

Recent Investigations on Use of a Fatty Quaternary Ammonium Chloride as a Soil Stabilizing Agent

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This paper reports the results of an investigation conducted to determine the soil-stabilizing potential of a fatty quaternary ammonium chloride. The study was divided into three general areas of interest. The initial portion of the paper deals with the laboratory investigation. Test procedures and results are given for the standard tests recommended by the Bureau of Public Roads for soil stabilization investigations, as well as procedures and results for non-standard tests used to determine the ability of the stabilizing agent to retard capillary absorption and frost heave. The results show that this material is an effective stabilizer for soils ranging from silts to highly plastic clays; however, it is most effective on materials containing moderate amounts of silt.

The second portion of the paper covers the actual field testing of the stabilizing agent. Two test sections totaling nearly 0.4 mi in length were constructed on an existing roadway. Results are presented for periodic strength and deflection measurements on one of the test sections. In addition, construction procedures for effectively applying this chemical are recommended.

Finally, based on the results of X-ray diffraction and other tests, a brief explanation of the possible stabilizing mechanism is presented.

• **THE RAPIDLY-DWINDLING** supply of suitable road-building aggregates in many areas of the United States has prompted numerous engineering investigations to determine means of improving or up-grading the more plentiful supply of poorer materials. Often, this improvement can be accomplished by the addition of chemicals to the soil. Engineering publications abound with results of research on the use of chemical soil stabilizers. From this multitude of research papers, it is easily observed that a practical, universal soil stabilizer has yet to be developed. Instead, certain chemicals are effective on one group of soils, but are ineffective on others. However, as opposed to the embryonic days of soil stabilization, the present-day engineer can usually select a material to suit his needs from the ever-increasing "library" of soil stabilizers. It is the purpose of this report to present the results of research on another chemical that should be added to the stabilizer "library."

The prime requirements for any stabilizer used in roadway construction are that it should retain or increase the shear resistance of the soil even in the presence of saturating amounts of water, and it should increase the volumetric stability of the soil. Chemical stabilizers may perform these functions by cementation and/or waterproofing action. The cementing-type stabilizers actually bond the soil grains together and improve the strength of the soil mass under certain conditions. Examples are portland cement and lime, although it is recognized that lime also stabilizes by virtue of cation exchange. Waterproofing stabilizers can render the soil grains hydrophobic thus improving their properties in the presence of water although they do not necessarily cement or bond the soil grains together.

The initial purpose of this investigation was determination of the stabilizing effect of a fatty quaternary ammonium chloride on several highly plastic clays located in the southwestern United States. These clays are well-known for their poor road-building characteristics, particularly in regard to volumetric changes. Later in the program, the scope was enlarged to include investigations on other soil types, potential of chemical to reduce frost heave, and construction of test roads to examine field application characteristics and techniques.

CHARACTERISTICS OF CHEMICAL STABILIZER

The chemical investigated in this research—known commercially as Aliquat H226 (trademark of General Mills, Inc.)—is a dihydrogenated tallow dimethyl ammonium chloride. Although Aliquat H226 is initially a wetting agent, once adsorbed on the surface of a material the surface becomes hydrophobic. For soil stabilization purposes it can be accurately defined as a waterproofing agent.

Aliquat H226 is normally supplied as 75 percent active material in isopropanol. In this state it can easily be dispersed in water heated to a temperature of 120 to 140 F. When dispersed, it forms a stable milky suspension of variable viscosity depending on the water content. Aliquat H226 is non-toxic and during approximately 3 years of laboratory and field research, no harmful effects were reported even in cases of direct contact with the skin.

PREVIOUS INVESTIGATIONS WITH LARGE ORGANIC CATIONS

In recent years, engineers and agronomists have reported numerous investigations concerning the adsorption of cationic organic complexes on clays. It has been shown that organic cations are at least partially exchanged for the inorganic cations and are subsequently held tightly to the clays. Clays saturated with organic cations exhibit hydrophobic or water-heating characteristics.

When introduced into clay-water suspensions, organic cations may be adsorbed between the clay layers or sheets, around the particle edges, or they may remain in suspension. Clays of the montmorillonite group, having the major portion of their exchange capacity between the layers or platelets, adsorb the majority of the organic cations on these positions with a resulting increase of the basal spacing. Jordan, investigating the effect of primary amines on montmorillonites, found that the basal spacing increased as the number of carbon atoms in the amine chain increased (1). Jordan's results indicate basal spacings of a maximum order of two molecular thicknesses of the cation. Other investigators have reported spacings equal to three molecular thicknesses of the adsorbed cation (2). Because large cations may occupy much of the surface area between the clay platelets, they leave little for the adsorption of water. Various investigations have shown that the water-adsorbing capacities of montmorillonite are reduced as the basal surfaces are coated with organic ions. As the size of the organic ion increases, the water-adsorbing capacity is generally reduced (3, 4, 5).

Little research has been performed on the amount of organic cations that might remain in suspension and affect the properties of the pore water. Brindley and Rustom have conducted studies on the adsorption of a non-ionic organic complex on montmorillonite in aqueous suspension (6). When the amount of organic material was less than 50 percent of the maximum organic adsorption, about 70 percent of the added organic material was adsorbed on the clay and 30 percent remained in suspension.

The influence of organic cations on clay minerals other than montmorillonite has not been investigated as thoroughly as organic-montmorillonite complexes. Experiments by Grim, Allaway, and Cuthbert have shown that water adsorption of kaolinite clays is reduced after treatment with organic ions (3). The decrease in water adsorption is relatively less for kaolinites than for montmorillonites.

Grossi and Woolsey studied the effect of a fatty quaternary ammonium salt on a Putnam silt loam (7). Small amounts of this organic chemical greatly increased the water-stability of the soil aggregates and aided in the aggregation of the soil. Treatment with this chemical also decreased the capillary moisture absorption and increased the immersed compressive strength. Although the properties of the soil were not given,

TABLE 1
SOIL PROPERTIES

Property	Sample ^a												
	RF-												
	176-1	176-2	176-4	176-5	176-6	176-9	176-10	176-28	176-34	176-36	251-74	251-102	251-109
Liquid limit (%)	74.2	52.1	60.0	70.7	64.2	--	61.4	39.4	67.7	25.4	38.0	21.7	58.1
Plastic limit (%)	25.9	18.6	26.5	21.5	29.2	--	28.7	15.6	27.3	19.0	24.5	19.3	28.9
Plastic index (%)	48.3	33.5	33.5	49.2	35.0	--	32.7	23.8	40.4	6.4	13.5	2.4	29.2
Std AASHO compact test													
Max. dry density (pcf)	94.3	103.8	94.0	99.8	89.6	91.2	85.3	110.1	94.5	112.0	106.1	103.6	100.0
Opt. moist. cont. (%)	24.9	18.2	24.3	22.1	27.9	23.6	29.4	15.9	24.0	14.8	18.8	18.0	22.4
Sand size (%)	10.0	8.0	1.0	0	--	--	12.0	15.0	--	--	6.0	8.0	--
Silt size (%)	33.0	44.0	42.0	69.0	--	--	48.0	60.0	--	--	72.0	81.0	--
Clay (%):													
Finer than 5 μ	57.0	48.0	57.0	31.0	--	--	40.0	25.0	--	--	22.0	11.0	--
Finer than 2 μ	53.0	28.0	44.0	27.0	--	--	28.0	22.0	--	--	16.0	9.0	--
Specific gravity	2.66	2.74	2.69	2.66	2.71	2.65	2.64	2.67	--	2.68	--	--	--
pH	4.6	7.96	7.74	7.18	6.03	7.70	7.96	5.54	--	5.2	--	--	--
Cation exch. cap. (meq/100 g)	32.5	28.0	32.3	28.6	--	--	51.7	11.4	--	--	--	--	31.4
Exchangeable cations (meq/100 g):													
Na	1.3	1.1	0.9	4.5	--	--	0.2	0.4	--	--	--	--	0.4
K	0.7	0.8	1.0	0.9	--	--	1.0	0.2	--	--	--	--	0.9
Ca	6.5	-- ^b	-- ^b	19.2 ^c	--	--	-- ^b	4.3	--	--	--	--	19.4
Mg	7.8	2.0	5.3	6.1	--	--	1.8	3.4	--	--	--	--	10.7

^aWhere value not given, test was not performed.

^bFree CaCO₃ present, hence exchangeable calcium not determined.

^cFree CaCO₃ possibly present.

the classification denotes only a small amount of clay fraction that was probably montmorillonite.

Davidson and Hoover experimented with a number of organic cationic chemicals as stabilizers for Iowa loess (8). In general, the organic cations increased the immersed compressive strength and decreased the water absorption and swelling of the loess. The only undesirable effect noted was a decrease in the air-day compressive strength of the soil. The clay fractions of the soils used in this study were predominately montmorillonite. The apparent success of Hoover and Davidson with one of the chemicals—Arquad 2HT (trademark of Armour & Co., Inc.)—on the loess soils, prompted the research described in this paper.

SOIL CHARACTERISTICS AND PREPARATION

In the initial phase of the research soils were selected on the basis of their reportedly poor engineering characteristics. Obtained primarily from Texas and Oklahoma, these soils are present in such large quantities that they must be utilized as highway building materials regardless of their poor properties. In later phases of the research, a few additional soils containing high percentages of silt were selected.

Properties of the soils used in this investigation are consolidated and given in Table 1. For ease of presentation, subsequent reference to soils is made by the laboratory identification number.

The soils were prepared for use by drying in a 140 F oven for a period of 12 to 24 hr depending on their original moisture content. The oven-dried materials were then ground in a muller until they passed a No. 18 sieve. All soils were fine grained and this type of grinding did not reduce the natural size of individual particles. After processing, the soils were stored in covered containers before use.

CHEMICAL PREPARATION

It was necessary to dilute the 75 percent active Aliquat H226 with water to reduce the viscosity so the solution could be easily mixed with the soils. The solutions were prepared in the following manner:

1. A weighed quantity (usually between 150 and 300 g) of 75 percent active Aliquat H226 was placed in a mixing bowl.
2. The amount of water required to produce the desired solution was heated to 140 to 150 F and poured into the mixing bowl.
3. The solution was vigorously stirred in a mechanical mixer until the odor of the solution indicated that most of the isopropanol had evaporated. The solution was then stored in a closed glass container.

A solution of 6.5 percent active Aliquat H226 by weight was found to be very convenient for the laboratory research.

LABORATORY TEST PROCEDURES

A variety of testing procedures have been used or recommended for the evaluation of soil-stabilizing agents. In an attempt to use an evaluation procedure that could be regarded as more or less standard, the research personnel turned to the Physical Tests

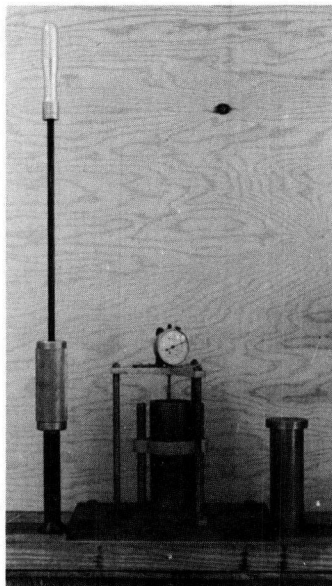


Figure 1. Vicksburg miniature compaction apparatus.

TABLE 2
MOISTURE CONTENT AND DENSITY
RELATIONS FOR ALIQUAT H226-
TREATED SOILS

Sample No.	Dry Soil Wt. (%)	Opt. Moist. Content (%)	Max. Dry Density (pcf)
176-1	0	24.9	94.3
	0.125	25.1	91.1
	0.250	26.5	91.0
	0.5	26.6	91.6
	1.0	23.3	92.6
	2.0	--	--
	3.0	--	--
176-2	0	18.2	103.8
	0.125	18.7	103.6
	0.250	21.0	101.0
	0.5	19.9	101.0
	1.0	20.3	101.0
	2.0	--	--
	3.0	--	--
176-4	0	24.3	94.0
	0.125	24.5	95.8
	0.250	24.5	94.9
	0.5	24.5	93.8
	1.0	24.5	93.7
	2.0	--	--
	3.0	--	--
176-5	0	22.1	99.8
	0.125	21.9	98.8
	0.250	22.7	98.5
	0.5	22.7	97.2
	1.0	22.5	97.7
	2.0	--	--
	3.0	--	--
176-6	0	27.9	89.6
	0.125	28.0	89.5
	0.250	27.3	90.4
	0.5	27.7	89.9
	1.0	28.4	88.8
	2.0	--	--
	3.0	29.0	85.8
176-9	0	23.6	91.2
	0.125	--	--
	0.250	--	--
	0.5	24.0	90.1
	1.0	25.5	90.8
	2.0	--	--
	3.0	--	--
176-10	0	29.4	85.3
	0.125	27.6	87.1
	0.250	28.2	86.8
	0.5	27.2	86.4
	1.0	27.8	85.4
	2.0	--	--
	3.0	--	--
176-28	0	15.9	110.1
	0.125	15.0	110.2
	0.250	16.6	107.4
	0.5	16.9	106.8
	1.0	16.4	105.4
	2.0	--	--
	3.0	--	--

Division, Bureau of Public Roads. For the most part the following procedures duplicate or closely parallel those procedures recommended by the Bureau of Public Roads for evaluation of chemical soil stabilizers.

Compaction Test

To determine the effect of Aliquat H226 on the compaction characteristics of soils, the standard AASHO compaction test (AASHO designation T99-57) was performed on soils in both the chemically treated and untreated states. Chemical concentrations of 0.125, 0.25, 0.5, and 1.0 percent of the dry soil weight were generally used if sufficient soil were available. The soil, water, and/or chemical solution were thoroughly mixed in a Lancaster PC mixer and then compacted in a standard AASHO mold. A portion of the mixture was also compacted in the Vicksburg miniature compaction apparatus shown in Figure 1. In the Vicksburg compaction procedure, a quantity of soil sufficient to produce a specimen 4 in. high and 2 in. in diameter was compacted in the mold in 4 equal layers. The number of blows per layer was selected to obtain a compaction curve similar to the standard AASHO curve. During the mixing and compaction process, it was observed that the addition of Aliquat H226 made the soils friable and easier to mix. It was also necessary to use a fresh specimen for each point on the compaction curve because soils treated with Aliquat H226 were effectively waterproofed to the extent that they did not readily accept additional water especially if some evaporation of the initial moisture had occurred.

Results of the standard AASHO compaction tests, Table 2, show that Aliquat H226 produces only minor changes in the maximum dry unit weights and optimum moisture contents. The general trend is a very slight reduction in unit weights with a slight but erratic variation in optimum moisture contents. An exception is RF 176-28 in which kaolinite is the predominant clay mineral. With high percentages of Aliquat H226 this soil became extremely spongy resulting in a fairly significant decrease in dry unit weight.

The Bureau of Public Roads has no criteria concerning the effect of stabilizers on the compaction characteristics of soils. However, with the possible exception of cementing-type stabilizers, significant

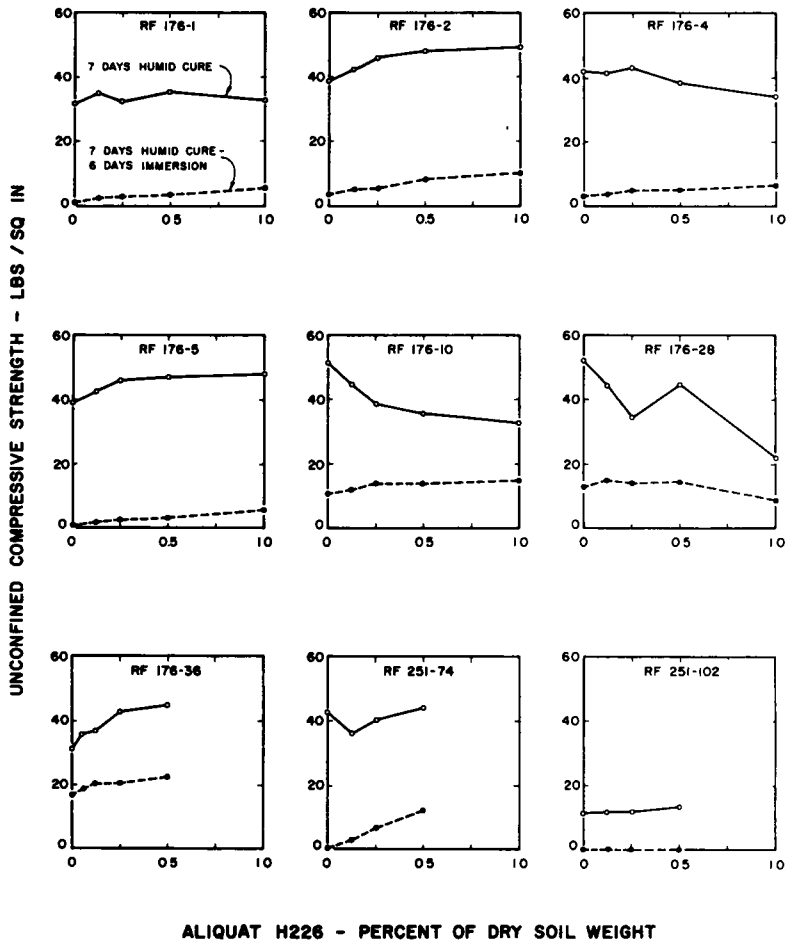


Figure 2. Unconfined compressive strength for 7 days of humid curing and 6 days of immersion.

decreases in the compacted unit weights are generally undesirable due to resulting decreases in soil strength.

Unconfined Compressive Strength

Specimens for the unconfined compression test were molded in the Vicksburg miniature compaction apparatus according to Bureau of Public Roads recommendations. Sufficient soil to make from 7 to 9 specimens was mixed with the amount of water or chemical solution needed to obtain the previously determined optimum moisture content. Specimens were then compacted to obtain the standard AASHO maximum unit weight with an allowable deviation of 0.25 pcf.

After being compacted and weighed, the specimens were placed in a humid room at 95 ± 5 percent relative humidity and 75 ± 5 F for 7 days. At the end of the 7-day humid-curing period each set of specimens was divided into two groups. One group was tested immediately to determine the unconfined compressive strength and the remaining group of specimens was completely immersed in water for 6 days and then tested. Compression tests were performed on a universal testing machine operated at a deformation rate of 0.05 in. per min. Results of these strength tests are shown in Figure 2.

The Bureau of Public Roads recommended that stabilized specimens meet the following specifications:

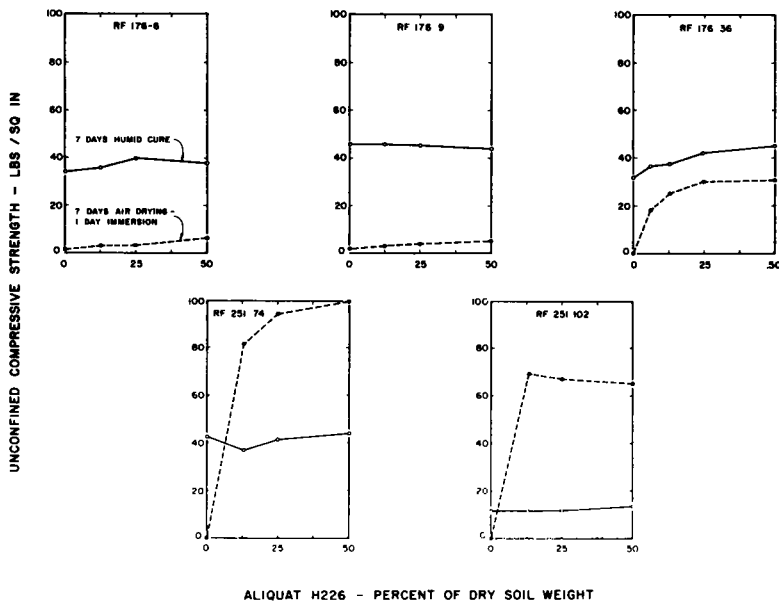


Figure 3. Unconfined compressive strength for 7 days of air drying and 1 day at immersion.

1. Attaining of a minimum compressive strength of at least 100 psi after 7 days of humid curing.
2. Loss of not more than 90 percent of their 7-day humid-cured strength after 6 days of immersion.

As seen from Figure 2, the effect of Aliquat H226 treatment on the 7-day humid cured specimens was variable; an increase in the chemical caused a strength increase in some of the soils and a decrease in others. RF 251-102 was virtually unaffected. In instances where the strength patterns appeared erratic, check tests disclosed no appreciable changes from the original data. Aliquat H226 treatment did increase the immersed strengths of 7 of the 9 soils reported. An increase in the chemical content generally increased the immersed soil strengths, but when used in economic quantities Aliquat H226 did not satisfy strength requirements of the Bureau of Public Roads.

With respect to other stabilization studies, the strengths shown in Figure 2 appeared comparatively low, and consideration was given to the curing conditions which were being used for this research. It is apparent that the condition of 7 days of humid curing before immersion is beneficial to cementing stabilizers such as lime and cement but this is not necessarily true for waterproofer. In their research on stabilization with large organic cations, Davidson and Hoover (8) obtained significant strength increases using a curing procedure of 7 days of air drying at approximately 35 percent relative humidity followed by 24 hr of immersion before the specimens were tested in compression.

The favorable results achieved by Davidson and Hoover prompted additional strength studies on 5 soils using the previously mentioned curing procedure. Results are shown in Figure 3. After the 7-day air drying period, untreated soils usually disintegrated or spalled badly within a few minutes after immersion. For the two clay soils RF 176-6 and RF 176-9, this curing procedure was less beneficial than 7 days of humid curing. The silty soils, RF 176-36, RF 251-74, and RF 251-102, were more favorably affected. RF 251-74 attained a strength of 100 psi with 0.5 percent Aliquat H226 and only slightly less strength with 0.25 percent. Figure 4 shows specimens of this soil after 24 hr of immersion.

Based on compressive strength alone, it appears that the original objective of stabilizing highly plastic clay soils with Aliquat H226 was only moderately successful.

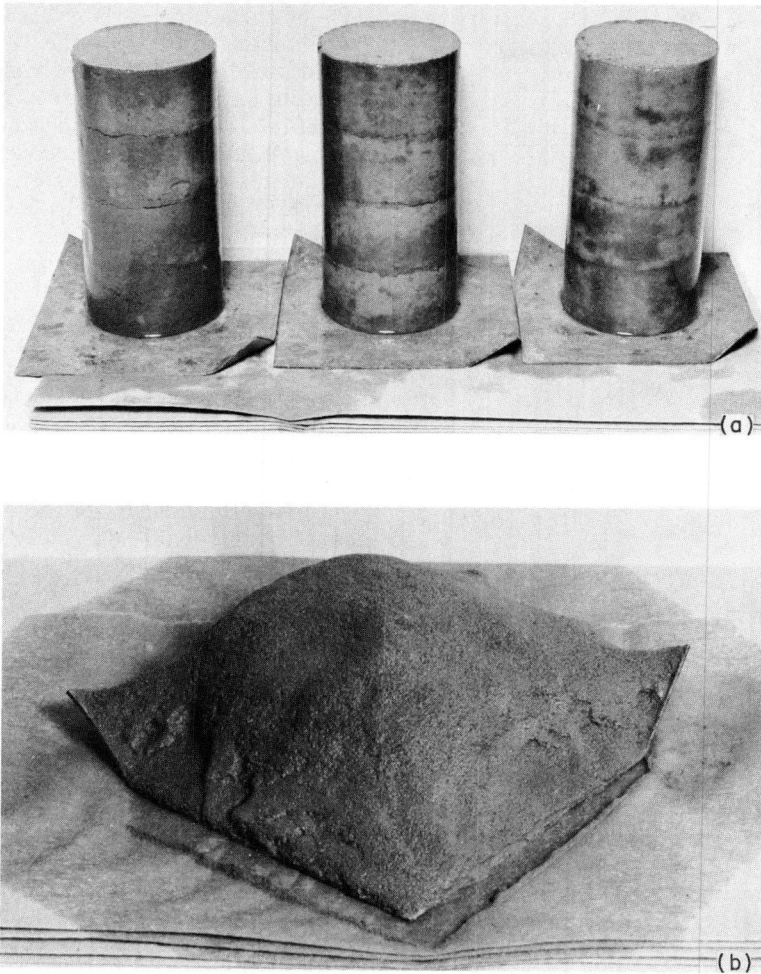


Figure 4. (a) Stabilized specimens of RF 251-74 after 7 days of air drying and 1 day at immersion. Aliquat H226 contents, left to right 0.125, 0.25, and 0.5 percent. (b) Untreated specimen after immersion.

On the other hand, the less plastic silty soils can be very effectively stabilized provided proper curing conditions are achieved. Preliminary studies have indicated that the optimum amount of drying varies with the properties of the soil.

Atterberg Limits

The effect of Aliquat H226 on the plasticity characteristics of the soils was evaluated with the Atterberg limits. Although the Bureau of Public Roads does not stipulate numerical criteria for this test, it is generally recognized that a decrease in the plasticity index is desirable.

Using the procedure recommended by the Bureau of Public Roads, samples were prepared for the tests by mixing approximately 600 g of soil with the required amount of Aliquat H226 solution and/or water needed to obtain the optimum moisture content determined from the compaction tests. After thorough mixing, each sample was divided into two equal parts and placed in separate air-tight jars. One portion was humid cured in the jar for 24 hr and the remaining portion cured for 8 days. At the end of their respective curing periods, the samples were removed from the jars, placed in open containers to air dry, and then crushed with a mortar and pestle until they passed a No. 40 sieve. The tests were then performed according to AASHTO designation T89-60 and

TABLE 3
 ATTERBERG LIMITS OF ALIQUAT
 H226-TREATED SOILS

Sample No.	Dry Soil Wt. (%)	Liquid Limit	Plastic Limit	Plasticity Index
176-1	0	74.2	25.9	48.3
	0.125	65.5	26.0	39.5
	0.250	62.0	30.0	32.0
	0.5	58.8	30.3	28.5
	1.0	55.0	31.0	24.0
176-2	0	52.1	18.6	33.5
	0.125	53.5	18.7	34.8
	0.250	49.5	19.5	30.0
	0.5	47.8	20.4	27.4
	1.0	44.2	20.4	23.8
176-4	0	60.0	26.5	33.5
	0.125	62.3	28.8	35.5
	0.250	59.0	27.4	31.6
	0.5	55.8	27.4	28.4
	1.0	50.3	30.9	19.4
176-5	0	70.7	21.5	49.2
	0.125	70.0	22.0	48.0
	0.250	68.4	23.2	45.2
	0.5	61.8	25.3	36.5
	1.0	57.0	28.4	28.6
176-10	0	61.4	28.7	32.7
	0.125	60.4	29.1	31.3
	0.250	60.0	31.0	29.0
	0.5	57.4	32.9	24.5
	1.0	54.0	36.1	17.9
176-28	0	39.4	15.6	23.8
	0.125	36.0	16.5	19.5
	0.250	35.5	19.0	16.5
	0.5	35.2	20.6	14.6
	1.0	33.8	20.5	13.3

T90-56. Because no significant differences were observed between the 1-day and 8-day cured specimens, the test results, given in Table 3, include only the values for 1-day humid curing. These results show that Aliquat H226 effectively reduced the plasticity indexes of all soils tested. This was generally accomplished by lowering the liquid limits and increasing the plastic limits. The most significant reductions occurred in those soils with the highest plasticity indexes. In many cases, small amounts of Aliquat H226 (0.125 to 0.25 percent) produced the greatest changes and additional quantities had slight effect. In general, it appears that Aliquat H226 in relatively small quantities will significantly reduce soil plasticity.

During the conduct of the Atterberg limit tests, considerable difficulty was experienced in mixing water into the Aliquat H226-treated specimens after the air-drying period. The water usually "balled up" on the soil and often 30 to 45 min of vigorous mixing was required to obtain a homogeneous mixture. This is further evidence of the excellent waterproofing characteristics of Aliquat H226. However, the fact that water could be eventually mixed into the soil seems to indicate that sufficient manipulation in the presence of water can at least partially overcome the hydrophobic characteristics imparted by the chemical.

Capillary Absorption Tests

Because of its excellent waterproofing characteristics it was thought that Aliquat H226 might also be effective in reducing moisture absorbed by capillarity. To test this theory, a rather simple laboratory procedure was used. Compacted specimens were placed on porous stones and then positioned in water so the water level was approximately $\frac{1}{4}$ in. below the base of the specimens. The specimens were covered with small jars to prevent moisture loss to the atmosphere and then weighed at predetermined time intervals to determine the amount of moisture absorbed.

The first soil tested in this manner was RF 251-109, a clay from O'Hare International Airport, Chicago, Ill. Because it had already been determined that drying affected the strength characteristics of treated soils, the program also included tests to determine the effect of drying on capillary absorption. This was accomplished by molding several specimens each of untreated, 0.125, and 0.5 percent Aliquat H226-treated soils at their optimum moisture contents and standard AASHTO unit weights. Some of the molds were allowed to air dry to approximately 2, 4, 8, and 16 percent less than the as-molded moisture content. The partially dried specimens were then wrapped in foil, waxed and allowed to stand for 7 days to permit moisture redistribution before being tested.

Figure 5 shows the untreated soils gained moisture rapidly after being subjected to capillarity. Both the amount of moisture and the rate of moisture absorption increased with an increase in the amount of drying back from the as-molded moisture content. On the other hand, treatment with Aliquat H226 significantly reduced the amount and the rate of capillary absorption. Moreover, both levels of Aliquat H226 treatment appeared to be equally effective. The results also show that drying is not required to

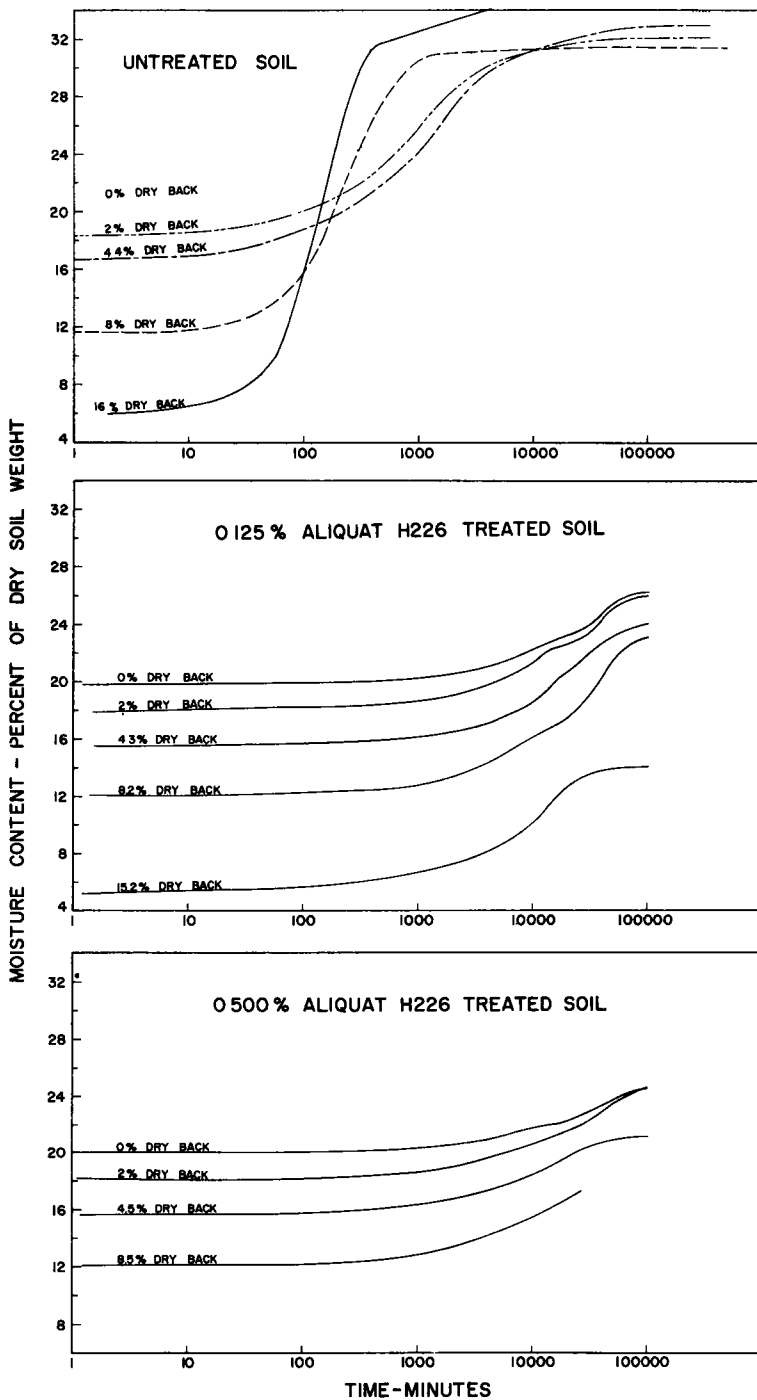


Figure 5. Results of capillary absorption tests on RF 251-109.

reduce capillary absorption of treated soils, but it does increase the effectiveness of the treatment significantly.

The effect of Aliquat H226 treatment was also evident in appearance and strength of the specimens as shown in Figure 6. With less than 1 day of capillarity the untreated

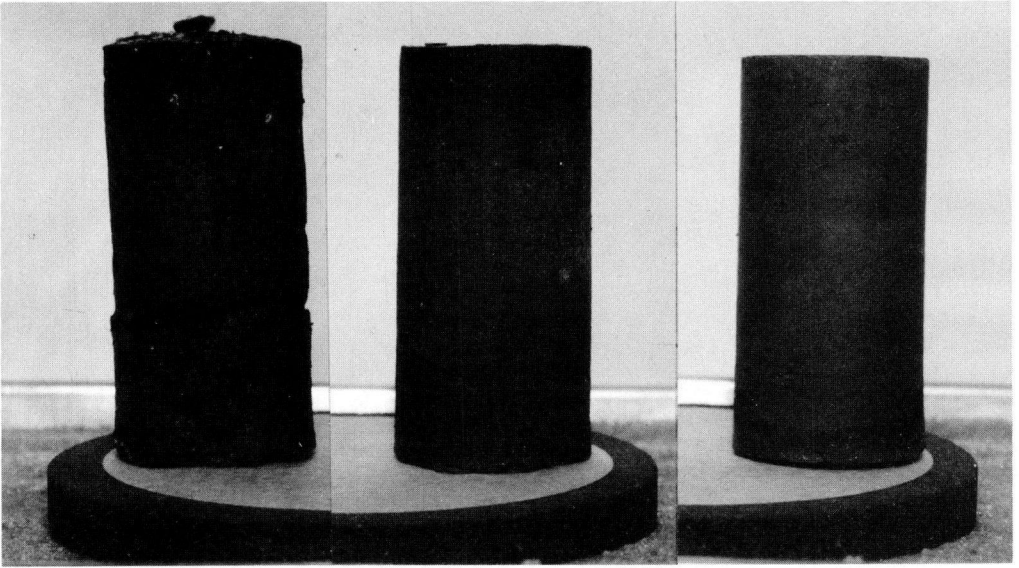


Figure 6. Capillary absorption specimens of RF 251-109. Treatment, left to right, untreated, 0.125 percent Aliquat H226, and 0.5 percent Aliquat H226.

soils became extremely fragile and required great care in handling. The treated soils exhibited high strength throughout the test period. Similar tests, not reported herein, were performed on several other soils confirming the observations made on the O'Hare Field clay. In all instances Aliquat H226 significantly reduced capillary moisture absorption.

As a means of comparing Aliquat H226 with other stabilizers, two soils (RF 176-5 and RF 176-34) were separately stabilized with 0.5 percent Aliquat H226 and with 4.0 percent lime and subjected to capillarity at their as-molded moisture contents. The results of these tests (Fig. 7) show Aliquat H226 to be superior to lime in reducing capillary absorption in these two soils.

COMBINATIONS OF ALIQUAT H226 AND OTHER STABILIZERS

From the test results shown in Figure 2, it was apparent that when used in economically competitive quantities on the highly plastic clays, Aliquat H226 could not satisfy the compressive strength requirements of the Bureau of Public Roads. The inherently low strength of the plastic soils necessitates the use of a cementing type of stabilizer rather than a waterproofer to attain the minimum strength requirement of 100 psi. However, it was felt that further addition of a waterproofer should retain the strength imparted by a cementing stabilizer during immersion, thereby resulting in stabilization superior to that obtained with either stabilizer separately. Accordingly, specimens were made using lime and portland cement in conjunction with Aliquat H226 and the effectiveness of these combinations was evaluated by unconfined compression tests. The results shown in Figure 8 for RF 176-5 are considered typical of tests conducted on several clay soils.

In general, it was found that small amounts of Aliquat H226 increased the strength of lime-stabilized specimens after 7 days of humid curing. When subjected to 6 days of immersion following the humid cure period, Aliquat H226 increased the strength of specimens containing small quantities of lime, but it was less effective at higher lime percentages. However, after the curing conditions of 7 days of air drying, lime-stabilized specimens collapsed when immersed unless they were treated with Aliquat H226.

Aliquat H226 had relatively minor effect on the strengths of cement-stabilized specimens except those cured with 7 days of air drying. At these conditions, it was again

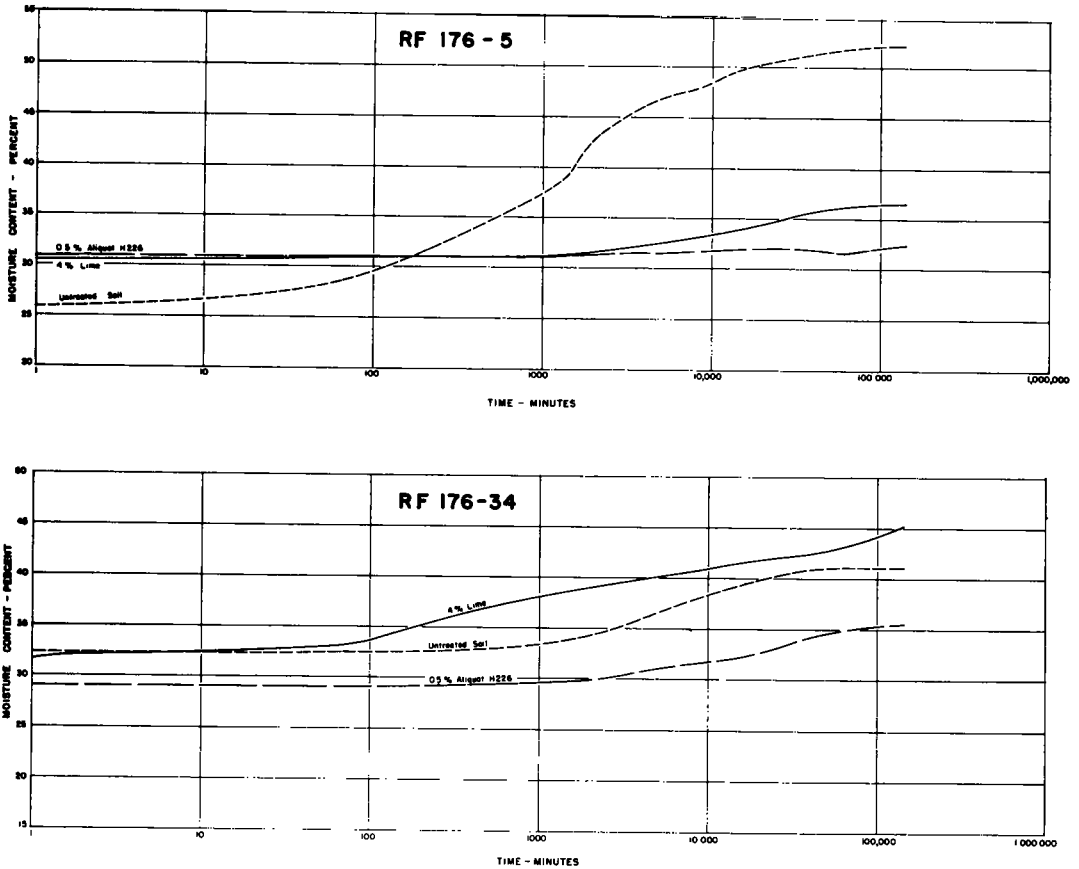


Figure 7. Results of capillary absorption tests on RF 176-5 and RF 176-34.

found that specimens which did not contain Aliquat H226 either disintegrated or had very low strengths when immersed.

FROST HEAVE STUDIES

Due to the ability of Aliquat H226 to reduce capillary absorption and render the soil grains hydrophobic, a brief study was conducted to determine its effectiveness as a frost heave inhibitor. Two soils, RF 251-74 and RF 251-102 were selected for the investigation. Soil properties are given in Table 1.

Apparatus

To perform tests under conditions resembling those encountered in the field, the freezing chest shown in Figure 9 was designed and constructed. Several of the more important features of the freezing chest are considered pertinent. First, the chest was designed so that 20 Harvard miniature compaction molds could be tested during each freezing cycle. A plexiglas window was placed in the front for observations and measurements. The sides of the molds were insulated with styrofoam to insure freezing of the samples from the top and 4 of the 20 molds were equipped with thermocouples to record the downward progression of the freezing plane. The rate at which the molds were frozen was thermostatically controlled. The freezing chest was placed in a large refrigerator to minimize the effect of fluctuations in laboratory temperature. To obtain a uniform temperature distribution throughout the chest, a small fan was installed to provide constant air circulation. Finally, a free water surface was made available to the bottom of the samples.

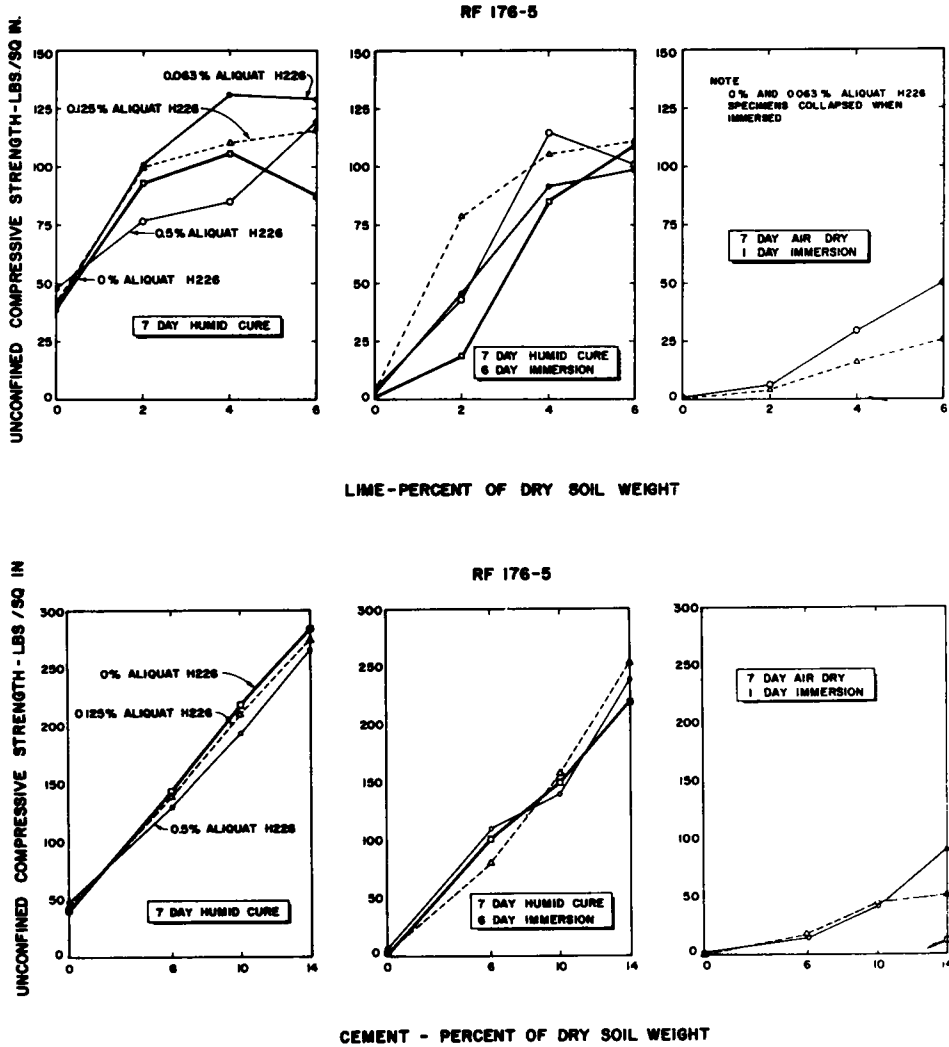


Figure 8. Unconfined compressive strength for RF176-5 using lime and portland cement in combination with Aliquat H226.

Laboratory Procedure

Test specimens were compacted in plexiglas molds using the Harvard miniature compaction apparatus and procedure. The specimens were generally broken down into four groups of five similarly stabilized specimens for each test cycle. One specimen in each group was instrumented with thermocouples (Fig. 10) and the heave of each treatment was taken as the average of the remaining four specimens. Each cycle contained an untreated group so that a comparison could always be obtained between the heave of the raw soil and treated specimens. Generally, the remaining three groups were stabilized with 0.125, 0.25, and 0.5 percent Aliquat H226.

Two different test methods were used. In the first method, specimens were placed on the base plate immediately after compaction and allowed to absorb water for 24 hr. The test was then carried out as described later. The second method allowed the specimens to dry back after compaction to approximately 50 percent of their as-molded moisture content, after which they were placed on the base plate to absorb water for 48 hr.

At the end of the soaking period, the heights of all specimens and the temperature gradient in the four instrumented specimens were recorded. The freezing chest was

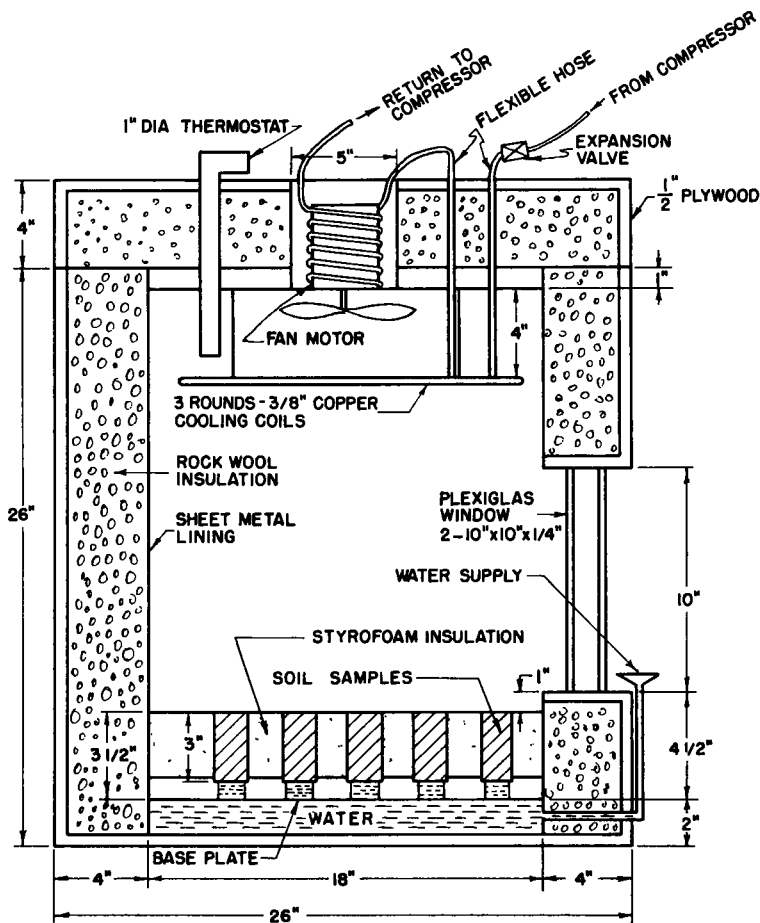


Figure 9. Cross-section of freezing chest.

sealed and the temperature inside the chest was gradually lowered so as to maintain a freezing gradient in the specimens of approximately $\frac{1}{4}$ in. per day. At predetermined time intervals, the specimen heights were measured and recorded. At the end of the freezing cycle the specimens were removed and allowed to thaw. Observations were made as to the conditions of the samples before and after thawing.

Results of Freeze Test

The effectiveness of Aliquat H226 as a stabilizer for frost susceptible soils was found to be markedly influenced by the curing method, as seen in Table 4.

Untreated specimens of RF 251-102 which were allowed to dry from the as-molded condition heaved 133 percent of their initial height. However, specimens tested simultaneously but treated with as little as $\frac{1}{8}$ percent Aliquat H226 did not show any distress or change in height. The effectiveness of Aliquat H226 under these conditions can probably be attributed to the hydrophobic characteristics of the chemical. As the soil is dried back to a point where the capillary pores are no longer filled with continuous columns of water, the Aliquat H226 coats the sides of the pores. When the specimens are subsequently subjected to freezing, the forces normally pulling water into the soil; that is, capillary forces and suction forces due to freezing, are not great enough to overcome the repulsive force of the Aliquat H226 for water.

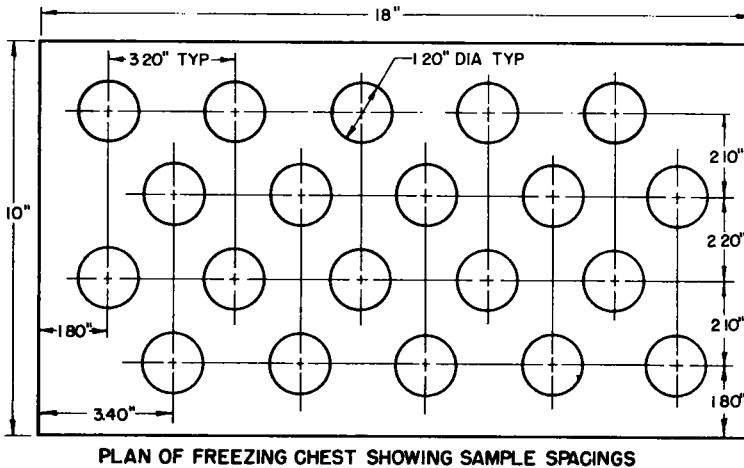
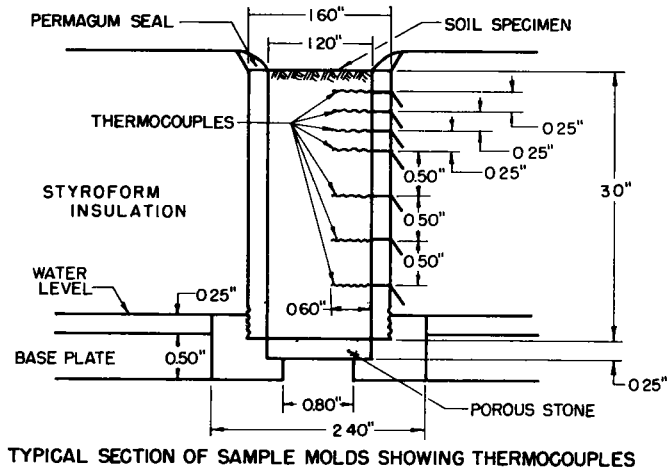


Figure 10.

The addition of Aliquat H226 did not improve the heave characteristics of soils tested at the as-molded moisture condition. The magnitude of the heave in the treated samples was, in fact, slightly greater than observed in the untreated soil. However, it was apparent that Aliquat H226 did influence the stability of the treated samples. This was evident several times when mechanical failures interrupted the freezing cycle and caused the ice on the cooling coils directly above the specimens to melt. The water dripping on the untreated specimens quickly disintegrated them but had no effect on the Aliquat H226-treated specimens. Also, when the tests were terminated and the specimens allowed to thaw after removal from the chest, the untreated specimens slumped whereas Aliquat H226-treated specimens retained their shape and strength. Apparently the migration of water within the specimens during freezing resulted in sufficient drying between the frost lenses to render the grains hydrophobic.

MINERALOGICAL STUDIES

Apparatus, Procedure, and Soils Studied

To investigate the action of Aliquat H226 on soils, a brief study was made of its influence on the basal spacings of certain clay minerals. This study was performed using

TABLE 4
RESULTS OF FROST HEAVE STUDIES

Soil	Average Compacted Density (pcf)	Treatment (% H 226)	Average Heave (cm)	Ratio of Heave ^a
RF 251-74	106 3	Untreated	0 81	--
	106 2	1/8	1 29	1.60
	106 2	1/4	1 33	1.64
	105 1	1/2	1 31	1.62
RF 251-74	105 6	Untreated	0 85	--
	104 9	1/8	1 52	1.79
	104.4	1/4	1 75	2.06
	102 4	1/2	1 20	1.41
RF 251-74	109 0	Untreated	1 31	--
	108 9	1/8	1 52	1.16
	109 3	1/4	1 40	1.07
	108 2	1/2	1 46	1.11
RF 251-102	103.2	Untreated	1 38	--
	102 2	1/8	1 64	1.19
	102.1	1/4	1 73	1.25
	102 0	1/2	1.80	1.30
RF 251-102 ^b	102.9	Untreated	2 5	--
	102 8	1/8	0	0
	103.0	1/4	0	0
	102.1	1/2	0	0

^aUntreated soil to treated soil

^bSamples cured by drying before soaking and freezing.

a Phillips electronic X-ray diffraction unit, equipped with wide-range goniometer and copper target. Three clays were selected for X-ray study: Volclay (a sodium-saturated montmorillonite) and Panther Creek bentonite (a calcium-saturated montmorillonite), both obtained from the American Colloid Company, and a kaolinite, known as Hydrite 10 obtained from the Georgia Kaolin Company.

The specimens for the study were prepared by placing 1 g of air-dried clay in a 100-ml centrifuge tube. To this was added 25 ml of solution containing the desired treatment. The solution was shaken for 15 min in a reciprocating test tube shaker, allowed to stand for 48 hr and then shaken again for 15 min. A portion of the solution was placed on glass slides and allowed to dry to a constant moisture content at room temperature in order to obtain maximum particle orientation. X-ray patterns were then obtained.

Results and Evaluation

Because sodium montmorillonite is the most active of the clay minerals, first considerations were focused on the effect of Aliquat H226 on this mineral. As seen in Table 5, the pure clay mineral has an (001) spacing of 12.45 Å. When 0.1 percent Aliquat H226 was added, no significant effect on the basal spacing was observed. However, 0.5 percent Aliquat H226 showed two equal intensity peaks at 13.19 Å and 23.88 Å. Because the peaks were of equal intensities, it would appear that approximately one-half of the clay had been expanded to 23.88 Å, whereas the remainder was unaffected. X-rays for the 1 percent Aliquat H226 solution indicated that most of the montmorillonite had been expanded to 27.6 Å, whereas the 14.25-Å peak with the intensity of 4 was probably caused by some of the clay mineral remaining relatively unaffected by the treatment. Percentages of Aliquat H226 larger than one are believed to have completely blotted out all indications of the clay minerals. The 2.0, 4.0, and 6.5 percent Aliquat H226 solutions gave (001) spacings of 37.6, 39.3, and 39.3 Å, respectively. These values check very closely with the 38.4-Å spacing found for the Aliquat H226 (Table 6).

To determine if the expansion of the Na-montmorillonite was permanent, samples treated in the preceding manner with two percent Aliquat H226 were washed and new X-ray patterns were obtained. One sample washed four times with water showed an (001) spacing of 27.6 Å which is identical to the high intensity peak obtained for the 1 percent treatment. A similar sample was washed four times in isopropanol, a known

TABLE 5
Na-MONTMORILLONITE X-RAY DATA

Treatment	Total Angle (deg 2 θ)	Angle 2 θ of Major Peaks	Basal Spacing (A)	Relative Intensity
1 g Na-montmorillonite in distilled water	40	7 1	12, 45	10
1 g Na-montmorillonite+ 25 ml 0 1% H226 sol	10	7 0	12, 63	10
1 g Na-montmorillonite+ 25 ml 0 5% H226 sol	10	6 65 3 7	13 19 23 88	10 10
1 g Na-montmorillonite+ 25 ml 1 0% H226 sol	10	3 2 6 3	27, 6 14 24	10 4
1 g Na-montmorillonite+ 25 ml 2, 0% H226 sol	10	2 35 4 3	37, 6 20, 6	10 4
1 g Na-montmorillonite+ 25 ml 4 0% H226 sol	20	2 25 4 50	39, 3 19 6	10 2
1 g Na-montmorillonite+ 25 ml 6 5% H226 sol	20	2 25 4 50	39, 3 19 6	10 2
1 g Na-montmorillonite+ 25 ml 2% H226 sol then washed 4 times with water	10	3 2 6 65	27, 6 13, 2	10 2
1 g Na-montmorillonite+ 25 ml 2% H226 sol then washed 4 times with isopropanol	10	3 4 6 8	26, 0 13 0	10 2
1 g Na-montmorillonite+ 25 ml isopropanol	10	6 9	12, 81	10

TABLE 6
ALIQUAT H226 X-RAY DATA

Treatment	Total Angle (deg 2 θ)	Angle 2 θ of Major Peaks	Basal Spacing (A)	Relative Intensity
Slide made of 6, 5% solution of H226	40	2 3	38, 41	10
		4, 5	19, 6	1
		6, 75	13, 1	2
		9, 0	9 8	1

solvent of Aliquat H226, resulting in an (001) spacing of 26.0 A. Because a separate slide of the Na-montmorillonite, prepared using isopropanol without additional treatment, resulted in a spacing of 12.8 A, it is evident that the expansion was caused entirely by the Aliquat H226. The isopropanol washing was much more vigorous than any treatment normally applied to soils in the field; therefore, it can be concluded for all practical purposes that Aliquat H226 in sufficient quantity will expand the Na-montmorillonite, and that this expansion will be unaffected by leaching action of ground water.

The X-ray study performed on Ca-montmorillonite was similar to that cited above for the Na-saturated mineral. The results are given in Table 7. Once again, it can be seen that for percentages of Aliquat H226 greater than two the high intensity Aliquat H226 peak at 38.4 A completely obscured the clay mineral peak. However, when the samples were washed with water and isopropanol, the (001) peaks showed a spacing of 29.45 A and 26.0 A, respectively. Once again, a close similarity can be observed between the high intensity peak of 28.5 A for the 1.0 percent treatment and 29.45 A for the 2.0 percent sample after the latter had been washed four times in water. For both the Aliquat H226 treated Na- and Ca-montmorillonite samples, four washings with isopropanol resulted in a basal spacing of 26.0 A.

Table 8 gives the results of a limited X-ray study performed on kaolinite. With a 2.0 percent Aliquat H226 treatment, two equal intensity peaks were found at 7.196 A and 32.7 A. After four washings with water or with isopropanol, the larger peak was eliminated leaving only the peak characteristic of kaolinite. With this limited data, no

TABLE 7
Ca-MONTMORILLONITE X-RAY DATA

Treatment	Total Angle (deg 2)	Angle 2 of Major Peaks	Basal Spacing (A)	Relative Intensity
1 g Ca-montmorillonite in distilled water	40	6, 25	14, 26	10
1 g Ca-montmorillonite in 25 ml 0.1% H226 sol	10	5, 95	14, 85	10
1 g Ca-montmorillonite in 25 ml 0.5% H226 sol	10	5, 90	14, 98	10
1 g Ca-montmorillonite in 25 ml 1.0% H226 sol	10	3, 1	28, 50	10
		4, 3	21, 04	9
		5, 8	15, 24	8
1 g Ca-montmorillonite in 25 ml 2.0% H226 sol	10	2, 3	38, 41	10
		4, 6	19, 21	5
1 g Ca-montmorillonite in 25 ml 2% H226 sol then washed 4 times with isopropanol	10	3, 5	26, 0	10
1 g of Ca-montmorillonite in 25 ml 2% H226 sol then washed 4 times with water	10	3, 0	29, 45	10

TABLE 8
KAOLINITE X-RAY DATA

Treatment	Total Angle (deg 2θ)	Angle 2θ of Major Peaks	Basal Spacing (A)	Relative Intensity
1 g kaolinite in distilled water	40	12, 4	7, 138	10
		24, 9	3, 576	5
		37, 7	2, 386	1
1 g kaolinite in 25 ml 2% H226 sol	16	2, 7	32, 7	10
		8, 0	11, 05	1
		12, 3	7, 196	10
1 g kaolinite in 25 ml 2.0% H226 sol then washed 4 times in isopropanol	16	12, 4	7, 138	10
1 g kaolinite in 25 ml 2% H226 sol then washed 4 times in water	16	12, 35	7, 167	10

definite conclusion can be reached as to the significance of the 32.7-A peak, but it is apparent that Aliquat H226 is not irreversibly adsorbed or held by the kaolinite.

From the mineralogical studies, several additional observations can be made which would tend to explain the behavior of some soils after treatment with Aliquat H226. According to Grim (2), the charge deficiency of montmorillonite is about -0.66 per unit cell. Thus, on the average, in each 1.5 unit cell there is a deficiency of positive charges equal to unity. Assuming unit cell dimensions of $a_0 = 5.2$ and $b_0 = 9.4$ A, the total surface area per unit deficiency of charge would be approximately 75 sq A. The Aliquat H226 cation, with a positive one charge, however, has an area in plan which is almost three times as large. From this comparison of areas it can easily be seen that with an optimum arrangement of the Aliquat H226 ions, it would be necessary to have a minimum of three layers of Aliquat H226 in the interlayer spaces to satisfy the charge deficiency. Because this optimum arrangement will probably never be achieved, more than three layers will be required to satisfy the charge deficiency. Recalling the X-ray evidence cited earlier, both the Ca- and Na-montmorillonite remained at c-axis spacings of 26.0 A after being saturated and washed with isopropanol. This represents an increase in basal spacing of about 16 A above that of the theoretical mineral, or a total of 4 layers of Aliquat H226 in the interlayer spaces.

TABLE 9
 ATTERBERG LIMITS OF CLAY MINERALS

Type of Mineral	Aliquat H226 (% dry soil wt)	Liquid Limit	Plastic Limit	Plasticity Index
Na-montmorillonite	Untreated	703	40	663
	0.25	664	43	621
	0.5	625	43	582
	1.0	547	49	498
	2.0	465	50	415
Ca-montmorillonite	Untreated	123.0	44.0	79.0
	0.25	113.8	47.8	66.0
	0.5	109.4	49.0	60.4
	1.0	100.2	54.3	45.9
	2.0	92.7	53.4	39.3
Kaolinite	Untreated	69.6	41.1	28.5
	0.125	82.9	44.6	38.3
	0.25	96.4	46.8	49.6
	0.5	105.4	50.6	54.8
	1.0	101.8	54.8	47.0

In addition to the previously mentioned relationships, a similar conclusion may be reached from a weight-charge relationship. Assuming that all of the Aliquat H226 would be effective, 0.5 g would have to be added to neutralize the charge deficiency of 1.0 g of clay. Once again, however, due to the extremely large size of the Aliquat H226 ion, it would appear to be practically impossible to locate all of the ions in the interlayer spaces. This is well illustrated by the X-ray patterns for both the Na- and Ca-montmorillonite samples. In Tables 5 and 7, 25 ml of 2.0 percent solution added to 1 g of clay would be approximately equal to the ratio stated. The (001) peak, however, corresponds very closely to that obtained for pure Aliquat H226, indicating that the amount of Aliquat H226 which has not been exchanged into the interlayer space is so great that it completely overshadows the expanded clay peak.

Table 9 gives the results of Atterberg limit tests performed on the three clay minerals. It was found that 2.0 percent Aliquat H226 (based on dry soil weight) reduced the liquid limit of Na-clay by 33 percent whereas the same amount reduced that of the Ca-clay by 24 percent. Thus, 2.0 percent Aliquat H226 sharply reduced the liquid limit even though this is only 0.04 of the amount required to completely satisfy the charge deficiency. The influence of Aliquat H226 on the Atterberg limits of kaolinite was not favorable. Addition of Aliquat H226 resulted in an increase in the liquid limit and the plasticity index.

The results of the X-ray analysis were not unexpected, and they confirmed the findings of others. It is apparent that up to 4 layers of Aliquat H226 molecules can be irreversibly adsorbed on the montmorillonite clays, but they are only loosely attached to the kaolinites. Even when used in quantities considerably less than required to satisfy the charge deficiency, Aliquat H226 significantly reduces the liquid limits and plasticity indexes of montmorillonites. This is probably due to the hydrophobic characteristics of the Aliquat H226 which lowers the adsorption of water in the interlayer spaces and to the flocculation resulting from reduction of the zeta potential. Lack of sufficient data precludes any definite statements concerning the effect of Aliquat H226 on kaolinite.

FIELD STUDIES

Although the laboratory investigation indicated that Aliquat H226 possessed some very desirable attributes as a soil stabilizer, it was apparent that the evaluation was only partially complete without field studies. Development of construction methods, correlation of field and laboratory tests, and determination of the efficiency and permanence of the treatment are items that can be determined only by construction of actual test sections. The two test sections reported were constructed to obtain this information.

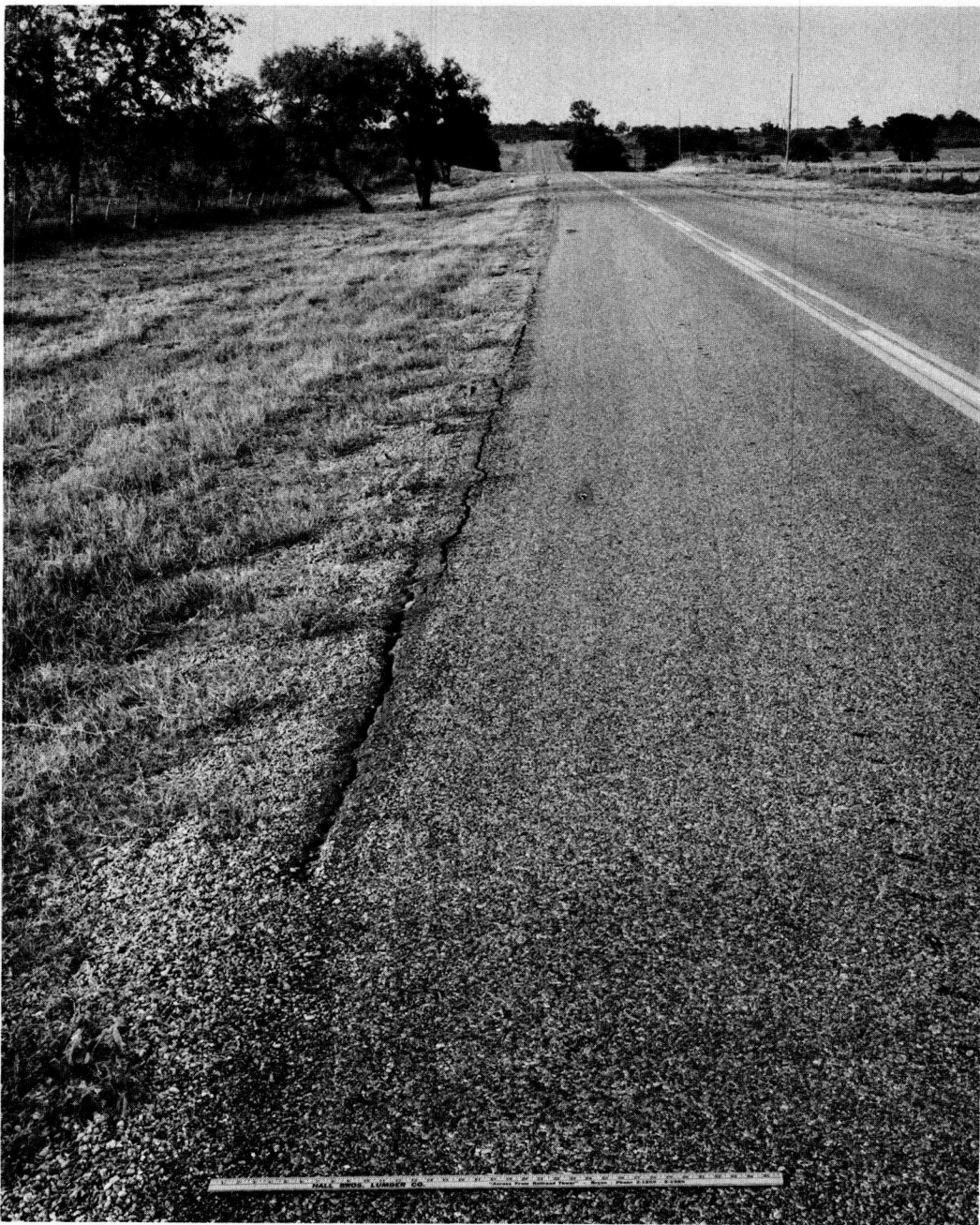


Figure 11. On this highly plastic clay, shrinkage cracks form at edge of pavement surface.

Test Section 1

The first test section was located on the Old San Antonio Road in Brazos Co., near Bryan, Texas. Classed as a State highway, this road receives an average daily traffic of 350 vehicles. Surface soils in the immediate area of the test section are characterized by extremely poor volumetric stability and low load-carrying capacity when saturated.

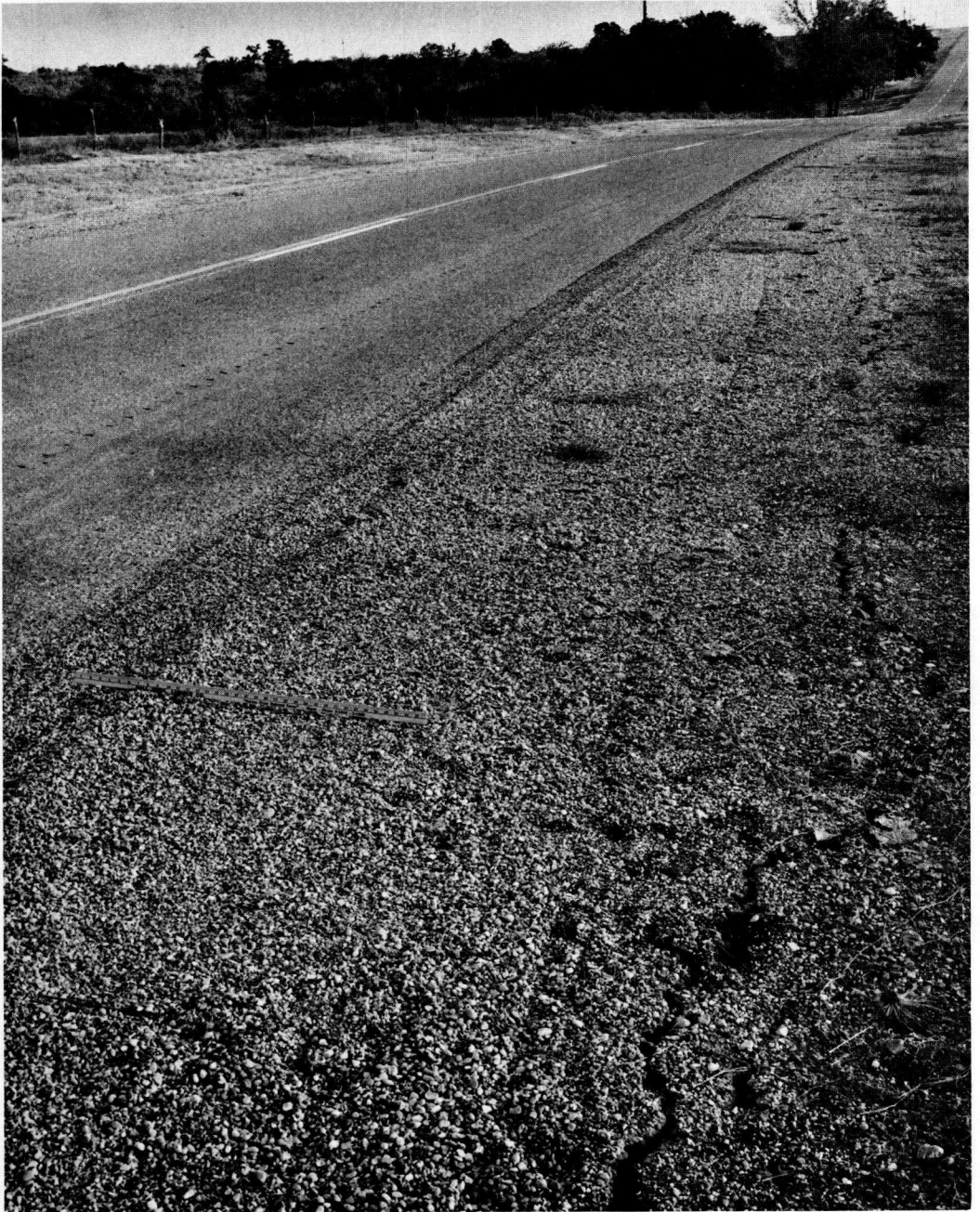


Figure 12. With addition of Aliquat H226 to subgrade soil, shrinkage cracks form at contact of stabilized and unstabilized areas.

In late October 1957, Texas Highway Department forces stabilized 700 ft of the subgrade soil. This period marked the rather drastic termination of a long drought in the area, and cool and rainy weather severely hampered construction operations. The major problem resulted from preparing a highly concentrated (approximately 17 percent) Aliquat H226 dispersion. When the isopropanol evaporated, the dispersion became extremely viscous in the unheated storage tank and required prolonged heating and agitation



Figure 13. Typical edge failure on test section before reconstruction.

before sufficient water could be added. The saturated subgrade did not readily absorb the chemical dispersion and the rainy weather made it necessary to place and compact the subgrade soil well above the optimum moisture content.

The spotty and ineffective stabilization in some areas of the test section limited subsequent evaluation to little more than visual observations. However, the section has borne traffic for more than four years without significant distress. Perhaps the most striking evidence of the Aliquat H226 treatment is noted in the position of the shrinkage cracks which are prevalent in the area. During the dry season large shrinkage cracks, which provide easy passage of water to the base course and subgrade, form at the edge of the pavement on the untreated control section (Fig. 11). On the stabilized section (Fig. 12) the cracks form well beyond the pavement edge at the contact between the stabilized and unstabilized soil.

Test Section 2

Plans for a second test section were formulated during the summer of 1959. Texas Highway Department personnel suggested another area on the Old San Antonio Road approximately 10 mi from the first section. The roadway in this area was receiving a large volume of heavy truck traffic which had resulted in rapid and severe distress. The majority of the failures had originated as edge failures as shown in Figure 13 and progressed toward the center of the roadway. The test section was ultimately selected in this area due to the desirable high traffic volume and because a low wet area at one end appeared ideally suited for testing the waterproofing qualities of Aliquat H226.

Laboratory classification tests, performed on soils obtained from several auger borings in the test area, indicated that the subgrade could be divided into three general groups. Similar soils were combined and each composite group was tested to determine the stabilizing effect of Aliquat H226. Because the subgrade soils in the general area are often stabilized with lime, lime-Aliquat H226 combinations were also investigated. Evaluation tests were performed in accordance with the testing procedures previously described.

TABLE 10
RESULTS OF UNCONFINED COMPRESSION TESTS ON COMPOSITE SAMPLES^a, TEST SECTION 2

Composite Group No.	Lime (%)	Unconfined Compression Strength (psi)															
		7-Day Humid Cure				7-Day Humid Cure +				7-Day Air Drying +							
		0 %		1/16 %		1/4 %		1/2 %		0 %		1/16 %		1/4 %		1/2 %	
		Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat	Aliquat
1	0	31.5	32.5	32.5	31.0	8.0	9.0	10.0	9.5	0	15.5	40.5	68.0				
	2	46.5	39.0	41.0	44.5	27.5	19.5	22.0	25.5	0	14.5	25.0	17.0				
2	4	62.5	61.0	62.0	53.5	51.5	47.5	47.0	52.5	4.5	17.8	21.5	19.0				
	0	28.0	26.5	24.0	25.3	7.0	7.5	9.5	9.5	0	7.5	19.5	31.0				
3	2	26.5	25.5	22.0	21.5	12.5	12.5	10.5	10.5	0	16.5	25.0	20.5				
	4	31.5	37.5	37.0	33.0	21.0	23.5	25.5	27.5	0	17.0	20.5	21.5				
4	0	32.0	32.5	28.5	31.0	3.0	4.0	9.0	8.5	0	2.0	9.5	12.5				
	2	31.5	32.0	33.5	33.5	12.0	13.0	14.0	14.5	0	4.0	11.0	16.0				
	4	62.5	63.0	62.5	67.5	21.5	19.5	21.0	23.0	0	2.0	4.5	4.5				

^a Percents of Aliquat H226 and lime are of dry soil weight.

Table 10 gives the results of unconfined compression tests at three different curing conditions and Table 11 gives the plasticity indexes. The unconfined compressive strength requirements of the Bureau of Public Roads were not attained for any of the treatments including lime by itself. With one exception all specimens which did not contain Aliquat H226 completely disintegrated in water after 7 days of air drying. Composite Group 1, which contained soils from the low, wet area of the roadway, was most effectively stabilized with Aliquat H226.

Based on these tests, and guided somewhat by construction considerations, the test section plan shown in Figure 14 was adopted. This plan called for five sections containing 1/2 percent Aliquat H226, 1/4 percent Aliquat H226 and 2 percent lime, 1/16 percent Aliquat H226 and 4 percent lime, 4 percent lime, and one untreated control section. A stabilized subgrade depth of 6 in. extending over a roadway width of 32 ft was considered desirable.

Construction Operations

It was evident from the first test section that the viscosity of the Aliquat H226 dispersion was a factor or prime consideration. A concentrated dispersion would result in viscosity too high to flow through gravity spray-bars, whereas a very dilute dispersion would cause considerable water to be added to the soil while obtaining the desired percentage of chemical. Based on laboratory tests and observations, a dispersion of 5 percent active Aliquat H226 by weight appeared most desirable.

Dispersing the Aliquat H226 in water requires both heat and agitation. This was easily solved with equipment commonly used by all asphalt paving contractors — a portable storage tank and recirculating asphalt car heater as shown in Figure 15. The desired amount of water and Aliquat H226 was added to the 10,000-gal storage tank and mixed by the recirculating heater which also heated the liquid to 140 F. No hazards were encountered with this

procedure and the entire operation took less than 2 hr. The resulting mixture was homogeneous and free of foaming.

Actual construction of the test section began by stripping the surface and base course from the subgrade and stockpiling this material at the edge of the shoulder. Just before the stabilizers were scheduled to be added a 1-in. rainfall halted construction operations. Although most of the area drained rapidly, the stockpiled base course provided a barrier which caused ponding on part of the $\frac{1}{2}$ percent Aliquat H226 section. This area became saturated and proved troublesome in subsequent operations.

Dry lime was added to the test section on the following day. About one-half of the required amount was added to the sections and lightly mixed into the soil, and the remaining lime was then added. Before spreading the lime (and the Aliquat H226), the soil was scarified to a depth of 4 in., rather than the full depth of 6 in. This procedure prevented the stabilizers from settling to the bottom of the layer where they could remain at a high concentration if subsequent mixing was not effective for the full 6-in. depth. After the lime was distributed, the soil was scarified to the full depth, thoroughly mixed with a Seaman pulvi-mixer, shaped, and lightly compacted to await the addition of Aliquat H226.

The Aliquat H226 sections were thoroughly pulverized to produce a loose porous layer that would readily absorb the dispersion. The desired amount of dispersion was added to the soil with a gravity spray-bar distributor as shown in Figure 16. Maintainers followed the distributor to surface-mix the chemical into the soil and the pulvi-mixer then mixed to the full stabilized depth of 6 in. Following the final mixing operation, the entire test section was compacted with a sheepsfoot roller and then surfaced-rolled with a light pneumatic compactor.

At no time during the construction operation did the addition of Aliquat H226 create any problems. In fact, it was observed that Aliquat H226 increased the workability of the plastic materials resulting in easier mixing and placement. The only construction problem that occurred during the entire operation could not be attributed to the Aliquat H226. The wet portion of the $\frac{1}{2}$ percent Aliquat H226 section required scarifying and drying for the full depth of 6 in. before compaction could be completed. Although the stabilized layer was compacted within the allowable moisture content and density range, the underlying soil remained at a high moisture content.

TABLE 11

PLASTICITY INDEX OF COMPOSITE GROUP SAMPLES^a, TEST SECTION 2

Composite Group No	Lime (%)	Plasticity Index			
		0% Aliquat	1/16 % Aliquat	1/4 % Aliquat	1/2 % Aliquat
1	0	19.0	18.5	18.5	15.5
	2	14.0	14.0	13.7	13.7
	4	10.5	12.5	12.0	12.0
2	0	26.0	23.3	19.5	17.5
	2	16.0	18.0	14.5	12.0
	4	14.0	14.5	14.0	12.8
3	0	31.5	32.1	28.5	27.5
	2	16.0	19.0	21.5	24.0
	4	16.5	15.5	17.5	17.0

^aPercent of Aliquat H226 and lime are of dry soil weight

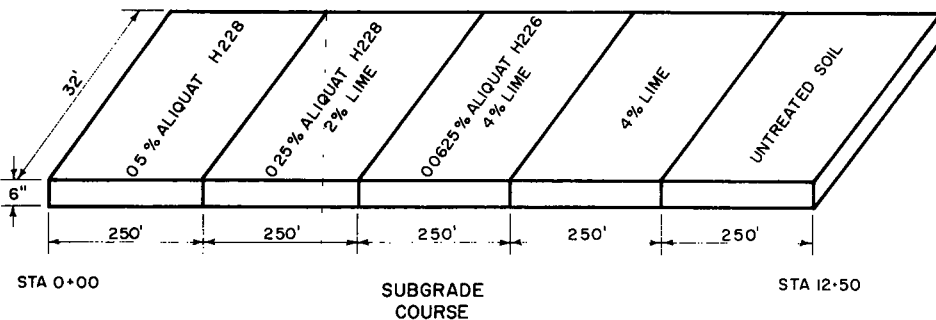


Figure 14. Plan at test section showing stabilizer contents and dimensions.

TABLE 12
RESULTS OF FIELD DENSITY TESTS, TEST SECTION 2

Section	Base Course			Subgrade		
	Unit Wt. (pcf)	Moist. Cont. (%)	Thickness (in.)	Unit Wt. (pcf)	Moist. Cont. (%)	% Std. Compact.
Untreated	134.2	1.7	7.25	119.0	13.4	--
	137.8	3.2	6.75	123.1	11.8	--
	130.1	6.7	7.25	126.9	9.9	--
	Avg.	134.0	3.9	7.08	123.0	11.7
4% lime	123.3	6.6	6.75	111.3	17.2	98.2
	128.2	8.0	6.25	110.7	18.2	97.7
	130.1	7.5	6.25	109.1	17.1	96.2
	Avg.	127.2	7.4	6.42	110.4	17.5
1/16% Aliquat H226, 4% lime	129.7	6.4	6.50	115.0	16.3	98.0
	130.2	6.7	7.25	112.9	16.6	96.2
	128.3	7.1	6.00	112.3	18.7	95.7
	Avg.	129.4	6.7	6.58	113.4	17.2
1/4% Aliquat H226, 2%lime	129.1	5.6	8.00	119.0	15.5	99.1
	131.4	6.1	7.25	124.4	13.6	103.7
	132.2	6.9	6.25	117.4	16.5	97.8
	Avg.	130.7	6.2	7.17	120.3	15.2
1/2% Aliquat H226	126.0	8.6	6.75	121.2	14.0	96.0
	130.4	5.0	7.00	119.9	10.8	94.9
	126.8	5.9	6.50	125.2	12.7	99.1
	Avg.	127.7	6.5	6.75	122.1	12.5

On completion of the subgrade, the original base course was bladed back over the roadway and compacted. The road remained in this condition without further maintenance until a single asphalt surface treatment was applied approximately 6 weeks later. During this period the road received continued repetitions of heavily loaded vehicles without visible signs of distress.

Construction Tests

During construction, control tests were performed to insure that moisture content and density specifications were being met. After the base course was placed and compacted, several locations in each section were tested to determine the final moisture contents and unit weights of the subgrade and the base course, and the Atterberg limits of the subgrade.

Results of the field density tests are given in Table 12. No control was exercised over the compaction or placement of the base course and the measured values were obtained only in case they were necessary to analyze future pavement behavior.

The relatively small range of Atterberg limit values (Table 13) indicates that the field mixing operation was very effective. With the exception of the 1/2 percent Aliquat H226 section, they also show the reduction of plasticity that was expected with stabilization. Plasticity indexes for the 1/2 percent Aliquat H226 section were higher than expected based on preliminary laboratory tests on composite group 1. It can only be assumed that sampling inconsistencies were responsible for this difference.



Figure 15. Recirculating asphalt heater and 10,000-gal storage tank used to mix Aliquat H226 solution. Aliquat H226 shipped in barrels shown in foreground.



Figure 16. Aliquat H226 solution being applied to road from water distributor.

TABLE 13
RESULTS OF ATTERBERG LIMIT TESTS, TEST SECTION 2

Section	Liquid Limit	Plastic Limit	Plasticity Index	Shrinkage Limit
Untreated soil	63.6	24.8	38.8	9.5
	45.7	18.8	26.9	8.9
Avg.	54.7	21.9	32.8	9.2
4% lime	44.4	30.6	13.8	21.5
	50.1	34.8	15.3	23.1
	34.4	25.2	9.2	20.0
	42.4	32.2	10.2	20.8
	45.5	24.9	20.6	12.4
Avg.	43.4	29.6	13.8	19.6
1/16% Aliquat H226, 4% lime	44.8	29.9	14.9	18.8
	42.2	31.5	10.7	24.3
	44.8	32.4	12.4	23.2
	42.0	31.8	10.2	23.0
	Avg.	43.5	31.4	12.1
1/4% Aliquat H226, 2% lime	40.7	23.9	16.8	17.2
	53.1	29.7	23.4	19.7
	45.3	27.7	15.6	18.4
	40.5	23.8	16.7	16.1
	40.1	23.4	16.7	15.8
Avg.	43.5	25.7	17.8	17.4
1/2% Aliquat H226	38.7	18.5	20.2	--
	37.2	15.7	21.5	11.9
	37.8	15.1	22.7	10.0
	39.7	17.4	22.3	11.8
	39.2	15.9	23.3	11.7
Avg.	38.5	16.5	22.0	11.4

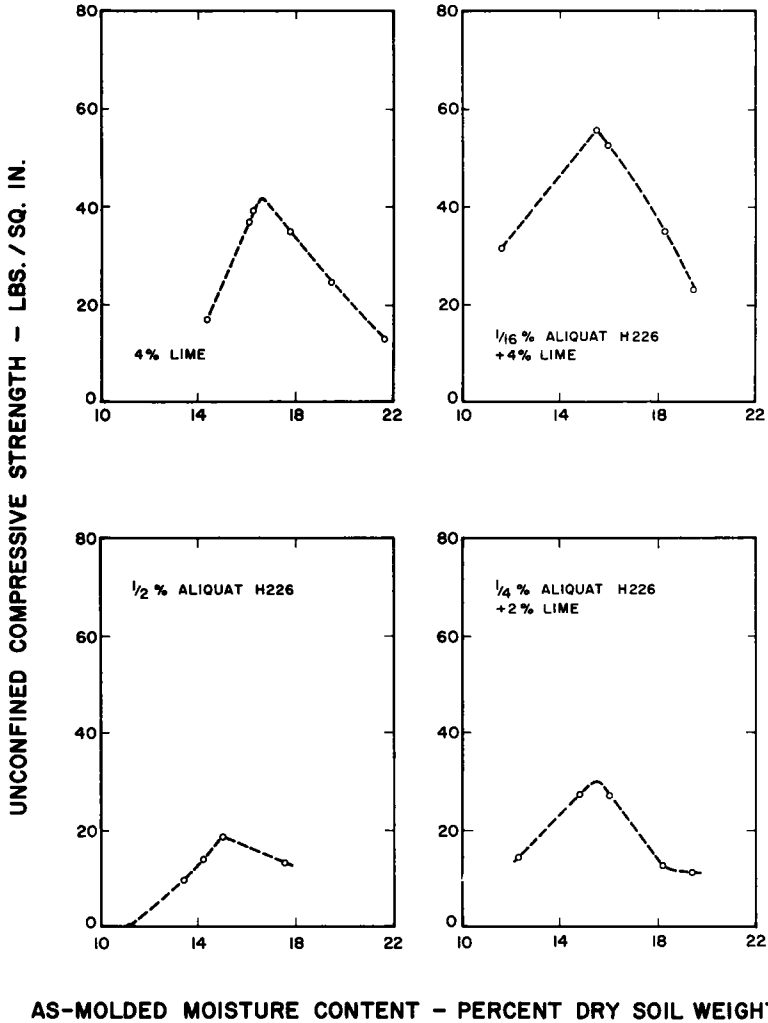


Figure 17. Unconfined compressive strength for test section specimens after 75 days of laboratory humid cure and 6 days of immersion.

Post-Construction Tests and Observations

Following subgrade completion, large composite samples from each treated section were taken to the laboratory and specimens were compacted in the Vicksburg miniature compactor at various moisture contents. These specimens were stored in a humid room for future testing. After 75 days of humid curing, selected specimens were removed from the humid room, immersed in water for 6 days, and tested to determine their unconfined compressive strengths. Results are shown in Figure 17. Similar tests, performed on specimens after nearly one year of humid curing, are shown in Figure 18.

At the laboratory curing conditions, the soil stabilized with $\frac{1}{16}$ percent Aliquat H226-4 percent lime not only has the highest strength, but appears to be gaining strength with time. The 4 percent lime-stabilized soil suffered an unexpected decrease in strength with additional humid curing, whereas those soils stabilized with $\frac{1}{4}$ percent Aliquat H226-2 percent lime and $\frac{1}{2}$ percent Aliquat H226 essentially retained their original strengths.

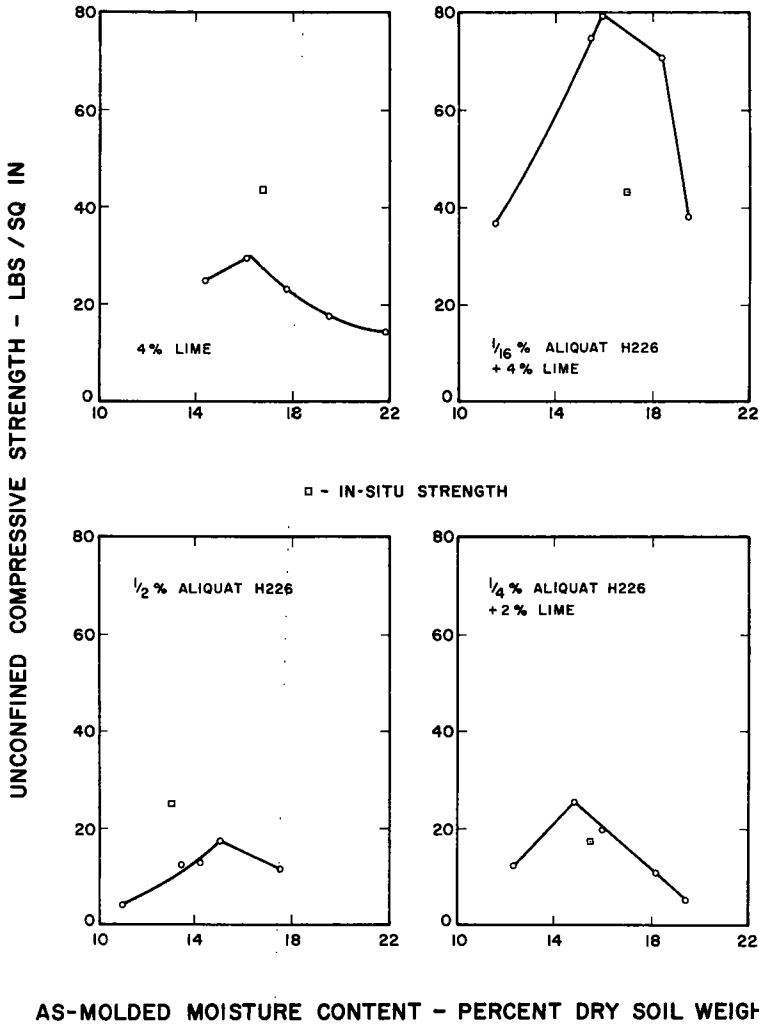


Figure 18. Unconfined compressive strength for test section specimens after 349 days of laboratory humid cure and 6 days of immersion.

Attempts to compare the laboratory strength results with field tests have been unsuccessful due to the difficulty experienced in obtaining undisturbed samples of the treated soils. Even with thin-walled samplers the recovery ratio is below 80 percent, indicating disturbed specimens. Figure 18 shows the average results of tests on field specimens obtained one year after construction, but little faith is placed in these values.

As an additional means of evaluating the performance of the roadway, deflection tests are being performed at approximately 6-mo intervals at 8 locations in each test section. Due to the relatively short life of the roadway, no definite conclusions can be reached from these measurements and they are not included herein.

As the roadway life increases, it will be possible to make more definite conclusions regarding the efficiency and permanence of Aliquat H226 stabilization. However, based on the available laboratory and field data, it appears that Aliquat H226 retains its effectiveness with time.

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