further evidence of the great affinity this soil has for water. The organic content is relatively high from an engineering

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[a] The upper limit of the colloid size range in most engineering grain-size classification systems is one micron (0.001 mm.).

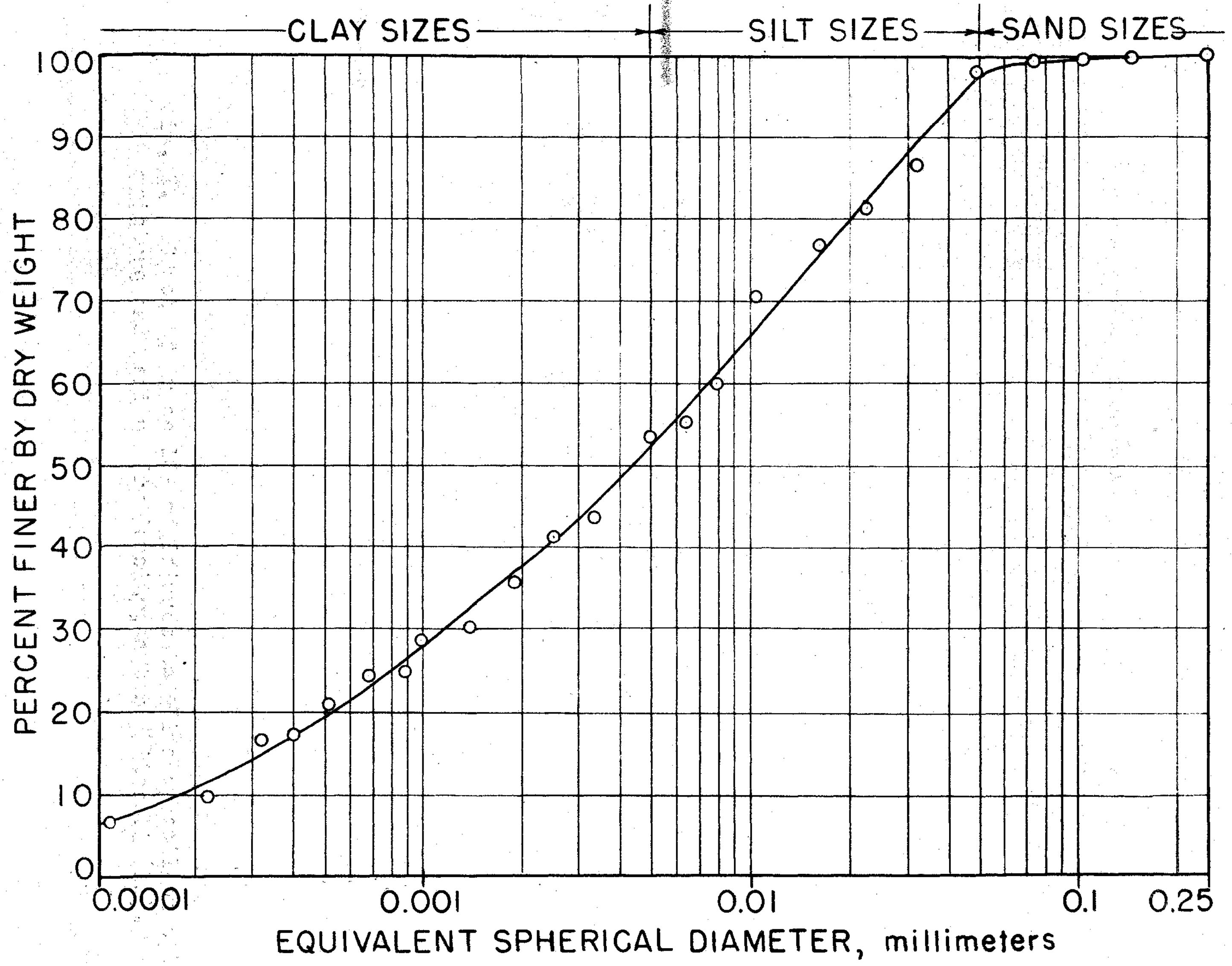

Fig. 7. Grain size distribution curve for Edina subsoil sample.

Table 7

Properties of Edina subsoil

Liquid limit, % dry wt. soil	78.0
Plastic limit, % dry wt. soil	26.3
Plasticity index, % dry wt. soil	51.7
Shrinkage limit, % dry wt. soil	6.0
Shrinkage ratio	2.02
Hygroscopic moisture[a], % dry wt. soil	7.02
Centrifuge moisture equivalent, % dry wt. soil	29.7
Specific gravity	2.74
Organic content, % dry wt. soil	0.72
pH value	4.90
Base exchange capacity[b], m.e./100 g.	40.0
Max. std. Proctor dry density[c], p.c.f.	88.2
Optimum moisture, % dry wt. soil	29.9
Max. mod. A.A.S.H.O. dry density[c], p.c.f.	104.4
Optimum moisture, % dry wt. soil	18.6

[a] After being exposed to air at room temperature (80° F. ± 2°) for 14 days during July, 1948.

[b] Determined by the Soils Subsection, Iowa Agricultural Experiment Station, Iowa State College, Ames, Iowa.

[c] After Whitesell (15).

standpoint. The pH value denotes acidity. The base exchange capacity gives additional verification of the highly active nature of the clay fraction and of the probable presence of montmorillonite type clay minerals. The moisture-density relationships show the advisability of using the modified A.A.S.H.O. test procedure for control purposes with this type of soil.

Edina subsoil was classified texturally[a] as silty clay. According to the revised Public Roads Administration classification system (29), it was an A-7-6(20) soil. Subgroup A-7-6 materials are typically plastic clay soils with high plasticity indexes in relation to liquid limit and which are subject to extremely high volume change. The group index value of (20) is reserved for the most plastic A-7-6 soils.

The thermal curve for the minus one micron fraction of Edina subsoil is shown in Fig. 8. It gives three thermal reactions as follows: (1) endothermic peak at 160° C., (2) endothermic peak at 550° C., and (3) exothermic peak at 900° C. In comparing it with the characteristic curves for the pure clay minerals (30, 31), it is evident that the colloid portion of Edina subsoil is predominantly montmorillonitic. The relatively weak endothermic reaction at 550° C. may indicate the presence of a small percentage of kaolinite.

b. <u>Effect of cationic admixtures</u>

(1) <u>Liquid limit</u>. The relationship between the liquid limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil is shown in Table 8. It will be noted that all of the chemicals were effective in reducing the magnitude of the liquid limit. It is apparent from the curves in Fig. 9 that, with all chemicals, the initial 10 percent saturation of the base exchange capacity was most effective in reducing the liquid limit of the soil. From 10 percent saturation on, the rate of decrease diminished. Armac T and Armac 18D were most effective in lowering the liquid limit up to 10 percent saturation. At 75 percent, however, Rosin Amine-D Acetate was most effective.

The lowering of the liquid limit can probably be explained by the

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[a] Based on 5 micron clay.

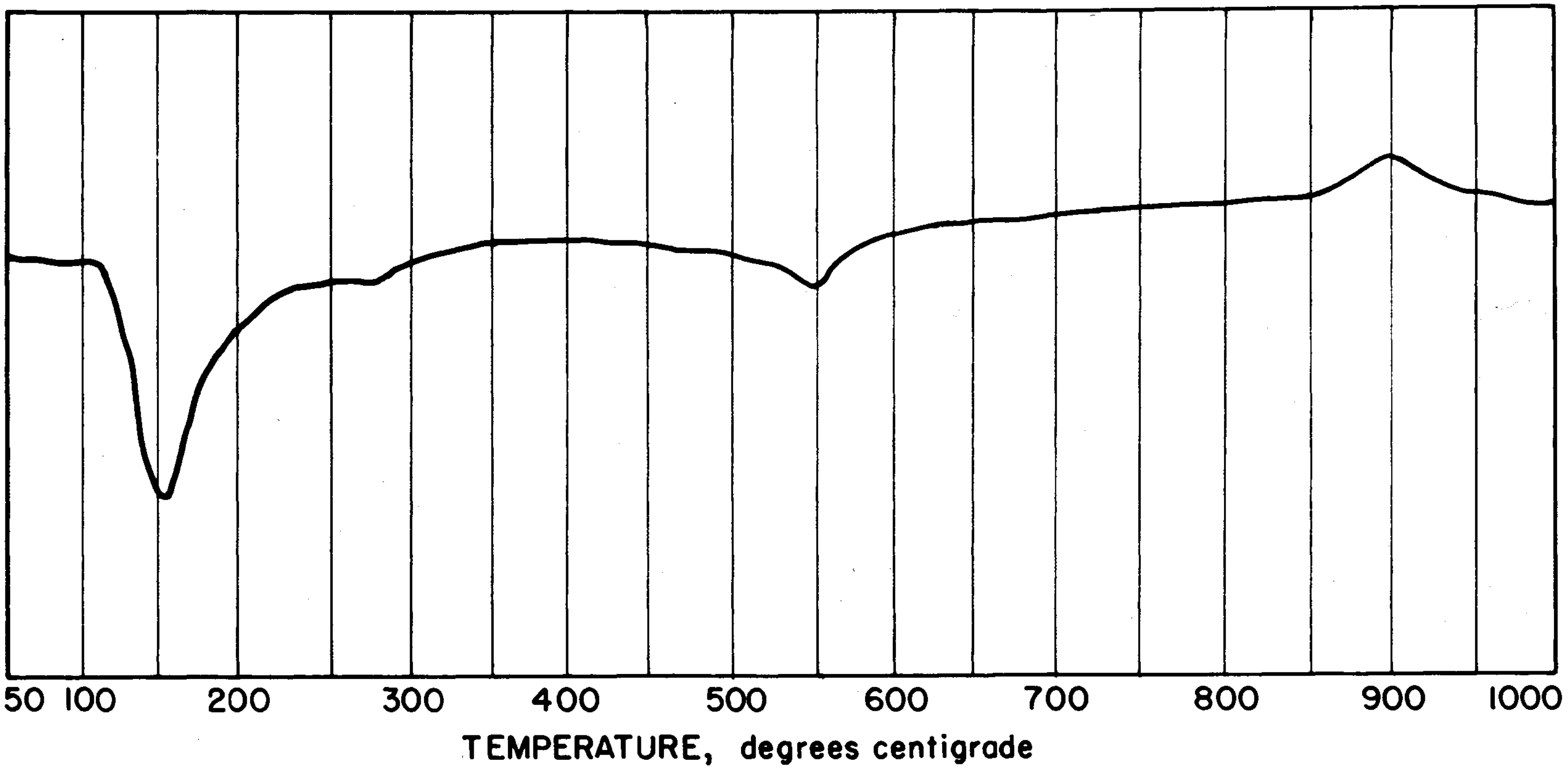

FIG. 8 THERMAL CURVE FOR MINUS ONE MICRON PORTION OF EDINA SUBSOIL

Table 8

Relationship between the liquid limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Liquid limit, % dry wt. mixture					
	Armac T	Armac 18D	Armac 12D	Rosin Amine-D Acetate	Amine 220	Ammonyx T
0	78.0	78.0	78.0	78.0	78.0	78.0
1	63.5	69.2	66.5	70.2	65.5	73.5
5	--	--	--	62.6	--	--
10	53.6	53.0	55.5	54.0	61.0	64.5
25	47.8	47.4	--	--	--	--
50	43.8	44.8	--	--	--	--
75	43.0	44.3	46.5	39.5	46.0	48.1

adsorption of the large organic cations on the surfaces of the clay fraction, resulting in the exclusion of water from the surfaces concerned. This would reduce the tendency of the clay fraction to hydrate and less water would be required to bring a treated soil up to the liquid limit moisture state.

(2) Plastic limit. The relationship between the plastic limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil is given in Table 9. All of the chemicals caused the magnitude of the plastic limit to increase. Fig. 10 shows that with all cationic materials, the initial 10 percent saturation of the base exchange capacity was most effective in increasing the plastic limit. Above 10 percent saturation the rate of increase was considerably less. Rosin Amine-D Acetate in amounts up to 10 percent saturation was especially effective in increasing the plastic limit, but admixtures of this chemical above 10 percent caused very little additional increase. The curves for

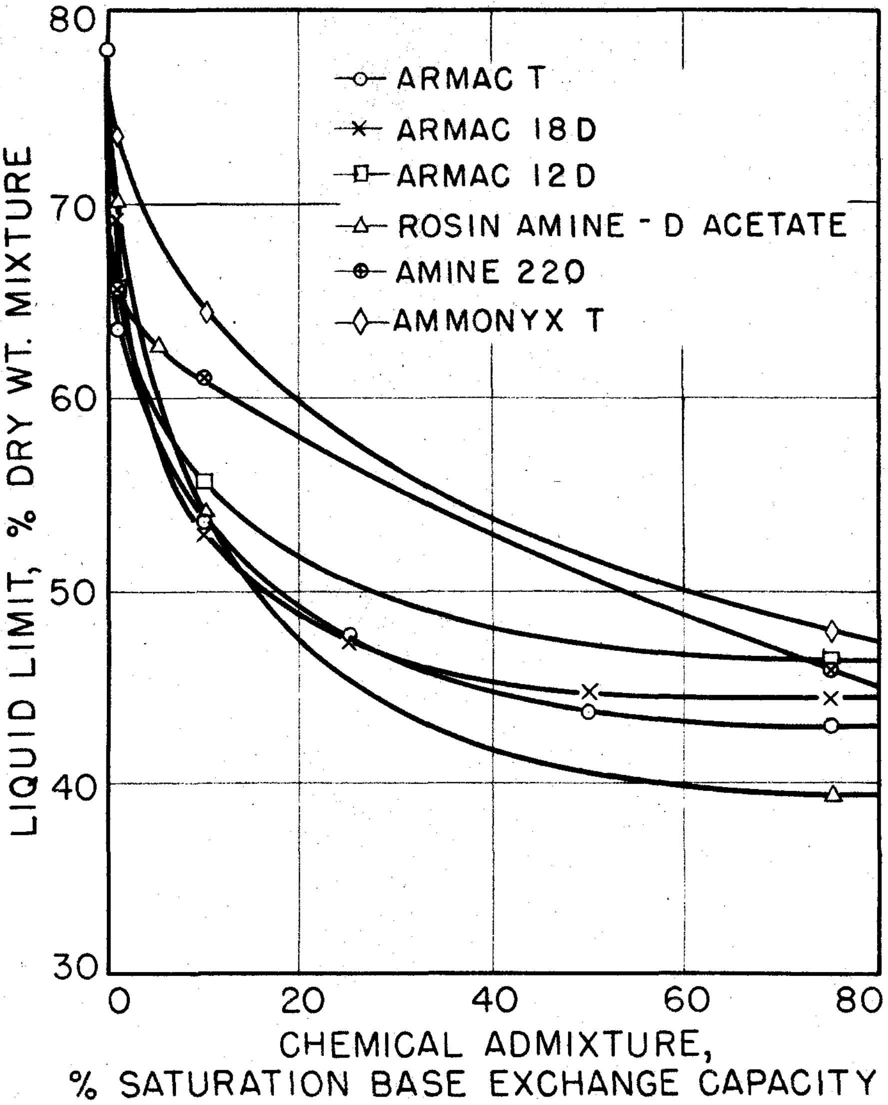

Fig. 9. Relationship between the liquid limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil.

Table 9

Relationship between the plastic limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Plastic limit, % dry wt. mixture					
	Armac T	Armac 18D	Armac 12D	Rosin Amine-D Acetate	Amine 220	Ammonyx T
0	26.3	26.3	26.3	26.3	26.3	26.3
1	29.4	29.5	30.8	30.1	30.6	29.5
5	--	--	--	36.6	--	--
10	33.8	33.5	35.3	38.4	33.4	33.4
25	36.5	36.0	--	--	--	--
50	38.0	37.8	--	--	--	--
75	38.6	38.4	38.7	39.1	37.8	37.8

the other 5 chemicals are grouped quite close together, with Armac 12D slightly more effective at 10 percent saturation. At 75 percent saturation it will be noted that all 6 cationic materials gave plastic limits of about the same magnitude.

The plastic limit moisture content is reached when water films have been built up on all surfaces to the point where particles can orient themselves and slide over one another when loaded. It is fairly well established that adsorption of large organic cations on clay surfaces creates areas that are not wetted by water. It is possible that these areas interfere with water film formation to the extent that more water is needed in order for orientation and subsequent sliding of the particles to take place. It is also conceivable that the large size of the adsorbed cations interferes with the orientation and sliding of the clay surfaces until water films that are sufficiently thick to bridge over the cations are built up.

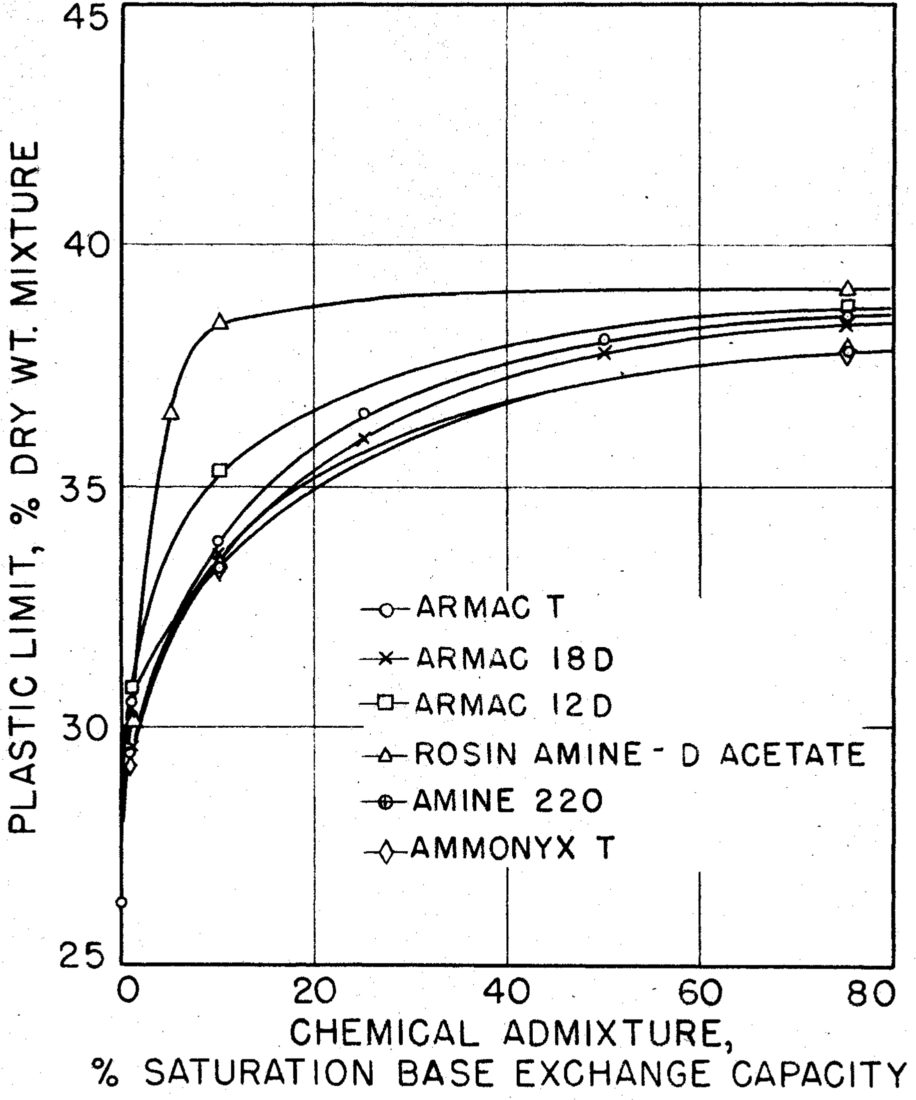

Fig. 10. Relationship between the plastic limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil.

(3) Plasticity index. Since the plasticity index is the numerical difference between the liquid limit and the plastic limit, it is to be expected from results already presented that its magnitude will be reduced by additions of cationic materials to Edina subsoil. This is shown to be true by Table 10. It is apparent from the curves in Fig. 11 that, for all 6 chemicals, the initial 10 percent saturation of the base exchange capacity was most effective in reducing the plasticity index. Admixtures above 10 percent continued to cause the plasticity index to decrease in value but at a diminishing rate. Rosin Amine-D Acetate caused the greatest reduction at all percentages above about 6 percent saturation, reducing the index to almost zero at 75 percent. The "Armacs" gave very similar reductions up to 10 percent admixture, with Armac T and Armac 18D more effective above 10 percent, in the order named.

Table 10

Relationship between the plasticity index and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Plasticity index, % dry wt. mixture					
	Armac T	Armac 18D	Armac 12D	Rosin Amine-D Acetate	Amine 220	Ammonyx T
0	51.7	51.7	51.7	51.7	51.7	51.7
1	34.1	39.7	34.7	40.1	34.9	44.0
5	--	--	--	26.0	--	--
10	19.8	19.5	20.2	15.6	27.6	31.1
25	11.3	11.4	--	--	--	--
50	5.8	7.0	--	--	--	--
75	4.4	5.9	7.8	0.4	8.2	10.3

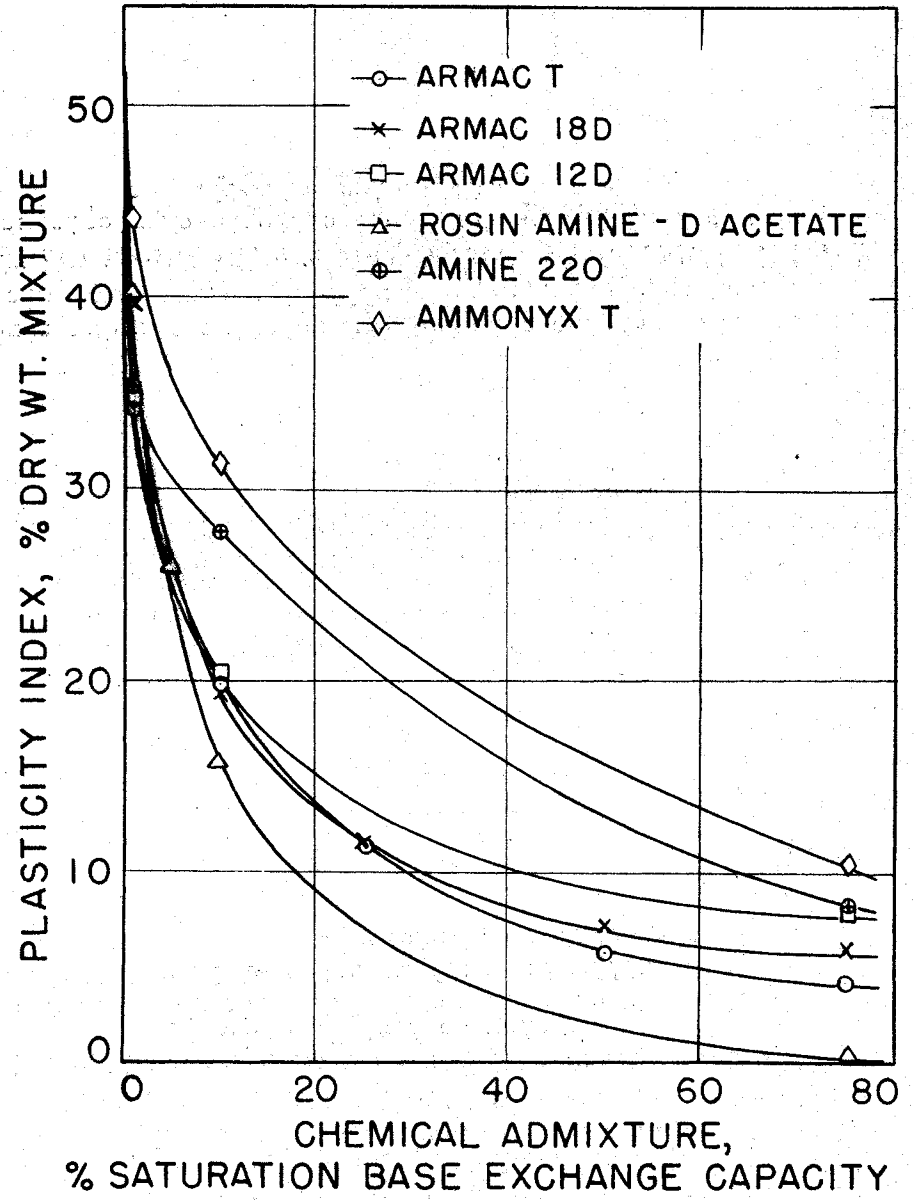

Fig. 11. Relationship between the plasticity index and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil.

Since the plasticity index is a qualitative measure of cohesion, it may be concluded that all of the cationic materials used were very successful in reducing the cohesiveness of Edina subsoil.

(4) Shrinkage limit. The effect of the cationic admixtures in raising the shrinkage limit of Edina subsoil is shown in Table 11.

Table 11

Relationship between the shrinkage limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Shrinkage limit, % dry wt. mixture					
	Armac T	Armac 18D	Armac 12D	Rosin Amine-D Acetate	Amine 220	Ammonyx T
0	6.0	6.0	6.0	6.0	6.0	6.0
1	7.7	8.9	6.7	8.8	6.8	8.1
5	--	--	--	9.8	--	--
10	12.4	11.2	11.5	16.8	12.0	16.0
25	13.1	13.0	--	--	--	--
50	18.3	18.0	--	--	--	--
75	23.6	23.3	19.3	37.6	19.6	28.5

The curves in Fig. 12 indicate that, with all chemicals, the initial 10 percent saturation of the base exchange capacity caused the greatest rate of increase. Above 10 percent saturation, the shrinkage limit continued to increase but at a diminished rate. Rosin Amine-D Acetate and Ammonyx T were most effective, in the order named. Armac T and Armac 18D gave very similar results and ranked third in order of effectiveness. Photographs of oven dried Edina subsoil shrinkage pats containing 0, 1, 10, 25, 50, and 75 percent saturation admixtures of Armac T and Armac 18D are shown in Figs. 13 and 14, respectively.

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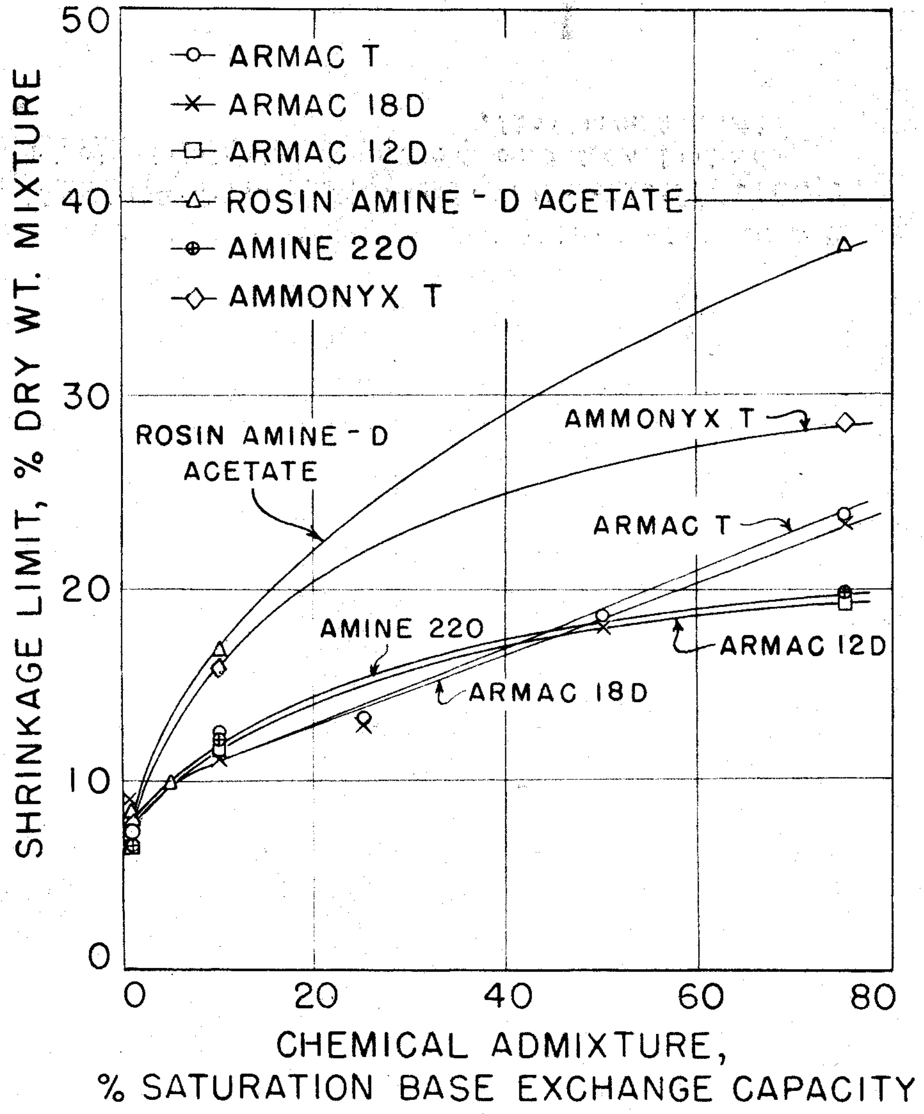

Fig. 12. Relationship between the shrinkage limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil.

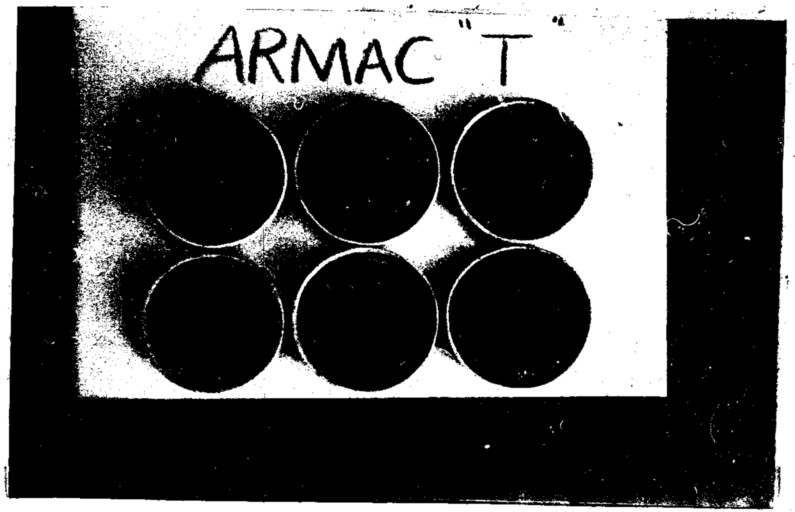

Fig. 13. Oven dried Edina subsoil shrinkage pats containing 0, 1, 10, 25, 50, and 75% saturation admixtures of Armac T.

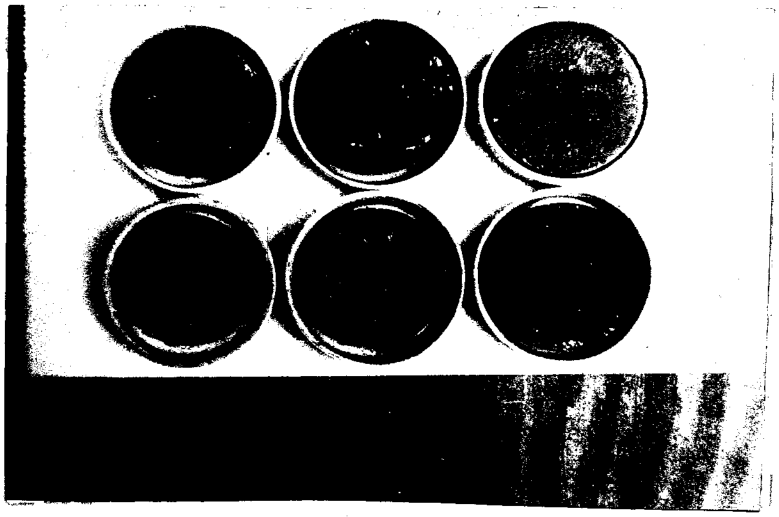

Fig. 14. Oven dried Edina subsoil shrinkage pats containing 0, 1, 10, 25, 50, and 75% saturation admixtures of Armac 18D.

As water evaporates from a soil mixture, capillary tension acting like a taut skin on the surface of the soil mass gradually draws the soil particles closer together until the shrinkage limit is reached. At this moisture content the resistance of the soil to further compression just equals the force exerted by evaporating moisture. The creation of water repellant areas on the clay surfaces due to adsorption of large organic cations probably tends to weaken the force of the evaporating moisture, resulting in less shrinkage and a higher shrinkage limit. This would be in agreement with the experimental results.

(5) Shrinkage ratio. The effect of the cationic materials in reducing the shrinkage ratio of Edina subsoil is shown in Table 12. From the curves in Fig. 15, it will be noted that above 10 percent saturation of the base exchange capacity the rate of reduction diminishes, signifying that the initial 10 percent saturation was most effective for all

Table 12

Relationship between the shrinkage ratio and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Shrinkage ratio					
	Armac T	Armac 18D	Armac 12D	Rosin Amine-D Acetate	Amine 220	Ammonyx T
0	2.02	2.02	2.02	2.02	2.02	2.02
1	1.93	1.95	1.91	1.94	2.01	1.98
5	—	—	—	1.83	—	—
10	1.72	1.78	1.83	1.56	1.74	1.56
25	1.66	1.70	—	—	—	—
50	1.59	1.51	—	—	—	—
75	1.30	1.37	1.39	1.22	1.55	1.35

Discussion of significance of results

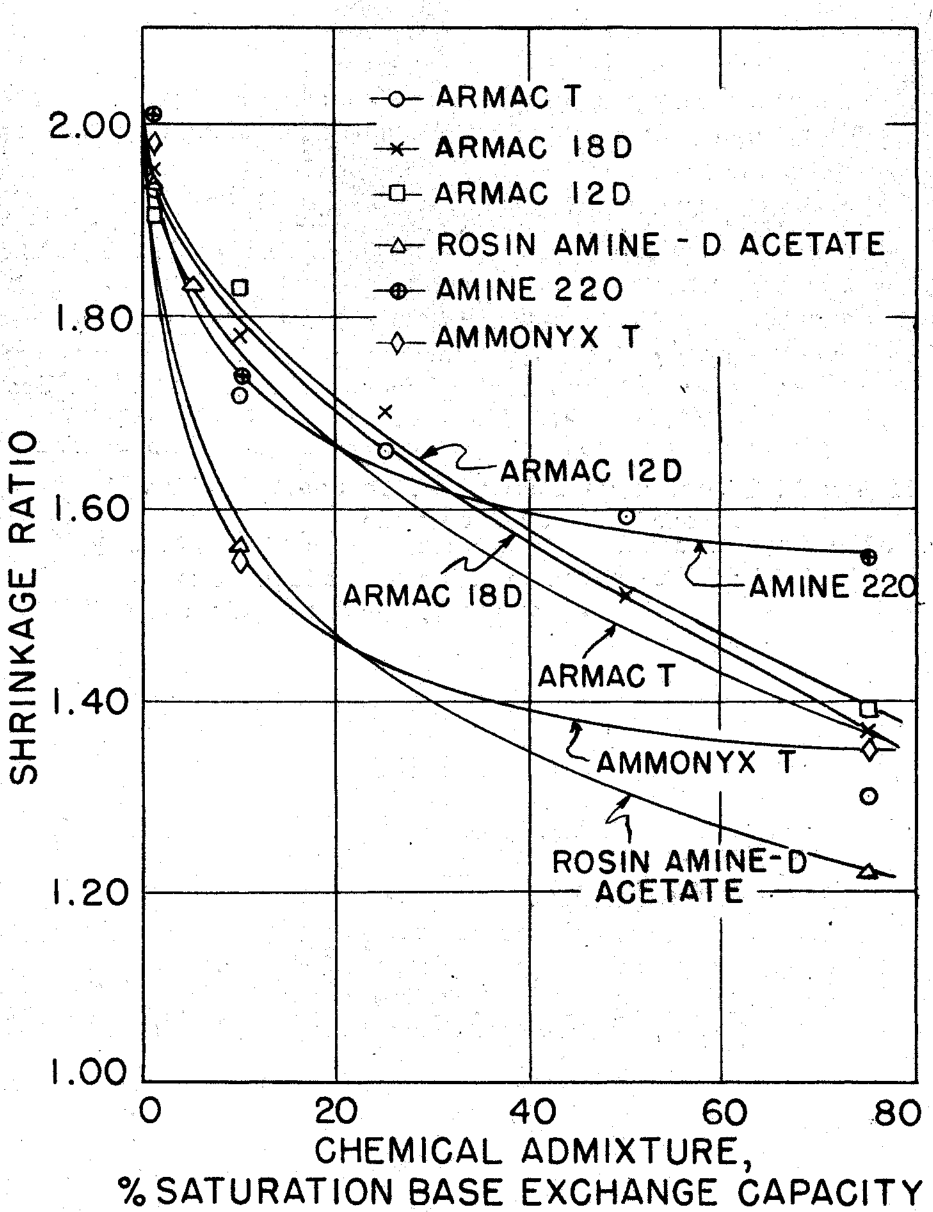

Fig. 15. Relationship between the shrinkage ratio and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil.

chemicals. Rosin Amine-D Acetate, Ammonyx T, and Armac T were most effective in lowering the shrinkage ratio, in the order named.

The shrinkage ratio results give further proof that all 6 cationic materials were effective in reducing shrinkage tendencies of Edina subsoil.

(6) Ratio of shrinkage limit to liquid limit. As previously stated, this ratio indicates the shrinkage properties of a soil. The smaller the shrinkage limit as compared with the liquid limit the greater will be the tendency for the soil to shrink (26). In this study the ratio, expressed as a percentage, is used only to determine the relative effect of chemical admixtures on the shrinkage tendencies of Edina subsoil.

The relative effect of the 6 cationic materials in reducing the shrinkage properties of Edina subsoil is shown in Table 13. From the

Table 13

Relationship between the ratio of the shrinkage limit to the liquid limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Shrinkage limit ÷ Liquid limit, %					
	Armac T	Armac 18D	Armac 12D	Rosin Amine-D Acetate	Amine 220	Ammonyx T
0	7.7	7.7	7.7	7.7	7.7	7.7
1	12.1	12.9	10.2	12.5	10.4	11.0
5	—	—	—	15.7	—	—
10	23.1	21.1	20.7	31.1	19.7	24.8
25	27.4	27.4	—	—	—	—
50	41.8	40.2	—	—	—	—
75	54.9	52.6	41.5	95.2	42.6	59.2

curves in Fig. 16, it is evident that, for all chemicals, the initial 10 percent saturation of the base exchange capacity was most effective in decreasing the shrinkage properties. Admixtures above 10 percent continued to cause the shrinkage properties to decrease in value but at a diminished rate. It will also be noted that above 10 percent the rate of reduction was directly proportional to the percent saturation, for all chemicals. Rosin Amine-D Acetate was especially effective in decreasing the shrinkage tendencies of Edina subsoil.

From the above results, it may be concluded that the large organic cations used were effective in reducing the shrinkage properties of Edina subsoil. Both swelling and shrinkage are dependent on the hydration characteristics of the clay fraction. As previously mentioned, the adsorption of large organic cations on the clay surfaces would tend to decrease the hydration tendencies of the surfaces concerned.

(7) Ratio of liquid limit to clay content. In studying the effect of admixtures on the properties of a soil, the ratio of the liquid limit to the clay content is indicative of the relative activity of the clay fraction. The higher this ratio, the more active the clay (26).

The effect of the 6 cationic materials on the relative activity of the 5 micron clay of Edina subsoil is shown in Table 14. As would be expected from previous test results, the activity was decreased by all chemicals. The curves in Fig. 17 show the relative effect of the 6 cationic chemicals. It will be noted that in all cases the initial 10 percent saturation of the base exchange capacity was most effective in decreasing the clay fraction activity. Admixtures above 10 percent continued to cause a decrease but at a diminishing rate.

From these results, it may be concluded that all large organic cations used decreased the activity of the clay surfaces to which they b

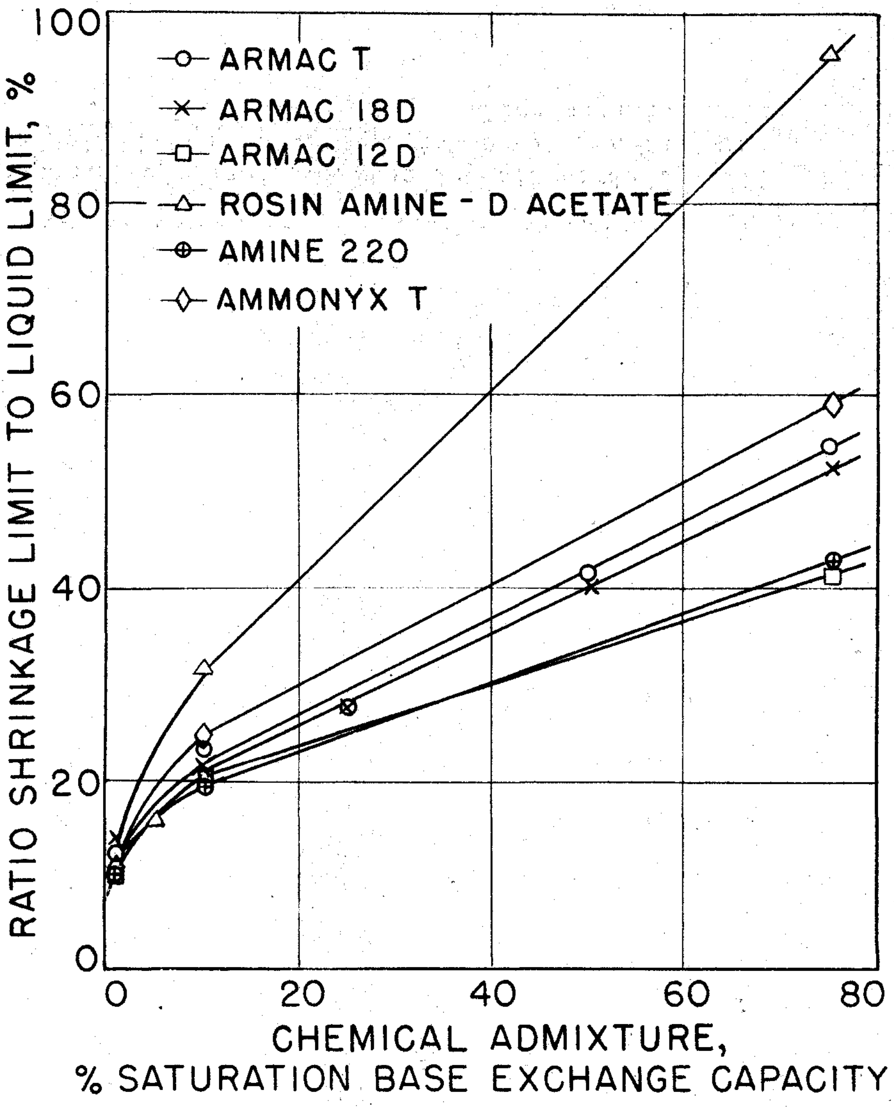

Fig. 16. Relationship between the ratio of the shrinkage limit to the liquid limit and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil.

Table 14

Relationship between the ratio of liquid limit to clay content and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Liquid limit ÷ percent clay (5 micron)					
	Armac T	Armac 18D	Armac 12D	Rosin Amine-D Acetate	Amine 220	Ammonyx T
0	1.49	1.49	1.49	1.49	1.49	1.49
1	1.21	1.32	1.25	1.34	1.25	1.41
5	—	—	—	1.20	—	—
10	1.03	1.01	1.06	1.03	1.17	1.23
25	0.91	0.91	—	—	—	—
50	0.84	0.86	—	—	—	—
75	0.82	0.85	0.89	0.76	0.88	0.92

were adsorbed. This is substantiated by all previous data presented, since all properties of a soil are intimately related to the activity of the clay fraction.

(8) Air dry strength. The effect of the 6 cationic chemicals on the relative air dry strength of Edina subsoil is shown in Table 15. It is evident that, with the exception of Rosin Amine-D Acetate, the loss in air dry strength was not great for admixtures up to 10 percent saturation of the base exchange capacity. Admixtures of Rosin Amine-D Acetate above 5 percent saturation caused a very great loss of air dry strength. The data for Armac T and Armac 18D show that the rate of strength loss increased appreciably with admixtures above 25 percent saturation.

The loss of air dry strength has been explained (12) on the basis of the work of Grim and Cuthbert (13), who found that the development of bonding strength in clay bodies was contingent upon the formation of

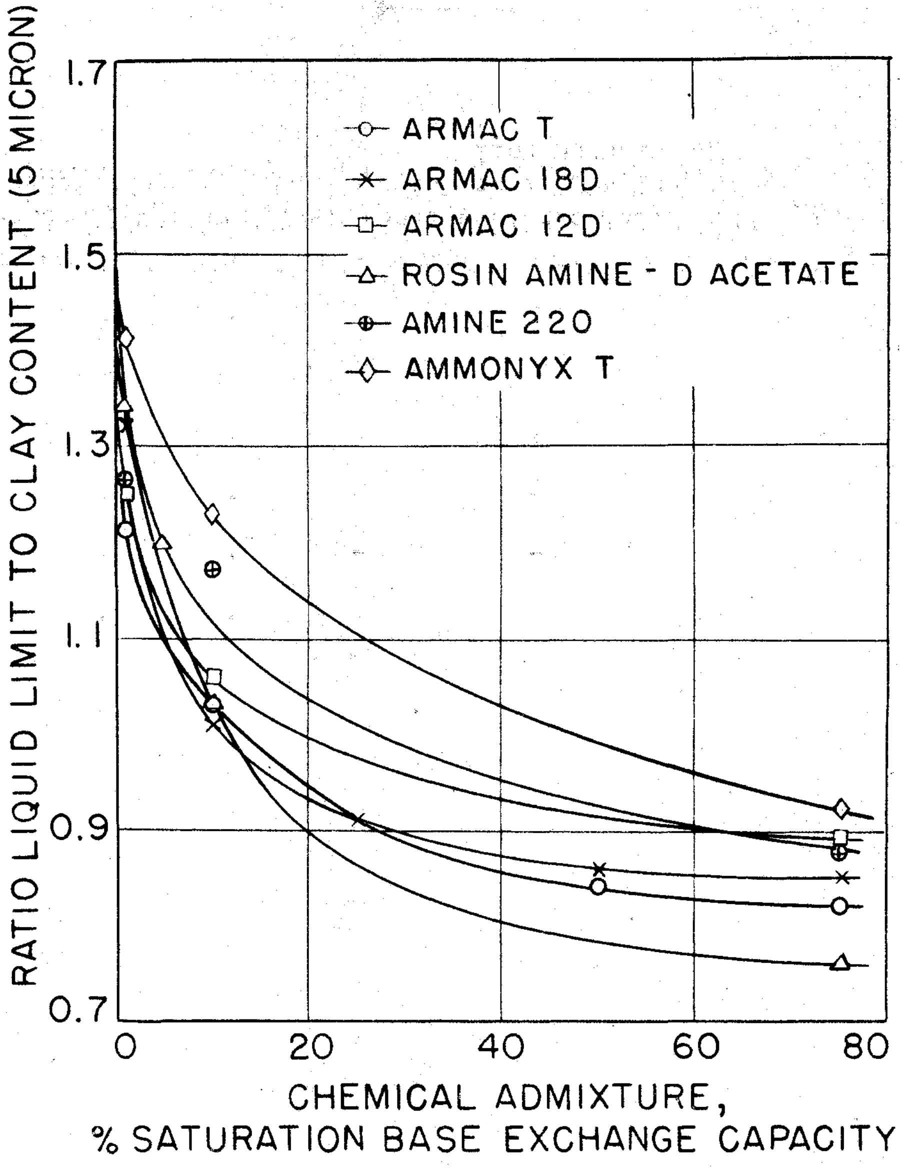

Fig. 17. Relationship between the ratio of liquid limit to clay content (5 micron) and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil.

Table 15

Relationship between relative air dry strength of shrinkage pats and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Relative air dry strength,* psi.					
	Armac T	Armac 18D	Armac 12D	Rosin Amine-D Acetate	Amine 220	Ammonyx T
0	2200 +	2200 +	2200 +	2200 +	2200 +	2200 +
1	2200 +	2200+	2200 +	2200 +	2200 +	2200 +
5	—	—	—	2200 +	—	—
10	2200 +	2040	2120	420	2200 +	2040
25	2120	1960	—	—	—	—
50	1000	720	—	—	—	—
75	400	40	350	10	160	120

*Each value is the average of several penetrometer tests on 2 pats.

films of water on the surfaces of the individual particles. Such films would not be continuous upon clays containing adsorbed organic cations of the type used in this study.

(9) Rate of slaking. Table 16 shows the relative effect of the 6 cationic materials on the slaking value of Edina subsoil. Ammonyx T had little, if any, beneficial effect on the slaking value. It is apparent that, with the exception of Armac T, the 75 percent saturation admixtures were not successful in preventing failure[a] due to slaking, and in some cases the slaking value was less than for the untreated soil. Observation of these test pats during disintegration, however, revealed that the individual pieces of treated soil that fell off were not wetted. Armac T admixtures of 10 percent saturation and above were successful in

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[a] The term "failure" is here used to denote falling through the ring.

Table 16

Relationship between slaking value of air dry shrinkage pats and percent chemical admixture for the 6 cationic chemicals used with Edina subsoil

Chemical admixture, % saturation B.E.C.	Slaking value,* minutes					
	Armac T	Armac 18D	Armac 12D	Rosin Amine-D Acetate	Amine 220	Ammonyx T
0	4.5	4.5	4.5	4.5	4.5	4.5
1	7.0	6.5	11.0	569.0	6.5	5.7
5	—	—	—	Didn't fail	—	—
10	Didn't fail	Didn't fail	Didn't fail	Didn't fail	Didn't fail	3.5
25	Didn't fail	Didn't fail	—	—	—	—
50	Didn't fail	Didn't fail	—	—	—	—
75	Didn't fail	32.0	14.5	1.5	2.5	13.0

*The term "didn't fail" indicates that the pat did not slake sufficiently to fall through the ring during the 7 day immersion period.

preventing failure during the 7 day immersion period. It will be noted that 1 percent saturation of Rosin Amine-D Acetate increased the slaking value appreciably and that 5 percent prevented failure. Photographs of chemically treated Edina subsoil pats that did not fail during the 7 day immersion period are shown in Figs. 18 through 21. In general, admixtures greater than 25 percent saturation of the soil's base exchange capacity did not appreciably increase air dry slaking resistance.

c. <u>General discussion</u>. On the basis of the test results with Edina subsoil and also on the ease with which they dissolved in the amounts of water used for mixing purposes, Rosin Amine-D Acetate and

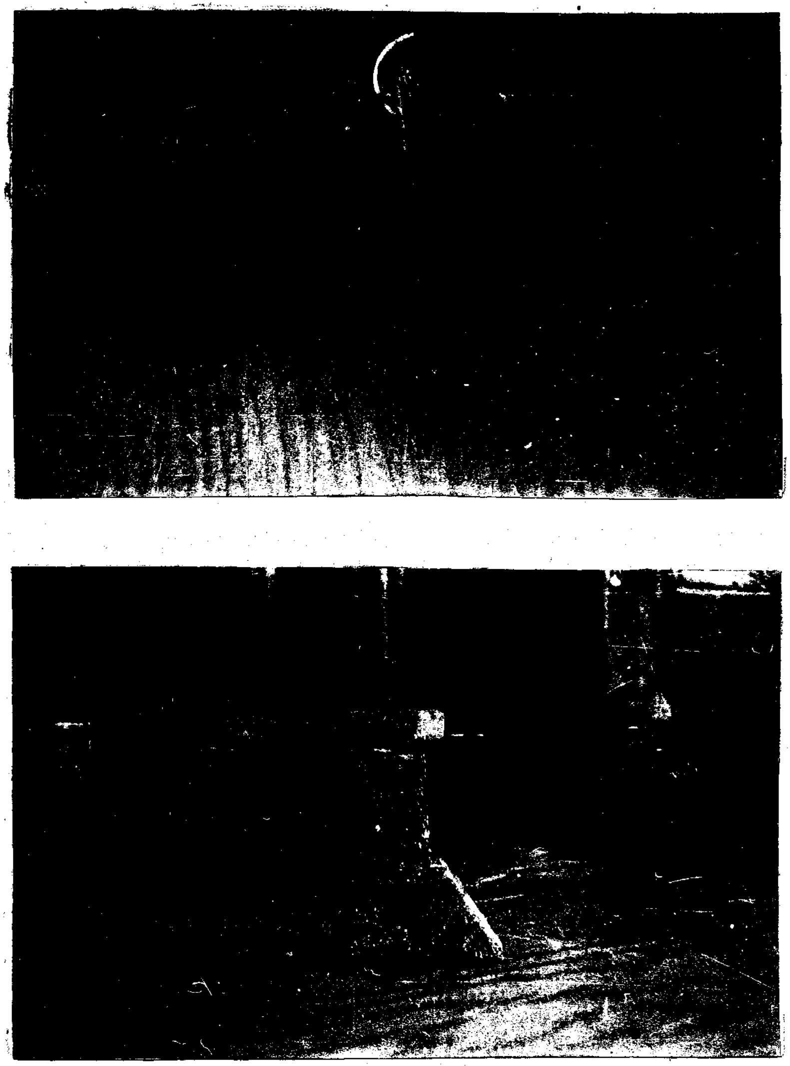

Fig. 18. Top and side views of Edina subsoil slaking pats containing 10% saturation admixtures of Armac 18D (left), Rosin Amine-D Acetate (center), and Armac T (right) after soaking 7 days in water.

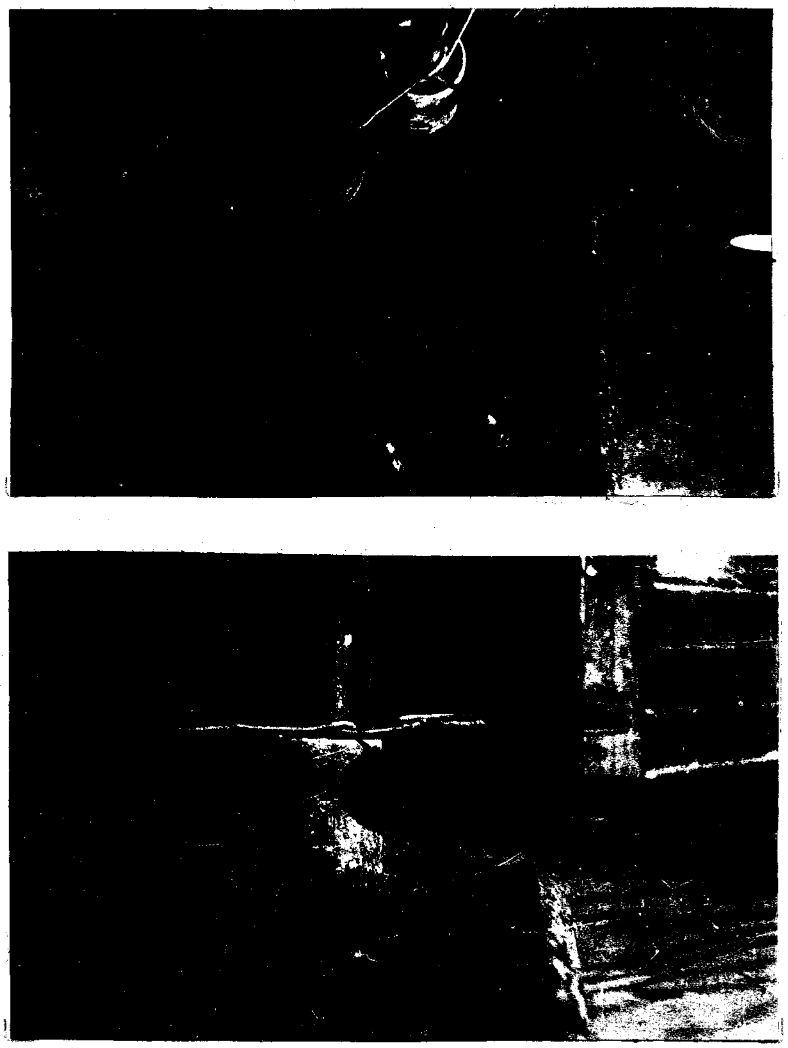

Fig. 19. Top and side views of Edina subsoil slaking pats containing 10% saturation admixtures of Amine 220 (left) and Armac 12D (right) after soaking 7 days in water.

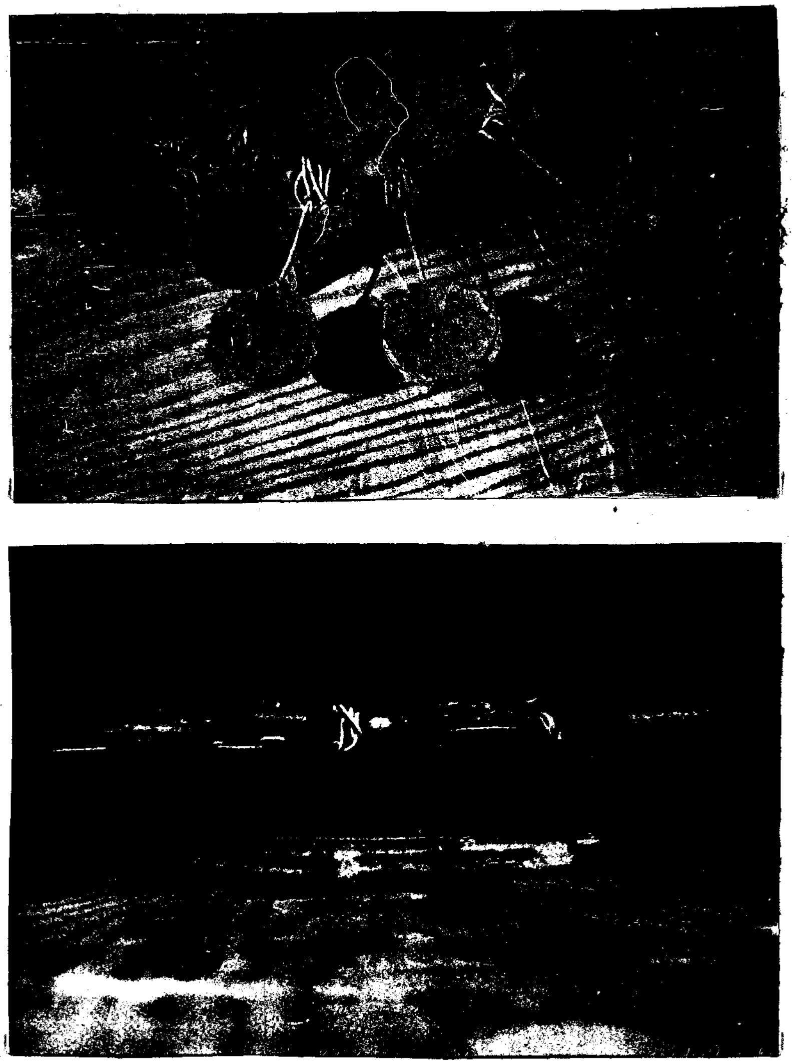

Fig. 20. Top and side views of Edina subsoil slaking pats containing (left to right) 50% saturation Armac 18D, 25% saturation Armac 18D, 50% saturation Armac T, and 25% saturation Armac T after soaking 7 days in water.

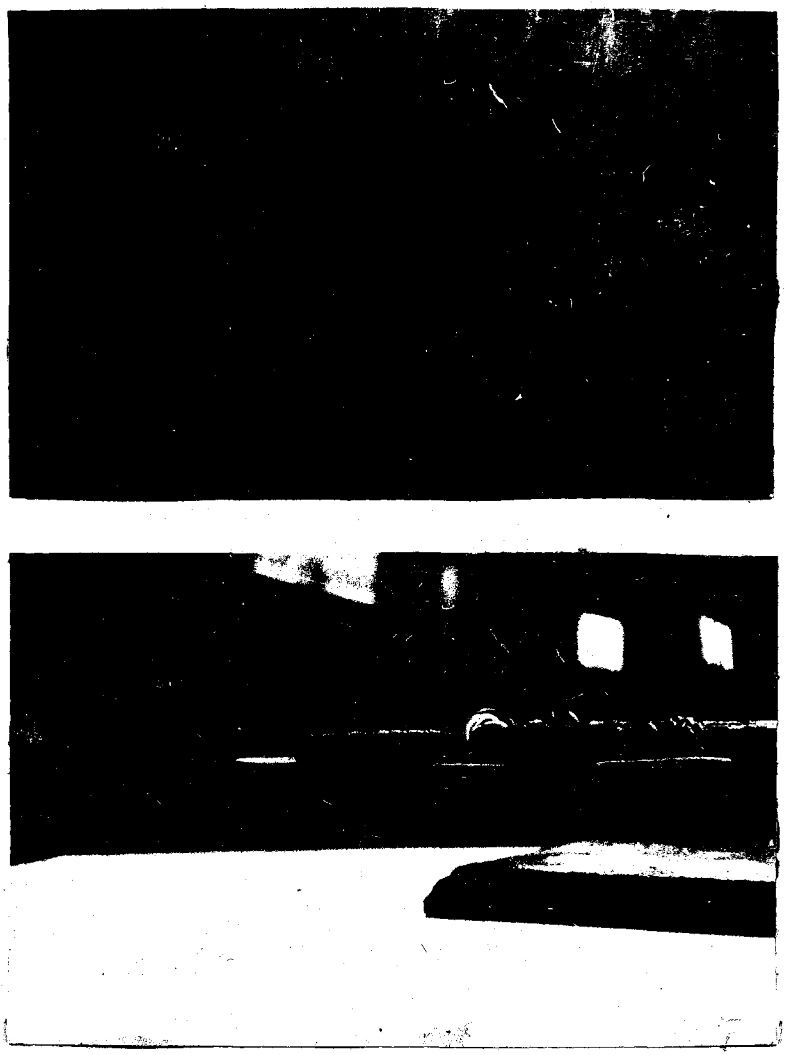

Fig. 21. Top and side views of Edina subsoil slaking pat containing 75% saturation admixture of Armac T after soaking 7 days in water.

Armac T appeared to be the most promising of the 6 cationic materials investigated. Only one method of adding the cationic material to the soil was used and all experimental findings should be evaluated with that in mind. The mixing procedure used, however, can probably be considered as giving close to optimum results.

B. Armac T as a Stabilizing Agent for Edina Subsoil

The objective in this part of the investigation was to study in greater detail the effectiveness of one promising cationic chemical as a stabilizing agent for Edina subsoil.

1. Materials

a. Soil. Edina subsoil was the only soil used in this study. It has been described in section A.

b. Cationic chemical. Armac T was selected as the cationic material to investigate in more detail. This chemical rated high among the 6 cationic materials evaluated in section A and was one of the most water soluble. It was available for use on a commercial scale and, in addition, is the cheapest "Armac" manufactured. It is a fatty acid amine acetate made from the fatty acids derived from beef tallow and has been described in detail in section A.

2. Method of procedure

a. Addition of Armac T. The procedure for preparing the soil and mixing the chemical was exactly the same as described in section A. Armac T was added to four, 6 pound samples (dry weight) of Edina subsoil in such quantities that the base exchange capacities of the samples were saturated 10, 25, 50, and 75 percent, respectively. In terms of the dry weight of the soil, these percentages are 1.29, 3.22, 6.44, and 9.66 percent, in the same order.

b. Description of tests. Tests were selected to further evaluate Armac T admixtures as stabilizing agents for Edina subsoil. Standard tests are not described in detail. Where needed, interpretation of physical meaning is given. Tests which were used to evaluate cationic materials in section A are not redescribed here, but their use is pointed out.

(1) Water absorption and swell. The purpose of this test was to measure the relative effect of Armac T admixtures to Edina subsoil on water absorption, swelling, and penetrometer penetration resistance after being immersed in water at optimum moisture and maximum modified A.A.S.H.O. density for 4 days. Armac T treated soil at optimum moisture content was compacted to maximum modified A.A.S.H.O. density in a standard 1/30 cubic foot mold, using the procedure of A.A.S.H.O. Designation: T99-38, with the exception that a 10 pound hammer with an 18 inch fall was used, and the sample was compacted in 5 equal layers. The upper extension and base plate were then removed, and the compacted soil leveled off to the top of the mold with a straightedge before being weighed.

In reassembling, the standard base plate was replaced with one containing a porous stone through which water could enter. A sheet of filter paper was inserted between the porous stone and the bottom of the sample. After the upper extension collar was replaced, a sheet of filter paper was laid on top of the sample followed by a perforated plate. No surcharge weight was used. An Ames dial and cross-bar assembly was then set on the mold extension. The assembled apparatus is shown in Fig. 22.

Immediately after immersion in distilled water, the initial dial

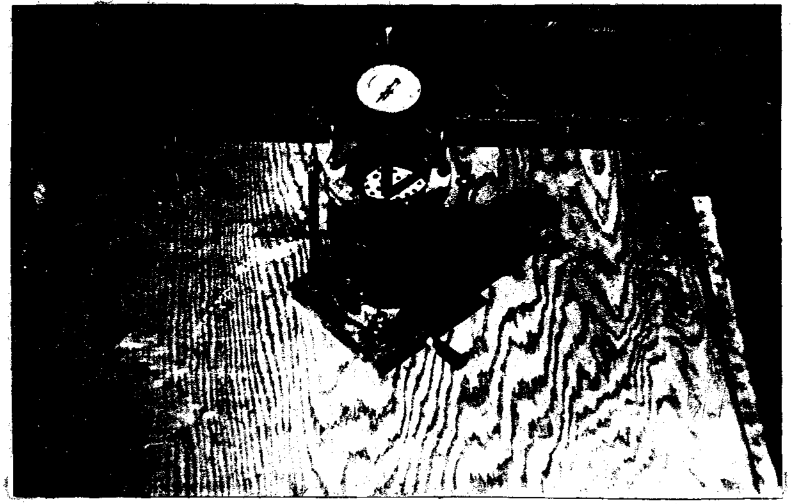

Fig. 22. Water absorption and swell test apparatus.

reading was noted. Swelling was measured by reading the dial at the end of 24 hour intervals. At the end of the 4 day soaking period, the apparatus was removed from the water, water poured off the specimen, and then allowed to drain for one minute. After removing the upper extension, the perforated plate, the bottom plate, and the filter paper, the mold plus wet specimen was weighed in order to determine the average moisture content of the treated soil after soaking.

The soaked specimen was tested for penetration resistance with a standard soil penetrometer, previously described in section A. This test consisted of measuring on the top and bottom surfaces of the soaked soil, the maximum force required to produce a penetration of 3 inches at a rate of about 1/2 inch per second with a 1/20 square inch needle.

After the penetration tests, the soil was removed from the mold and moisture samples taken from near the top, middle and bottom of the specimen.

(2) Unconfined compression relationships. The purpose of this test was to determine the effect of Armac T admixtures to Edina subsoil on its shearing strength and modulus of deformation.

The shearing strength of soil consists of two components: the cohesion, c, and the internal friction angle, ϕ. The values of these components may be substituted in the Coulomb formula

$$s = c + p \tan \phi$$

where p is the effective pressure on the failure plane, to obtain the shearing strength at any point in a soil mass in pounds per square foot or other suitable units. An emperical procedure that has become common in the interpretation of the unconfined compression test (32) is

$$s = \tfrac{1}{2}\,(\text{compressive strength})$$

where s is the shearing strength of the soil. The latter equation was used in this investigation.

According to the Mohr strength theory the angle of failure, α, of a soil cylinder should be

$$\alpha = 45 - \tfrac{1}{2}\phi \ .$$

By measuring the angle of failure of a test cylinder, it is possible to obtain a value for the internal friction angle, ϕ, from this equation. Then by constructing a Mohr circle for the unconfined compression test and drawing a line tangent to the Mohr circle at a slope equal to ϕ, the value of the cohesion, c, may be read where the extended tangent line intercepts the minor principal plane, which is laid off in cohesion units.

When a cylinder is loaded in the unconfined compression test, the ratio of the unit stress to the unit strain will usually be a fairly constant value in the early stages of the loading and a graph of the stress versus strain will rise on a reasonably straight line and then curve rapidly as the strain begins to increase at a faster rate than the stress. The approximate value of the stress-strain ratio which is representative of this early loading is called the modulus of deformation. It is a property of soil similar to the modulus of elasticity of other structural materials, but is applicable only to compressive stresses and strains.

Two, 2 inch diameter by 4 inch high cylinders were molded at optimum moisture and maximum modified A.A.S.H.O. density for each combination of Armac T and Edina subsoil. After removal from the mold each cylinder was capped with paraffin, wrapped in several layers of wax paper, and then dipped in paraffin to seal the wax paper. The sealed cylinders were stored for 24 hours in order to permit capillary adjustment of the moisture films to take place. At the end of the storage period the wax paper was removed and one set of cylinders immersed in distilled water. The other set of cylinders was immediately tested to failure in unconfined compression. Stress and strain readings were taken at frequent intervals during the loading and the angle of failure measured at the end of each test with a protractor. After 24 hours immersion, the soaked set of cylinders was tested in a similar manner.

(3) Hygroscopic moisture. This test was conducted in accordance with A.A.S.H.O. Designation: T88-42, after samples of Armac T treated Edina subsoil had been stored in open containers at room temperature (80° F. 3°) for 14 days during July, 1948. The hygroscopic moisture values, determined in this manner, indicate only the relative effect of Armac T admixtures on the water affinity of Edina subsoil.

(4) Centrifuge moisture equivalent. The C.M.E. was determined in accordance with A.A.S.H.O. Designation: T94-42, with the exception that the Armac T treated samples had to be initially wetted by sucking distilled water through them with an aspirator.

The C.M.E. when performed in the above manner gives a value of capillary potential equal to minus 16.4 feet of water. Therefore, theoretically, this constant represents the moisture content which the soil would contain if it were in equilibrium with a water table approximately 16 feet below. However, this must be considered as a qualitative value only, since as Spangler (33) has pointed out, the sample in the centrifuge is not in the same physical state as the soil in the subgrade.

Besides representing a point on the soil sorption curve, the centrifuge moisture equivalent (1) serves to distinguish soils which are permeable from those which are impermeable when compressed by a centrifugal force equal to 1000 times gravity; (2) serves to disclose to some extent the degree of capillarity possessed by permeable soils; and

(3) furnishes a means of distinguishing permeable soils of the non-expansive type from those of the expansive varieties. In general, soils having centrifuge moisture equivalents less than about 12 exhibit no shrinkage, and frost heave and capillarity are not important (34).

(5) *pH value.* The effect of the Armac T admixtures to Edina subsoil on its pH value was determined by use of a Beckman pH meter as described in section A of this investigation.

(6) *Water solubility.* The purpose of the water solubility test was to determine to what extent Armac T could be washed out of Edina subsoil. Approximately 200 grams of air dry Edina subsoil containing 3.22 percent by weight Armac T were soaked in 3 liters of distilled water for 24 hours with occasional stirring, and then washed onto filter paper in 2 Buchner funnels to which suction was applied by means of an aspirator. The deposited samples were next leached 50 times with 100 c.c. portions of distilled water. The washed soil was removed from the funnels, air dried, and then ground with mortar and pestle to pass the No. 40 sieve.

The procedure for determining the extent to which Armac T was washed out of the soil was entirely qualitative in character. Tests which had previously been made on unwashed 3.22 percent Armac T treated Edina subsoil were performed on the washed soil so that a comparison of test results would indicate any effects due to the washing. The following previously described tests and ratios were used for this purpose: (1) liquid limit, (2) plastic limit, (3) plasticity index, (4) shrinkage limit, (5) shrinkage ratio, (6) ratio of shrinkage limit to liquid limit, (7) ratio of liquid limit to clay content, (8) relative air dry strength, and (9) rate of slaking.

3. Presentation and discussion of results

In the discussion of results in this part of the investigation, admixtures of Armac T are described on a percent by dry weight of the soil basis. Most tables and figures, however, have both percent by weight and percent saturation of the base exchange capacity designations.

a. Review. Results of tests on Armac T treated Edina subsoil previously presented and discussed in section A are summarized in Table 17 and shown by curves in Figs. 23 through 26. No further comments will be made on these data.

Table 17

Summary of relationships between some soil properties indicative of stability and percentage Armac T admixture to Edina subsoil

Test	Armac T admixture, % dry wt. soil					
	0.00	0.13	1.29	3.22	6.44	9.66
Liquid limit, % dry wt. mixture	78.0	63.5	53.6	47.8	45.8	43.0
Plastic limit, % dry wt. mixture	26.3	29.4	33.8	36.5	38.0	38.6
Plasticity index, % dry wt. mixture	51.7	34.1	19.8	11.3	5.8	4.4
Shrinkage limit, % dry wt. mixture	6.0	7.7	12.4	13.1	18.3	23.6
Shrinkage ratio	2.02	1.93	1.72	1.66	1.59	1.30
S.L. ÷ L.L.,%	7.7	12.1	23.1	27.4	41.8	54.9
L.L. ÷ % clay	1.49	1.21	1.03	0.91	0.84	0.82
Relative air dry strength, psi.	2200 +	2200 +	2200+	2120	1000	300
Slaking value, min.	4.5	7.0	Didn't fail	Didn't fail	Didn't fail	Didn't fail
Test	0	1	10	25	50	75
	Armac T admixture, % saturation B.E.C.					

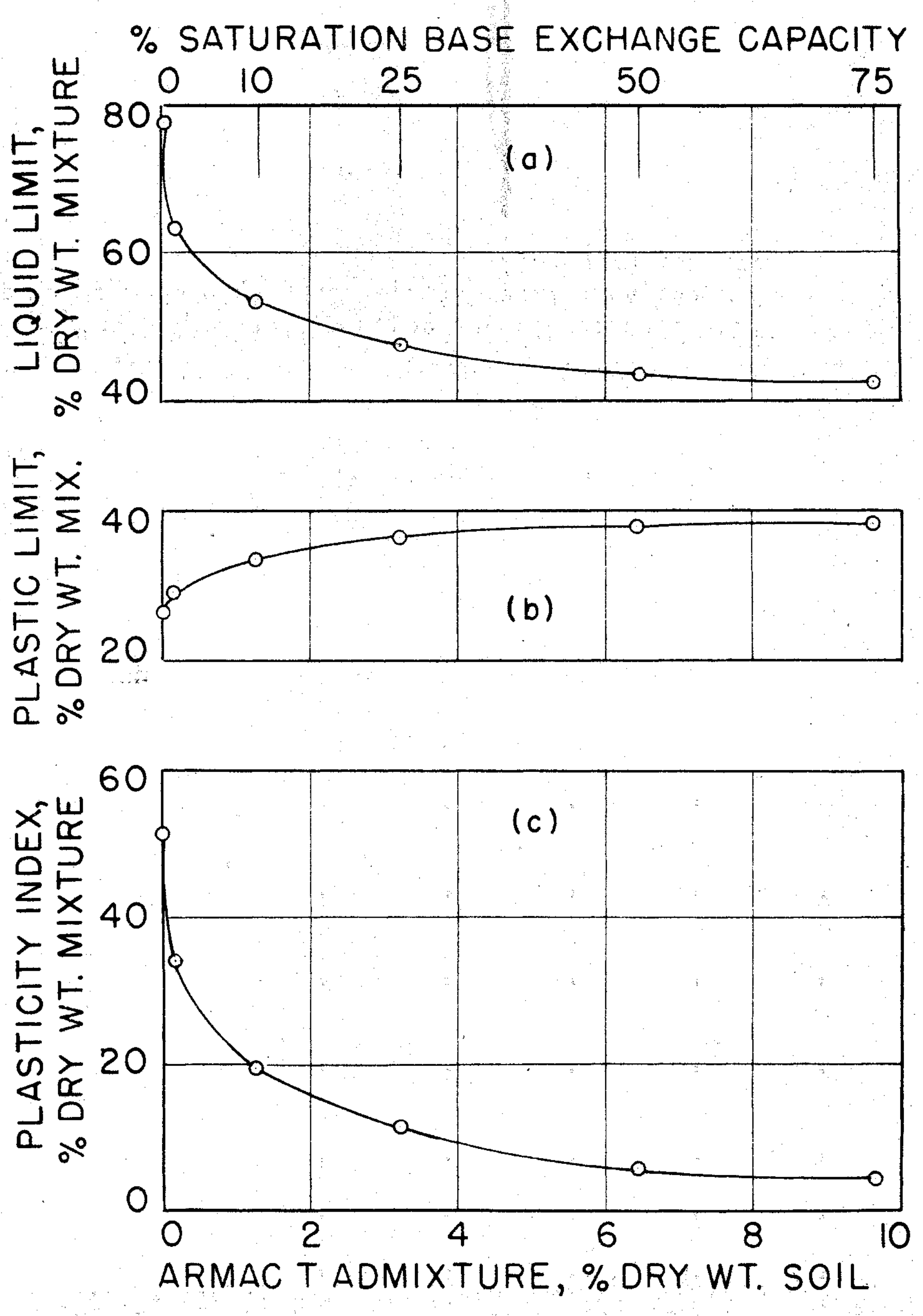

Fig. 23. Relationship between Atterburg limits of Edina subsoil and percent Armac T admixture.

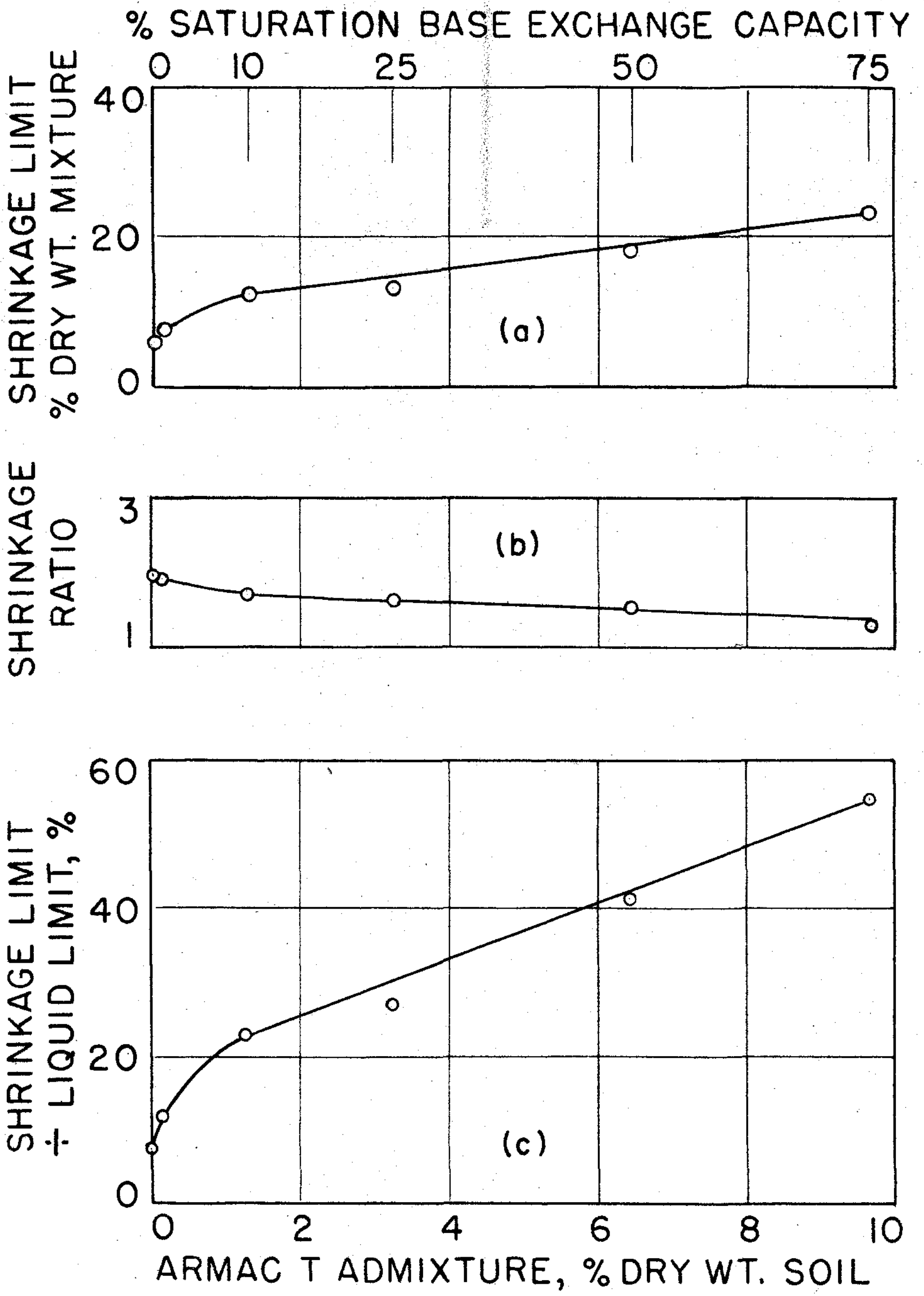

Fig. 24. Relationship between shrinkage properties of Edina subsoil and percent Armac T admixture.

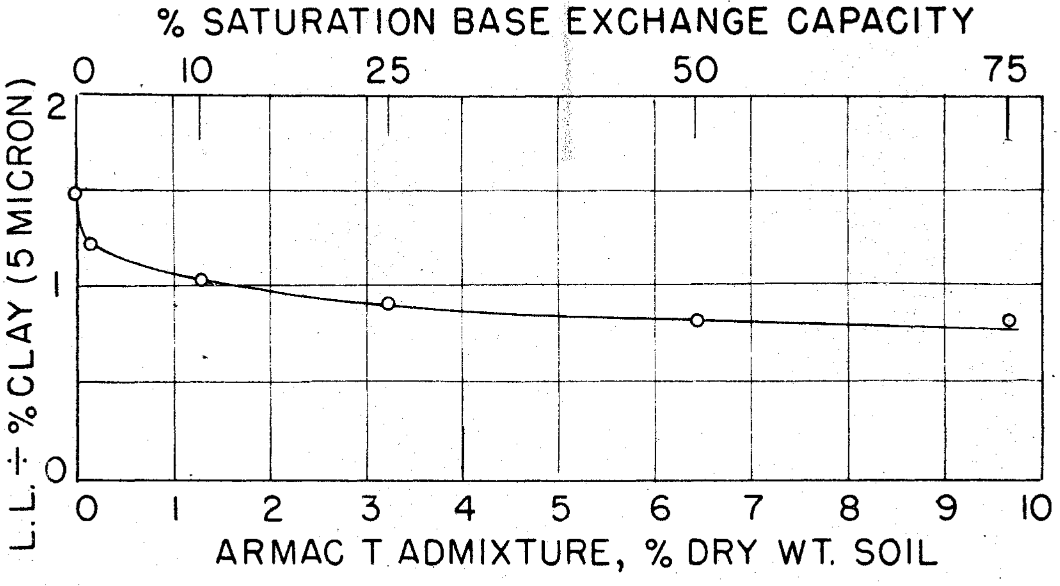

Fig. 25. Effect of Armac T admixtures to Edina subsoil on ratio of liquid limit to clay content (5 micron).

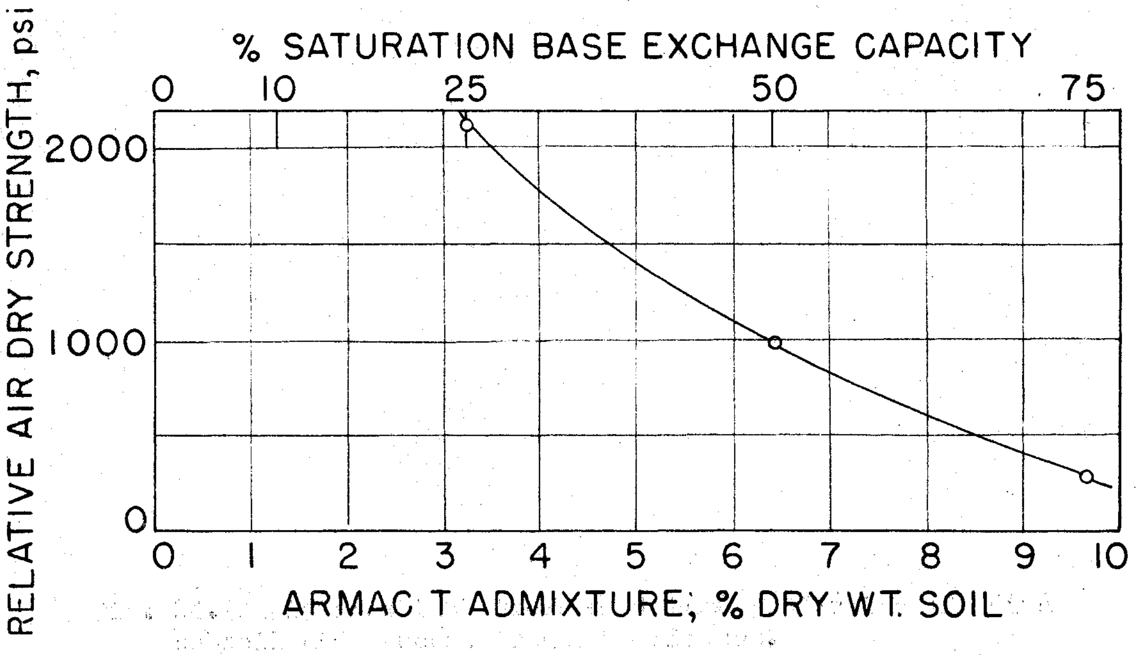

Fig. 26. Relationship between relative air dry strength of Edina subsoil shrinkage pats and percent Armac T admixture.

Soil mixtures are not apt to shrink appreciably after compaction when their shrinkage limits are equal to or exceed the optimum moisture content required for maximum density, which in most cases would be either maximum standard Proctor density or maximum modified A.A.S.H.O. density. The effect of Armac T admixtures to Edina subsoil on the ratio of the shrinkage limit to optimum moisture is shown in Table 18 for both maximum standard Proctor density and maximum modified A.A.S.H.O. density. It is apparent from the curves in Fig. 27 that none of the percentages of Armac T used would be effective in preventing shrinkage of Edina subsoil if standard Proctor density control was used. If modified A.A.S.H.O. density control was used, it would take at least 6 percent of Armac T to prevent shrinkage.

Table 18

Effect of Armac T admixtures to Edina subsoil on ratio of shrinkage limit to optimum moisture for maximum density

Armac T admixture		S.L. ÷ optimum moisture	
% saturation B.E.C.	% dry wt. soil	for max. std. Proctor density	for max. mod. A.A.S.H.O. density
0	0.00	0.20	0.32
10	1.29	0.40	0.66
25	3.22	0.44	0.75
50	6.44	0.64	0.99
75	9.66	0.83	1.28

b. <u>Water</u> <u>absorption</u> <u>and</u> <u>swell</u>. The effect of Armac T admixtures to Edina subsoil on water absorption and penetrometer penetration resistance after immersion in distilled water at optimum moisture and maximum A.A.S.H.O. density for 4 days is shown in Table 19. Due to the manner of conducting this test, the top of the immersed specimen was the only

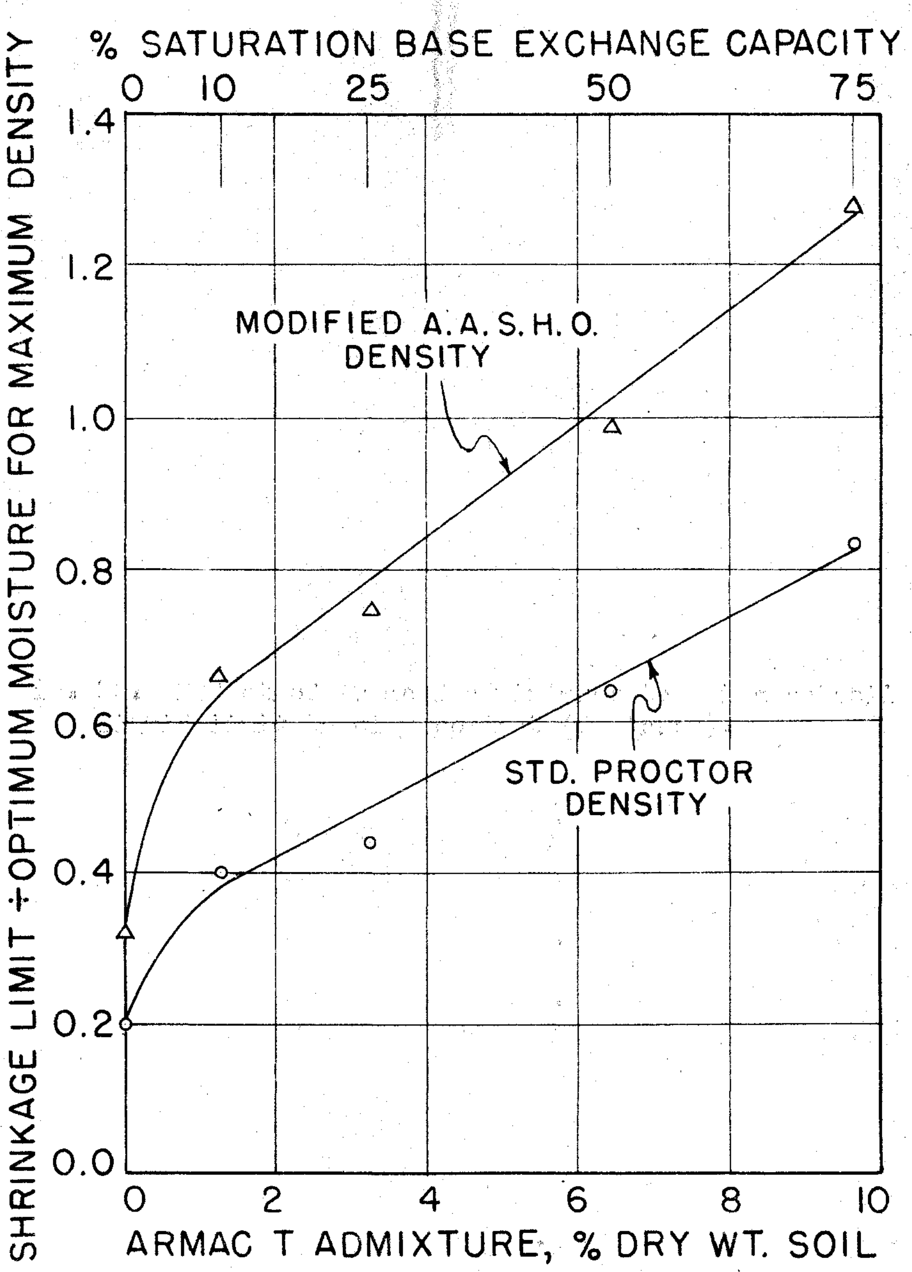

Fig. 27. Effect of Armac T admixtures to Edina subsoil on ratio of shrinkage limit to optimum moisture for maximum density.

Table 19

Effect of Armac T admixtures to Edina subsoil on water absorption and penetrometer penetration (3 inches) resistance after immersion at optimum moisture and maximum A.A.S.H.O. density for 4 days

Armac T admixture		Absorption, % dry wt. mixture				Penetration resistance, psi.	
% saturation B.E.C.	% dry wt. soil	Top	Middle	Bottom	Ave.[b]	Top	Bottom
0	0.00	39.48	0.53	11.33	14.92	840	2200 +
10	1.29	16.60	0.60	3.40	3.92	2200 +	2200 +
25	3.22	3.90	0.70	2.00	2.42	2200 +	2200 +
50	6.44	2.05	0.75	0.80	1.04	2200 +	2200 +
75	9.66	1.95	0.50	1.70[a]	0.73	2200 +	2200 +

[a] The porous base plate was not used. The mold was set on a wire screen supported by a rubber ring to enable water to enter from the bottom.

[b] These values obtained by expressing the total moisture increase as a percentage of the dry weight of the mixture.

surface free to expand, which probably explains the greater water absorption in the upper part of the soaked cylinders. Water had access to the bottom of all specimens, but this surface was restrained by the porous stone base of the Proctor mold. It will be noted that relatively little water reached the middle of the cylinders during the 4 day soaking period. The average absorption values were obtained by expressing the total moisture increase as a percentage of the dry weight of the specimen and not by averaging the top, middle, and bottom absorption values. The average absorption curve in Fig. 28 shows that admixtures of Armac T up to 6.44 percent were very effective in reducing the water absorption of Edina subsoil in the optimum moisture and maximum A.A.S.H.O. density condition. Admixtures greater than 6.44 percent, however, apparently had relatively little added effect. It will also be noted that the rate of reduction was especially great for treatments up to 1.29 percent.

Penetrometer penetration readings for 3 inches penetration with the 1/20 square inch needle could be obtained only on the top surface of the soaked specimen containing zero percent Armac T. All other soaked specimens are recorded as having a penetration resistance of 2200 .

The effect of Armac T in reducing the swelling tendencies of Edina subsoil during the 4 day soaking test is shown in Table 20. Curves plotted from these data are presented in Fig. 29. It will be noted that in all cases the rate of swelling was greatest during the initial 24 hours of soaking. Admixtures of Armac T up to 3.22 percent reduced the swelling of Edina subsoil greatly. Increasing the dosage above 3.22 percent apparently did not cause much further decrease in the magnitude of the swelling.

It is concluded from the absorption and swelling study that Armac T admixtures to Edina subsoil inhibited the adsorption of water on the

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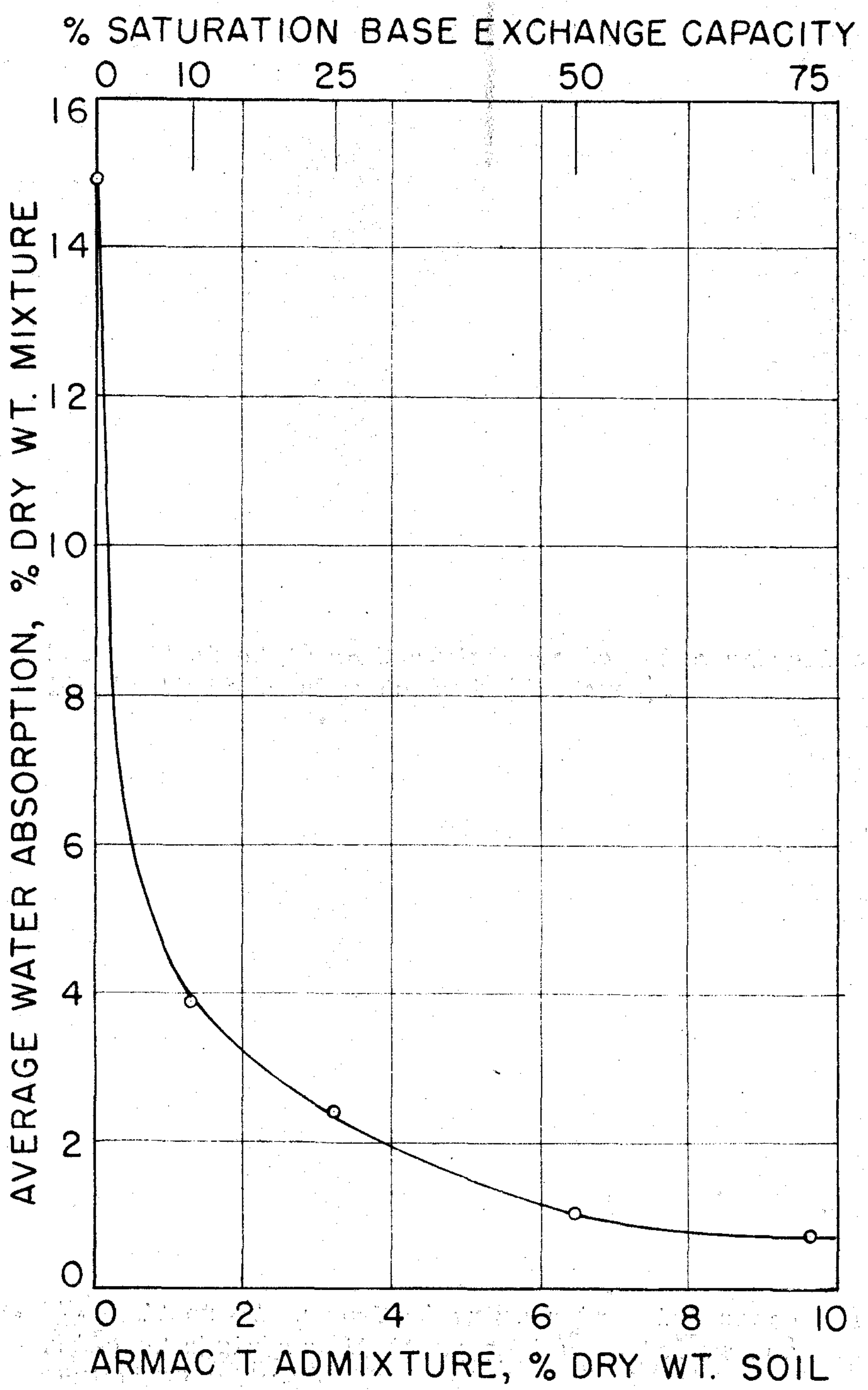

Fig. 28. Relationship between percent Armac T admixture to Edina subsoil and average water absorption after 4 day soaking test. Specimens compacted to maximum modified A.A.S.H.O. density at optimum moisture.

Table 20

Relationship between percentage Armac T admixture to Edina subsoil and swelling during 4 day soaking test after being immersed at optimum moisture and maximum A.A.S.H.O. density

Armac T admixture		Swell as function of time, % initial height			
% saturation B.E.C.	% dry wt. soil	24 hrs.	48 hrs.	72 hrs.	96 hrs.
0	0.00	13.31	16.06	17.35	18.30
10	1.29	2.42	3.51	4.33	5.05
25	3.22	0.84	1.13	1.36	1.53
50	6.44	0.56	0.73	0.87	0.96
75	9.66	0.51	0.69	0.78	0.87

surfaces of the clay fraction, thus reducing the hydrating tendencies of the surfaces involved. Since hydration of the clay fraction is largely responsible for the water absorption and swelling properties of soil, this conclusion can be used to explain the reduced water absorption and swelling of Edina subsoil when treated with Armac T. Reduced water absorption and swelling would naturally tend to increase the penetration resistance of a soil. Clark (14) found that the addition of cetyl pyridinium bromide did not prevent water from moving through the soil pore spaces. This seems to be substantiated in the present study by the fact that the amount of water reaching the middle of all specimens was approximately the same after 4 days soaking.

c. Unconfined compression relationships. Unconfined compression stress-strain relationships at optimum moisture and maximum modified A.A.S.H.O. density for Edina subsoil treated with varying percentages of Armac T are given in Table 21. Stress-strain curves are shown in Fig. 30. The modulus of deformation, maximum compressive strength, and axial strain corresponding to maximum axial stress were determined from the

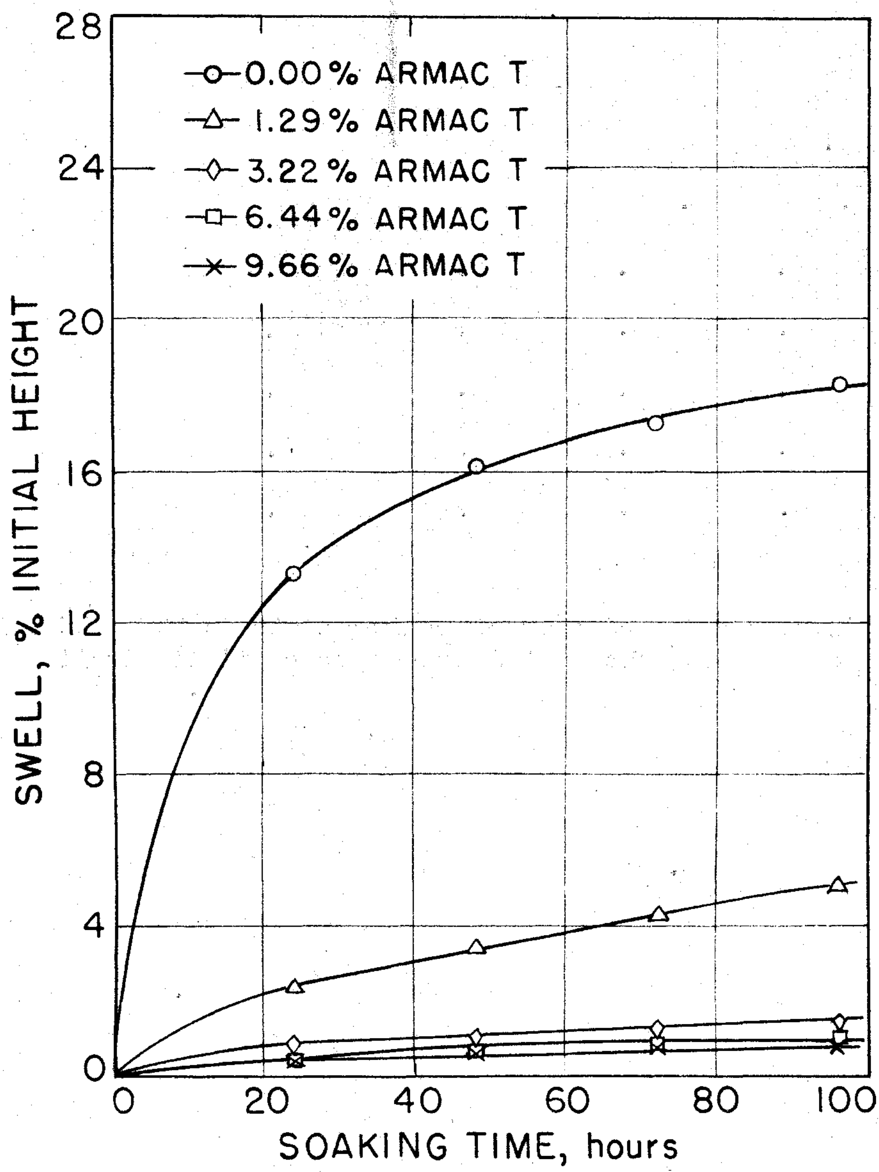

Fig. 29. Relationship between percent Armac T admixture to Edina subsoil and swelling during 4 day soaking test. Specimens compacted to maximum modified A.A.S.H.O. density at optimum moisture.

Table 21

Unconfined compression stress-strain relationships at optimum moisture and maximum modified A.A.S.H.O. density for Edina subsoil treated with varying percentages of Armac T[a]

Axial strain, $\frac{\Delta h}{h}$ in %	Axial stress as function of % (dry wt. soil) admixed Armac T, psi.				
	0.00%	1.29%	3.22%	6.44%	9.66%
0.00	00.00	00.00	00.00	00.00	00.00
0.10	15.00	15.00	13.00	08.00	10.00
0.20	30.00	30.00	26.00	16.00	20.00
0.30	45.00	45.00	39.00	24.00	30.00
0.40	60.00	60.00	52.00	32.00	40.00
0.50	75.00	75.00	65.00	40.00	50.00
0.75	113.00	113.00	98.00	61.00	61.00
1.00	140.00	140.00	125.00	78.00	66.50
1.20	155.00	154.00	140.00	85.00	68.50
1.35	164.00	162.00	150.00	87.50	68.50
1.60	178.00	172.00	163.00	89.20	64.00
1.80	187.50	179.50	171.50	89.20	57.00
2.00	196.00	184.50	178.00	84.50	50.00
2.40	212.00	194.00	191.20	65.00	
2.60	220.00	198.50	191.20	54.50	
3.00	232.00	204.50	150.00		
3.20	238.50	207.00			
3.50	246.00	194.50			
4.00	257.00	162.00			
4.80	271.00				
5.00	271.00				
5.50	254.50				
6.00	234.00				

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[a] 2 inch diameter by 4 inch high test cylinders used.

stress-strain curves. These properties are presented in Table 22 and represented by curves in Figs. 31 and 32. It will be noticed that the modulus of deformation reached a minimum value at 6.44 percent admixture of Armac T. The reason for this is not known. The maximum compressive strength of Edina subsoil was decreased by the Armac T admixtures, especially by dosages larger than 3.22 percent. Axial strain corresponding to maximum axial stress was also reduced by Armac T admixtures. It will

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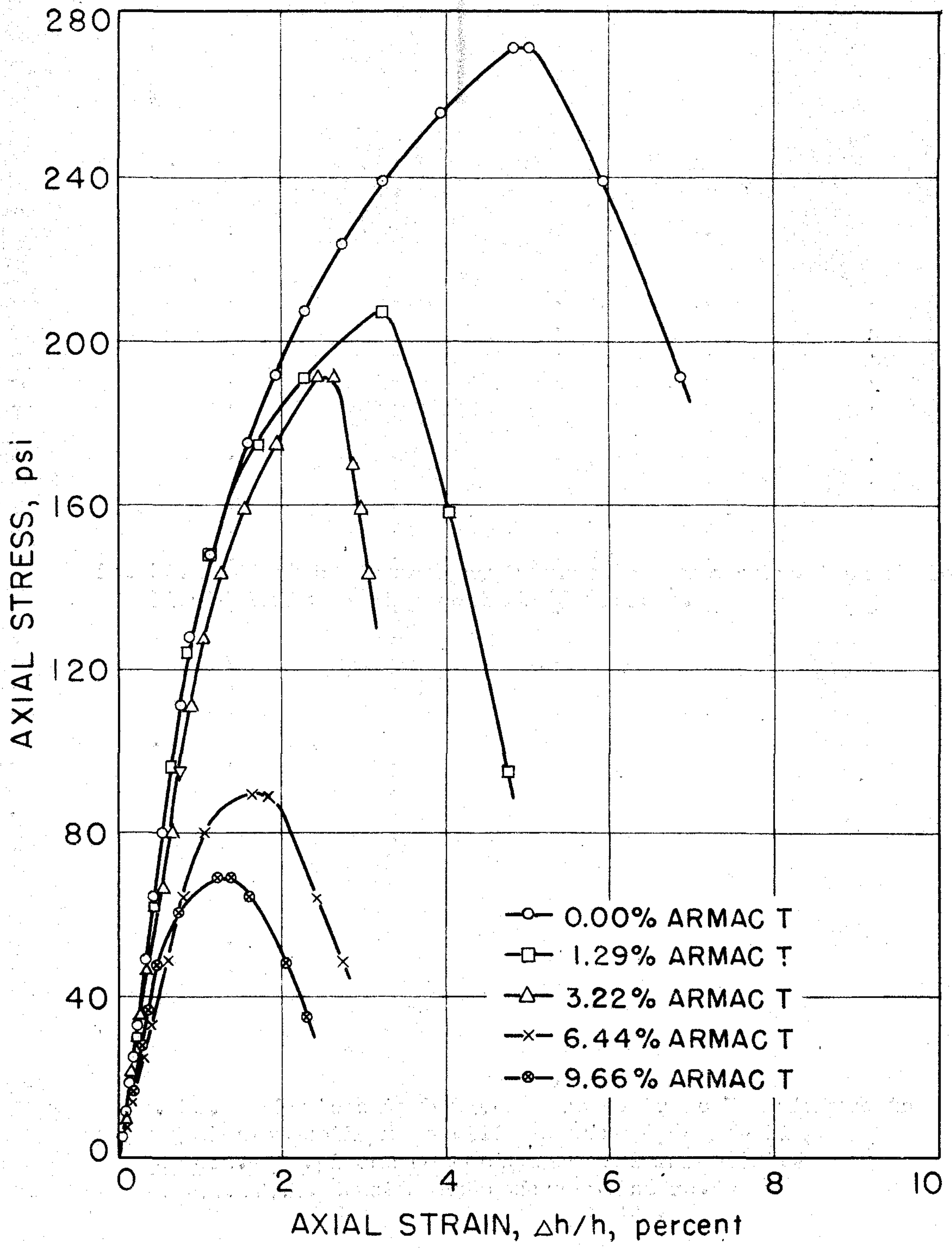

Fig. 30. Optimum moisture and maximum modified A.A.S.H.O. density unconfined compression stress-strain curves for Edina subsoil treated with varying percentages of Armac T.

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Table 22

Optimum moisture and maximum modified A.A.S.H.O. density stress-strain properties of Edina subsoil treated with varying percentages of Armac T[a]

Armac T admixture		Modulus of deformation, psi.	Maximum compressive strength, psi.	Axial strain at max. axial stress, $\frac{\Delta h}{h}$ in %
% saturation B.E.C.	% dry wt. soil			
0	0.00	15000	271.00	4.80
10	1.29	15000	207.00	3.20
25	3.22	13200	191.20	2.40
50	6.44	8200	89.20	1.60
75	9.66	10000	68.50	1.20

[a] Based on unconfined compression tests.

be noted from the curve in Fig. 32 that the rate of decrease was considerably less for admixtures larger than about 1.29 percent.

Sketches of the failure planes of the 2 inch diameter by 4 inch high test cylinders are shown in Fig. 33. The magnitude of the angle of failure, α , was measured with a protractor and is indicated on the sketches. Internal friction angles, ϕ , corresponding to angles of failure were obtained by use of the Mohr strength theory formula previously discussed. The internal friction angles were then used in conjunction with Mohr circles for the maximum unconfined compressive strengths of the test cylinders to determine values of cohesion, c. This graphical procedure is shown in Fig. 34.

The strength properties of Armac T treated Edina subsoil, as determined in the above manner, are summarized in Table 23. Shearing strength values are based on the empirical relationship that the shearing strength equals one-half the maximum unconfined compressive

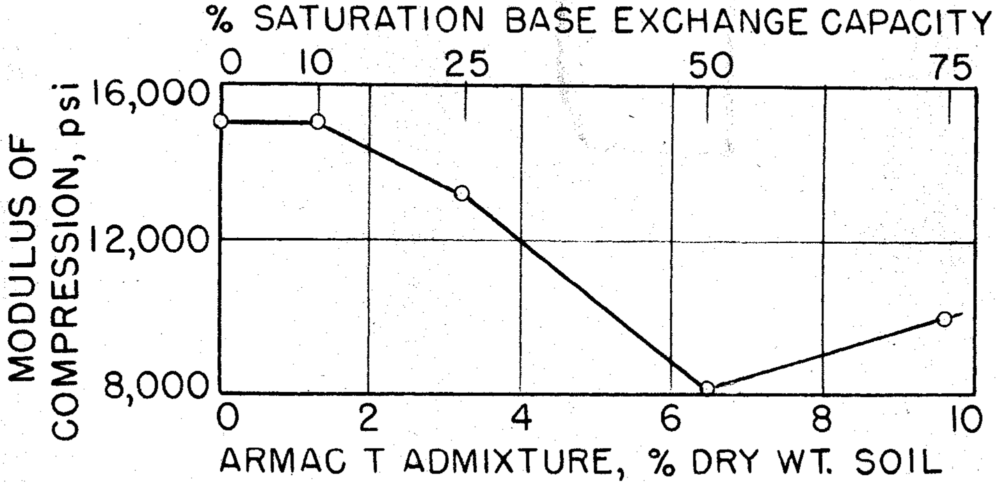


Fig. 31. Effect of Armac T admixtures to Edina subsoil on its modulus of deformation as determined by unconfined compression tests on specimens compacted to maximum modified A.A.S.H.O. density at optimum moisture.

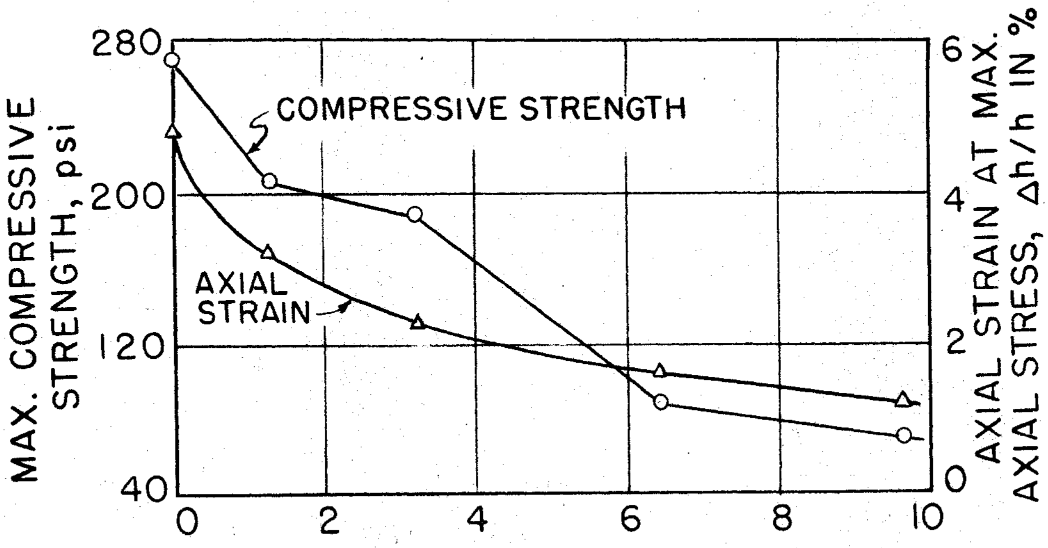
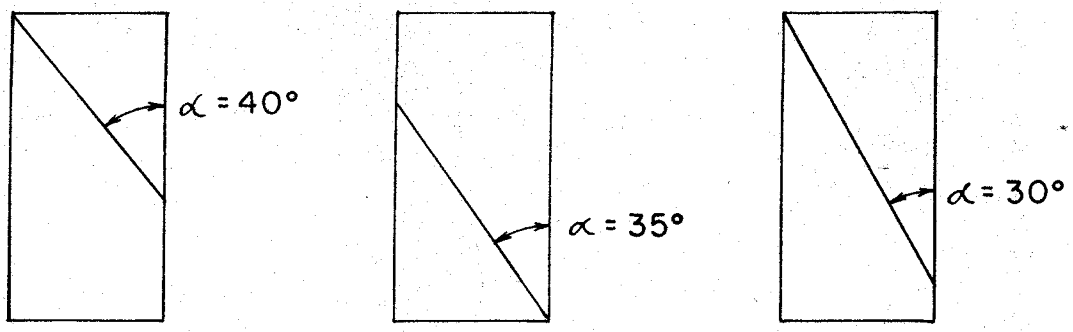


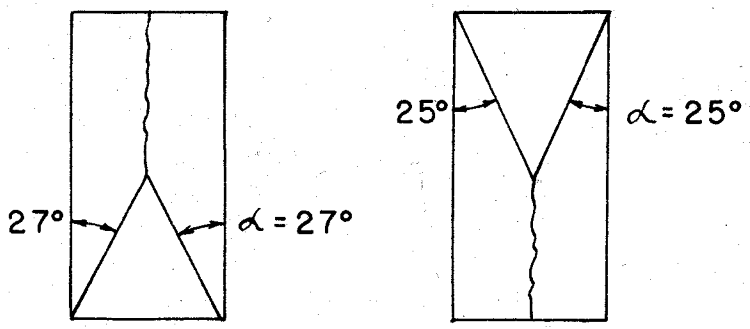
Fig. 32. Effect of Armac T admixtures to Edina subsoil on its maximum compressive strength and corresponding axial strain as determined by unconfined compression tests on specimens compacted to maximum modified A.A.S.H.O. density at optimum moisture.



(a) EDINA SUBSOIL WITH 0 PERCENT ARMAC T.

(b) EDINA SUBSOIL WITH 1.29 PERCENT ARMAC T.

(c) EDINA SUBSOIL WITH 3.22 PERCENT ARMAC T.



(d) EDINA SUBSOIL WITH 6.44 PERCENT ARMAC T.

(e) EDINA SUBSOIL WITH 9.66 PERCENT ARMAC T.

Fig. 35. Unconfined compression test failure planes of 2 inch diameter by 4 inch high Armac T treated Edina subsoil cylinders compacted to maximum modified A.A.S.H.O. density at optimum moisture.

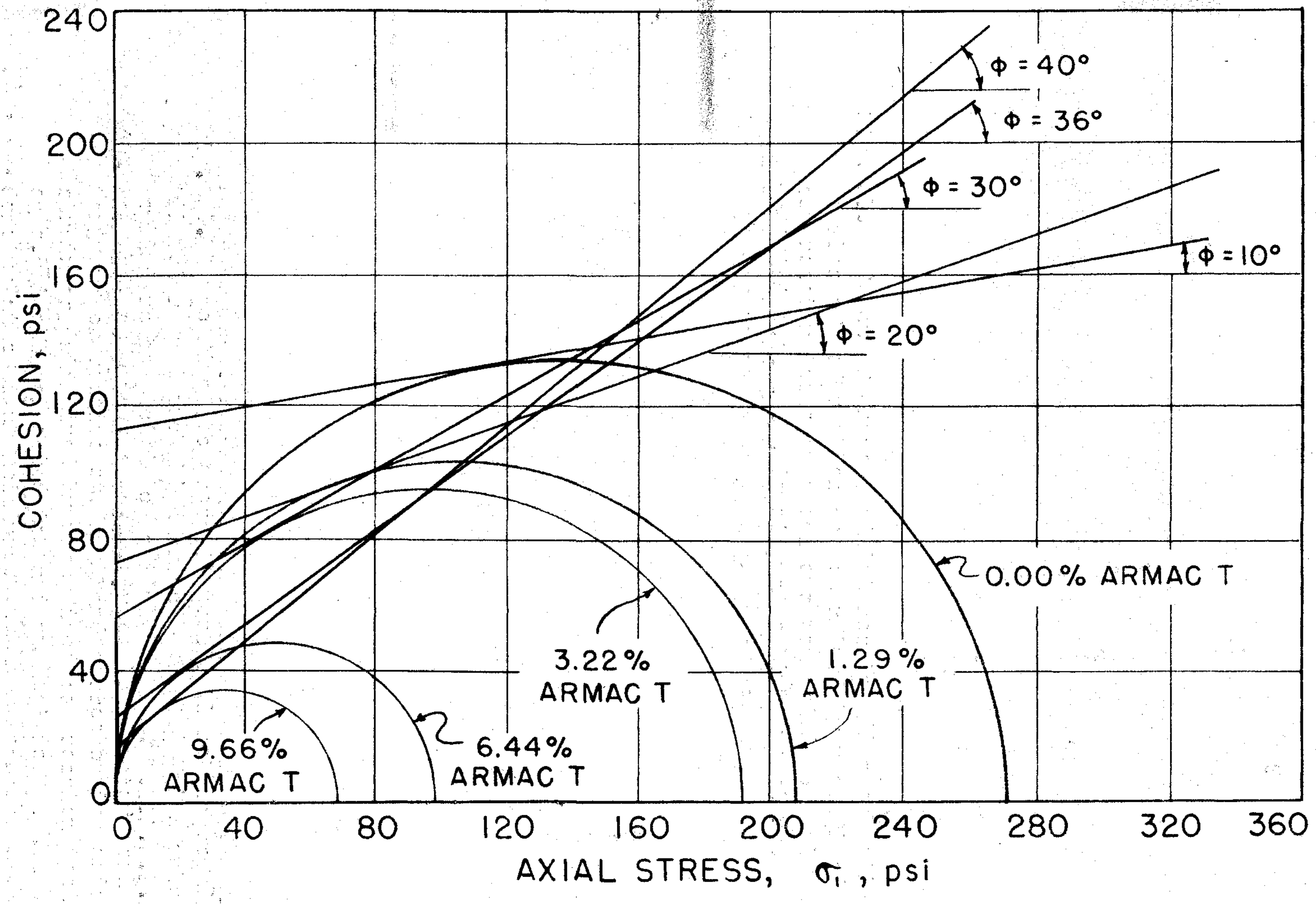


Fig. 34. Graphical determination of cohesion at optimum moisture and maximum modified A.A.S.H.O. density by means of Mohr circles for unconfined compression tests of Edina subsoil specimens treated with varying percentages of Armac T.

Table 23

Optimum moisture and maximum modified A.A.S.H.O. density strength properties of Edina subsoil treated with varying percentages of Armac T[a]

Armac T admixture		Angle of failure, α, degrees	Internal friction angle, ϕ, degrees	Cohesion, c, psi.	Shearing strength[b], psi.
% saturation B.E.C.	% dry wt. soil				
0	0.00	40	10	114.00	135.50
10	1.29	35	20	72.00	103.50
25	3.22	30	30	55.50	95.60
50	6.44	27	36	25.50	44.60
75	9.66	25	40	16.50	34.25

[a] Based on unconfined compression tests.

[b] Based on empirical relationship that the sheering strength = $\frac{1}{2}$ maximum compressive strength.

strength (32). The results presented in Table 23 are shown by curves in Figs. 35 and 36. Fig. 35 indicates that as the amount of Armac T added to Edina subsoil was increased, the magnitude of the internal friction angle increased and the magnitude of the cohesion decreased. From Fig. 36 it is apparent that the shearing strength of Edina subsoil was decreased by admixtures of Armac T, especially by those larger than 3.22 percent.

The physical appearance of the soaked set of test cylinders after 24 hours in water is shown by Fig. 37. The cylinder containing zero percent Armac T disintegrated during the first 12 hours. With the exception of a few faint cracks in the specimen containing 1.29 percent Armac T, the cylinders showed no ill effects due to immersion.

Unconfined compression stress-strain relationships for the water soaked specimens are given in Table 24. Stress-strain curves are shown

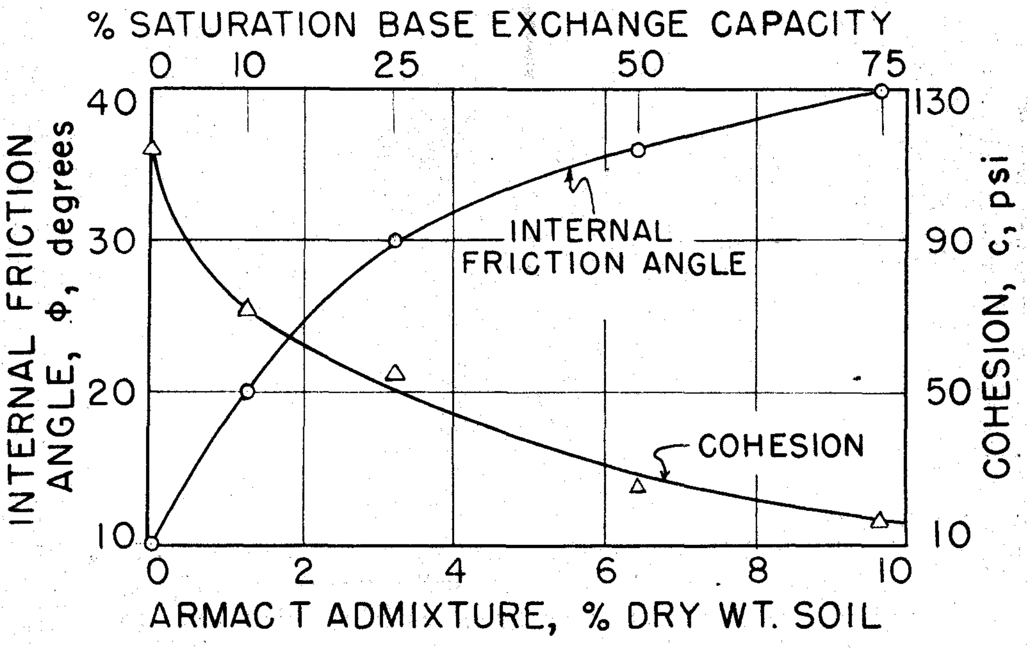


Fig. 35. Effect of Armac T admixtures to Edina subsoil on its internal friction angle and cohesion based on unconfined compression tests at optimum moisture and maximum modified A.A.S.H.O. density.

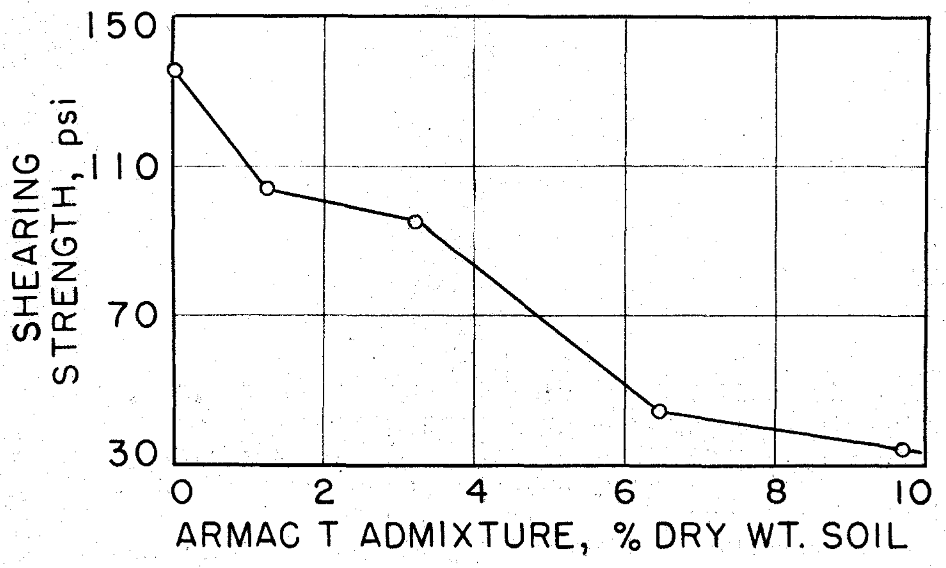


Fig. 36. Effect of Armac T admixtures to Edina subsoil on its shearing strength based on unconfined compression tests at optimum moisture and maximum modified A.A.S.H.O. density.

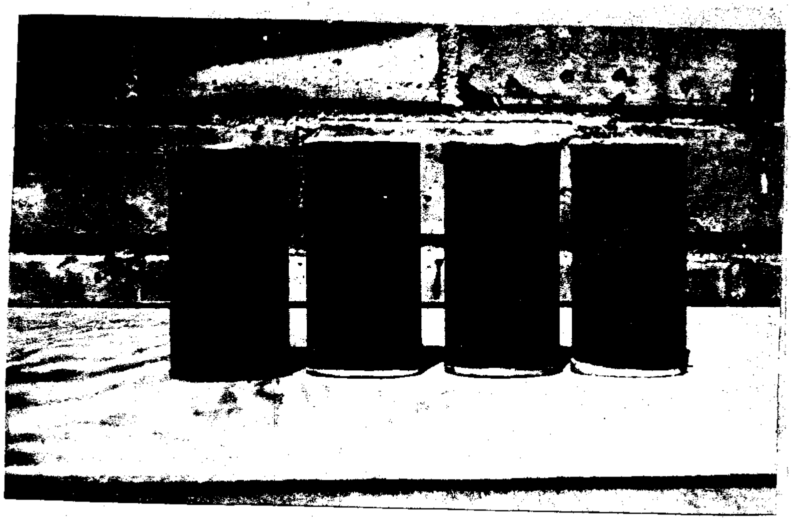


Fig. 37. View of 2 inch by 4 inch Armac T treated Edina subsoil cylinders, compacted at optimum moisture to maximum modified A.A.S.H.O. density, after soaking 24 hours in water. The cylinders contained (left to right) 1.29, 3.22, 6.44, and 9.66% chemical by dry soil weight.

Table 24

Unconfined compression stress-strain relationships for Edina subsoil treated with varying percentages of Armac T after soaking cylinders molded at optimum moisture and maximum modified A.A.S.H.O. density 24 hours in water[a]

Axial strain, $\frac{\Delta h}{h}$ in %	Axial stress as function of % (dry wt. soil) admixed Armac T, psi. 0.00%	1.29%	3.22%	6.44%	9.66%
0.00		0.00	0.00	0.00	0.00
0.10		3.60	4.70	4.20	4.20
0.20		7.20	9.40	8.40	8.40
0.30		10.80	14.10	12.60	12.60
0.40		14.40	18.80	16.80	16.80
0.50		18.00	23.50	21.00	21.00
0.75		27.00	35.25	31.50	29.75
1.00		36.00	47.00	42.00	34.00
1.25		45.00	58.75	51.00	36.00
1.45		51.50	68.50	56.00	36.60
1.75		62.00	79.75	60.50	35.00
2.00		68.75	84.75	60.50	
2.40		78.50	89.20	51.50	
2.75		84.00	78.50	37.00	
3.10		86.00			
3.50		83.00			
4.00		75.50			

[a] 2 inch diameter by 4 inch high test cylinders used.

in Fig. 38. Water absorption, modulus of deformation, maximum compressive strength, and axial strain data are summarized in Table 25 and shown by curves in Figs. 39 and 40. It is apparent that increasing the dosage of Armac T to 3.22 percent caused a relatively large reduction in water absorption by Edina subsoil. It will be noted also that the Edina subsoil specimen containing 3.22 percent Armac T had the highest soaked modulus of deformation and the highest soaked compressive strength. Comparison of the data in Table 25 and Table 22 reveals that the axial strain values corresponding to maximum axial stress were relatively unaffected by the soaking. Maximum compressive strength values, however, were considerably

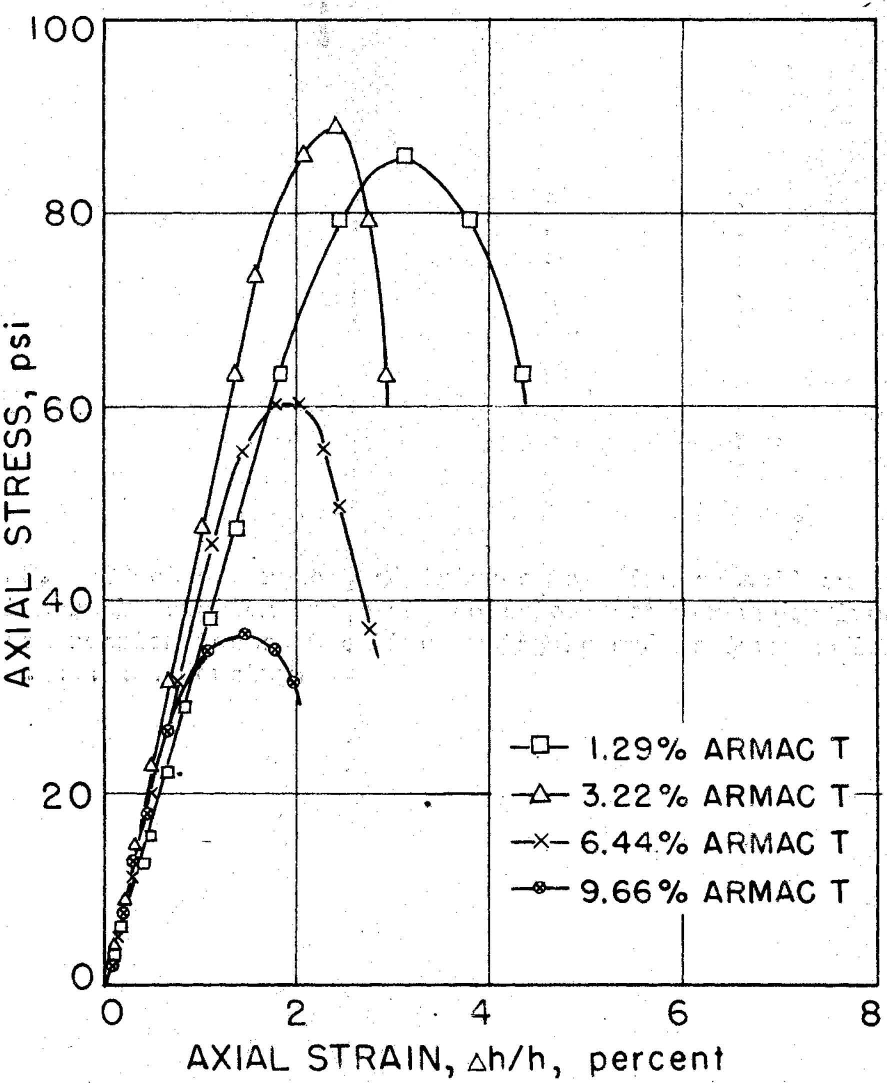


Fig. 38. Unconfined compression stress-strain curves for Edina subsoil treated with varying percentages of Armac T after soaking specimens molded at optimum moisture and maximum modified A.A.S.H.O. density for 24 hours in water.

Table 25

Water absorption and unconfined compression stress-strain properties of Armac T treated Edina subsoil after immersion at optimum moisture and maximum modified A.A.S.H.O. density for 24 hours

Armac T admixture		Water absorption, % dry wt. mixture	Modulus of deformation, psi.	Maximum compressive strength, psi.	Axial strain at max. axial stress, $\frac{\Delta h}{h}$ in %
% saturation B.E.C.	% dry wt. soil				
0	0.00	--	--	--	--
10	1.29	4.72	3500	86.00	3.10
25	3.22	2.83	4650	89.20	2.40
50	6.44	1.95	4300	60.50	1.75
75	9.66	1.87	4300	36.60	1.45

reduced, with the reduction in strength greatest for specimens containing the lower percentages of Armac T. Modulus of deformation values were also greatly reduced by soaking the optimum moisture cylinders.

The unconfined compression test failure planes of the soaked cylinders are shown by Fig. 41, together with measured values of the angle of failure. Internal friction angles were computed from the angles of failure as previously described. Fig. 42 shows the graphical determination of cohesion values.

Unconfined compression strength properties of the soaked specimens are summarized in Table 26 and shown in curve form by Figs. 43 and 44. It will be noted that the cylinder containing 3.22 percent Armac T had the greatest cohesion and shearing strength, but that these values were only slightly higher than those of the cylinder containing 1.29 percent. Comparison of the data in Table 26 and Table 23 reveals that the internal friction angle of the specimen treated with 1.29 percent Armac T was

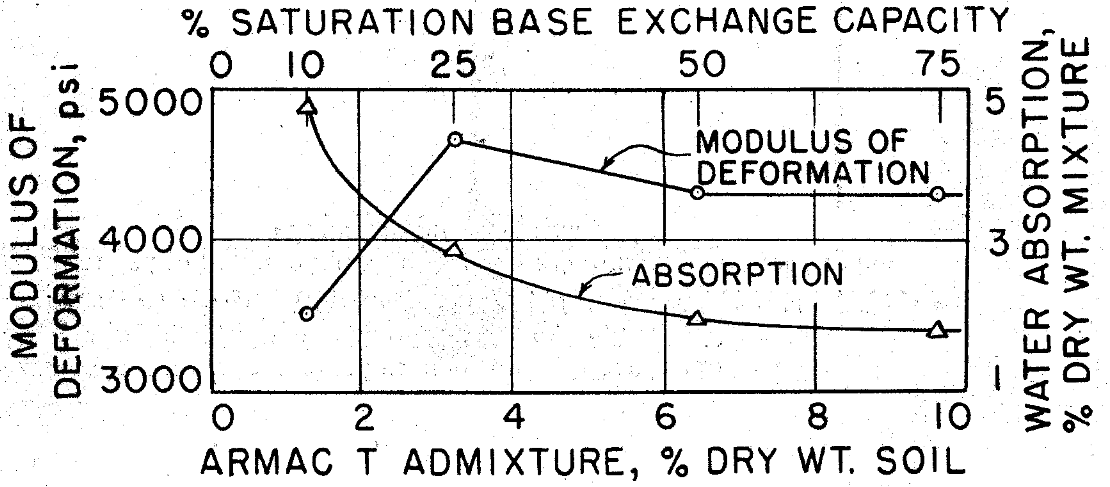


Fig. 39. Water absorption and unconfined compression modulus of deformation of Armac T treated Edina subsoil after soaking specimens molded at optimum moisture and maximum modified A.A.S.H.O. density for 24 hours in water.

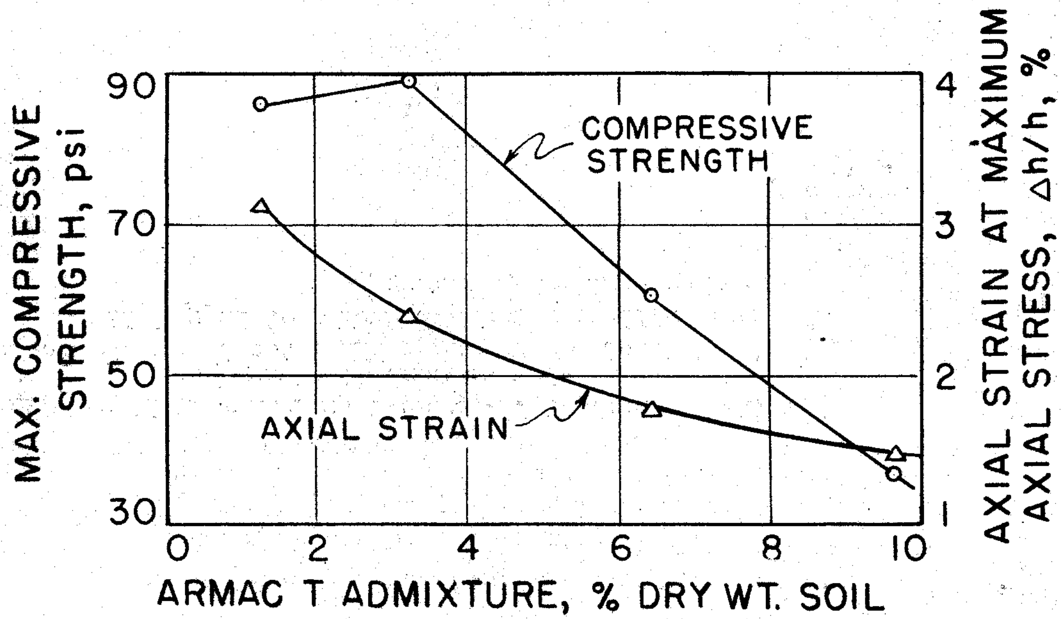
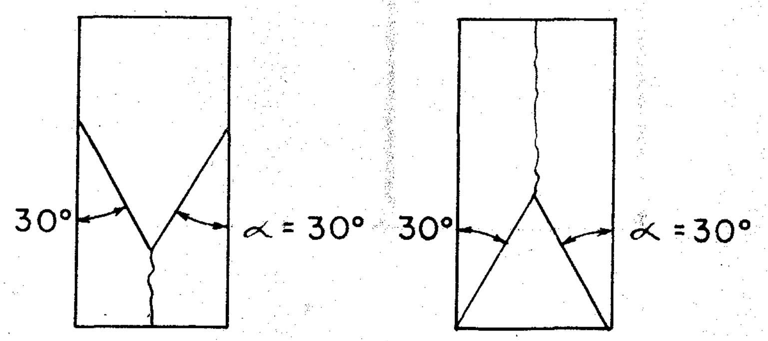
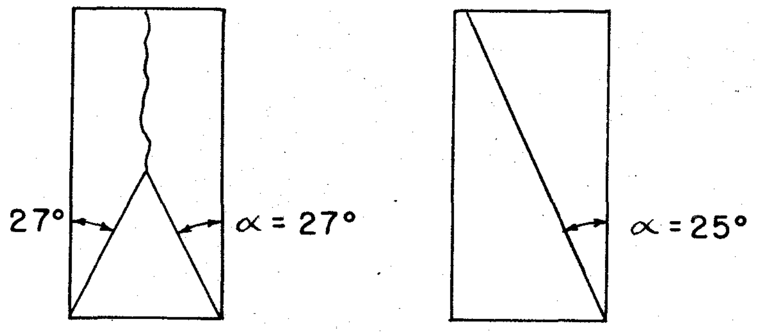


Fig. 40. Unconfined compression maximum compressive strength and corresponding axial strain of Armac T treated Edina subsoil after soaking specimens molded at optimum moisture and maximum modified A.A.S.H.O. density for 24 hours in water.



(a) EDINA SUBSOIL WITH 1.29 PERCENT ARMAC T.

(b) EDINA SUBSOIL WITH 3.22 PERCENT ARMAC T.



(c) EDINA SUBSOIL WITH 6.44 PERCENT ARMAC T.

(d) EDINA SUBSOIL WITH 9.66 PERCENT ARMAC T.

Fig. 41. Unconfined compression test failure planes of 2 inch diameter by 4 inch high Armac T treated Edina subsoil cylinders after being soaked in water for 24 hours. Specimens compacted to maximum modified A.A.S.H.O. density at optimum moisture.

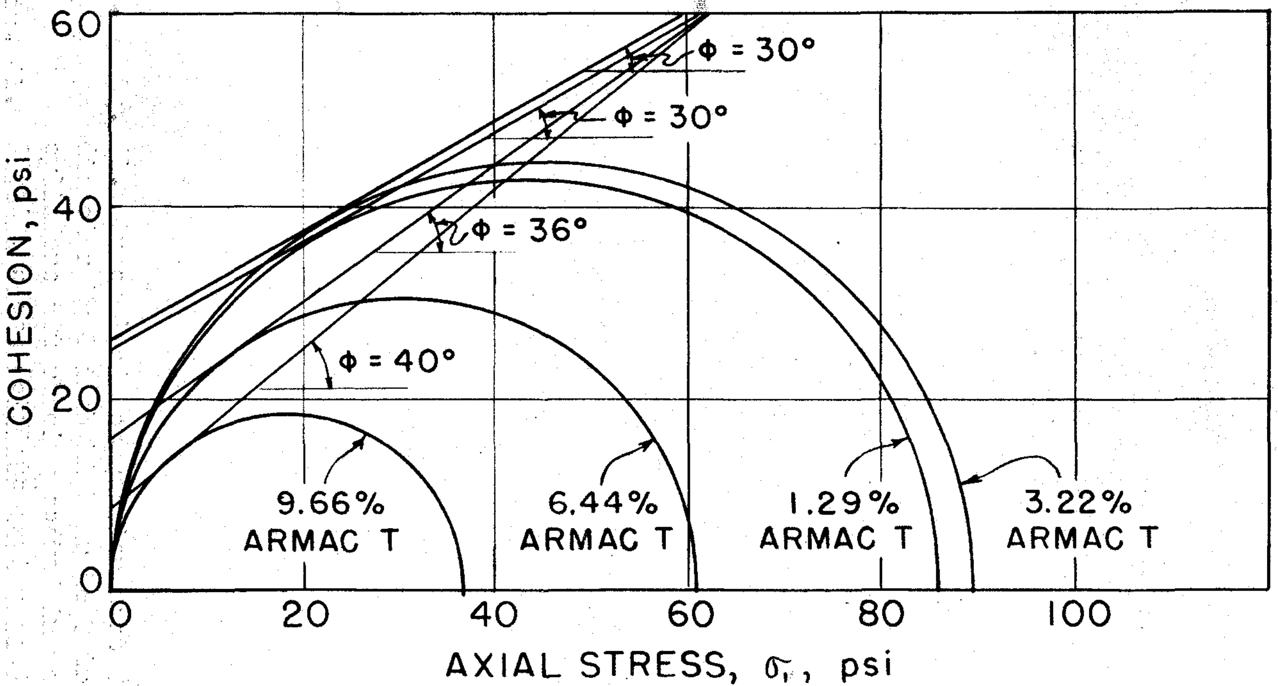


Fig. 42. Graphical determination of cohesion by means of Mohr circles for unconfined compression tests of Armac T treated Edina subsoil cylinders after 24 hours soaking in water. Specimens compacted to maximum modified A.A.S.H.O. density at optimum moisture.

Table 26

Unconfined compression test strength properties of Armac T treated Edina subsoil after water soaking at optimum moisture and maximum modified A.A.S.H.O. density for 24 hours

Armac T admixture		Angle of failure, α, degrees	Internal friction angle, ϕ, degrees	Cohesion, c, psi.	Shearing strength[a], psi.
% saturation B.E.C.	% dry wt. soil				
0	0.00	--	--	--	--
10	1.29	30	30	25.00	43.00
25	3.22	30	30	26.00	44.60
50	6.44	27	36	15.75	30.25
75	9.66	25	40	8.75	18.50

[a] Based on empirical relationship that the shearing strength = $\frac{1}{2}$ maximum compressive strength.

reduced by soaking, but that internal friction angles of the other cylinders were unchanged. However, both the cohesion and shearing strength of each treated cylinder was considerably reduced by the 24 hours immersion.

The explanation previously given to explain loss of relative air dry strength can also be used to explain the decrease in optimum moisture shearing strength, namely, that adsorption of Armac T on the clay surfaces interfered with the formation of continuous water films which are necessary for development of cohesion. Increase of the internal friction angle by Armac T admixtures was not sufficient to compensate for the loss of cohesion. When optimum moisture cylinders were soaked in water, however, the role of Armac T in reducing absorption and swelling prevented disintegration of the treated specimens. The absorption that did take place apparently increased the thickness of the optimum moisture water films to the extent that cohesion was decreased. This would

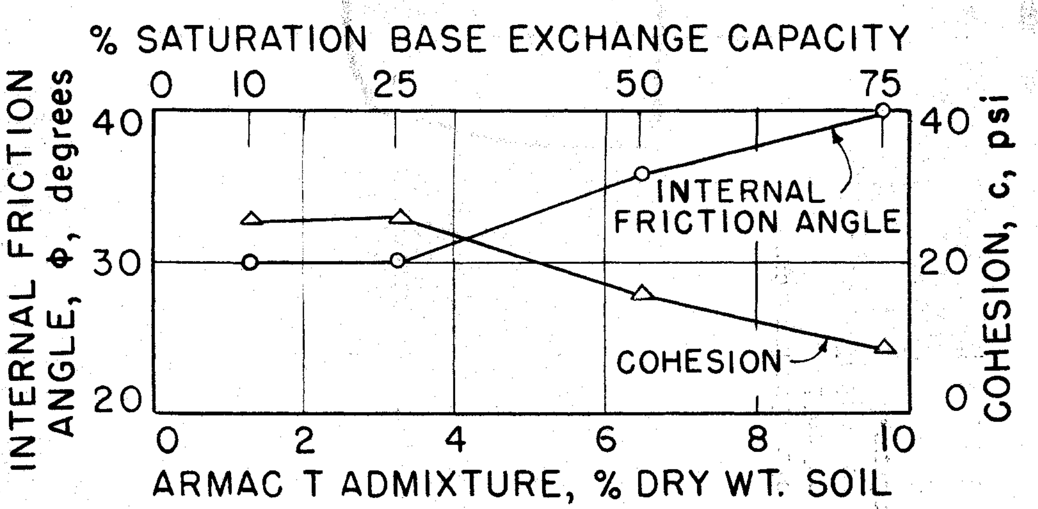


Fig. 43. Effect of Armac T admixtures to Edina subsoil on its internal friction angle and cohesion based on unconfined compression tests after water soaking for 24 hours. Specimens compacted to maximum modified A.A.S.H.O. density at optimum moisture.

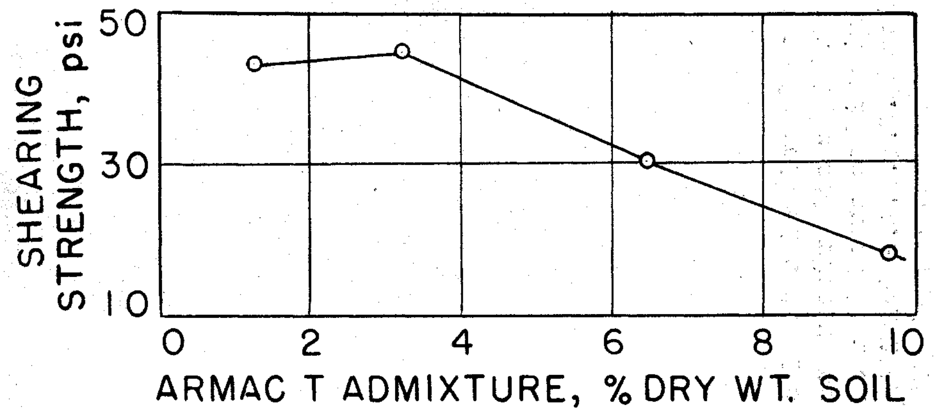


Fig. 44. Effect of Armac T admixtures to Edina subsoil on its shearing strength based on unconfined compression tests after water soaking 24 hours. Specimens compacted to maximum modified A.A.S.H.O. density at optimum moisture.

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explain the lower shearing strengths observed for the soaked cylinders.

From the standpoint of shearing strength and modulus of deformation, there appears to be an optimum Armac T admixture for soils that need protection from water. For Edina subsoil under the test conditions employed, 3.22 percent was the amount found to be most effective.

d. <u>pH value</u>. The effect of Armac T admixtures to Edina subsoil on its pH value is shown in Table 27 and in Fig. 45a. It will be noted that all mixtures were acid. The addition of the cationic material did not noticeably affect the dispersability of the soil which was initially in the partially dispersed state.

Table 27

Effect of Armac T admixtures to Edina subsoil on pH and water holding properties

Armac T admixture % saturation B.E.C.	 % dry weight soil	Hygroscopic moisture, % dry wt. mixture	C.M.E.[a], % dry weight mixture	pH
0	0.00	7.02	29.7	4.9
10	1.29	5.90	28.1	5.0
25	3.22	4.62	25.2	5.4
50	6.44	3.94	18.4	5.2
75	9.66	3.64	17.6	5.2

[a] All C.M.E. values are the average of 2 determinations.

e. <u>Centrifuge moisture equivalent</u>. The effect of Armac T on the centrifuge moisture equivalent of Edina subsoil is shown in Table 27. The curve in Fig. 45b indicates that additions of this cationic material up to 6.44 percent decreased the C.M.E. considerably, but that further increase in the amount of chemical admixture had relatively little added effect. These results are further evidence that Armac T decreases the

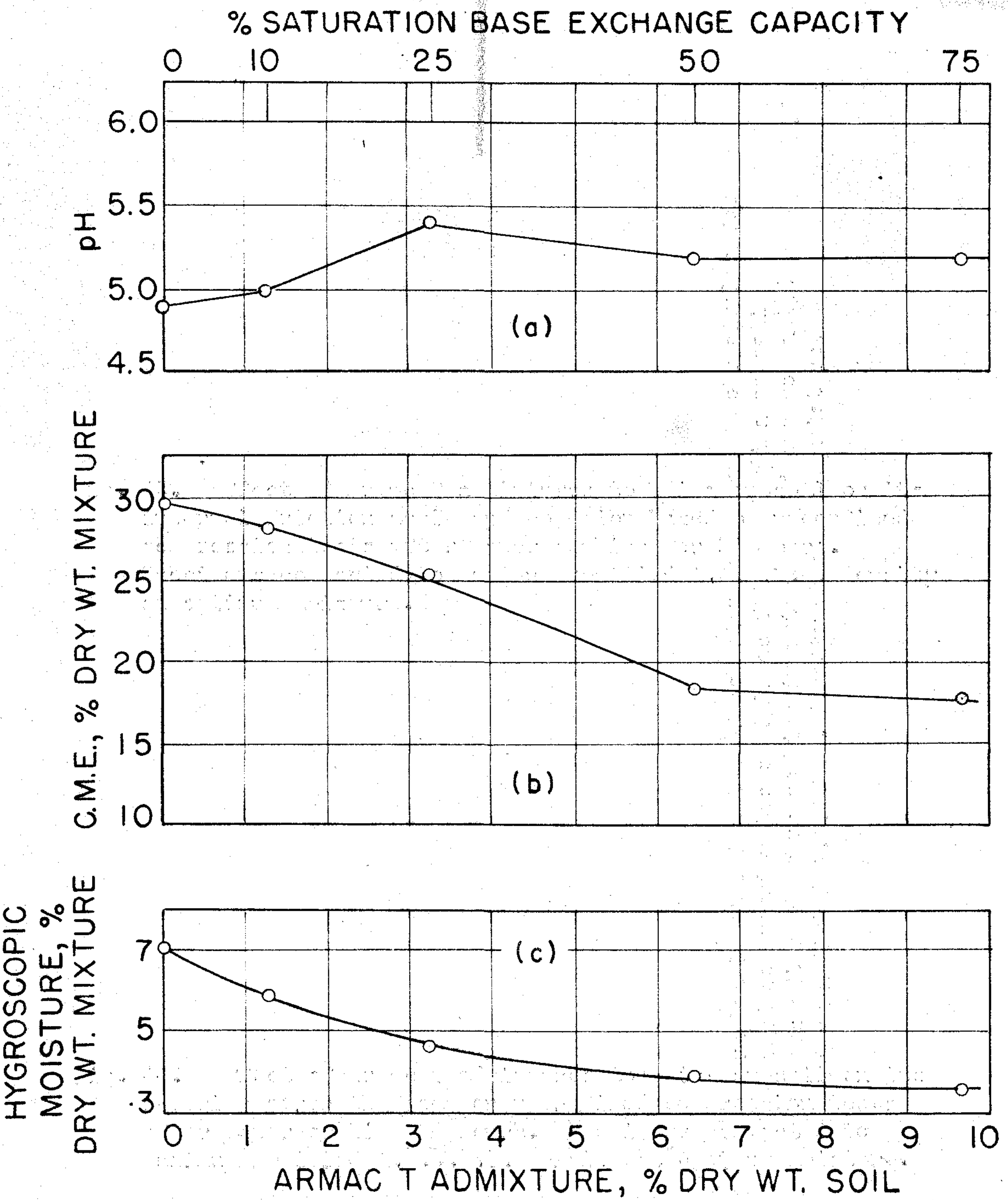

Fig. 45. Effect of Armac T admixtures to Edina subsoil on its pH and water-holding properties.

water holding capacity of Edina subsoil.

f. Hygroscopic moisture content. The effectiveness of Armac T in reducing the hygroscopic moisture affinity of Edina subsoil is shown in Table 27. It will be noted in Fig. 45c that increasing the dosage over 6.44 percent had relatively little added effect.

g. Water solubility. The results of the qualitative determination of the extent to which Armac T could be washed out of air dry Edina subsoil with distilled water are shown in Table 28. A comparison of the properties of washed and unwashed samples of the same mixture, keeping in mind the experimental accuracy of the tests used to determine these properties, indicates that very little if any Armac T was removed. The

Table 28

Effect of washing air dry Armac T treated Edina subsoil with distilled water on the effectiveness of Armac T, as indicated by some soil properties related to stability

Test	Edina subsoil with 3.22% (dry wt. soil) Armac T	
	Unwashed	Washed[a]
Liquid limit, % dry weight mixture	47.8	46.5
Plastic limit, % dry weight mixture	36.5	33.7
Plasticity index, % dry weight mixture	11.3	12.8
Shrinkage limit, % dry weight mixture	13.1	12.4
Shrinkage ratio	1.66	1.73
S.L. ÷ L.L., %	27.4	26.6
L.L. ÷ % clay (5 micron)	0.91	0.89
Relative air dry strength, psi.	2120	2130
Slaking value, min.	Didn't fail	Didn't fail

[a] Edina subsoil with 3.22% Armac T admixture was soaked in distilled water for 24 hours with occasional stirring and then leached 50 times in a Buchner funnel with 100 c.c. portions of distilled water.

slaking pat prepared from the washed material is shown in Fig. 46 after 7 days immersion. The slaking pat prepared from the unwashed material is shown in Fig. 20 (25 percent saturation Armac T pat) after a similar period of immersion.

C. Effect of Type of Clay Mineral and Kind of Inorganic Cations Present

The purpose of this phase of the investigation was to determine the effect of the predominant type of clay mineral and kind of inorganic cations present on the performance of Armac T as a soil stabilizing agent.

1. Materials

a. Soils. Two synthetic soils were prepared for this study so that the predominant type of clay mineral would be known. Florida kaolin was used as the clay fraction of one, and Wyoming bentonite for the other. They will be referred to hereafter as the kaolinite and montmorillonite soils, respectively.

The gradations of the 2 synthetic soils are shown in Table 29, and their grain size distribution curves in Fig. 47. The non-clay fraction of the kaolinite soil was Des Moines River sand which had been treated with several dosages of hydrogen peroxide to remove organic matter. Clean Ottawa sand was used in preparing the non-clay portion of the montmorillonite soil. Both clays were mixed with enough distilled water to satisfy their hydration requirements and then allowed to soak for 48 hours before mixing with the non-clay size material. Mixing was accomplished by hand in large pans. After air drying, the synthetic soils were ground with mortar and pestle to pass the No. 40 sieve.

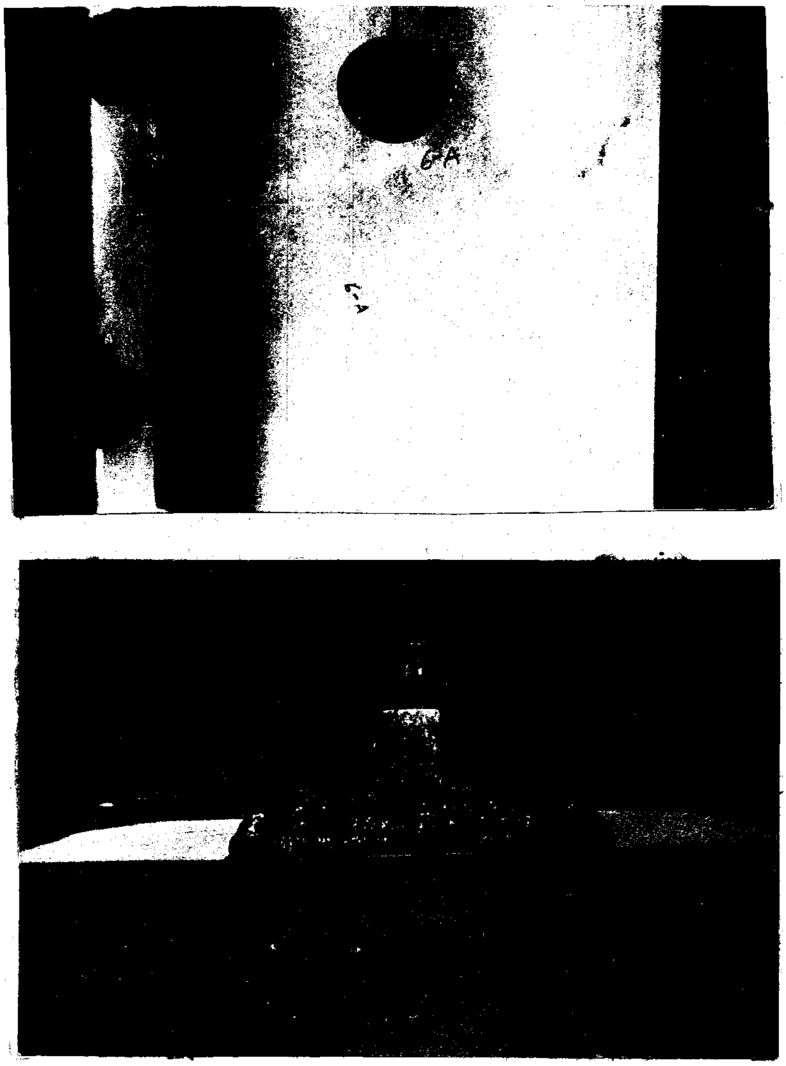

Fig. 46. Top and side views of slaking pat prepared from washed 3.22% (by dry soil wt.) Armac T treated Edina subsoil after being soaked in water for 7 days.

Table 29

Grain size distribution for synthetic kaolinite and montmorillonite soils[a]

Sieve number	Equivalent spherical diameter, mm.	Percent finer by dry soil weight	
		Kaolinite soil	Montmorillonite soil
40	0.420	100.00	100.00
60	0.250	100.00	81.50
100	0.147	75.50	65.00
150	0.104	64.50	56.00
200	0.074	56.50	48.50
270	0.050	50.00	41.40
	0.005	36.90	18.70
	0.002	28.50	15.30
	0.001	23.00	12.50
	0.0002	7.00	9.00
	0.0001	1.50	7.00

[a] Values taken from plotted grain size distribution curves.

The cationic nature of the Florida kaolin was not known. The Wyoming bentonite contained predominantly sodium cations, and the synthetic soil containing it will be referred to in this study as Na-montmorillonite soil. In order to study the effect of kind of inorganic cations present on the performance of Armac T, samples of the Na-montmorillonite soil were converted into what will be referred to herein as hydrogen- and calcium-montmorillonite soils.

As the first step in converting to H- and Ca-montmorillonite soils, 500 grams of the Na-montmorillonite soil were added to 5000 c.c. of 0.1 N HCl. With occasional shaking and stirring, the sample was allowed to soak for 48 hours, then allowed to settle out. After syphoning off the clear supernatant liquid, the soil was washed onto filter paper in Buchner funnels to which suction was applied by means of an aspirator. The material deposited in the funnels was then leached 5 times with 100

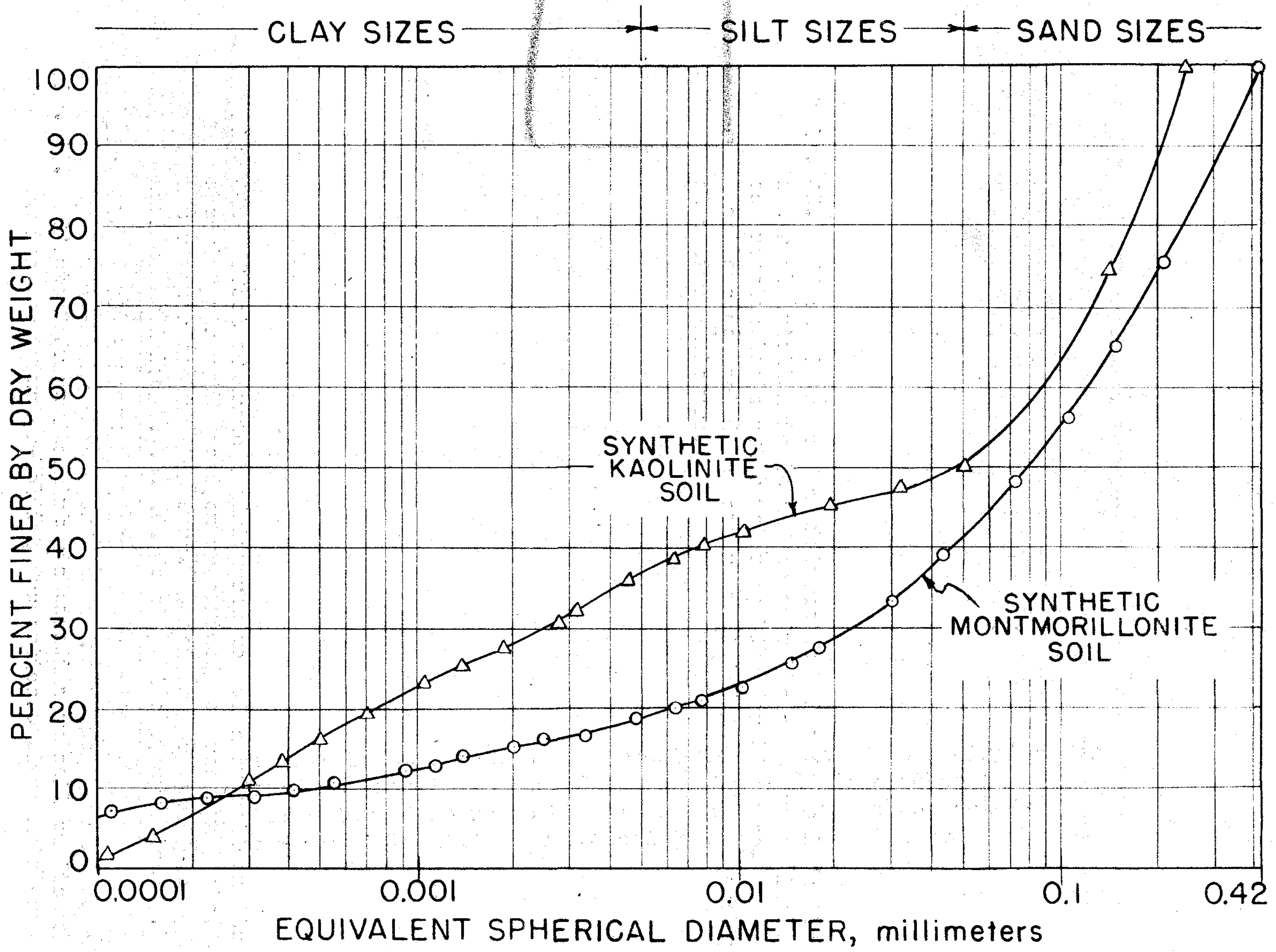

Fig. 47. Grain size distribution curves for synthetic kaolinite and montmorillonite soils.

c.c. portions of 0.1 N HCl followed by several leachings with distilled water to remove soluble ions. When the movement of water through the samples by suction slowed, the washing out of soluble ions was continued by means of a long-armed centrifuge. After air drying, the H-montmorillonite soil was ground with mortar and pestle to pass the No. 40 sieve and 250 grams stored for testing.

The remaining 250 gram sample of air dry H-montmorillonite soil was added to approximately 3000 c.c. of filtered limewater which had been prepared by soaking 5 grams of dehydrated lime (CaO) in 3000 c.c. of distilled water for 14 days. The soil was kept in the limewater for 48 hours with intermittent shaking and stirring, after which it was allowed to settle out and the clear supernatant liquid syphoned off. Following 3 washings in a large crock with 3000 c.c. portions of distilled water to remove soluble ions, the Ca-montmorillonite soil was air dried and then ground with mortar and pestle to pass the No. 40 sieve.

b. Cationic chemical. Armac T was the only cationic chemical used. It has been described in section A of this investigation.

2. Method of procedure

a. Addition of Armac T. Armac T was mixed with the synthetic soils following the same procedure used in mixing it with Edina subsoil. The base exchange capacities of the synthetic soils were not known and Armac T admixtures were made on a percent by dry weight of the soil basis. The admixtures made were 1 and 3 percent for the kaolinite and Na-montmorillonite soils, and one percent for the H- and Ca-montmorillonite soils.

b. Tests. The tests and ratios used to evaluate the performance of Armac T with the synthetic soils were the same as those previously used and described in section A, namely: (1) liquid limit, (2) plastic limit, (3) plasticity index, (4) shrinkage limit, (5) shrinkage ratio, (6) ratio of shrinkage limit to liquid limit, (7) ratio of liquid limit to clay content, (8) relative air dry strength, and (9) rate of slaking.

3. Presentation and discussion of results

a. Synthetic kaolinite soil

(1) Atterburg limits. The effect of Armac T admixtures on the liquid limit, plastic limit, and plasticity index of the kaolinite soil is shown in Table 30 and by curves in Fig. 48. It will be noted that both the liquid limit (Fig. 48a) and plastic limit (Fig. 48b) were increased by the cationic material. This was contrary to the action of

Table 30

Effect of Armac T admixtures to the synthetic kaolinite soil on some soil properties related to stability

Test	Armac T admixture, % dry soil wt.		
	0.0	1.0	3.0
Liquid limit, % dry wt. mixture	29.2	35.4	39.0
Plastic limit, % dry wt. mixture	19.0	26.2	32.5
Plasticity index, % dry wt. mixture	10.2	9.2	6.5
Shrinkage limit, % dry wt. mixture	13.6	17.8	19.8
Shrinkage ratio	1.80	1.63	1.50
S.L. L.L., %	46.5	50.3	50.8
L.L. % clay (5 micron)	0.79	0.96	1.06
Relative air dry strength, psi.	420	80	40
Slaking value, min.	6.0	Didn't fail	Didn't fail

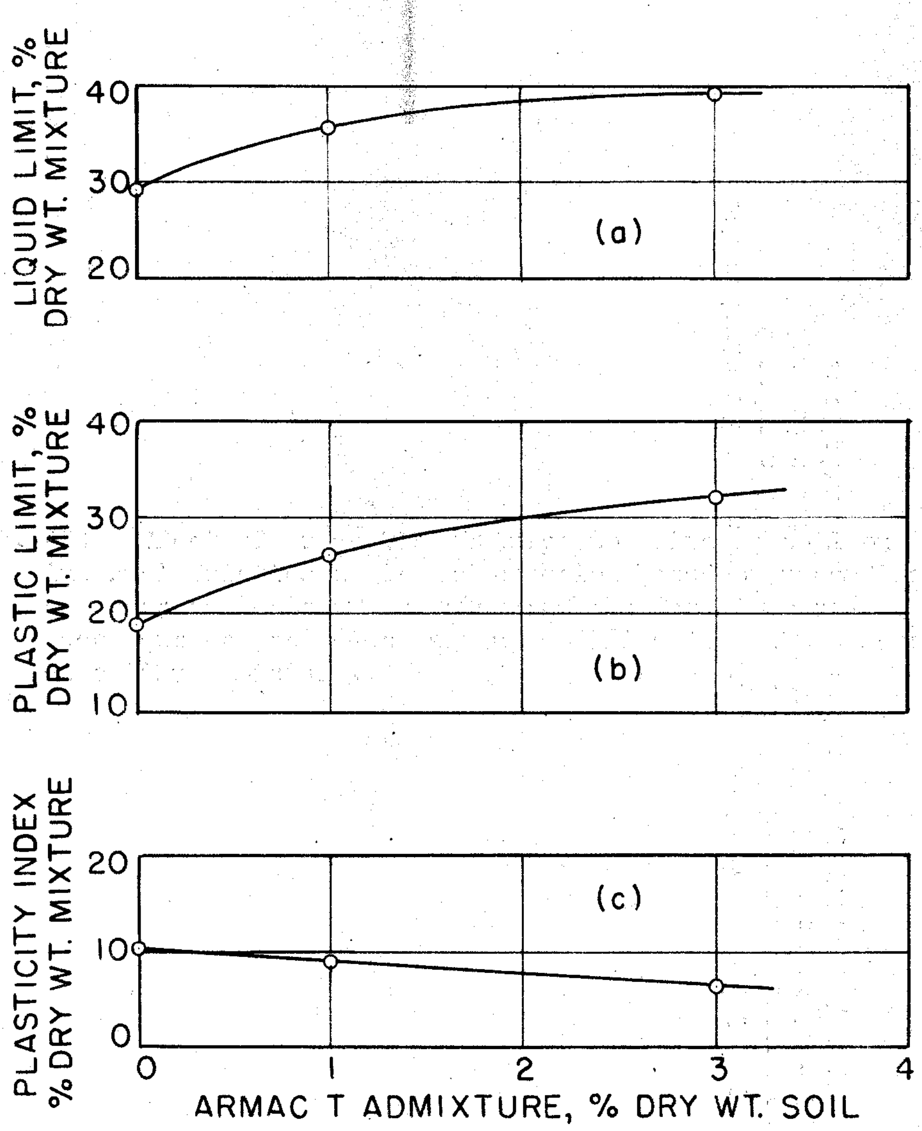

Fig. 48. Relationship between Atterburg limits of synthetic kaolinite soil and percent Armac T admixture.

Armac T on Edina subsoil, in which case the liquid limit was reduced. Since the plastic limit increased at a greater rate than the liquid limit, the plasticity index was slightly reduced (Fig. 48c) by the admixtures.

(2) Shrinkage properties. Table 30 and Fig. 49 show the effect of Armac T admixtures to the kaolinite soil on its shrinkage properties. Substantiating results observed with Edina subsoil, the shrinkage limit was increased (Fig. 49a) and the shrinkage ratio decreased (Fig. 49b). The ratio of shrinkage limit to liquid limit was increased (Fig. 49c), indicating that Armac T admixtures decreased the shrinkage properties of the kaolinite soil. It is apparent from Fig. 49c that the rate of decrease in shrinkage properties was greatest for the initial 1 percent admixture. The volume change of the oven dried shrinkage pats is shown in Fig. 50.

(3) Ratio of liquid limit to clay content. The data given in Table 30 and plotted in Fig. 51 show that admixtures of Armac T to the kaolinite soil increased the ratio of liquid limit to 5 micron clay content. These results are just the opposite of those observed with Edina subsoil, since they would indicate that the relative activity of the clay fraction was slightly increased by the cationic chemical.

(4) Relative air dry strength. It is evident from Table 30 and Fig. 52 that Armac T admixtures to the kaolinite soil caused a large reduction in relative air dry strength as measured with the soil penetrometer. Fig. 52 shows that the rate of reduction was greatest for admixtures up to 1 percent, with larger amounts causing comparatively little additional strength loss.

(5) Rate of slaking. Table 30 shows that both 1 and 3 percent additions of Armac T were effective in preventing failure of air dry

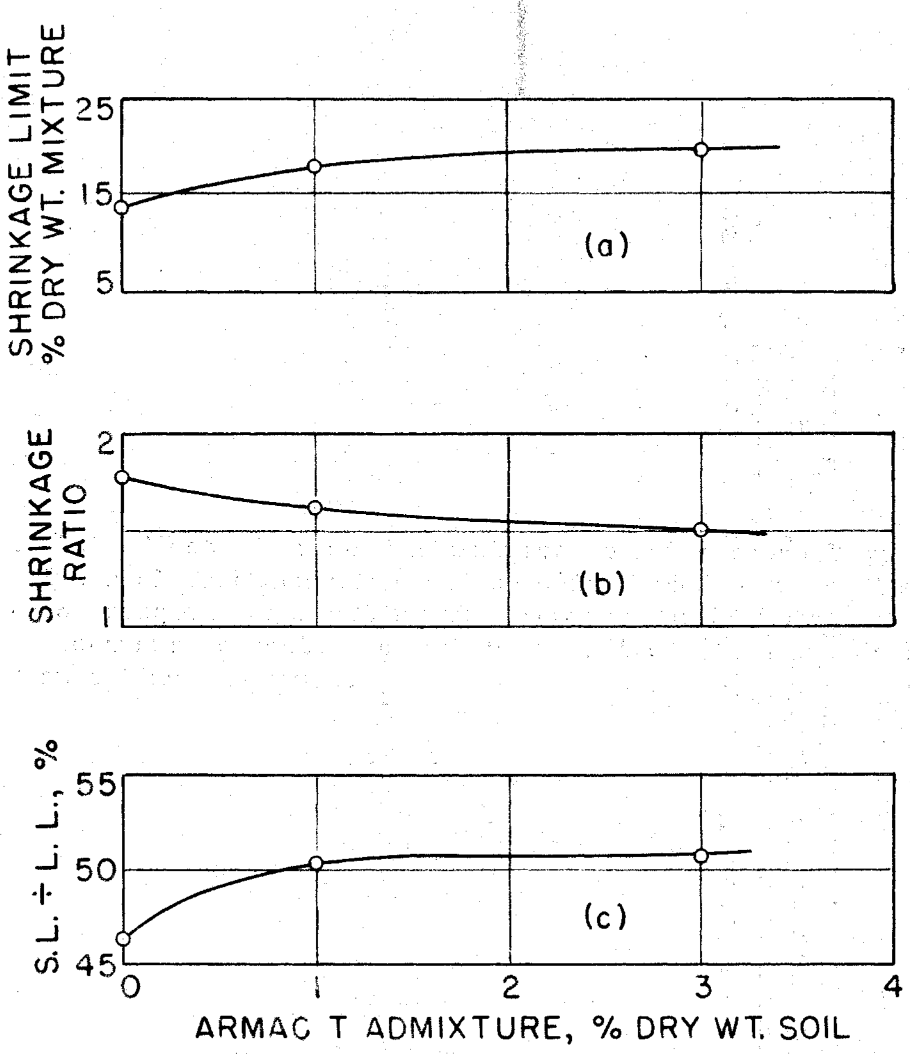

Fig. 49. Relationship between shrinkage properties of synthetic kaolinite soil and percent Armac T admixture.

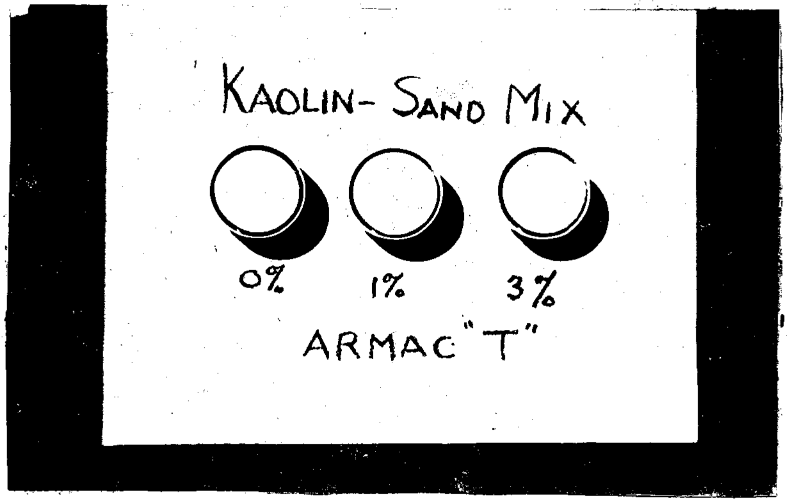

Fig. 50. Oven dried synthetic kaolinite soil shrinkage pats containing (left to right) 0, 1, and 3% Armac T by dry soil weight.

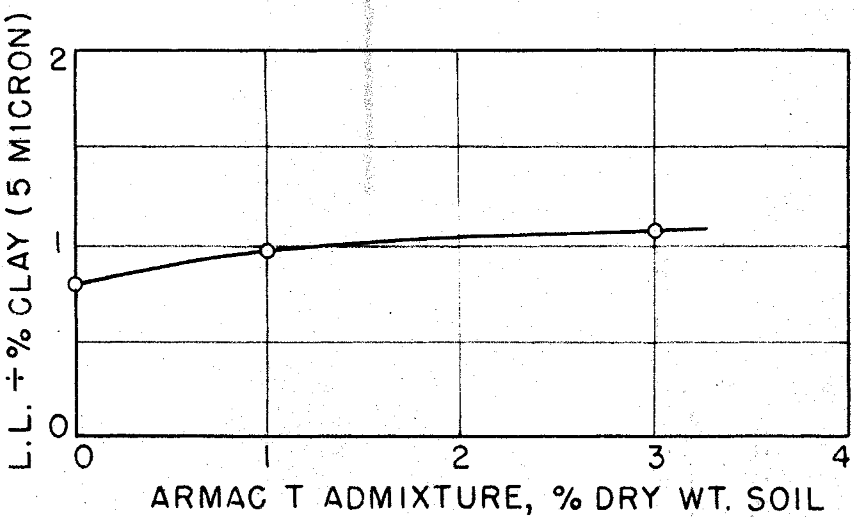

Fig. 51. Effect of Armac T admixtures to synthetic kaolinite soil on ratio of liquid limit to clay content (5 micron).

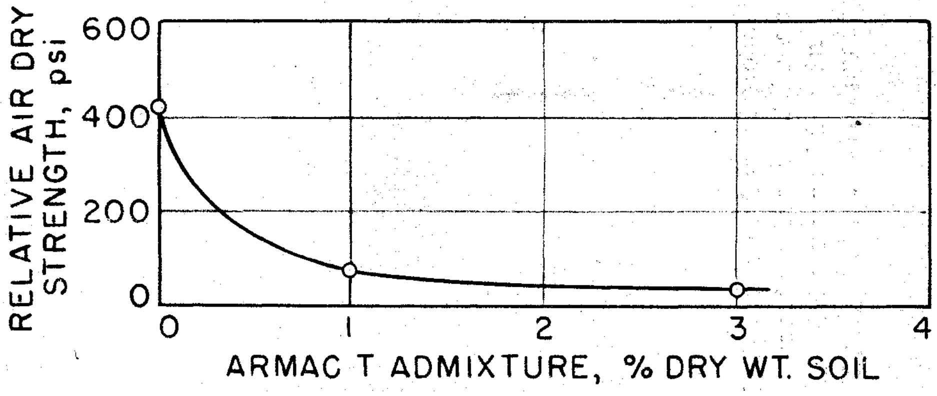

Fig. 52. Relationship between relative air dry strength of synthetic kaolinite shrinkage pats and percent Armac T admixture.

kaolinite soil slaking pats. The untreated slaking pat failed in 6 minutes. The appearance of the 2 treated pats after soaking 7 days in distilled water is shown in Fig. 53. Water apparently had no effect on them.

b. Synthetic Na-montmorillonite soil

(1) Atterburg limits. The effect of Armac T on the liquid limit, plastic limit, and plasticity index of the Na-montmorillonite soil is given in Table 31 and shown by curves in Fig. 54. Unlike the kaolinite soil, this material had its liquid limit considerably reduced (Fig. 54a) by the cationic admixtures. The plastic limit was slightly reduced (Fig. 54b) which was contrary to results with Edina subsoil and the kaolinite soil. The plasticity index, which is the numerical difference between the liquid limit and plastic limit, was greatly

Table 31

Effect of Armac T admixtures to the synthetic Na-montmorillonite soil on some soil properties related to stability

Test	Armac T admixture, % dry wt. soil		
	0.0	1.0	3.0
Liquid limit, % dry wt. mixture	52.5	22.4	20.7
Plastic limit, % dry wt. mixture	20.8	18.4	16.9
Plasticity index, % dry wt. mixture	31.7	4.0	3.8
Shrinkage limit, % dry wt. mixture	18.5	16.6	16.2
Shrinkage ratio	1.69	1.66	1.62
S.L. ÷ L.L., %	35.2	74.2	78.2
L.L. ÷ % clay (5 micron)	2.81	1.20	1.11
Relative air dry strength, psi.	540	400	80
Slaking value, min.	540-1440	Didn't fail	Didn't fail

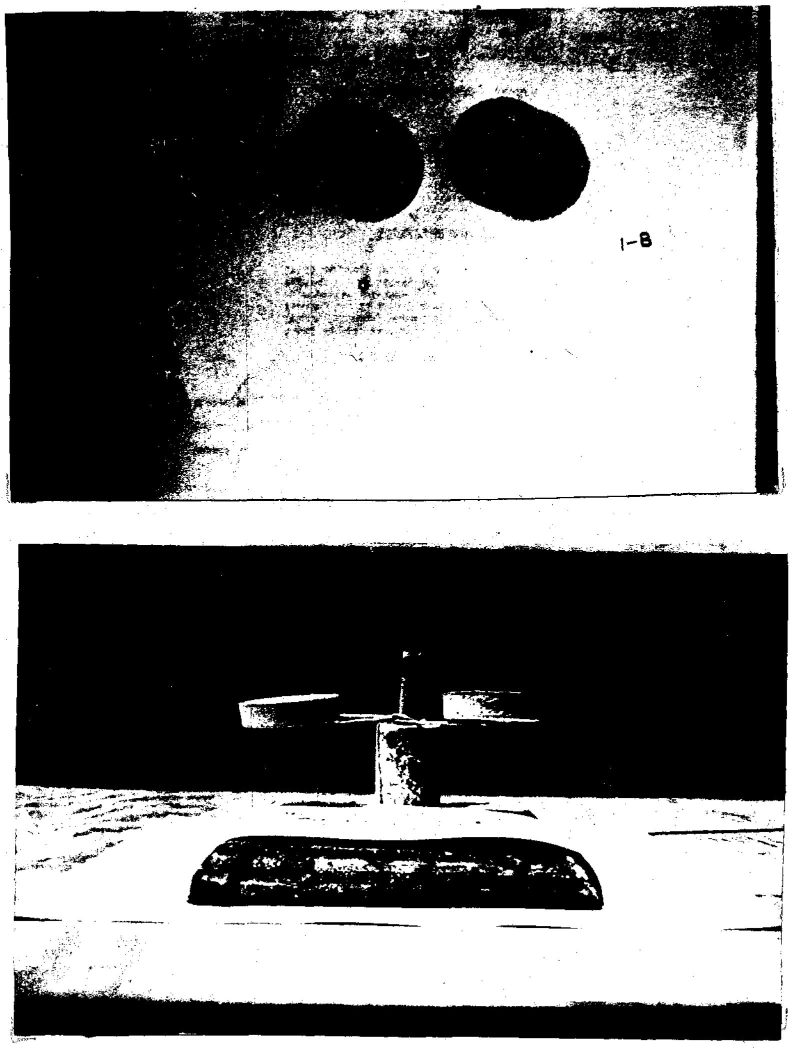

Fig. 53. Top and side views of synthetic kaolinite soil slaking pats containing 1% (left) and 3% (right) Armac T by dry soil weight after being soaked in water for 7 days.

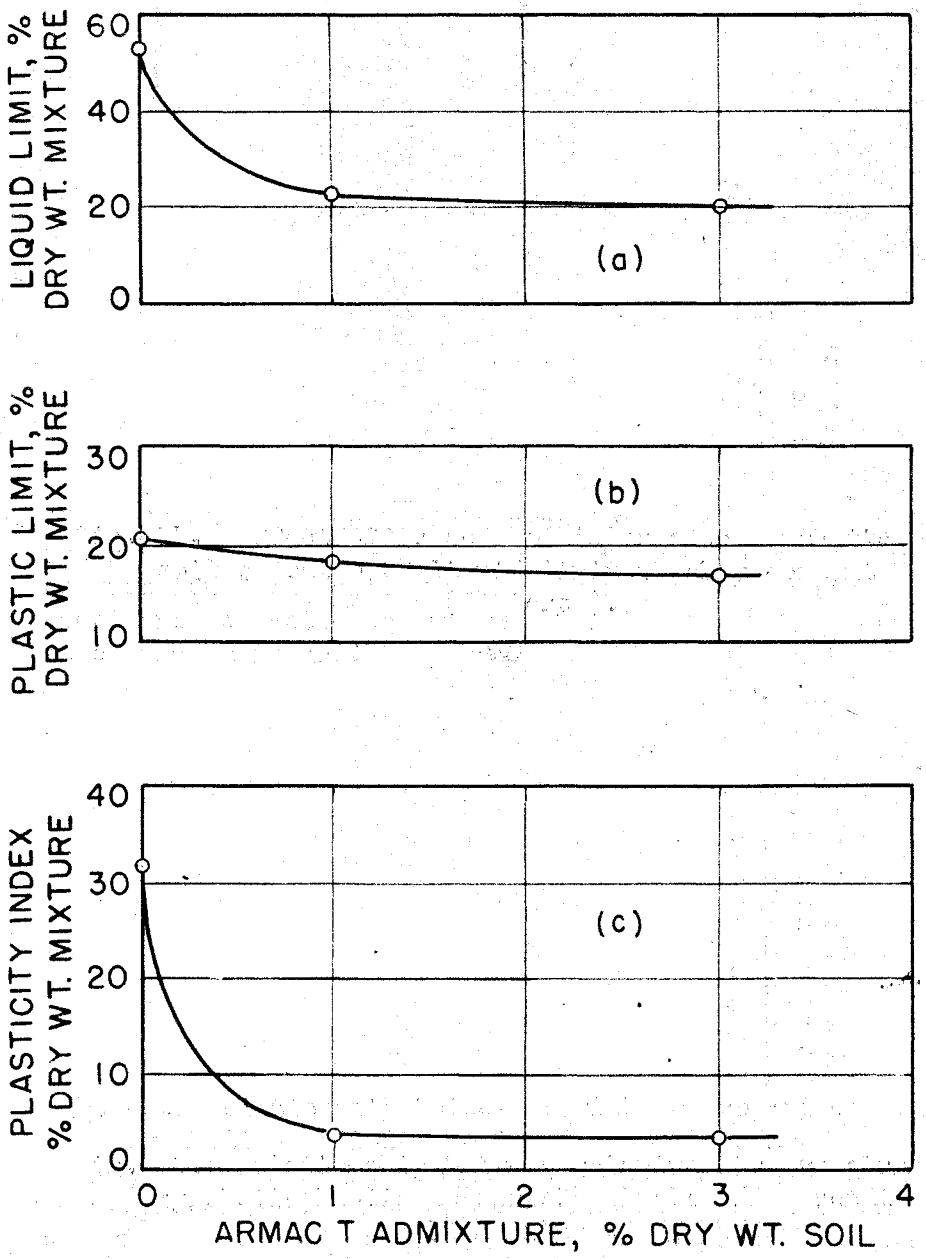

Fig. 54. Relationship between Atterburg limits of synthetic Na-montmorillonite soil and percent Armac T admixture.

decreased by Armac T (Fig. 54c). It is apparent from the 3 curves in Fig. 54 that dosages of chemical larger than 1 percent had relatively little additional effect on the plasticity values of the Na-montmorillonite soil.

(2) Shrinkage properties. Table 31 and Fig. 55 show the effect of Armac T on the shrinkage properties of the Na-montmorillonite soil. It will be noted in Figs. 55a and 55b that both the shrinkage limit and shrinkage ratio were slightly decreased. Edina subsoil and the kaolinite soil had their shrinkage limits increased by Armac T. The ratio of shrinkage limit to liquid limit (Fig. 55c), however, indicates that Armac T was very effective in reducing the shrinkage properties of the Na-montmorillonite soil, especially in amounts up to 1 percent. Admixtures larger than 1 percent continued to decrease shrinkage but at a considerably diminished rate. This is verified by the relative volume change of the oven dried shrinkage pats pictured in Fig. 56.

(3) Ratio of liquid limit to clay content. The data given in Table 31 and plotted in Fig. 57 show that admixtures of Armac T to the Na-montmorillonite soil decreased the activity of the 5 micron clay considerably. It is apparent from the curve in Fig. 57 that admixtures larger than 1 percent had relatively little added effect.

(4) Relative air dry strength. Table 31 and Fig. 58 show that Armac T admixtures to the Na-montmorillonite soil caused a large reduction in relative air dry strength. Fig. 58 indicates that the rate of reduction was almost directly proportional to the amount of chemical added.

(5) Rate of slaking. The slaking values given in Table 31 show that both 1 and 3 percent additions of Armac T were effective in preventing failure of the air dry Na-montmorillonite slaking pats during

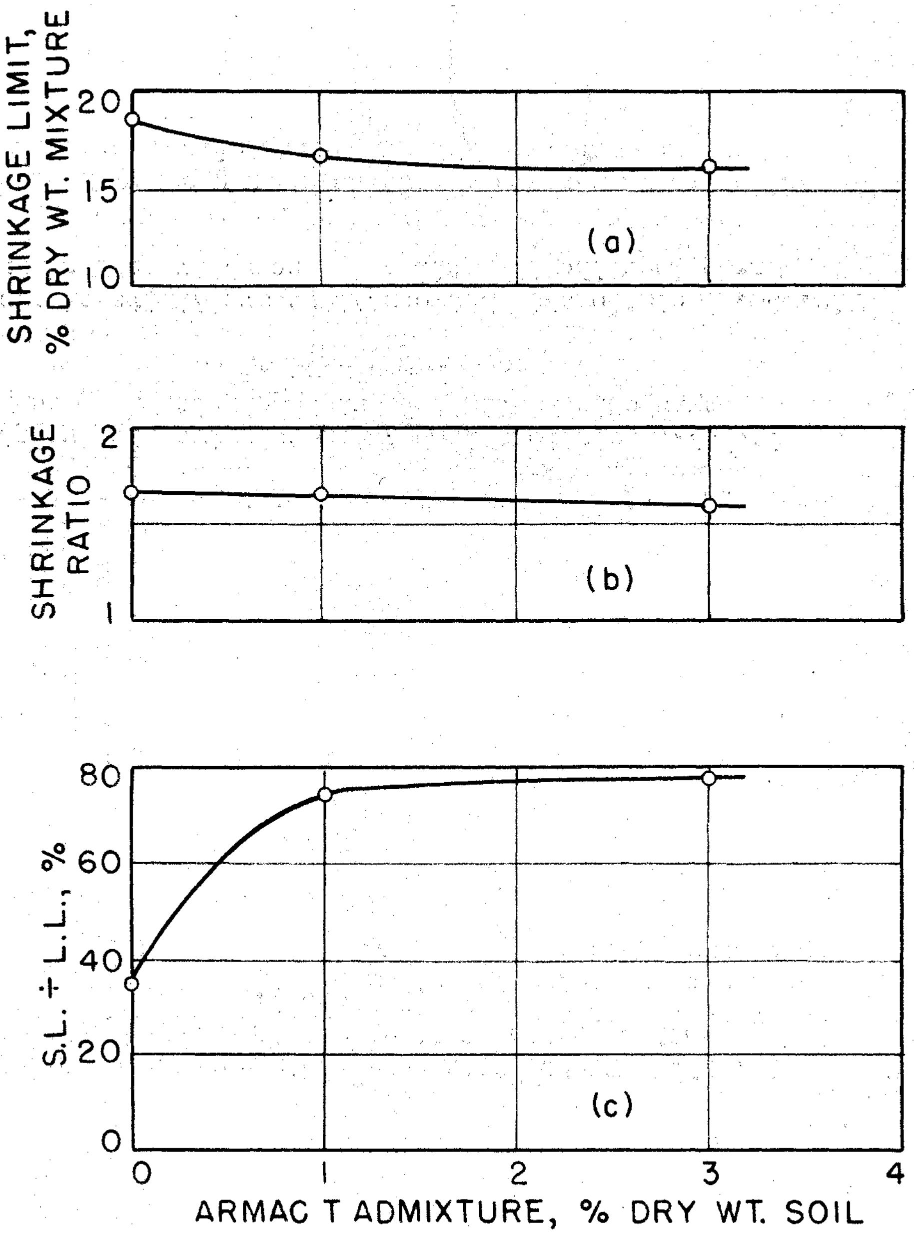

Fig. 55. Relationship between shrinkage properties of synthetic Na-montmorillonite soil and percent Armac T admixture.

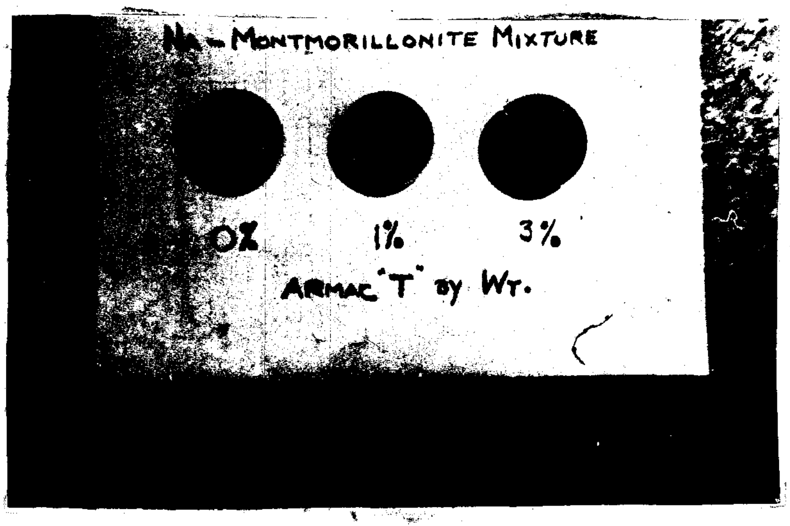

Fig. 56. Oven dried synthetic Na-montmorillonite soil shrinkage pats containing (left to right) 0, 1, and 3% Armac T by dry soil weight.

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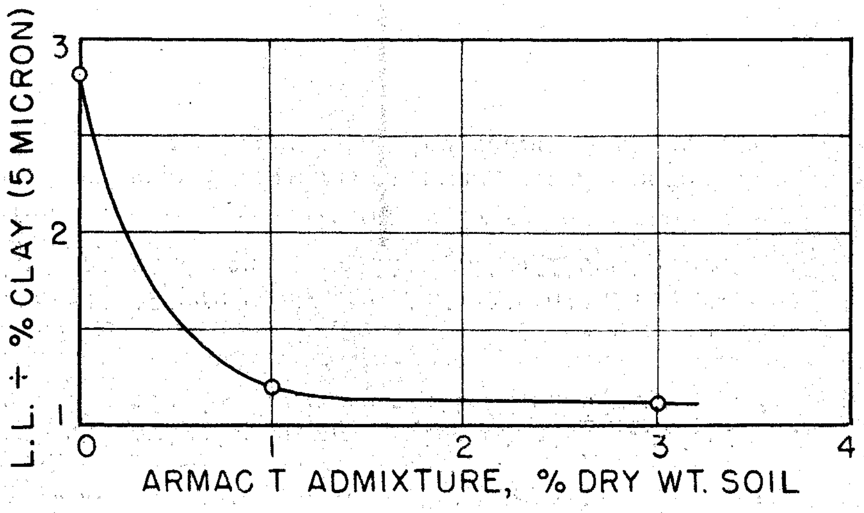

Fig. 57. Effect of Armac T admixtures to synthetic Na-montmorillonite soil on ratio of liquid limit to clay content (5 micron).

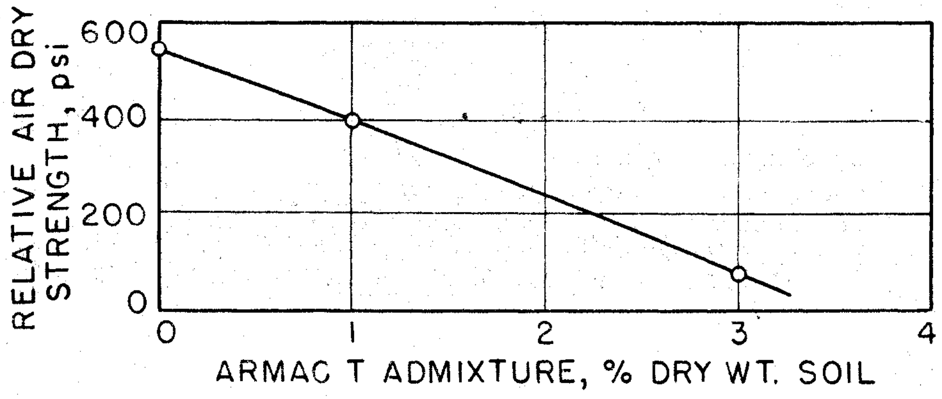

Fig. 58. Relationship between relative air dry strength of synthetic Na-montmorillonite shrinkage pats and percent Armac T admixture.

the 7 days immersion in distilled water. The untreated slaking pat disintegrated at a very slow rate compared with the other untreated pats previously studied. The appearance of the chemically treated pats after 7 days in water is shown by Fig. 59. Neither pat showed any ill-effects due to water soaking.

c. Homoionic montmorillonite soils. Table 32 shows the effect of 1 percent Armac T on some properties of the Na-, Ca-, and H-montmorillonite soils. A comparison of the 3 soils prior to treatment with Armac T reveals that the Na- soil had the highest Atterburg limits and shrinkage properties, with Ca- and H- soils having values of nearly equal magnitude. The H-montmorillonite soil, however, had the highest air dry strength and displayed the greatest resistance to slaking. Its appearance after 7 days in distilled water is shown by Fig. 60.

The addition of 1 percent Armac T tended to reduce and more nearly equalize the Atterburg limits and shrinkage properties of the 3 soils. This should be the trend if the large organic cations exchange for the 3 kinds of inorganic cations to the same extent. The relative volume change of the treated and untreated oven dried shrinkage pats is shown in Fig. 61.

It will be noted in Table 32 that 1 percent Armac T reversed the order of relative air dry strength, with the Na-montmorillonite soil showing the least strength loss. None of the treated slaking pats showed any ill-effects due to water soaking. The physical appearance of the Armac T treated Ca- and H-montmorillonite soil slaking pats after 7 days immersion is shown in Fig. 62. The Na-montmorillonite soil slaking pat containing 1 percent admixture is pictured in Fig. 59 after a similar soaking period.

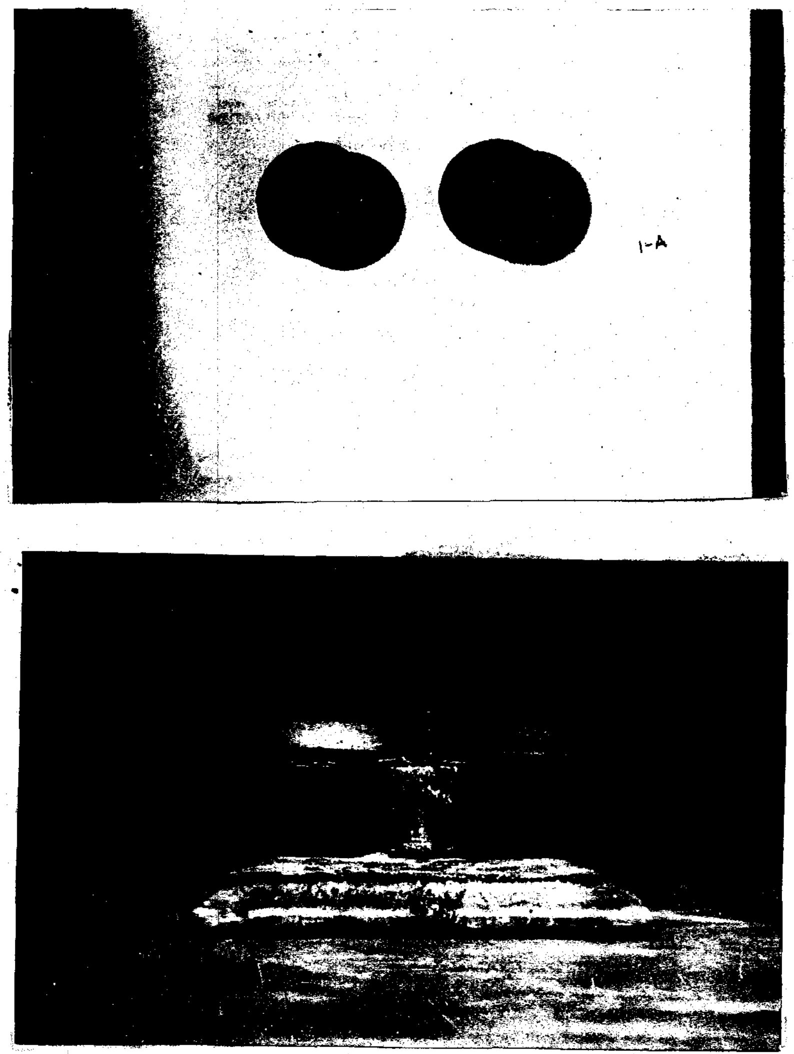

Fig. 59. Top and side views of synthetic Na-montmorillonite soil slaking pats containing 1% (left) and 3% (right) Armac T by dry soil weight after being soaked 7 days in water.

Table 32

Effect of type of inorganic cations present in the synthetic montmorillonite soil on the effectiveness of Armac T admixtures

Test	% Armac T admixture to Na-montmorillonite soil, % dry wt. soil		% Armac T admixture to Ca-montmorillonite soil, % dry wt. soil		% Armac T admixture to H-montmorillonite soil, % dry wt. soil	
	0.0	1.0	0.0	1.0	0.0	1.0
Liquid limit, % dry wt. mixture	52.5	22.4	21.0	17.6	21.2	19.7
Plastic limit, % dry wt. mixture	20.8	18.4	15.9	14.7	17.6	16.5
Plasticity index, % dry wt. mixture	31.7	4.0	5.1	2.9	3.6	3.2
Shrinkage limit, % dry wt. mixture	18.5	16.6	14.8	16.5	15.3	15.5
Shrinkage ratio	1.59	1.67	1.82	1.78	1.80	1.71
S.L. ÷ L.L., %	35.2	74.2	70.5	93.8	72.1	78.7
L.L. ÷ % clay	2.81	1.20	1.12	0.94	1.13	1.05
Relative air dry strength, psi.	540	400	640	160	1400	40
Slaking value, min.	540-1440	Didn't fail	2.0	Didn't fail	Didn't fail	Didn't fail

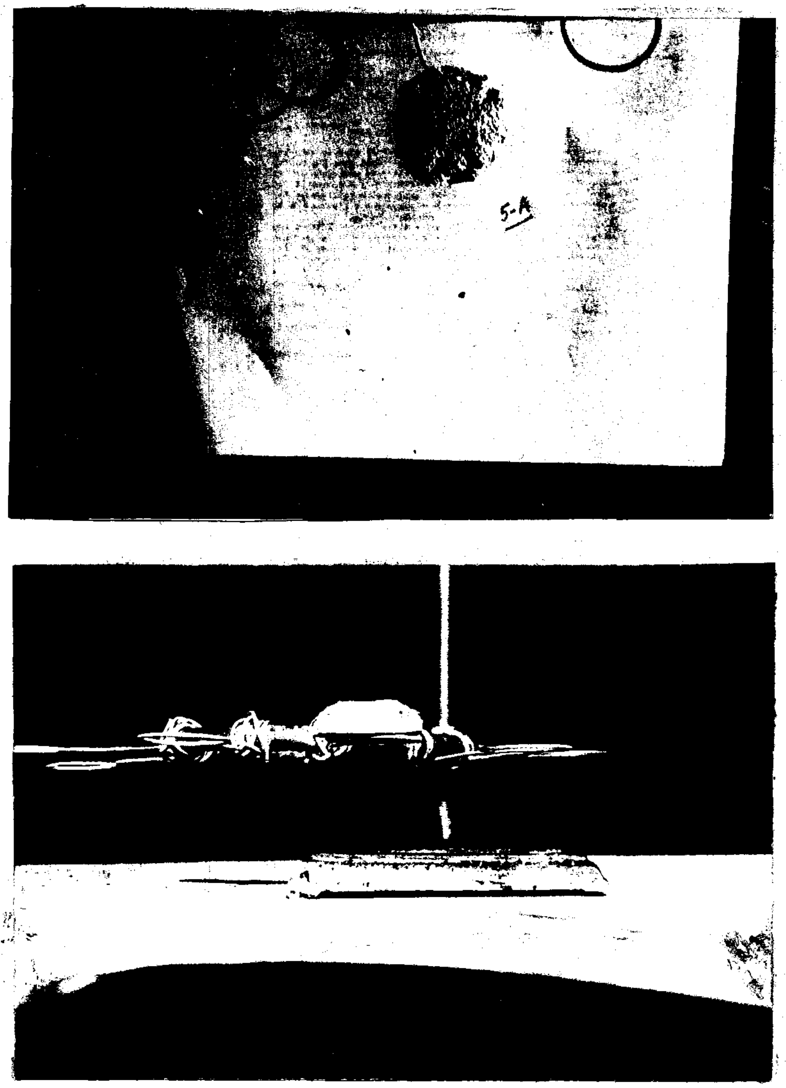

Fig. 60. Top and side views of synthetic H-montmorillonite soil slaking pat containing 0% Armac T after being soaked 7 days in water.

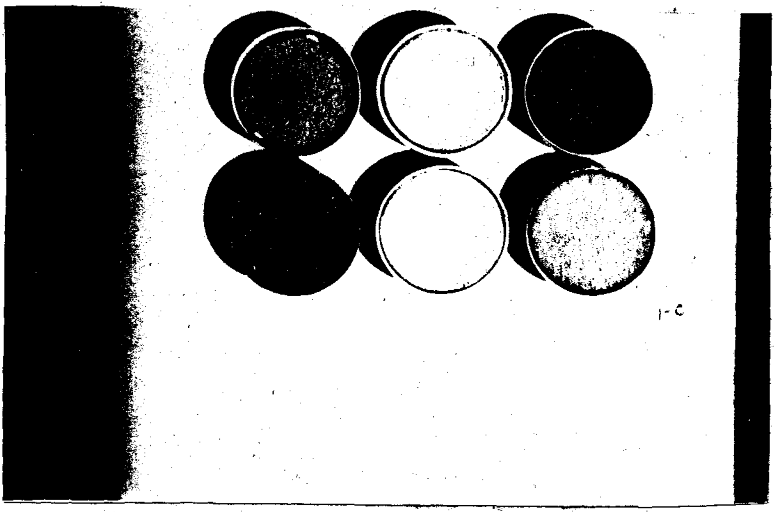

Fig. 61. Oven dried shrinkage pats; top row (left to right) Na-, Ca-, and H-montmorillonite soils containing 0% Armac T; bottom row (left to right) Na-, Ca-, and H-montmorillonite soils containing 1% Armac T by dry soil weight.

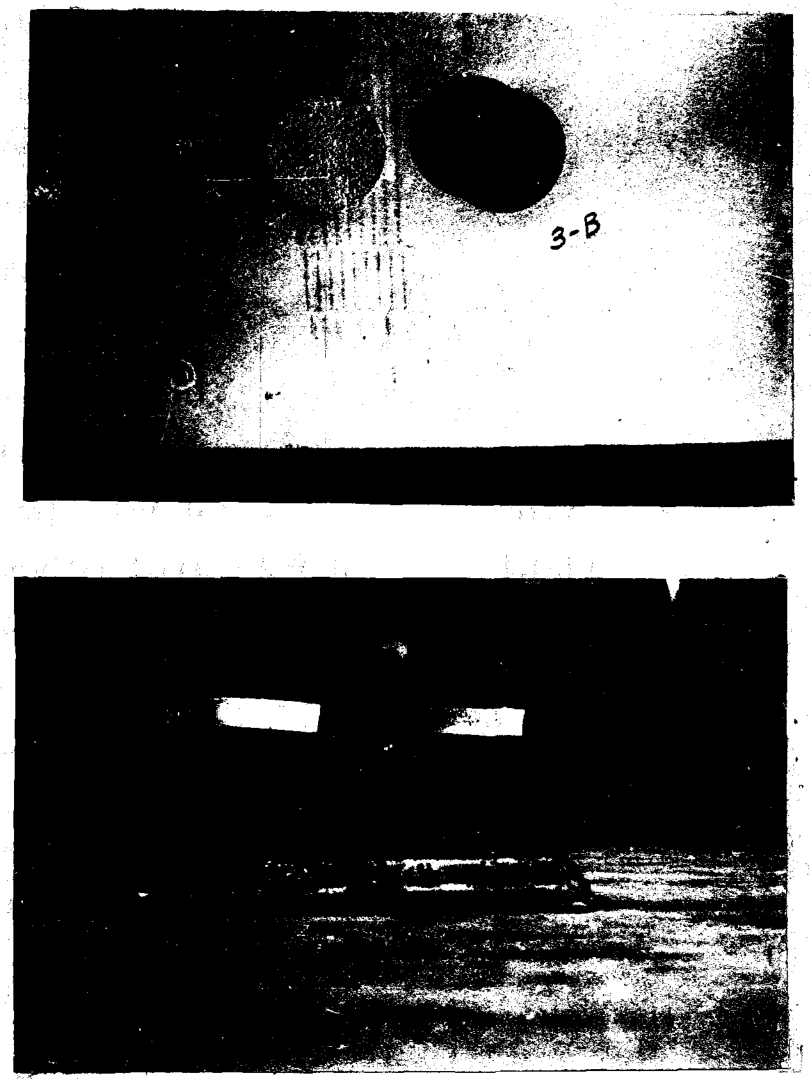

Fig. 62. Top and side views of synthetic Ca-montmorillonite soil (left) and H-montmorillonite soil (right) slaking pats containing 1% Armac T by dry soil weight after being soaked in water for 7 days.

d. *General discussion.* A comparison of the effect of Armac T on the synthetic kaolinite and Na-montmorillonite soils shows that it reduced the cohesiveness, shrinkage properties, and air dry strength of both. The magnitude of the decrease in both cohesiveness and shrinkage properties was much greater for the Na-montmorillonite soil, while the reduction in air dry strength was by far the greatest for the kaolinite soil, especially for the initial 1 percent admixture of Armac T. The data on the effect of Armac T on these properties of the 3 homoionic montmorillonite soils seems to indicate that the difference in the magnitude of the reductions may be partly due to the presence of sodium cations in the montmorillonite soil.

The air dry slaking resistance of both the kaolinite and Na-montmorillonite soils was increased tremendously by Armac T. One percent by dry soil weight was sufficient to prevent both soils from showing any noticeable ill-effects due to water soaking. This was true also for the Ca- and H-montmorillonite soils. No strength tests were run on the treated soils after soaking. Such tests should be included in any future investigations.

The effect of the kind of inorganic cations present in the kaolinite soil on the performance of Armac T was not investigated. Previous work by the writer (4) had shown that the kind of counter ions present was not so important with synthetic kaolinite soils as with synthetic montmorillonite soils, due mainly to the much lower base exchange capacity of the former.

D. Effect of Armac T on 4 Additional Iowa Soils

The objective in the last phase of the research was to round out the investigation of Armac T as a soil stabilizing agent by a study of its effect on 4 additional Iowa soils whose clay mineral content was approximately known.

1. Materials

a. Soils. The 4 soils used are referred to as Nevada clay, Nebraskan gumbotil, Missouri loess[a], and Mississippi loess[a]. With the exception of Nebraskan gumbotil, the soils were 100 percent finer than the No. 40 sieve. Only the binder fraction (passing the No. 40 sieve) of the gumbotil was used.

(1) Nevada clay. The sample[b] of Nevada clay was obtained at the shale and clay pit of F. C. McHose and Son on the west side of West Indian Creek west of Nevada, Iowa where the shales and clays have been used in the manufacture of heavy clay products for many years. Clay from this pit has also been used satisfactorily as a binder material in soil stabilization work on roads and streets. This reddish colored clay is a member of the Des Moines series and a differential thermal analysis of a sample of it indicated the presence of kaolinite type clay minerals (35). Its gradation is given in Table 33. Texturally it was a clay and according to the revised P.R.A. classification system it was an A-7-6(12) soil.

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[a] The names Missouri loess and Mississippi loess were used by Fung (37) to describe loess soils from Harrison County and Johnson County, Iowa, respectively, and do not have pedological or geological significance.

[b] Sampled by Mr. K. B. Mellerop.

Table 33

Grain size distribution

Sieve number	Equivalent spherical diameter, mm.	Percent finer, by dry soil wt.			
		Nevada clay[a]	Nebraskan gumbotil[b]	Missouri loess[c]	Mississippi loess[c]
40	0.420	100.00	100.00	100.00	100.00
60	0.250	100.00	98.50	100.00	100.00
100	0.147	100.00	97.75	99.80	100.00
150	0.104	100.00	97.50	99.20	100.00
200	0.074	100.00	96.40	98.00	99.00
270	0.050	100.00	90.60	88.00	92.50
	0.005	91.30	45.10	12.00	28.50
	0.001	45.60	26.00	6.00	21.00

[a] After Mellerop (35)
[b] After Patel (36)
[c] After Fung (37)

(2) Nebraskan gumbotil. Nebraskan gumbotil is of glacial origin and the name has been applied to the highly weathered upper layers of Nebraskan glacial till. The sample[a] of gumbotil was obtained in Cass County from the back slope of a cut section on Iowa 92, approximately 4 miles east of U.S. 71, near Atlantic. A differential thermal analysis of this material indicated the presence of montmorillonite type clay minerals (36). The gradation of the binder fraction is shown in Table 33. It was classified texturally as clay and according to the revised P.R.A. classification system was an A-7-6(20) soil.

(3) Missouri loess. The soil referred to as Missouri loess (37) was sampled[b] in Harrison County near the bottom of a 60 foot road cut on Iowa 127, about 4 miles west of Magnolia. Clay mineral studies of

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[a] Sampled by Mr. O. H. Patel.
[b] Sampled by Mr. P. K. Fung.

this soil have indicated the presence of montmorillonite and possibly illite (38). Its gradation is shown in Table 33. Texturally Missouri loess was a silty loam and according to the revised P.R.A. classification system it was an A-4(8) soil.

(4) Mississippi loess. The sample[a] of Mississippi loess (37) was obtained about 7 feet from the top of a road cut on Iowa 261 in Johnson County. The exact stationing according to Iowa Highway Commission files was 46 64, Project FA-765-A. Clay mineral studies on this material have also indicated the presence of montmorillonite and possibly illite (38). The sample's gradation is given in Table 33. Mississippi loess was classified texturally as silty clay loam and according to the revised P.R.A. classification system it was an A-7-6(10) soil.

b. Cationic chemical. Armac T was the only cationic chemical used. It has been described in section A.

2. Method of procedure

a. Addition of Armac T. One percent Armac T by dry soil weight was mixed with each soil, following the same procedure used in mixing it with Edina subsoil.

b. Tests. The tests and ratios used to evaluate the performance of 1 percent Armac T with the 4 soils were the same as those previously used and described in section A, namely: (1) liquid limit, (2) plastic limit, (3) plasticity index, (4) shrinkage limit, (5) ratio of shrinkage limit to liquid limit, (6) ratio of liquid limit to clay content, (7) relative air dry strength, and (8) rate of slaking.

3. Presentation and discussion of results

The relative amount of clay in each soil together with its probable

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[a] Sampled by Mr. P. K. Fung.

mineralogical nature should be kept in mind when comparing the test results. Table 33 shows that Nevada clay had 91.3 percent 5 micron clay, Nebraskan gumbotil had 45.1 percent, Mississippi loess had 28.5 percent, and Missouri loess had 12.0 percent.

a. Atterburg limits. The effect of 1 percent Armac T on the plasticity values is shown in Table 34 and by curves in Fig. 63. It will be noted that Nebraskan gumbotil had much higher untreated values than the other 3 soils, despite the fact that Nevada clay had approximately twice as much 5 micron clay. This is probably further indication of the presence of montmorillonite type clay minerals in the gumbotil.

With the exception of Nebraska gumbotil, liquid limits were reduced only slightly (Fig. 63a) by 1 percent Armac T. The plastic limits of Nevada clay and Mississippi loess were increased while those of gumbotil and Missouri loess were decreased (Fig. 63b). The decrease in the plasticity index of gumbotil was large compared to the decrease for the other soils (Fig. 63c).

b. Shrinkage properties. The data in Table 34 and the curves in Fig. 64 indicate that 1 percent of Armac T tended to reduce the shrinkage properties of all soils. The rate of reduction was greatest for the Nebraskan gumbotil and Nevada clay which were the soils with the highest clay contents. The relative volume change of treated and untreated oven dried shrinkage pats is shown in Fig. 65.

c. Ratio of liquid limit to clay content. The effect of Armac T in reducing the relative activity of the 5 micron clay fractions is shown in Table 34 and in Fig. 66. Apparently the rate of reduction was greatest for the Nebraskan gumbotil and Mississippi loess. It is noteworthy that these were probably the 2 soils containing the most montmorillonite type clay minerals.

Table 34

Effect of Armac T admixtures on some soil properties related to stability

Test	Armac T admixture, % dry soil wt.							
	Nevada clay		Nebraskan gumbotil		Missouri loess		Mississippi loess	
	0.0	1.0	0.0	1.0	0.0	1.0	0.0	1.0
Liquid limit, % dry wt. mixture	42.3	40.2	69.0	41.2	32.2	29.7	36.9	35.8
Plastic limit, % dry wt. mixture	23.7	28.0	28.0	23.8	26.2	24.5	21.7	23.7
Plasticity index, % dry wt. mixture	18.6	12.2	41.0	17.4	6.0	5.2	15.2	12.1
Shrinkage limit, % dry wt. mixture	17.1	20.1	9.4	10.7	20.7	20.0	14.8	16.0
Shrinkage ratio	1.82	1.51	2.00	1.79	1.67	1.55	1.83	1.67
S.L. ÷ L.L., %	40.4	50.0	13.6	26.0	64.3	67.3	40.1	44.7
L.L. ÷ % clay (5 micron)	0.46	0.44	1.53	0.91	2.68	2.48	1.30	1.26
Relative air dry strength, psi.	740	240	2120	1240	500	70	1860	380
Slaking value, min.	4.5	Didn't fail	9.5	Didn't fail	1.0	Didn't fail	6.5	Didn't fail

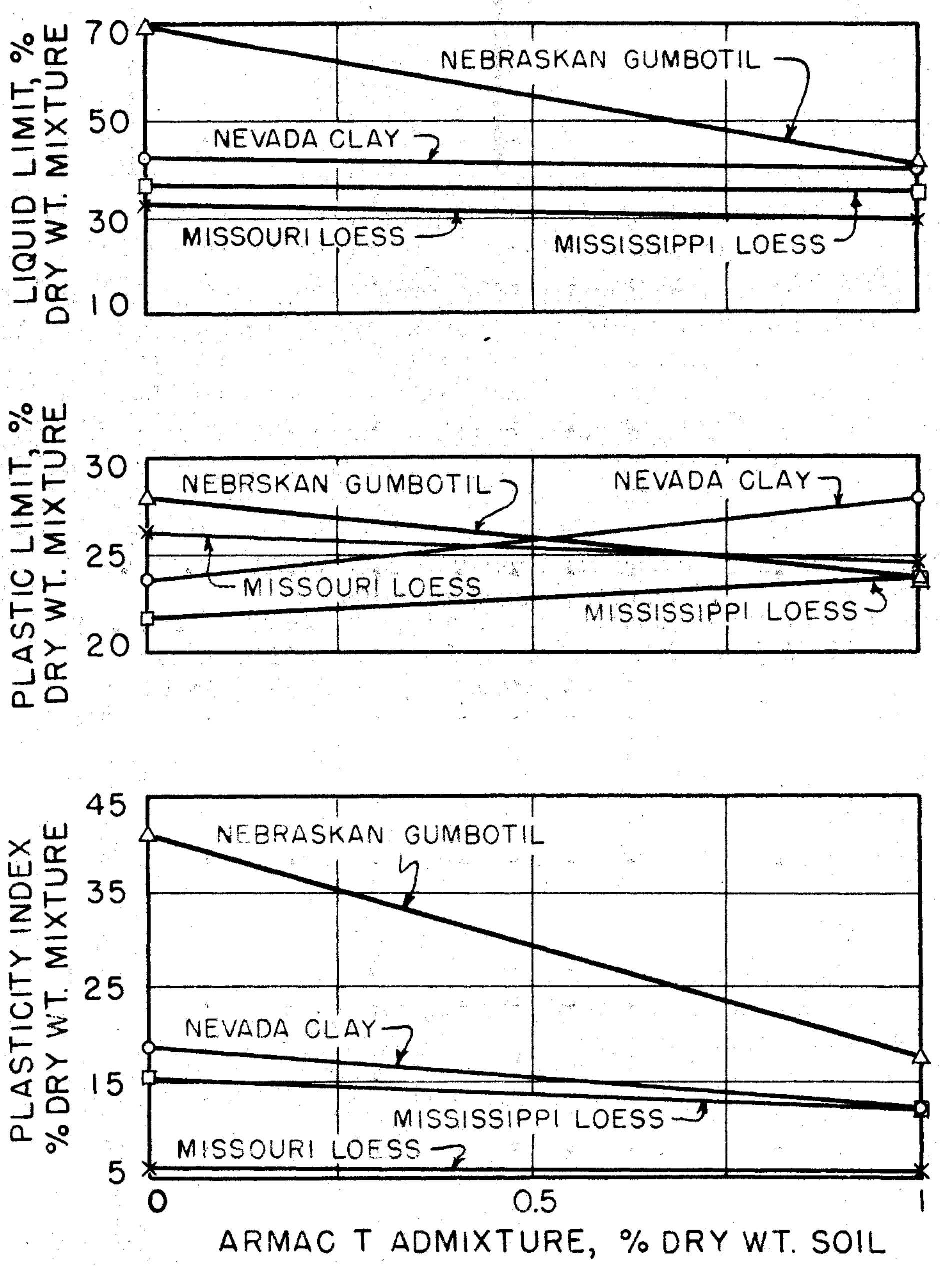

Fig. 63. Effect of 1% Armac T on Atterburg limits.

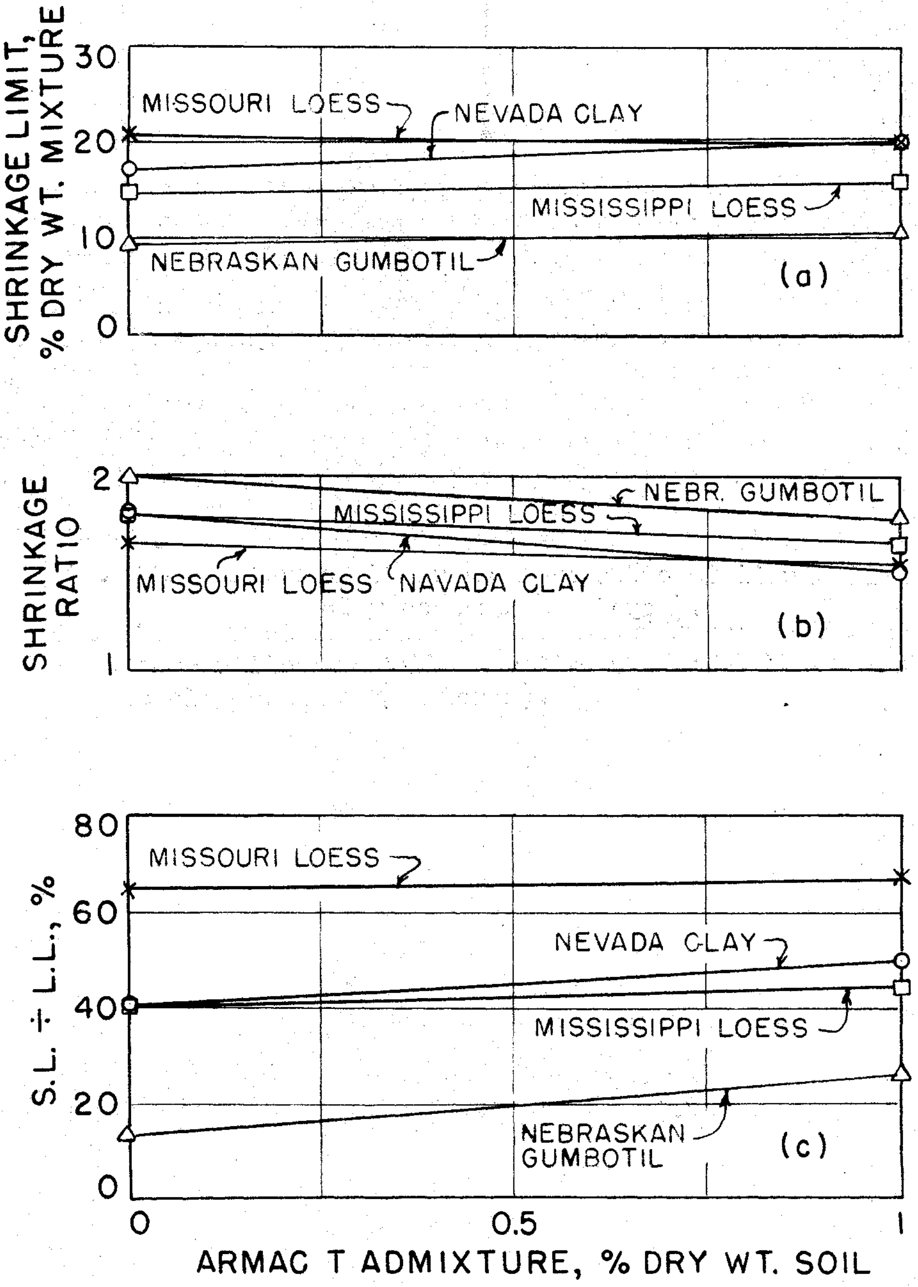

Fig. 64. Effect of 1% Armac T on shrinkage properties.

Fig. 65. Oven dried shrinkage pats; top row (left to right) Nebraskan gumbotil, Nevada clay, Mississippi loess, and Missouri loess containing 0% Armac T; bottom row (left to right) Nebraskan gumbotil, Nevada clay, Mississippi loess, and Missouri loess containing 1% Armac T by dry soil weight.

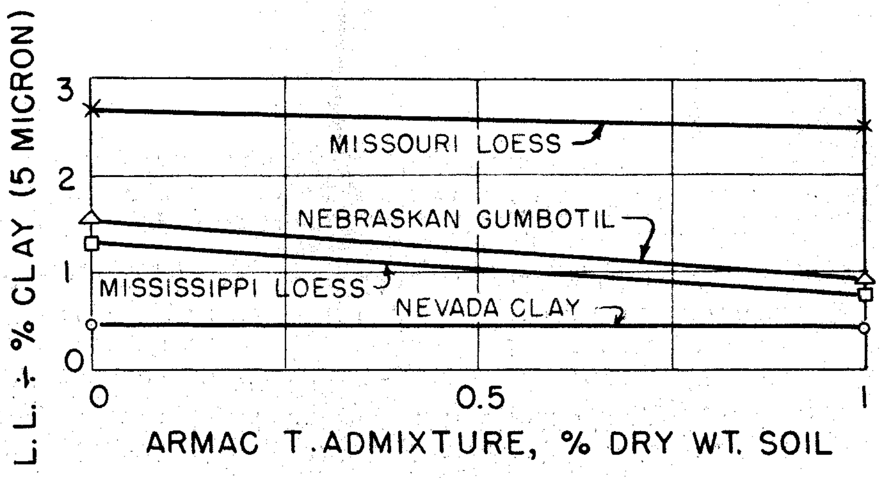

Fig. 66. Effect of 1% Armac T on ratio of liquid limit to clay content (5 micron).

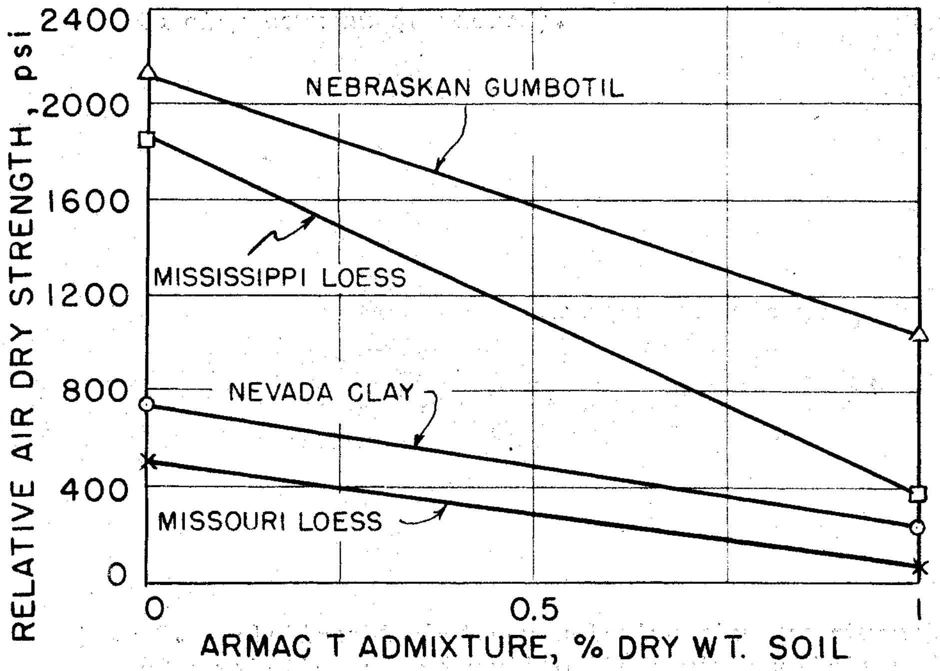

Fig. 67. Effect of 1% Armac T on relative air dry strength of shrinkage pats.

d. Relative air dry strength. It is apparent from Table 34 and Fig. 67 that 1 percent Armac T considerably reduced the air dry strengths of the 4 soils. Fig. 67 shows that Nebraskan gumbotil and Mississippi loess had the highest untreated and treated strengths, despite the fact that the magnitude of strength loss was greatest for these 2 soils.

e. Rate of slaking. The data in Table 34 show that 1 percent Armac T prevented all slaking pats from failing during the 7 day soaking period. Untreated slaking pats failed after a few minutes immersion in water. The physical appearance of the Armac T treated pats at the end of the slaking period is shown in Fig. 68. It will be noted that the 2 loess soils were least affected by the soaking.

f. General discussion. The qualitative effect of Armac T on the 4 soils was about the same, that is, it decreased their cohesiveness, shrinkage properties, and air dry strength; and it greatly increased their air dry slaking resistance. The data in Table 34 indicate that the quantitative effect of Armac T was a function of both the amount of clay and the type of clay minerals present, and that the magnitude of the reduction of cohesiveness, shrinkage properties and air dry strength was greatest for montmorillonite type clay minerals. On the basis of the appearance of the Nevada clay and Nebraskan gumbotil slaking pats after 7 days in water, it would seem that small admixtures of Armac T improve the slaking resistance of high clay content soils containing predominantly kaolinite type clay minerals more than those containing predominantly montmorillonite type minerals.

g. Future research. The present investigation, while only scratching the surface of the subject, does indicate that large organic cations have considerable promise as soil stabilizing agents. This field has been virtually untouched by engineering researchers, and the

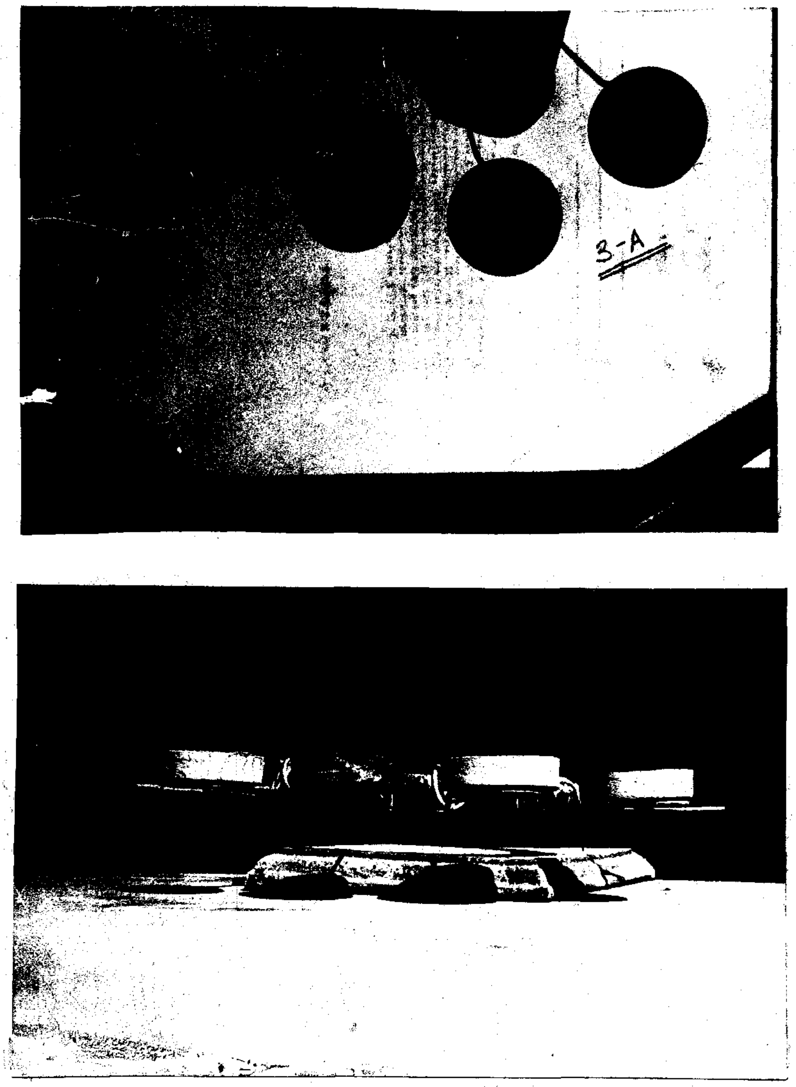

Fig. 68. Top and side views of (left to right) Nebraskan gumbotil, Nevada clay, Mississippi loess, and Missouri loess slaking pats containing 1% Armac T by dry soil weight after soaking 7 days in water.

possibilities for the use of cationic chemicals in soil engineering may prove numerous. There are undoubtedly hundreds of organic chemicals and combinations of chemicals that should be investigated with the many different types of soil.

The data presented in this report have indicated that the quantitative effect of cationic chemicals on soil is a function of at least 3 variables, namely: (1) amount of clay, (2) type of clay minerals, and (3) kind of inorganic cations associated with the clay. Accordingly, future studies of cationic materials as soil stabilizing agents should be conducted with these variables known as accurately as is possible. Synthetic soil mixtures offer one possibility for such studies. In order that results may be compared most effectively, cationic admixtures should be made preferably on a percent saturation of the soil's base exchange capacity basis.

Only one mixing method was used in the present investigation. From a practical as well as an economical standpoint this method would probably not be suitable for most field uses. Therefore, other methods of mixing cationic chemicals with soil need to be studied.

The following are just a few of the many possible uses of cationic chemicals with soil that may prove worthy of researches:

1. As admixtures to improve the properties of plastic fine grained soils for soil cement stabilization.
2. As admixtures to improve the properties of plastic fine grained soils for bituminous soil stabilization.
3. As admixtures to improve the properties of soils for use in mud jack operations.
4. As admixtures to stabilize plastic fine grained soils.

5. As admixtures to lower the liquid limit and plasticity index of soils and soil mixtures which are just slightly above specification requirements, and at the same time to decrease their water absorption tendencies.
6. As admixtures to decrease the water absorption of soils and soil mixtures which meet engineering specifications.
7. As a spray to reduce the water affinity of soils upon which Portland cement concrete is laid.
8. As a spray to combat soil erosion.

IV. SUMMARY AND CONCLUSIONS

The purpose of the investigation reported herein was to determine the effect of certain large organic cations on physico-colloidal properties related to soil stability. This was accomplished by 4 studies, namely: (1) a study to evaluate 6 water soluble cationic chemicals as stabilizing agents for a highly plastic fine grained soil from southern Iowa; (2) a more detailed study of one of the more promising cationic chemicals, known commercially by the trade name Armac T, with the same fine grained soil; (3) a study of the effect of type of clay mineral and kinds of inorganic cations present on the performance of Armac T; and (4) a brief study of Armac T as a stabilizing agent for 4 additional Iowa soils. Only one method of adding the cationic materials to the soil was used and all experimental findings and conclusions drawn therefrom apply only for this mixing procedure. Further study of this phase of the subject is needed before organic chemicals of the type reported on can be used on a practical basis. The mixing procedure used herein, however, can probably be considered as giving close to optimum results.

A. Evaluation of Cationic Chemicals

The 6 water soluble organic chemicals used in this study are available commercially under the trade names Armac T, Armac 18D, Armac 12D, Rosin Amine-D Acetate, Amine 220, and Ammonyx T. They are all cationic in character, furnishing large organic cations when dissolved in water. The composition and constants of the 6 chemicals are presented.

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The soil used was Edina silt loam B horizon clay from Wayne County, Iowa. In this report it is referred to as Edina subsoil. Texturally it classified as silty clay and according to the revised Public Roads Administration classification system it was an A-7-6(20) soil. A differential thermal analysis of the colloid portion indicated that montmorillonite type clay minerals were predominant with the possibility of a small percentage of kaolinite. Engineering properties of this soil are given.

The chemicals were added to the soil samples in such quantities that the base exchange capacities of the samples were saturated 1, 10, and 75 percent with Armac 12D, Amine 220, and Ammonyx T; 1, 5, 10, and 75 percent with Rosin Amine-D Acetate; and 1, 10, 25, 50, and 75 percent with Armac T and Armac 18D. The relationships between percent saturation of base exchange capacity and percent by dry soil weight are given for the 6 cationic materials. Each chemical admixture was dissolved in an amount of distilled water equal in weight to the soil sample to be treated before mixing with the soil. The mixing procedure and subsequent preparation of the mixtures for testing are covered in the report.

The tests and ratios used to evaluate the performance of the cationic chemicals as soil stabilizing agents for Edina subsoil were: (1) liquid limit, (2) plastic limit, (3) plasticity index, (4) shrinkage limit, (5) shrinkage ratio, (6) ratio of shrinkage limit to liquid limit, (7) ratio of liquid limit to 5 micron clay content, (8) relative air dry strength, and (9) rate of slaking. The methods of performing these tests together with physico-colloidal meanings are given.

The following is a summary of the more important results obtained in this experimental study and the conclusions drawn therefrom:

1. All cationic chemicals decreased the plasticity index of Edina

subsoil by lowering its liquid limit and raising its plastic limit.

2. The initial 10 percent saturation of the soil's base exchange capacity caused the sharpest increase of the plastic limit and the sharpest decrease of the liquid limit and plasticity index.

3. Since the plasticity index is a qualitative measure of cohesion, it may be concluded that all cationic materials were effective in reducing the cohesiveness of Edina subsoil.

4. The data showed that the relative effectiveness of the 6 chemicals in reducing cohesion was: Rosin Amine-D Acetate > Armac T > Armac 18D > Armac 12D > Amine 220 > Ammonyx T.

5. All cationic chemicals reduced the shrinkage properties of Edina subsoil, raising its shrinkage limit and lowering its shrinkage ratio.

6. The initial 10 percent saturation of the soil's base exchange capacity caused the sharpest decrease in shrinkage properties.

7. The data showed that the relative effectiveness of the 6 chemicals in reducing shrinkage properties was: Rosin Amine-D Acetate > Ammonyx T > Armac T > Armac 18D > Amine 220 > Armac 12D.

8. All cationic chemicals decreased the relative activity of the 5 micron clay fraction of Edina subsoil, with the decrease sharpest for the initial 10 percent saturation of the soil's base exchange capacity.

9. The data showed that the relative effectiveness of the 6 chemicals in reducing the activity of the clay fraction was: Rosin Amine-D Acetate > Armac T > Armac 18D > Armac 12D > Ammine 220 > Ammonyx T.

10. With the exception of Rosin Amine-D Acetate, the loss of air dry strength was not great for cationic admixtures up to 10 percent saturation of the soil's base exchange capacity. Rosin Amine-D Acetate in admixtures larger than 5 percent saturation caused very great loss of air dry strength. For Armac T and Armac 18D the loss was only gradual up to 25

percent saturation. All 75 percent saturation admixtures reduced the air dry strength of Edina subsoil greatly.

11. Armac T decreased the air dry strength of Edina subsoil less than the other 5 chemicals, for instance, the air dry strength of the soil was almost as great with 75 percent saturation Armac T as with 10 percent saturation Rosin Amine-D acetate.

12. Ten percent saturation of Edina subsoil's base exchange capacity with all cationic materials except Ammonyx T greatly improved its air dry slaking resistance in distilled water. Ammonyx T had practically no beneficial effect on the slaking properties of Edina subsoil. Five percent Rosin Amine-D Acetate was very beneficial.

13. In general, admixtures greater than about 25 percent saturation did not appreciably increase the slaking resistance of Edina subsoil in distilled water.

14. With the exception of Armac T, the 75 percent admixtures were not successful in preventing slaking, and in some cases the rate of slaking was greater than for the untreated soil.

15. On the basis of the test results and usability, Rosin Amine-D Acetate and Armac T appeared to be the most promising of the 6 organic chemicals investigated.

B. Armac T as a Stabilizing Agent for Edina Subsoil

Armac T was selected as the cationic material to investigate in more detail with Edina subsoil. It is available for use on a commercial scale and, in addition, is the cheapest "Armac" manufactured.

The cationic material was added to the soil samples in such quantities that the base exchange capacities of the samples were saturated

10, 25, 50, and 75 percent, respectively. In terms of the dry weight of the soil, these percentages were 1.29, 3.22, 6.44, and 9.66 percent, in the same order. The mixing procedure and subsequent preparation of the mixtures for testing were the same as in Section A.

Tests were performed to evaluate the effect of Armac T admixtures on the following properties of Edina subsoil: (1) water absorption and swelling, (2) optimum moisture and water soaked unconfined compression strength properties, (3) hygroscopic moisture, (4) centrifuge moisture equivalent, and (5) pH value. In addition, a test was performed to determine to what extent Armac T could be washed out of Edina subsoil. The methods of performing these tests together with their meanings are given. Distilled water was used in all tests.

The following is a summary of the more important results obtained in this experimental study and the conclusions drawn therefrom:

1. Test results indicated that if standard Proctor density control was used in compacting Edina subsoil, none of the percentages of Armac T used would be effective in preventing shrinkage as the soil air dried.

2. Test results indicated that if modified A. A. S. H. O. density control was used in compacting Edina subsoil, it would take at least 6 percent Armac T by dry soil weight to prevent shrinkage as the soil air dried. This amount of Armac T would be enough to saturate the soil's base exchange capacity nearly 50 percent.

3. Admixtures of Armac T up to 6.44 percent by dry soil weight (50 percent saturation) were very effective in reducing the water absorption of Edina subsoil in the optimum moisture and maximum modified A. A. S. H. O. density condition. Admixtures greater than 6.44 percent had relatively little added effect. The rate of reduction was especially great for treatments up to 1.29 percent by dry soil weight (10 percent saturation).

4. All admixtures of Armac T considerably increased the soaked penetration resistance of Edina subsoil.

5. Admixtures of Armac T up to 3.22 percent by dry soil weight (25 percent saturation) reduced the swelling of Edina subsoil greatly. Increasing the dosage above 3.22 percent did not cause much further decrease in the magnitude of the swelling.

6. The data indicated that Armac T inhibited the adsorption of water on the surfaces of the clay fraction, thus reducing the hydrating and swelling tendencies of the surfaces involved, but that it did not prevent water from moving through the soil pore spaces.

7. Admixtures of Armac T increased the internal friction angle and decreased the cohesion of Edina subsoil when in the optimum moisture and maximum modified A. A. S. H. O. density condition.

8. The optimum moisture and maximum modified A. A. S. H. O. density shearing strength of Edina subsoil was decreased by admixtures of Armac T, especially by those larger than 3.22 percent by dry soil weight (25 percent saturation).

9. The optimum moisture and maximum modified A. A. S. H. O. density modulus of deformation of Edina subsoil reached a minimum value with 6.44 percent Armac T by dry soil weight (50 percent saturation).

10. Optimum moisture and maximum modified A. A. S. H. O. density unconfined compression axial strain corresponding to maximum axial stress was reduced by Armac T admixtures, with the rate of decrease considerably less for admixtures larger than about 1.29 percent by dry soil weight (10 percent saturation).

11. From the standpoint of shearing strength and modulus of deformation, there appears to be an optimum Armac T admixture for soils that need protection from water. For Edina subsoil under the test conditions

employed, 3.22 percent by dry soil weight (25 percent saturation) was the amount found to be most effective.

12. Armac T admixtures slightly decreased the acidity of Edina subsoil. They did not noticeably affect the dispersability of the soil which was initially in the partially dispersed state.

13. Additions of Armac T up to 6.44 percent by dry soil weight (50 percent saturation) considerably decreased the centrifuge moisture equivalent of Edina subsoil. Further increase in the amount of chemical admixture had relatively little added effect.

14. The hygroscopic moisture affinity of Edina subsoil was considerably reduced by additions of Armac T, especially by dosages up to 6.44 percent by dry soil weight (50 percent saturation).

15. The qualitative determination of the extent to which Armac T could be washed out of air dry Edina subsoil with distilled water indicated that very little, if any, Armac T was removed.

C. Effect of Type of Clay Mineral and Kind of Inorganic Cations Present

The effect of major type of clay mineral present on the performance of Armac T was studied by means of 2 synthetic soils; Florida kaolin being used as the clay fraction of one and Wyoming bentonite, which contained predominantly sodium cations, for the other. These synthetic soils are referred to in the report as kaolinite soil and Na-montmorillonite soil, respectively. The gradation of both soils is given in the report. In order to study the effect of the kind of inorganic cations present on the performance of Armac T, samples of Na-montmorillonite soil were converted into soils that are referred to as Ca- and H-montmorillonite soils.

The methods of preparing these homoionic soils are described.

Armac T was mixed with the synthetic soils following the same procedure used in mixing it with Edina subsoil. The base exchange capacities of the synthetic soils were not known and all admixtures were made on a percent by dry weight of the soil basis. The admixtures made were 1 and 3 percent for the kaolinite and Na-montmorillonite soils, and 1 percent for the Ca- and H-montmorillonite soils.

The tests and ratios used to evaluate the performance of Armac T with the synthetic soils were the same as those previously used in section A, namely: (1) liquid limit, (2) plastic limit, (3) plasticity index, (4) shrinkage limit, (5) shrinkage ratio, (6) ratio of shrinkage limit to liquid limit, (7) ratio of liquid limit to 5 micron clay content, (8) relative air dry strength, and (9) rate of slaking.

The following is a summary of the more important results obtained in this experimental study and the conclusions drawn therefrom:

1. A comparison of the effect of Armac T on the synthetic kaolinite and Na-montmorillonite soils shows that it reduced the cohesiveness, shrinkage properties, and air dry strength of both. The magnitude of the decrease in both cohesiveness and shrinkage properties was much greater for the Na-montmorillonite soil, while the reduction in air dry strength was by far the greatest for the kaolinite soil, especially for the initial 1 percent admixture of Armac T. The data on the effect of Armac T on these same properties of the 3 homoionic montmorillonite soils seems to indicate that the difference in the magnitude of the reductions may be partly due to the presence of sodium cations in the montmorillonite soil.

2. The slaking resistance of both the kaolinite and Na-montmorillonite soils was increased tremendously by Armac T. One percent by dry soil weight was sufficient to prevent both soils from showing any noticeable

ill-effects due to water soaking. This was true also for the Ca- and H-montmorillonite soils.

3. The data indicate that Armac T replaced sodium, calcium, and hydrogen ions to about the same extent.

D. Effect of Armac T on 4 Additional Iowa Soils

The 4 soils used in this study were: (1) Nevada clay, an A-7-6(12) clay soil from Story County containing predominantly kaolinite type clay minerals; (2) Nebraskan gumbotil binder fraction, an A-7-6(20) clay soil from Cass County containing predominantly montmorillonite type clay minerals; (3) Missouri loess, an A-4(8) silty loam soil from Harrison County containing montmorillonite and possibly illite type clay minerals; and (4) Mississippi loess, an A-7-6(1) silty clay loam soil from Johnson County also containing montmorillonite and possibly illite type clay minerals.

One percent Armac T by dry soil weight was mixed with each soil, following the same procedure used in mixing it with Edina subsoil.

Tests and ratios used to evaluate the performance of the cationic material with the 4 soils were the same as those previously used in section A, namely: (1) liquid limit, (2) plastic limit, (3) plasticity index, (4) shrinkage limit, (5) ratio of shrinkage limit to liquid limit, (6) ratio of liquid limit to 5 micron clay content, (7) relative air dry strength, and (8) rate of slaking.

The following is a summary of the more important results obtained in this experimental study and the conclusions drawn therefrom:

1. The qualitative effect of Armac T on the 4 soils was about the same, that is, it reduced their cohesiveness, shrinkage properties, and

air dry strength; and it greatly increased their air dry slaking resistance.

2. The test results indicate that the quantitative effect of Armac T was a function of both the amount of clay and the type of clay minerals present, and that the rate of reduction of cohesiveness, shrinkage properties, and air dry strength was greatest for montmorillonite type clay minerals.

3. The data indicate that small admixtures of Armac T improve the air dry slaking resistance of high clay content soils containing predominantly kaolinite type clay minerals more than those containing predominantly montmorillonite type minerals.

The investigation reported herein, while only scratching the surface of the subject, does indicate that large organic cations have considerable promise as soil stabilizing agents. This field has been virtually untouched by engineering researchers, and the possibilities for the use of cationic chemicals in soil engineering may prove numerous.

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