Additives as Aids to Asphalt Stabilization of Fine-Grained Soils

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The object of this investigation was to examine the effect of certain selected chemical additives in low concentration (less than 1 percent by weight) on the stabilization of fine-grained soil (a clayey silt from Massachusetts) with asphalt.

Soil samples were stabilized with either asphalt-gasoline cutbacks or asphalt-in-water emulsions, the chemical additives examined either being incorporated with the asphalt, or used to pretreat the soil before asphalt addition. Properties of the stabilized soil examined were primarily unconfined compressive strength after curing, and compressive strength and water absorption after water immersion.

It was found that addition of phosphorus pentoxide, certain epoxy resins, and certain organic isocyanates to asphalt cutback significantly improved the strength characteristics of asphalt stabilized soil. Addition of antistripping additives to asphalt cutback was found generally to reduce strength and increase water-absorption, but pretreatment of soil with such additives before incorporation of asphalt cutback was found to have a beneficial effect on strength and water resistance.

Soil stabilized with asphalt emulsions containing soap as the emulsifier was found to have quite high dry strength, but the strength after water immersion was far lower than that of cutback-stabilized soil. On the other hand, soil stabilized with emulsions containing antistripping additives as emulsifiers exhibited wet strengths comparable with, and in some instances, superior to those stabilized with cutbacks. Mixing water-content, and type of emulsifier, appear to be major factors effecting stabilization.

It is concluded from this work that chemical additives hold considerable promise in asphalt stabilization practice, offering opportunities for broader and more effective use of asphalt for treatment of fine-grained soils.

• THE object of this research was to explore the possibility of improving the utility of asphalt as a stabilizer for fine-grained soils by the use of trace quantities of chemical additives known to react with asphalt, or with soil-mineral surfaces.

Studies were performed on a clayey silt from Massachusetts, which was treated with 5 percent by weight of a straight-run asphalt (applied either as a gasoline cutback, or as an aqueous emulsion), to which had been added small quantities of antistripping additives (fatty amines, amine salts, quaternaries, etc.) substances which combine chemically with asphalt (P_2O_5 , diisocyanates, epoxy resins), or (in the case of asphalt emulsions) various types of emulsifiers. Primary measurements made were (1) as-cured unconfined compressive strength and density, and (2) compressive strength, density, and water absorption after 7 days' water immersion. Limited studies were also made of the effect of such variables as mixing uniformity, curing time, immersion time, degree of aeration, molding water content, and asphalt content on the strength of specimens of stabilized soil.

The salient results of this investigation were as follows:

1. Certain antistripping additives, when incorporated with cutback-stabilized soil, brought about a significant improvement (30-50 percent) in wet strength and water resistance, but had little effect upon dry strength. Many antistripping additives, however, which are believed to be effective in asphalt-stabilization of coarse aggregate, proved to be detrimental to fine-grained soil stabilization. The degree of improvement obtained with beneficial additives appeared to be greatly dependent upon the method of incorporation; e.g., lauryl amine was most effective when used to pretreat the soil before cutback incorporation, while octadecyl amine acetate was most effective when dissolved in the cutback. 2. Certain chemicals (specifically, P_2O_5 and the aromatic diisocyanates) when added in low concentrations (5-10 percent of the asphalt, or 0. 25-0. 50 percent of the soil) to cutback, significantly increased (by 30-50 percent) the compressive strength of stabilized soil, both after curing and after water immersion. P_2O_5 appeared to accelerate the rate of strength development during cure, minimized the effect of variation in gasoline content of the cutback on strength, and largely eliminated variations in strength due to differences in degree of aeration prior to compaction.

3. Soil stabilized with asphalt emulsions were, in general, inferior in physical properties to those stabilized with gasoline cutback. However, soil treated with cationic-stabilized (i.e., amine and/or quaternary-stabilized) emulsions were in general far superior (in terms of rewet strength and water absorption) to those treated with soap (sodium oleate)-stabilized emulsions. Certain cationic-emulsion formulations were substantially better than others, the best ones containing lauryl and octadecyl amines. Increasing the mixing water content of the soil-asphalt system markedly improved the degree of stabilization accomplished with cationic asphalt emulsions (giving rewet strengths comparable with the best cutback-stabilized formulations), but had little beneficial effect upon soap-stabilized, emulsion-treated soil.

4. A correlation has been found between rewet compressive strength of asphaltstabilized soil and the volatiles content of the soil at time of test, that appears to be independent of the chemical treatment to which the soil or asphalt has been subjected. This correlation makes it possible to estimate the degree of improvement in asphalt stabilization which can be accomplished by the use of additives of the types examined in this work. The applicability of this correlation to different soils, and to different asphalts, remains to be tested.

It is concluded that the use of certain antistripping additives, reactive chemicals such as P_2O_5 , and cationic emulsifiers holds considerable promise for improving and broadening the utility of asphalt cutbacks or emulsions for fine-grained soil stabilization, but that care must be exercised in both the selection of additives and their method of incorporation in soil, if their maximum benefits are to be realized.

INTRODUCTION

General Objective

In all likelihood, the most important objective of soil stabilization is the elimination of the dependency of soil engineering properties (mainly load-bearing capacity) on moisture content. 'Possibly the most obvious way in which the water-sensitivity of soils can be eliminated is to coat the individual soil particles with a coherent film of a stable, water-insoluble resinous substance which will prevent water from reaching the particle surfaces, and/or prevent water from migrating by capillarity into a consolidated, porous soil mass; use of a tacky resinous material provides further advantages, in that it causes the individual particles to adhere to one another, and thus contributes to the tensile, unconfined compressive, and shear strength of the compacted soil mass.

Undoubtedly the most attractive substances (from the standpoint of availability and cost) falling into the above category are the petroleum-derived asphalts, and the heavy tars and pitches resulting from the destructive distillation of bituminous coal. These substances are complex mixtures composed primarily of high molecular weight hydrocarbons of varying degrees of saturation, but also containing widely variable amounts of organically combined oxygen, nitrogen, sulfur, phosphorus, vanadium, iron, etc. They are characterized by water-insolubility and -insensitivity, tackiness and viscoelastic behavior resembling that of many high polymers, and a fairly high resistance to deterioration under normal weathering conditions.

The use of asphalt for the stabilization and/or waterproofing of coarse aggregate (gravel and sand) has been widespread and extensive for many years, and its use for stabilization of fine-grained soils has been receiving increasing attention. Its suitability as a soil stabilizer is, however, limited by certain physical and physicochemical properties both of the asphalt and of the soil to which it is applied. The three most important factors limiting its effectiveness as a stabilizer are believed to be: (1) the virtual impossibility of distributing asphalt uniformly through a fine-textured granular solid such as a soil, (2) the inability of asphalt to adhere to (and thus to coat) wet soil particles, and (3) the sensitivity of the asphalt-soil bond (when developed) to destruction by water. The first factor arises from the high viscosity and water-immiscibility of asphalt (both of these properties, unfortunately being necessary for successful stabilization); the second and third arise from the typical hydrophilic character of most soil minerals, and the strongly hydrophobic properties of asphalt.

With gravels and sands, these factors are fortunately of relatively minor importance because (1) the surface area (per unit mass) to be asphalt-coated is small (and thus uniformity of distribution of the asphalt is not critical), (2) the quantity of water present or needed to permit proper handling of aggregate is rather small, and can be easily removed by evaporation, and (3) the dependence of the properties of the aggregate on moisture content is relatively low. As one proceeds to soils of finer and finer particle size, these factors become of rapidly increasing significance until, with plastic soils containing large amounts of colloidal minerals, incorporation of asphalt is virtually ineffective as a means of stabilization or waterproofing. It is probably safe to say that the stabilizing ability of asphalt varies inversely with the specific surface area of the soil, or with its water adsorptive capacity.

To facilitate distribution of asphalt through fine-grained soils, and thus to improve its stabilizing action by minimizing the first factor cited above, two basic approaches have been followed in practice. One is to increase the fluidity of the asphalt at usetemperatures by diluting it with a solvent (gasoline, naphtha, kerosene, etc.); the other is to emulsify the asphalt in water. Both processes yield fairly mobile liquids which can be admixed and blended with fine-grained soils far more effectively than asphalt alone. This technique still does not, however, give adequate uniformity of distribution of asphalt and, of course, in no way aids the adhesion process which is so important to effective stabilization.

Research in chemical soil stabilization over the past several years has revealed techniques and materials for altering the properties of soil mineral surfaces, and for altering the properties of soil binders, to give improved physical properties to the stabilized soil. The object of the investigation reported herein has been to attempt to apply this knowledge to the problem of asphalt-stabilization of fine-grained soils, and to explore the possibility of employing small quantities of chemical additives (to soil or asphalt) to enhance further the suitability of asphalt as a soil stabilizer.

Mechanism of Cutback Stabilization

Stabilization of soils with asphalt cutback is normally carried out by (1) blending the soil (at or near its optimum water content for compaction) with the cutback, (2) compacting the mixture, and (3) "curing" the mixture by allowing water and cutback solvent to evaporate over a period of time. Inasmuch as the blending process involves mixing a water-wet soil with a water-immiscible fluid which does not adhere to the soil particles, the mixing process can be envisioned as one of subdivision of the cutback fluid into rather small droplets (much larger than clay size) which remain insulated from the soil particles by films of water. On compaction, the mass is probably composed of a skeletal structure of soil, with water and cutback-globules trapped in the voids. As water evaporates from the mixture, it becomes possible for the asphalt cutback to wet out and adhere to a larger and larger fraction of the soil particle surfaces. As this wetting-out process proceeds, the asphalt would be expected to distribute itself more and more uniformly through the soil, provided it possessed sufficient fluidity to do so. This fluidity depends primarily upon the rate of evaporation of the cutback solvent; rapid-curing cutbacks (such as those prepared with gasoline) would be expected to lose solvent and thus thicken very rapidly, with the result that little improvement in asphalt distribution might result during curing. With slow-curing cutbacks, the converse would be true; however, the slower the rate of solvent evaporation, the slower the rate of development of cohesive strength in the asphalt, and thus the slower the rate of strength-buildup on curing. This suggests that an optimum rate of solvent evaporation exists wherein these two factors are in balance.

Offhand, it would seem advantageous to mix cutbacks with dry soil in order to avoid

this solvent evaporation problem; unfortunately, most fine-grained soils are either unmanageable, or highly agglomerated in the dry state, with the result that uniform distribution of the asphalt (on a gross scale), and compaction becomes next to impossible. Thus, despite its disadvantages, water must be considered an essential ingredient of the stabilization process.

On immersion in water after curing, water is undoubtedly imbibed very rapidly by those regions of the mixture which have not been adequately protected by asphalt; this should result in an initial rapid loss in strength. In view of the water sensitivity of the asphalt-soil bond, water should gradually find its way into the asphalt-soil interface and destroy this bond; the rate of detachment should be dependent upon the firmness and extensiveness of the bond developed, and the fluidity of the asphalt. This would indicate that there should be, on continued water immersion, a further gradual reduction in strength (and increase in water absorption), the rate of strength loss being greater for incompletely cured mixtures, or those prepared with less viscous asphalts.

In the light of the above, any chemical modification of the cutback-soil system which would permit (1) improved distribution of asphalt during mixing, (2) improved adhesion of asphalt to soil either in the presence of water or in its absence, and/or (3) improved resistance to deterioration of the soil-asphalt bond by water, would have promise of improving soil stabilization by this method.

Mechanism of Emulsion Stabilization

Stabilization of soils with asphalt emulsions is typically performed by (1) blending the emulsion with wet soil (with the total water content at or near optimum), (2) compacting, and (3) curing as with cutbacks. During the mixing process (in contrast to treatment with cutbacks), since the asphalt is initially dispersed as microscopic droplets in water, uniform distribution of the asphalt through the soil should be far simpler to accomplish, provided the asphalt particles retain their identity until mixing is complete. If coagulation or agglomeration of the emulsified particles takes place on mixing, this will result in the formation of rather massive globs of asphalt which (because of their high viscosity) will be virtually impossible to break down and redistribute. The efficiency of distribution therefore depends on the stability of the emulsion in contact with the soil, which is in turn determined by the type and amount of emulsifying agent used. Hence asphalt emulsions which will break on agitation, on change in temperature, or on contact with the electrolytes present in soil-water, are likely to yield very inhomogeneous mixtures with soil.

Assuming that, during mixing, the emulsion remains stable, the compacted mass of soil can be envisioned as an assemblage of solid particles most of the void spaces between which contain numbers of very small globules. During curing, the water evaporates, exposing dry soil surface to which the asphalt particles can adhere. Since, however, there is no asphalt solvent present, there can be only very slow redistribution of asphalt by wet-out and flow (as postulated for cutbacks) because of the semisolid character of the asphalt; hence the formation of continuous films of asphalt around the soil particles takes place slowly, if at all. The final cured product might thus be imagined as a mass of soil particles whose surfaces are "peppered" with small droplets of asphalt.

On subsequent immersion in water after curing, the behavior of emulsion-stabilized soils should be somewhat different from that of cutback-stabilized soils. First, because of lack of continuity of the asphalt phase, water should be imbibed rather rapidly by the entire mass, with consequent rapid strength loss. Second, because of the presence of the emulsifier in the soil, even the asphalt-coated regions of the soil are rendered readily water-wettable, and the rate of detachment of asphalt from the soil consequently increased; this should result in still more rapid strength-loss and water absorption.

In view of the inability of the asphalt to flow and redistribute on curing, it is clear that the efficiency of utilization of asphalt in emulsion-stabilization is controlled almost exclusively by the uniformity of distribution during mixing; this, as indicated, necessitates use of highly stable emulsions. On the other hand, loss in strength on water immersion after curing is accelerated by the presence of residual emulsifier, so that soils treated with more stable emulsions (which of necessity contain larger amounts of emulsifiers, or chemically more stable ones) are almost certain to be less effectively stabilized. This presents an impasse which, it would appear, is difficult to overcome, and which would impose serious limitations in the use of asphalt emulsions for stabilization of fine-grained soils.

Most of these shortcomings of asphalt emulsions could be minimized if it were possible to add to the emulsion, or even better, to use as emulsifiers, chemicals which (1) would permit the dispersed asphalt globules to adhere to the soil surfaces, particularly in the presence of water, (2) improve the tenacity of the soil-asphalt bond, and (3) not exhibit the undesirable effects of emulsifiers present in the soil after curing.

Antistripping Additives

The process whereby water causes detachment of asphalt from the surface of mineral aggregate is usually designated as "stripping," and as noted above, is caused by the natural selective wetting of mineral surfaces by water. Certain compounds (notably fatty acids, fatty amines, quaternary ammonium salts, amides, imidazolones, etc.), when dissolved in low concentration (~1 percent) in asphalt, are found greatly to facilitate asphalt coating of wet aggregate, and to improve markedly the resistance of the mineral-asphalt bond to detachment by water. Such materials are commonly referred to as "antistripping additives," and have become very popular for use in paving asphalts.

An antistripping additive appears to perform these functions by adsorbing strongly on mineral surfaces, and forming very thin films which are preferentially oil-wettable. To be effectively utilized, it is necessary that the additive be present in proper concentration at every point of contact between asphalt and soil and/or mineral. If the additive is present in the asphalt, and the asphalt used to treat wet aggregate or soil, the additive must diffuse out of the asphalt and into the water films surrounding the mineral particles before adsorption and alteration of wetting characteristics can occur. With coarse aggregate, where the specific surface area of the mineral is small, and where the asphalt can (during mixing) reach all the mineral surface readily, essentially complete treatment of the mineral with the additive can be accomplished in a short time. On the other hand, with a fine-grained soil of high specific surface area, the efficiency of mixing asphalt (even as a cutback) with the soil is so poor, the rate of diffusion of the additive through the asphalt so slow, and the quantity of surface to be treated so large, that only a small fraction of the soil particles can be expected to be properly treated with the additive during the blending process. Thus, the use of antistripping agents dissolved in the asphalt phase may prove to be of limited value in the cutbackstabilization of many fine-grained soils.

Most antistripping additives, however, are (or can be easily rendered slightly watersoluble; thus treatment of a wet soil with an aqueous solution of one of these additives is possible. Addition of such a solution to a water-wet soil should result in rapid and effective treatment of a large fraction of the exposed surface, since (1) all the soil particles are wet by and exposed to the water, (2) diffusion of the additive to the particle surfaces from any point in the mixture is unimpeded, and (3) blending of watersoluble additives with soils is relatively simple and rapid. Evidently, therefore, pretreatment of a soil with an antistripping additive in aqueous solution, followed by blending with asphalt cutback, might be expected to give better stabilization than direct blending with cutback containing dissolved additive.

Another way in which the value of antistripping additives may be effectively utilized in the asphalt stabilization of fine-grained soils is to employ these compounds as emulsifiers for asphalt. An asphalt emulsion stabilized with an antistripping additive will in all probability have the advantages for fine-grained soil stabilization noted earlier, but will not have the accompanying disadvantages. The asphalt, being finely dispersed in water, will distribute fairly easily and uniformly through the soil. Since the emulsifier adsorbs on the soil surfaces and renders them oil-wettable, this will cause the asphalt droplets promptly to deposit on and adhere to the soil particles; this will permit coating of the soil, and development of cohesive strength, before curing (i. e., drying) takes place. Also, since the emulsifier is adsorbed by the soil, no free emulsifier remains available after curing to accelerate water-absorption and attendant strengthloss on rewetting.

The use, therefore, of antistripping additives as aids to the asphalt stabilization of fine-grained soils appears to hold considerable promise as a means of improving stabilization efficiency, provided due consideration is given to the mechanism of their action and the physical processes taking place during the mixing and curing stages. This study aims to show how these additives may best be utilized for this purpose.

Chemical Additives Reactive with Asphalt

Ill-defined as the chemical composition and structure of asphalt may be, it is generally agreed that this complex mixture contains a large proportion of unsaturated hydrocarbons and varying amounts of heterocyclic compounds, which can under proper conditions react with a variety of chemical additives. Such reactions must lead to changes in the physical and chemical properties of the asphalt, and it is only reasonable to imagine that some of these changes will be beneficial to the use of asphalt as a soil stabilizer. Of particular interest are reactions which can be made to occur rather slowly at ambient temperature, since these can be allowed to take place in situ in the soil after mixing with asphalt and compaction. One objective of this study has been to find chemical additives which react with asphalt in this fashion, and to determine what improvements in soil stabilization can result therefrom.

EXPERIMENTAL PROCEDURE

Preparation of Soil

The soil used in this study was a clayey silt from Massachusetts, designated M-21, with the following mineralogical and physical characteristics:

Composition:	
Fines (<0.07 mm.):	31%
Consisting of:	
Illite	30% (Interstratified with 5% vermiculite)
Quartz	35%
Feldspar	20%
Free Fe ₂ O ₃	2. 9%
Portion coarser than 0.0	7 mm.:
Predominantly quart	z and feldspar
Engineering Properties:	

Optimum Moisture Content for Compaction:	1 2%
Maximum Dry Density (Standard Proctor):	123 pcf.
Liquid Limit:	20%
Plastic Limit:	15%
Plasticity Index:	5%

After air drying to the moisture content convenient for grinding, the soil was ground in a ball mill and screened through U.S. Standard Sieve No. 10 (sieve opening = 2mm.). After air drying to equilibrium moisture content, and after moisture content determination, the soil was used for sample perparation.

Preparation of Stabilizers

Asphalt Used. The asphalt employed in this study was product of the Shell Oil Co., and had the following characteristics:

Stream-refined, vacuum-distilled asphalt (designated "straight-run"), 40-50 penetration, Code No. HOA-2635 (derived from East Texas-Louisiana Mixed Crudes) Asphalt Cutbacks. In order to obtain the desired weight ratio of cutback components (asphalt: gasoline), predetermined quantities of asphalt and gasoline were shaken together in an airtight container until dissolved. The composition of asphalt cutback was examined periodically and, if necessary, needed adjustments were made.

Asphalt Emulsions. Apparatus used in asphalt emulsion preparation was either a variable speed agitator (Duplex Dispersator made by Premier Mill Corp.), or two stage colloid mill (made by Manton-Gaulin Manufacturing Co.).

The asphalt and water were preheated separately to approximately 90 deg. C., and mixed together, usually by gradually adding asphalt to water until the desired weight proportion of emulsion components (1 water: 1 asphalt) was obtained. Emulsifying agents were added either to the water or asphalt phase, the choice being determined by the ease of emulsification, amount of foaming, and final droplet size. For comparative purposes, emulsion composition and microscopic particle size determinations were carried out with each freshly prepared emulsion. Particle sizes of emulsified asphalt prepared with colloid mill usually were smaller than those obtained with a dispersator.

Preparation of Test Samples

Basically, sample preparation of soil stabilized with asphalt cutbacks and asphalt emulsions was the same.

Mixing. The Brabender Plastograph equipped with a finger-prong mixer and automatic mixing torque recorder was used as mixing apparatus in most of the experiments. A two stage mixing procedure was employed. The first step consisted of premixing of soil and water, or soil, water and additive. Generally a three minute mixing period was sufficient to reach equilibrium mixing torque, which was indicative of good water distribution throughout the soil. The second step was mixing of soil-water mixture with stabilizer, asphalt cutback or asphalt emulsion. The addition of stabilizer to the soil-water mixture was carried out in the same manner in all experiments. The weighed quantity of stabilizer was poured into a groove cut in the middle of the mixture between the two parallel rotating mixer shafts. The mixer was kept covered when possible to minimize evaporation of volatile ingredients. In order to standardize mixing throughout the experiments, two minutes' mixing time was selected. Investigations of mixing time effect on properties of asphalt stabilized soil had inducated that mixing for two minutes resulted in a homogeneous mixture, and further mixing did not appreciably change the strength characteristics of stabilized soil samples.

The major difference between the sample preparation procedure for asphalt cutbacks and that for asphalt emulsions was the difference in mixing-water content. The asphalt cutback samples were mixed and compacted at the optimum water content determined in the Harvard Minature Compaction Apparatus. This water content proved to be unsatisfactory with asphalt emulsions in general, and particularly with sodium oleate emulsion; the emulsion broke immediately upon contact with soil, preventing adequate distribution and blending of stabilizer and soil. Therefore, higher water contents were required to achieve adequate mixing.

Specimens containing chemically modified asphalt cutbacks were in most cases mixed by hand, rather than by machine. The procedure involved blending soil and cutback with a spatula in a shallow dish for about 20 minutes, or until the mixture appeared reasonably uniform.

<u>Compaction and Molding of Test Samples</u>. To assure better uniformity of samples and to aid in the reproducibility of results, all samples were compacted statically to approximately the same density (\sim 120 pcf.). This density was equivalent to the density obtained from samples compacted dynamically at optimum water content in a Harvard Minature Compaction Apparatus, following standard procedure (3 layers, 25 blows, 40 lb. load).

In order to compact the samples statically, the Harvard Minature Compaction Apparatus was modified by equipping its mold with an extension cylinder and sliding piston. (Dimensions of the mold: length = 2.816 inches, diameter 1.312 inches.) In the compaction of samples treated with asphalt cutbacks, a fixed weight of mixture was compacted to constant volume of 62.6 cm.³ by means of an hydraulic press, the compressive force being applied vertically. In the case of soil samples treated with asphalt emulsions, the excess water, which was required for better mixing, was eliminated by application of higher pressures at slower loading rates until again a fixed weight of the solids was confined into the volume of the mold.

Although detailed examination of the ease of compaction was not undertaken, generally it could be stated that the samples treated with cutbacks required less force for compaction than those treated with asphalt emulsions.

<u>Curing and Testing of Samples</u>. In order to reduce the effect of daily variations in ambient relative humidities and temperatures, all six cylindrical test samples were placed for curing in open desiccators over saturated aqueous potassium carbonate solution, which provided a constant relative humidity of approximately 43 percent. Weight loss and changes in volume by mercury displacement method were recorded periodically throughout the curing period of fourteen days. Three samples were tested in the laboratory testing machine for as-cured unconfined compressive strength. The remaining three samples were immersed in water for a period of seven days, and, after recording of changes in weights and volumes, were tested for unconfined compressive strength. In all cases, the residual volatiles content at testing was determined by drying the broken samples in an oven at 110 deg. C. for 24 hours.

RESULTS AND DISCUSSION

Stabilization with Asphalt Cutbacks

Behavior of Cutback-Stabilized Soil on Curing and Water Immersion. Figure 1 shows the changes in weight and volume which cutback stabilized soil undergoes when cured at 43 percent R. H. and room temperature. Approximately 80 percent of the total weightloss and shrinkage occurs in the first 24 hours. During the first two hours, the loss in







Figure 2. Water absorption and expansion of cutback-stabilized M-21 soil on rewetting.

weight in grams is nearly equal to the shrinkage in cc., indicating that the volume of the soil sample is able to adjust to the loss of water and gasoline. After this period, the shrinkage is farlless than the weight loss, indicating that the soil structure has become too rigid to yield to the capillary forces produced by liquid evaporation. In all probability, rather high stresses develop in the soil after the two-hour drying period, with consequent distortion and weakening of bonds between asphalt and soil particles.

The drying characteristics of simple soil-water systems, it will be noted, are essentially the same as those of cutback stabilized soil (allowance being made for the fact that cutback stabilized soil has a higher solids and total volatiles content, due to the

TABLE 1

EFFECT OF MIXING ON CUTBACK STABILIZATION OF M-21 SOIL

Mixing Water Content: 11%; Asphalt Content; 5.3% on Soil Cutback Composition: 2: 1, Straight-Run-Asphalt to Gasoline

	14 Days'	Cure	7 Days' Water Immersion					
Mixing Time sec.	Volatiles Content %	Compressive Strength ps1.	Volatiles Content %	Water Absorption %	Compressive Strength psi.			
7.5	0.76	245	5.4	4.65	• 69			
15	0.87	259	5.1	4.26	68			
30	0.82	253	5.3	4.50	73			
60	0.85	223	5.3	4.50	103			
120	0.83	236	4.9	4.10	122			

asphalt and gasoline present). From this, it may be deduced that asphalt cutback does not significantly alter the soil's compaction characteristics or its water-vapor permeability.

Water absorption and swelling of cutback stabilized soil on immersion in water are illustrated in Figure 2. Absorption and swelling are evidently more gradual processes than drying and shrinking; furthermore, both continue at significant rates even after long periods of time. Since water absorption is far greater than swelling, it can be concluded that the majority of the water absorbed is consumed in filling air voids in the soil mass. Improvement in the uniformity of mixing of soil with cutback (see below) appears to reduce both water absorption and swelling, as might be expected.

Effect of Uniformity of Mixing. Table 1 and Figure 3 show the variations in compressive strength, volatiles content, and water absorption as a function of time of





mixing in the Brabender finger-prong mixer. It will be noted that improved mixing reduces the as-cured compressive strength slightly, but markedly increases the rewet strength. These observations can be explained as follows: The dry strength of untreated soil, compacted at optimum water content, exceeds the dry strength of cutbacktreated soil, indicating that soil-to-soil bonds (under dry conditions) are stronger than soil-asphalt bonds; improved mixing, which leads to a more thorough distribution of the asphalt, causes a larger fraction of the soil particles to become bonded to one another by asphalt, with consequent strength loss. On the other hand, under wet conditions, soil-to-soil bonds have relatively little strength; hence, the load-carrying members in the wet soil are soil-asphalt bonds. Obviously, therefore, an improvement in asphalt distribution will result in more effective utilization of its bonding ability, and therefore result in an increase in strength.

Effect of Antistripping Additives. The behavior of soil stabilized with asphalt cutback containing small amounts (1 percent on the asphalt, or 0.05 percent on the dry soil) of various antistripping additives, is shown in Table 2. In all instances, presence of the additives causes a reduction in rewet strength, and a corresponding increase in water absorption.

All of these additives are surface active, fatty, nitrogenous compounds with rather low solubility in water, and high solubility in organic solvents; yet, to perform their

TABLE 2

	EFFECT OF ANTISTRIPPING AGENTS ON PHYSICAL PROPERTIES OF M-21 SOIL STABILIZED WITH ASPHALT-CU
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	At Molding		1	4 Days' Cur	e	7 Days' Water Immersion			
Additive % on Asphalt	Volatiles Content %	Density pcf	Volatiles Content %	Density pcf.	Com- pressive Strength psi.	Volatiles Content %	Water Absorp- tion %	Density pcf.	Com- pressive Strength psi.
None	11 1	120.0	0 93	121. 2	318	4 74	3 82	119 2	106
Priminox 10, 1%	11.0	119 2	0 87	121.9	266	5 33	4.50	121. 2	97
Pave. 1%	· 11.5	118.0	0 93	121.2	283	6 34	5.44	119 2	65
Arquad 2HT, 1%	11.5	118.0	092	121, 2	305	5. 75	4.82	119.2	84
Victamine D, 1%	11. 2	118.8	0.82	121. 2	380	5.49	4.68	120. 0	90
Armeen 18D 1%	10. 8	119.1	0. 75	121.9	337	5 15	4 35	120, 0	102

Mixing Water Content: 11%, Asphalt Content: 5.3% on Soil,

Mixing Time 2 min., Cutback Composition: 2:1, Asphalt to Gasoline

function as "antistripping agents," they must adsorb on the wet soil particles. When added in solution in asphalt cutback, conditions are very unfavorable for migration of the additives to the soil particle surfaces, and uniform distribution thereon. That part of the additive which has not been adsorbed by the soil at the completion of the curing period is available to function as a wetting agent when the soil is immersed in water, thus facilitating water absorption. It is of interest that the greater loss in rewet strength occurs with the less water-soluble additives, indicating (as might be expected) that more nearly complete adsorption by the soil is realized with the more water-soluble species.

If this explanation is correct, then addition of antistripping additives to wet soil before cutback incorporation should favor their adsorption by the soil, thus making fuller use of their ability to improve the soil-asphalt bond, and minimizing their ability to accelerate water absorption. Results of such tests are shown in Table 3.

Armeen 12D, when added to the wet soil, is not only far more effective than when added to cutback, but also causes a substantial (39 percent) improvement in rewet strength and reduction in water absorption relative to the control. Arquad 2HT, while reducing water absorption, does not greatly increase rewet strength; however, addition to soil gives far better results than addition to cutback. Armeens 16D and 18D, when added to the soil, appear to have little beneficial or detrimental effect. The fatty quaternary ammonium salts, Arquad 12 and Arquad 18, cause a substantial reduction in rewet strength. These two compounds are highly water-soluble, and it is believed that they adsorb less firmly on the soil than do the amines, with the result that they are basically less effective antistripping agents.

Priminox 10 and Victamine D perform more poorly when added to the wet soil than when dissolved in the cutback, strengths in all cases being lower than the controls. These compounds, it is believed, are too water-insoluble to be uniformly distributed by direct blending with wet soil, with the result that they are even less effectively contacted with the soil by this means than when added in solution in the cutback.

These observations lead to the conclusion that, to be effective for improving the properties of cutback stabilized soil, antistripping additives must have a certain minimum degree of water-solubility, yet must not be so water-soluble as to be incapable of firm adsorption by soil surfaces.

The water-solubility of the fatty amines can be greatly increased by converting them into salts via reaction with acids. Solubilization in this manner would be expected to facilitate their distribution in and adsorption by wet soil provided increasing their solubility in this fashion will not reduce their adsorptive affinity for soil. Use of the amine salts, therefore, may hold promise of still greater improvements in the properties of cutback stabilized soil.

Results of tests made with the fatty amine acetates, added both to the cutback, and to the wet soil prior to cutback incorporation are shown in Table 4. It will be observed that, except for Armeen 18D (octadecyl amine), conversion to the acetate salt reduces

At	Molding		14	Days' Cur	e	7 Days' Water Immersion					
Additive	Volatiles Content	Density pcf	Volatiles Content %	Density pcf.	Com- pressive Strength psi.	Volatiles Content %	Water Absorption %	Density pcf.	Com pressive Strength psi	Ratio Rewet C S. Cured C. S.	
None	11.0	119 1	1.07	122 2	299 ± 15	49	3.98 ± 0.04	119 6	110 ± 2	0.37	
Armeen 12D	10 4	119.6	0.98	120, 9	300 ± 14	3.6	2 69 ± 0.28	120.9	153 ± 3	0,51	
Armeen 16D	10, 7	118.7	0.96	122, 2	270 ± 17	3.9	2.85 ± 0.03	119.6	111 ± 6	0, 41	
Armeen 18D	11 9	117. 3	1, 16	119, 1	303 ± 7	5.8	4.6 ± 0.22	118.5	114 ± 5	0, 38	
Arguad 12	11 8	117, 3	1, 32	119, 9	279 ± 4	5.3	4.0 ± 0.12	118.0	86 ± 1	0.31	
Arguad 18	11.9	117.3	1 31	119.9	276 ± 3	5.3	4.1 ± 0.18	118.0	74 ± 6	0, 27	
Arguad 2HT	10, 4	119, 1	0 97	119.9	351 ± 12	4.0	3.11 ± 0.1	119.6	112 ± 7	0.32	
Primonox 10	11.3	118.7	0. 99	1 20. 0	218 ± 9	58	4.8 ± 0.12	118.7	69 ± 3	0. 325	
Victamine D	11. 8	118.0	1 45	120 0	256 ± 15	7.1	5.6 ± 0.18	118.0	50 ± 9	0.19	
Mixing Water	Content. 11	.0%, Asph	alt Concent		% on Soil						

TABLE 3

EFFECT OF ANTISTRIPPING AGENTS ON PROPERTIES OF ASPHALT-CUTBACK STABILIZED M-21 SOIL

Mixing Water Content. 11.0%, Asphalt Concentration, 5 3% on Soil Asphalt-Cutback Composition: 2.1 Asphalt to Gasoline, Additive Concentration: 2% on Asphalt; Mixing Time, 2 min.

Additives Added with Water

Muxing Water Content: 11%, Asphalt Concentration: 5.3% on Soil Asphalt-Cutback Composition. 2:1 Asphalt to Water, Additive Concentration, 0.1% on Soil Mixing Time. 2 min.

	At Molding 14 Days' Cure					7 Days' Water Immersion						
Additive	Volatiles Content	Density pcf.	Volatiles Content	Density pcf.	Com- pressive Strength psi.	Volatiles Content %	Water Absorption %	Density pcf.	Com- pressive Strength psi	Ratio. Rewet C. S. Cured C. S.		
Armeen 12D ^a	12 1	117.4	0. 88	121 0	239 ± 12	7.0	6.0 ± 0.73	117, 5	72 ± 9	0. 30		
Acetate Armeen 16D ^a	11. 9	11 6. 9	0. 87	119. 9	284 ± 7	7. 2	6. 15 ± 0, 19	117.9	67 ± 4	0. 24		
Acetate Armeen 18D ^a	11. 3	118, 0	1 18	119. 1	298 ± 23	6.3	5.2 ± 0.31	118.5	106 ± 10	0. 36		
Acetate Rosin Amine I	D ^a 12. 1	118.0	1 03	119. 9	261 ± 16	5.3	4.67±0.25	119. 9	114 ± 9	0.43		
Acetate Armeen 12D ^b	12.5	118, 0	1. 10	121. 1	256 ± 1	6. 1	4.96 ± 0.66	118.5	85 ± 11	0, 33		
Armeen 16Db	12.5	117.4	1 07	1 2 1. 1	290 ± 2	7 55	6.4 ± 0.46	117.9	77 ± 8	0. 26		
Acetate Armeen 18D ^b	11 8	116.9	1. 26	1 20. 5	280 ± 13	5.3	4.09 ± 0.17	119.9	161 ± 4	0.57		
Rosin Amine I Acetate	D ^b 11 5	117.4	0, 97	121. 1	291 ± 20	5.4	4.27±0.2	120.4	826 ± 0	0, 28		

rewet strength of the stabilized soil (whether the salt is added to the soil or cutback) relative to that obtained with the free amine when added to the mixing water. With Armeen 18D, on the other hand, addition of the acetate salt in the cutback yields substantially higher rewet strength than does any alternative method of treatment. These results strongly suggest that the two major factors controlling the effectiveness of antistripping additives in fine-grained soils are (1) uniformity of coverage of the soil sur-



Figure 4. Effect of various antistripping additives on strength of cutback-stabilized M-21 soil.

face, and (2) firmness of attachment of the additive to the soil. Evidently the shorterchain (12 and 16 carbon) free amines are soluble enough in water to distribute uniformly around the soil particles, and yet are firmly held on the soil surfaces by adsorptive forces, but when converted to their far more soluble acetate salts, become far less firmly adsorbed by the soil. With the long chain (18 carbon) free amine, the water solubility is too low for efficient distribution, and even when converted to the acetate, is insufficiently soluble in water to permit uniform coating of the soil particles when added as an aqueous dispersion. Solution of the acetate salt in the cutback yields superior results, evidently because the high solubility of the salt in the cutback permits more uniform additive-distribution than can be achieved by direct addition to wet soil.

Figure 4 summarizes the results obtained with the various antistripping additives used. Of all the antistripping additives examined, only lauryl amine (added to the mixing water), and octadecyl amine acetate (added to the cutback) significantly increased the rewet strength of cutback stabilized soil; improvement was about 50 percent in both cases. Other additives, or other methods of incorporation, resulted in either no improvement, or appreciable loss in rewet strength. Evidently, therefore, antistripping agents as a general class of compounds are not uniformly effective in fine-grained soils, although compounds with appropriate water-solubility and adsorptive affinity for soil can be decidedly beneficial.

The rate of loss of volatiles during curing, and rate of water absorption during immersion, for cutback-stabilized soil containing the two most effective antistripping agents (2 percent on asphalt) found in this study, are compared with controls in Figure 5. It will be noted that systems containing the additives lose volatiles more slowly than controls during curing, and, in general, absorb water more slowly on immersion. The reduced rate of drying may be caused by the fact that the additives permit the asphalt cutback to wet the soil surface, with the result that slugs of cutback actually plug many of the capillaries through which water and gasoline vapor would normally excape. The reduced rate of water imbibition on immersion reflects, it is believed, the ability of the additives to increase to water-soil contact angle, thus reducing the capillary forces drawing water into the interior of the soil mass.

Effect of Reactive Chemical Additives. Another method by which asphalt stabilization of soils might be improved is by chemical alteration of the asphalt to improve its physical properties (i. e., strength, plasticity, age-stability, etc.), its adhesive affinity for soil, or both. Changes of this type may be brought about by adding to asphalt small quantities of reactive chemicals which are known, or suspected, to combine with reactive constituents of asphalt.

To explore this possibility, many potentially reactive compounds were added to asphalt cutback, and changes in the physical appearance of the mixture with time (e.g., increase in viscosity, phase-separation, etc.) were observed. Those compounds which appeared to have the greatest effect in these tests were then used in conjunction with asphalt cutback for soil stabilization tests. The results of these tests, showing the effects of selected chemicals on rewet strength and water absorption of stabilized soil, are presented in Table 5. The data show quite conclusively that additives of this type have a marked beneficial effect on



Figure 5. Drying and rewetting properties of cutback-stabilized M-21 soil containing antistripping additives.

TABLE 5

EFFECT OF CHEMICAL ADDITIVES ON REWET STRENGTH OF ASPHALT CUTBACK STABILIZED M-21 SOIL

2 weeks cure at 50% R.H., 25 deg. C 1 week 1mmersion at 25 deg. C Cutback: 2 parts straight-run asphalt per 1 part gasoline 5% asphalt on soil 11% molding water

Additive	Concen- tration % on Asphalt	% Residual Volatiles after Curing	% Water Absorption	Rewet Compressive Strength psi.	% Improve- ment
None		1.0	4.2	129	_
DDI ^a	10	0.9	2.5	230	78
TDI a	10	1.0	3.0	268	108
TTIA	10	1.0	5.0	150	16
P2O5	20	4.4	2.8	245	90
P ₂ O ₅	10	3.9	2.5	202	56
Epon 828 +	10	0.8	2.9	152	18
DETA	2		-		

^a DDI: Diphenyl methane diisocyanate

TDI: Toluene diisocyanate

TTI: Triphenylmethane triisocyanate

Epon 828: An epoxy resin manufactured by Shell Chemical Corp.

DETA: Diethylene triamine

TABLE 6

EFFECT OF P2O5 ON ASPHALT-CUTBACK STABILIZATION 2:1 CUTBACK

% P2O5	Curing Time Days	Resid. Vols.	Cured Comp. Strength	Water Absorp- tion	Rewet Comp. Strength	% Improve- ment in Rewet Strength
0	2	1.48	199	7.17	18.5	_
	7	1.65	226	5.15	67	-
	14	1.75	270	4.83	84	-
5%	2	1, 34	193	6.34	40	116
	7	1.65	281	6.16	73	9
	14	1.55	336	5.03	94	12
10%	2	1.94	208	5.94	65	252
	7	1.65	279	5.70	109	63
	14	2.02	353	5.61	110	31

Cured at 50% R. H., 27 deg. C Immersed for 7 days at 27 deg. C M-21 soil; straight run asphalt, 2 parts per 1 part gasoline 5% asphalt on soil; 11% molding water As-molded density: 119-121 pcf.

the rewet strength of cutback-stabilized soil, in some instances doubling it. The most attractive compound in the above table, from the point of view of cost and availability, is phosphorus pentoxide. While this product is currently being used in the manufacture of air-blown asphalt with unusual properties¹, there has been, to the

¹Shearon, W. H., Jr., and Hoiberg, A. J., Ind. Eng. Chem. 45, 2122 (1953).

	Afte	r Curing		After 7	Days' Immers	sion
	. .		_			% Improvement in Rewet
~	Curing	Residual	Compressive	Water	Compressive	Strength
% P2O5	Time	Volatiles	Strength	Absorption	Strength	Relative to
on Asphalt	Days	%	psi.	%	psi.	Control
None	2	5.4	156 ± 2	5.1	32 ± 3	-
None	7	2. 1	169 ± 9	4.2	74 ± 4	-
None	14	1.9	245 ± 4	5.2	70 ± 3	-
5%	2	3.7	140 ± 7	-	36 ± 0	13
	7	2.3	242 ± 12	4.1	80 ± 0	8
	14	1.2	214 ± 7	5.1	103 * 3	43
10%	2	3.3	160 ± 7	6.3	54 ± 4	69
	7	1.4	230 ± 23	5.2	130 ± 0	76
	14	1.2	337 ± 11	5.2	115 ± 2	60
10% Cured at 50 Immersed	2 7 14 0% R. H. for 7 day	3.3 1.4 1.2 , 27 deg. C ys at 27 deg	$ \begin{array}{c} 160 \pm 7 \\ 230 \pm 23 \\ 337 \pm 11 \\ \hline 3. C \end{array} $	6. 3 5. 2 5. 2	54 ± 4 130 ± 0 115 ± 2	43 69 76 60

 TABLE 7

 EFFECT OF P₂O₅ ON ASPHALT CUTBACK STABILIZATION 1:1 CUTBACK

5% asphalt on soil; 11% molding water

As-molded density; 116-119 pcf.

authors' knowledge, no reference to its use as an asphalt additive at ambient temperatures immediately prior to incorporation of asphalt with soil or aggregate. A more detailed study of P_2O_5 -modified asphalt cutback as a soil stabilizer was therefore undertaken to determine the effects of the additive (in varying concentrations) on strength, curing rate, water absorption, etc. The results of this study are presented in Tables



Figure 6. Curing characteristics of P₂O₅modified, cutback-stabilized M-21 soil (2:1 cutback).

6 and 7, and Figures 6 and 7. The data reveal the following:

1. When samples are cured under "standard" conditions, P_2O_5 improves both as-cured and rewet compressive



Figure 7. Curing characteristics of P₂O₅modified, cutback-stabilized M-21 soil (1 1 cutback).

TABLE 8

EFFECT	OF	MIXING	TIME	ON	PROPERTIES	OF	M-21	SOIL	STAB	ILIZED	WITH	PHOSPHORUS	PENTOXIDE	TREATED,
					STR	AIG	HT-RU	IN ASI	PHALT	CUTB/	ACK			

	At Mol	dung	14	Days' Cure			7 Days' Wat	on	
Mixing Time sec.	Volatiles Content %	Density pcf.	Volatiles Content %	Density pcf.	Com- pressive Strength psi.	Volatiles Content %	Water Absorption %	Density pcf.	Com- pressive Strength ps1.
15	12.3	114.5	1.7	116.8	358 ± 12	6.1	4.5 ± 0.2	116.3	116 ± 8
30	11.6	117.1	1.3	120.5	399 ± 37	6,0	4.5 ± 0.2	117.3	113 ± 10
60	11.8	117.3	1.2	120. 3	400 ± 6	6.0	4.5 ± 0.2	118. 2	129 ± 11
120	11.8	117.5	1, 4	120, 5	412 ± 18	5.5	4.2 ± 0.1	118, 7	141 ± 4

strength of stabilized soil, the percentage improvement being nearly proportional to its concentration. Mean improvement in rewet strength at the 10 percent concentration level (on asphalt, or 0.5 percent on soil) is about 50 percent.

2. Total volatiles content (after 14 days' cure and 7 days' immersion) of P_2O_5 containing soil samples is about the same as that of specimens prepared without P_2O_5

3. Reduction in the ratio of asphalt to gasoline in the cutback appears to accelerate the development of rewet strength on curing, but reduces the ultimate final rewet strength, of samples prepared with unmodified cutback. In the presence of P_2O_5 , however, the asphalt: gasoline ratio appears to be of minor importance either in curing rate, or final cured strength.

4. Presence of P_2O_5 greatly increases the rate of strength-development during cure. For example, specimens containing 10 percent P_2O_5 develop, after 3-4 days' curing, strengths equivalent to two weeks' cure of unmodified cutback-stabilized soil.

The nature of the action of P_2O_5 on asphalt and asphalt-soil mixtures remains obscure. It is believed, however, that the compound adds to unsaturated, acidic, or basic bodies in the asphalt forming phosphate or phosphonate adducts which exhibit better adhesion to soil than asphalt itself. Since asphalt thickens appreciably on standing when P_{in} is present, it is also possible that the

 P_2O_5 is present, it is also possible that the compound catalyzes polymerization of naphthenic, olefinic, or aromatic constituents of asphalt also. Since the observed rewet strength improvements produced by P_2O_5 are not accompanied by a marked reduction in water absorption (as noted for antistripping additives), it appears unlikely that P_2O_5 functions primarily as a "waterproofing" additive. This belief is further supported by the observation that, whereas "waterproofing" additives such as the fatty amines reduce as-cured strength below that of controls, P_2O_5 actually increases it.

The effect of mixing uniformity on ascured and rewet strength of P_2O_5 -modified cutback was also determined, as shown in Table 8 and Figure 8. It will be noted that, whereas improved mixing yielded slightly lower dry strengths, and much higher rewet strengths with unmodified cutback, it resulted in slight improvements in both dry and rewet strengths for P_2O_5 modified cutback. From these observations, it can be deduced that (1) P_2O_5 facilitates distribution of asphalt in the soil (since there is less to be gained from longer mixing, relative to the control), and



Figure 8. Effect of mixing on strength of P₂O₅-modified, cutback-stabilized M-21 soil.

(2) P_2O_5 improves the asphalt-soil bond (since the as-cured strength is not reduced by better mixing, as with the control). The relatively low dependence of the strength of P_2O_5 -modified, asphalt-stabilized soil on mixture uniformity is probably very desirable from the standpoint of field operations.

Another factor which may be of considerable importance in the field is the dependence of the properties of cutback-stabilized soil upon the degree of aeration and attendant loss of volatiles before compaction. Table 9 shows the effect of aeration for 3 hours (with the loss of about 2 percent volatiles) before compaction upon the dry and rewet strengths of unmodified and P_2O_5 -modified, cutback-stabilized M-21 soil. In the absence of P_2O_5 , aeration results in a marked increase in as-cured strength, and reduction in rewet strength, relative to samples compacted immediately after mixing;

> TABLE 9 EFFECT OF AERATION ON PROPERTIES OF ASPHALT-CUTBACK STABILIZED M-21 SOIL

	At Me	olding	1	4 Days' Cu	ге		7 D	ays' Wate:	r Immersion	
Additive	Volatiles Content %	Density pcf.	Volatiles Content	Density pcf.	Com- pressive Strength psi.	Volatiles Content %	Water Absorption %	Density pcf.	Com- pressive Strength psi.	Ratio: <u>W. C. S.</u> D. C. S.
None	12.0	-	0 8	-	236	4.9	4.1		122	0.52
None	10.0	119.5	1.1	121. 1	355 ± 20	6.8	5,5±0,1	118.9	73 ± 9	0 21
10% P ₂ O ₅ on Asphalt	11, 8	117.5	1.4	120. 5	412 ± 18	5. 5	4.2 ± 0.1	118.7	141 ± 4	0.34
10% P ₂ O ₅ on Asphalt	10 . 2	120.8	1. 3	121.7	405 ± 12	6. 6	5. 3	119.4	142 ± 7	0, 35

Mixing Water Content: 11%; Asphalt Content 5, 3% on Soil:

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Mixing Time: 2 min.; Cutback Composition: 2:1 Straight-Run Asphalt to Gasoline

TABLE	10
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EFFECT OF EMULSIFYING AGENTS ON PROPERTIES OF ASPHALT-EMULSION STABILIZED M-21 SOIL

	At M	loiding	14	a Days' Cu	re		7 Days' W	ater Immei	sion	
Emulsifier	Water Content %	Density pcf.	Water Content	Density pcf.	Com- pressive Strength psl	Water Content	Water Absorption %	Density pcf.	Com- pressive Strength psi.	Ratio: Rewet C. S. Cured C. S.
Sodium Oleate	13. 1	117. 3	0.91	119.9	332 ± 40	10. 1	9. 11 ± 0. 21	116.8	32, 1 ± 1	0, 098
Sodium Oleate	13. 1	117, 3	0.98	121.7	396 ± 46	9.0	8.05 ± 0.83	120. 0	48. 2 ± 13. 6	3 0. 109
Armeen 18D Acetate	13.9	115.6	1, 10	118, 7	258 ± 3	8. 1	7.0 ± 0.25	118.5	72.0±3	0. 282
Armeen 18D Acetate	13.6	116, 7	1.05	120. 7	292 ± 3	8, 25	7.28 ± 0.19	120.5	74.1 ± 7	0. 254
Armeen 18D Chloride Arquad 18	1 2. 8	118.0	0.84	1 20, 0	313 ± 11	10, 2	9. 21 ±0. 6	117. 3	57 ±8	0. 181
Armeen 18D Chloride Arguad 12	12, 7	118, 0	1, 18	121, 1	332 ± 5	8, 03	7.04 ± 0.03	117. 3	85.9±9	0, 260
Armeen 18D Chloride Armeen 12D Chloride	13.0	117. 3	1. 04	121, 1	353 ± 22	8, 5	7.45 ± 0.1	119,9	82. 8 ± 2	0. 236
Armeen 16D Chloride Arquad 18	13. 1	117.3	0, 83	119.8	349 ± 7	9. 7	8.72 ± 0.1	117.8	68.3±1	0, 196
Armeen 16D Chloride Arguad 12	1 2. 6	118, 5	0,92	120. 7	314 ± 11	9.1	7.94 ± 0.6	119.2	77.0±5	0. 247
Armeen 16D Chloride Armeen 12D Chloride	12.9	116.7	0. 89	120, 7	357 ± 5	9.0	8.0 ± 0.12	118.0	88, 7 ± 7	0, 246
Armeen 12D Chloride	14, 1	114.9	1. 11	120.0	268 ± 13	7.6	6.25 ± 0.35	119.0	95 ± 1	0. 355
Armeen 12D Chloride Arguad 18	12, 3	118.5	0, 92	122. 2	334 ± 12	7. 1	6.03 ± 0.6	1 20. 0	91.6±14	0, 277
Armeen 12D Chloride Arguad 12	13, 1	116, 2	0.83	119 . 3	285 ± 18	9. 9	8.76 ± 0.65	118.0	63.8±7	0. 228

Mixing Water Content: 18.7%, Asphalt Concentration = 5.3% on Soil

Emulsion Composition: 1. 1 Asphalt to Water, 2% Emulsifier in Asphalt Mixing Time 2 min.



Figure 9. Effect of various emulsifiers on strength of asphalt emulsion-stabilized M-21 soil.

these trends suggest that aeration reduces the efficiency of coating of soil particles by asphalt, thus reducing the degree of waterproofing. In other words, compaction may be regarded as a continuation of the mixing process, and should be carried out while the asphalt cutback is still quite fluid in order to insure improved asphalt distribution. In the presence of P_2O_5 , however, aeration appears to make very little difference in as-cured and rewet strength, an observation which further corroborates the belief that P_2O_5 facilitates rapid wet-out of the soil by the asphalt during mixing. Thus, if the soil-coating process is completed during mixing (as postulated with the P_2O_5 systems), then compaction contributes little to the efficiency of asphalt distribution.

Asphalt Emulsion Stabilization

Effect of Choice of Emulsifying Agent. The behavior of M-21 clayey silt stabilized with 5 percent straight-run asphalt incorporated as 1:1 aqueous emulsions (at an initial total water content of about 18 percent) and employing various surface active agents as emulsifiers, is shown in Table 10 and more simply in Figure 9. The salient features of these results are as follows:

1. Soil stabilized with emulsions containing soap (sodium oleate) as the emulsifier exhibits, on drying and curing, substantially higher strength than does soil treated with amine- or quaternary-stabilized emulsions. As a matter of fact, the dry strength of an oleate-containing system is often higher than that of dry, compacted, untreated soil.

2. On the other hand, soil treated with oleate-stabilized emulsions exhibit significantly higher water absorption on 7 days' immersion, and have far lower rewet strength than soil treated with amine- or quaternary-stabilized emulsions.

3. There is considerable variation in rewet strength of cationic emulsion-stabilized soils with the type of emulsifier. The twelve-carbon amine chloride (lauryl) has the greatest beneficial effect on rewet strength, the higher alkyl amine salts or their mixtures showing progressively poorer characteristics. Similarly, admixtures of the amines with octadecyltrimethyl ammonium chloride (Arquad 18) show best results with the C-12 amine, and poorer results with increasing alkyl chain length. On the other hand, admixtures of the amines with the twelve carbon quaternary (Arquad 12) shows the reverse trend, rewet strength increasing with chain length of the amine.

The maximum rewet compressive strength achieved (with lauryl amine chloride) was about 95 psi., roughly twice that obtained with sodium oleate emulsion, and about equal to that obtained with straight-run asphalt cutback.

Differences in rewet characteristics of soils stabilized with the anionic (oleate) emulsion and with the cationic emulsions (as a group) can largely be explained by the ability of amines and quaternaries to adsorb on negatively charged soil particles and render them hydrophobic. This process not only aids distribution of asphalt on the soil, but also materially lessens or destroys the water wettability of soil particles not coated with asphalt. The high as-cured strength of oleate-emulsion treated soil is evidently caused by the dispersive effect of the alkaline soap on the clay minerals present; this belief is supported by the observation that the shrinkage on drying of these systems is generally greater than that of soils stabilized with cationic emulsions.

Reasons for differences between the various cationics are more elusive. It would appear, however, that proper solubility-adsorptivity balance of the emulsifier is of primary importance here, as it was with cutbacks containing these additives. The C-12 amine chloride is the most soluble of the amine salts studied, and gives best results evidently because it is distributed through and adsorbed by the soil most uniformly during mixing. Mixtures of amines and the C-18 quaternary show similar trends probably for the same reason (the quaternary functioning as a solubilizer for the amine in this case). On the other hand, the amines are rendered so water soluble by the C-12 quaternary that the shorter chain (12 carbon) amine is no longer able to adsorb as firmly on the soil as are the higher amines, with the result that waterproofing action increases with increasing amine chain length. The fact that the C-12 amine-C-18 quaternary, and C-18 amine-C-12 quaternary mixtures give about the same rewet strength is consistent with this explanation.

Rates of Curing and Water Absorption

A limited amount of data was obtained on the rate of loss of volatiles from emulsionstabilized soils on curing, and the rate of absorption of water in immersion. These data are summarized in Figure 10. It will be noted that cationic asphalt emulsionstabilized soil cures more rapidly, and imbibes water on immersion more slowly, than

soil treated with anionic (oleate) emulsion. systems is undoubtedly caused by the increase in the water-soil contact angle (resulting from amine adsorption) which reduces the capillary forces acting on the water and ficilitates its migration to and evaporation from the sample surface. The relatively slower rate of water imbibition by the amine-containing systems can similarly be explained by increase in watersoil contact angle, which reduces the capillary forces tending to draw water into the interparticle voids.

Effect of Mixing

Data showing the effect of mixing time in the Brabender Plastograph on the properties of M-21 soil stabilized with a sodium oleate-asphalt emulsion are presented in Table 11 and Figure 11. Improved mixing appears to increase both dry and rewet strengths appreciably (the latter, more than the former), but to have little effect on water absorption. The increase in dry strength with mixing is probably



EFFECT OF MIXING TIME ON PROPERTIE	IS OF	ASPHALT-EMULSION	(SODIUM	OLEATE) STABILIZED	M-2	21
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Mixing Water Content.	18.7%, Asphalt Concentration = 5.3% on Soil	
Emulsion Composition.	1.1 Aspiant to water, by Smanarer on inspirate	

_									
Water ontent %	Density pcf.	Water Content %	Density pcf.	Com- pressive Strength psi.	Water Content %	Water Absorption %	Density pcf.	Com- pressive Strength psi.	Ratio: Rewet C. S. Cured C. S.
10.4 10.7 10.2 es molde	121, 3 119, 3 123, 1 d after aera	0, 91 1, 01 0, 91	123 6 122.3 124.4 oximately 4	330 ± 39 313 ± 42 447 ± 23 hours.	10 42 9.58 9 13	8.71 ± 0.11 8.34 ± 0.16 8.15 ± 0.2	118. 1 119. 9 120. 5	25.4 ± 7.2 34.7 ± 5.8 46 ± 8.5	0.075 0.113 0.104
	ntent %), 4), 7), 2 s molde on prep:	ntent Density % pcf. 0, 4 121, 3 1, 7 119, 3 1, 2 123, 1 s molded after aera on prepared using '	nient Density Content % pcf. % 0,4 121,3 0,91 1,7 119,3 1.01 1,2 123,1 0.91 1,2 123,1 0.91 s molded after aeration of approximation of approximation prepared using "Dispersation"	nient Density Content Density % pcf. % pcf. 0,4 121,3 0,91 123,6 1,7 119,3 1,01 122,3 1,2 123,1 0,91 124,4 s molded after aeration of approximately 4 on prepared using "Dispersator," "	nient Density Content Density Strength % pcf. % pcf. psi.), 4 121, 3 0, 91 123 6 330 ± 39), 7 119, 3 1.01 122, 3 313 ± 42), 2 123, 1 0.91 124, 4 447 ± 23 s molded after aeration of approximately 4 hours. on prepared using "Dispersator," " "	ntent Density Content Density Strength Content $\frac{9}{26}$ pcf. pcf. psi. $\frac{9}{26}$ $\frac{1}{21}$ 3 0.91 123 6 330 ± 39 10 42 1.7 119.3 1.01 122.3 313 ± 42 9.58 1.2 123.1 0.91 124.4 447 ± 23 9.13 s molded after aeration of approximately 4 hours. on prepared using "Dispersator." 4 4	nient Density Content Density Strength Content Absorption $\frac{9}{5}$ pcf. psi. $\frac{9}{5}$ $\frac{9}{5}$ $\frac{9}{5}$ $\frac{9}{5}$ $\frac{1}{5}$ pcf. psi. $\frac{9}{5}$ $\frac{9}{5}$ $\frac{9}{5}$ $\frac{1}{5}$ 121.3 0.91 123.6 330 ± 39 10 42 8.71 ± 0.11 $\frac{1}{5}$ 1.01 122.3 313 ± 42 9.58 8.34 ± 0.16 $\frac{1}{5}$ 1.23.1 0.91 124.4 447 ± 23 9.13 8.15 ± 0.2 s molded after aeration of approximately 4 hours. p repared using "Dispersator." "Dispersator." "Dispersator."	nient Density Content Density Strength Content Absorption Density $\frac{9}{5}$ pcf. $\frac{9}{5}$ pcf. $\frac{9}{5}$ $\frac{11}{5}$ $\frac{118,1}{11,11}$ $\frac{118,1}{11,2,3}$ $\frac{119,3}{122,3}$ $\frac{133 \pm 42}{123,12}$ 9.58 8.34 ± 0.16 $\frac{119,9}{119,9}$ $\frac{123,1}{23,1}$ 0.91 $124,4$ 447 ± 23 9.13 8.15 ± 0.2 $120,5$ s molded after aeration of approximately 4 hours. 0 proper dusing "Dispersator," 0 <td>nientDensityContentDensityStrengthContentAbsorptionDensityStrength$\frac{9}{5}$pcf.$\frac{9}{5}$$\frac{9}{5}$$\frac{9}{5}$$\frac{9}{5}$$\frac{9}{5}$$\frac{9}{5}$$\frac{9}{5}$$\frac{9}{5}$$\frac{1}{2}$$\frac{11}{2}$$\frac{3}{2}$$\frac{3}{3}$$\frac{3}{2}$$\frac{9}{2}$$\frac{8}{7}$$\frac{1}{2}$$\frac{11}{118}$$\frac{1}{25}$$\frac{4}{7}$$\frac{2}{5}$$\frac{1}{2}$$\frac{11}{2}$$\frac{11}{22}$$\frac{3}{3}$$\frac{13}{2}$$\frac{4}{2}$$\frac{9}{5}$$\frac{8}{5}$$\frac{34}{2}$$\frac{19}{2}$$\frac{34}{7}$$\frac{7}{5}$$\frac{8}{5}$$\frac{1}{2}$$\frac{123}{2}$$\frac{1}{24}$$\frac{447}{2}$$\frac{9}{2}$$\frac{13}{8}$$\frac{15}{5}$$\frac{10}{2}$$\frac{120}{5}$$\frac{46}{5}$$\frac{4}{5}$s molded after a cration of approximately 4 hours.$\frac{1}{2}$$\frac{1}{2}$$\frac{1}{2}$$\frac{1}{2}$$\frac{1}{2}$$\frac{1}{2}$$\frac{1}{2}$</td>	nientDensityContentDensityStrengthContentAbsorptionDensityStrength $\frac{9}{5}$ pcf. $\frac{9}{5}$ $\frac{9}{5}$ $\frac{9}{5}$ $\frac{9}{5}$ $\frac{9}{5}$ $\frac{9}{5}$ $\frac{9}{5}$ $\frac{9}{5}$ $\frac{1}{2}$ $\frac{11}{2}$ $\frac{3}{2}$ $\frac{3}{3}$ $\frac{3}{2}$ $\frac{9}{2}$ $\frac{8}{7}$ $\frac{1}{2}$ $\frac{11}{118}$ $\frac{1}{25}$ $\frac{4}{7}$ $\frac{2}{5}$ $\frac{1}{2}$ $\frac{11}{2}$ $\frac{11}{22}$ $\frac{3}{3}$ $\frac{13}{2}$ $\frac{4}{2}$ $\frac{9}{5}$ $\frac{8}{5}$ $\frac{34}{2}$ $\frac{19}{2}$ $\frac{34}{7}$ $\frac{7}{5}$ $\frac{8}{5}$ $\frac{1}{2}$ $\frac{123}{2}$ $\frac{1}{24}$ $\frac{447}{2}$ $\frac{9}{2}$ $\frac{13}{8}$ $\frac{15}{5}$ $\frac{10}{2}$ $\frac{120}{5}$ $\frac{46}{5}$ $\frac{4}{5}$ s molded after a cration of approximately 4 hours. $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$ $\frac{1}{2}$

caused by more complete breakdown of soil agglomerates, and hence more extensive particle-to-particle contact in the dried soil. Increase of rewet strength with mixing reflects, it is believed, improved distribution of the asphalt (and thus more asphaltsoil bonds per unit volume), but the lack of a simultaneous reduction in water absorption indicates that the percentage of soil particle surface covered by asphalt remains nearly unchanged with mixing. Studies of the effect of mixing on amine-stabilized systems are currently being conducted.

Effect of Initial Water Content

The effects of varying the initial (molding) water content on the properties of soils treated with oleate- and octadecylamine-asphalt emulsions are of considerable interest, and are summarized in Table 12 and Figure 12. With sodium oleate emulsion, an in-



Figure 11. Effect of mixing on strength of emulsion-stabilized M-21 soil (sodium oleate emulsifier).

crease in initial water content from about 19 percent to 27 percent is accompanied by a marked decrease in dry and rewet strengths (and corresponding increase in water absorption), and above a water content of about 27 percent, by a gradual improvement in these properties with increasing initial water content. With octadecylamine emulsion, in contrast, raising the initial water content from 19 percent to 80 percent results in a slight improvement in as-cured strength and marked improvement in rewet strength (and reduction in water absorption). The explanation proposed for these trends is as follows:

Oleate-stabilized emulsions are easily coagulated by acid (pH = < 7) or polyvalent metal ions such as calcium or magnesium. A soil such as M-21 exhibits a pH around 5.5-6.0, and contains detectable quantities of soluble calcium and magnesium salts. When admixed with such a soil at low to moderate water contents therefore, the emulsion tends to coagulate fairly rapidly; however, at low water contents, the emulsion particles are rapidly dispersed between soil particles during mixing so that coagulation is mechanically hindered. This leads to fairly uniform distribution of the asphalt in the soil, and relatively high

SOIL

		TABLE 12					
EFFECT OF INITIAL W	ATER CONTENT O	N PROPERTIES OF	ASPHALT	EMULSION	STABILIZED	M-21	SOIL

		At Molding	:	14	4 Days' Cu	re			7 Days	' Water Imr	nersion
Emulsifier	Mixing Water Content %	Water Content %	Density pcf.	Water Content	Density pcf.	Com- pressive Strength psi.	Water Content %	Water Absorption %	Densıty pcf.	Com- pressive Strength psi.	Ratio: <u>Rewet C. S.</u> Cured C. S.
Sodium Oleate	18.7	13.0	117. 1	0, 98	121. 8	396 ± 46	9.0	8.05 ± 0.91	120. 0	48. 2 ± 13.	3 0.117
Sodium Oleate	23. 2	11.5	120.4	0, 90	122. 3	318 ± 16	11.4	10.37 ± 0.35	117. 1	25 ± 3.	5 0.079
Sodium Oleate	27.4	12.4	119.7	1. 05	121.6	237 ± 20	-	-	-	24.1 ± 3	0, 102
Sodium Oleate	31. 3	11.8	1 20, 7	1, 08	120, 4	252 ± 17	11.2 :	10.03 ± 0.12	116. 0	30.5 ± 2.4	0, 122
Sodium Oleate	80. 0	10, 5	123, 6	1. 02	123, 9	293 ± 12	10, 1	8, 68 ± 0, 21	120,4	42, 4 ± 3, 1	0, 144
Armeen 18D Acetate	18, 7	13.9	115.8	1. 13	118.6	258 ± 3	8. 1	7.00 ± 0.25	118, 7	72 ± 3	0. 278
Armeen 18D Acetate	27.4	11.5	121. 2	0.96	121.6	310 ± 11	7.93	6.74 ± 0.23	119 . 2	100 ± 4	0, 322
Armeen 18D Acetate	80, 0	11.4	121.6	1.07	122, 1	314 ± 13	7, 03	5. 84 ± 0. 25	121.4	123 ± 14	0, 394

2% Emulsifier on Asphalt

strength. At somewhat higher water contents, where the soil particles are separated further by water and where the rate of mixing is appreciably lower, coagulation of emulsion droplets can occur before prevented from doing so by the soil particles; this causes poorer distribution of the asphalt, and lower strength. At very high water contents, however (where the mixture is a virtual slurry), the concentration of coagulating electrolytes in the water is reduced (thus delaying or preventing emulsion coagulation) and mixing is again rapid; these conditions once more favor improved asphalt distribution, and improved strength.

1000 õ SODIUM OLEATE EMULSION 800 OCTADECYL AN FMU SION 700 600 500 400 AS CURED 300 1S d 200 WATER FOR COM ACTION STRENGTH 100 90 80 70 COMPRESSIVE REWET 60 50 30 20 MOL DING WATER CONTENT

Figure 12. Effect of mixing water content on strength of emulsion-stabilized M-21 soil.

With amine-stabilized emulsions, on the other hand, coagulation is not induced by acid or polyvalent cations, and hence these emulsions are stable in soil-water. However, the positively charged emulsion droplets deposit, or plate out on the soil particles, and are removed from the water in this fashion. Since the total exposed surface of the soil particles has a capacity for retaining a quantity of emulsified asphalt far in excess of the amount added, it is clear that inefficient mixing of the emulsion with the wet soil will result in overtreatment of those soil particles which come in contact with the emulsion first, and undertreatment of the remainder of the soil. This situation will, of course, be favored at low water contents where the soil particle concentration is high, and where the distances which an emulsion droplet has to cover before meeting a soil particle are small. At high water contents, however, where the soil particles and asphalt droplets are separated by appreciable distances, enough time becomes available to uniformly distribute the droplets throughout the aqueous phase before much of the asphalt is deposited on the soil particles, with the result that the uniformity of asphalt distribution is enhanced. This, then, can account for the marked

EFFECT OF ASPHALT CONTENT ON PROPERTIES OF ASPHALT EMULSION (SODIUM OLEATE) STABILIZED M-21 SOIL

	At M	olding		14 Days' Cure			7 Days' Water Immersion					
Asphalt Concen- tration %	Water Content %	Density pcf.	Water Content %	Density pcf.	Com- pressive Strength psi.	Water Content %	Water Absorption %	Density pcf.	Com- pressive Strength psi.	Ratio: Rewet C. S. Cured C. S.		
2, 65	13.4	121.6	1, 08	122. 7	356 ± 44	11.9	10. 73 ± 0. 32	118, 5	19.3 ± 4.1	0.057		
5.30	11.5	120, 5	0.91	122, 4	318 ± 16	11, 4	10.37 ± 0.35	117. 2	24.9 ± 3.5	0.077		
7.90	11.0	120, 0	0, 90	120.0	376 ± 17	8, 2	7.27 ± 0.26	118, 2	53.0±4	0, 141		

improvement in rewet strength (and reduction in water absorption) with increasing initial water content, since these properties are most sensitive to the uniformity of distribution of asphalt and antistripping additive on the soil surfaces.

Effect of Asphalt Content

Effects of varying the asphalt concentration from 2.65 percent to 7.9 percent on the soil weight in M-21 soil, using an oleate-asphalt emulsion, are shown in Table 13 and Figure 13. As might be expected, increasing the asphalt concentration causes a marked increase in rewet strength and decrease in water absorption, indicating that more asphalt leads to more thorough waterproofing of the soil. Effect of asphalt content on ascured strength is minor, indicating that asphalt plays little part in the cohesion of dry fine-grained soils. It is of interest that M-21 soil with asphalt content of 7.9 percent, using an oleate emulsion, yields a rewet strength which is still about half that obtained with an amine emulsion at an asphalt content of 5.3 percent. How asphalt content influences the strength characteristics of soils stabilized with amine emulsions remains to be determined.



Figure 13. Effect of asphalt content on strength of emulsion-stabilized M-21 soil (sodium oleate emulsifier).



Figure 14. Rewet strength of asphalt-stabilized soil versus volatiles content. generalized correlation.

Effect of Additives on Asphalt Stabilization - General Correlation

Examination of all the data obtained in this study reveals a striking across-theboard interdependence of rewet compressive strength on the volatiles content of the specimen at the time of test. This is illustrated graphically on Figure 14, where the log of the rewet compressive strength is plotted against volatiles content for (1) asphalt cutbacks (both cracked and straight-run, and with variable asphalt-gasoline ratio), (2) cutback-stabilized soils containing antistripping additives, (3) cutback-stabilized soils modified with reactive compounds such as P_2O_5 and isocyanates, (4) soap-stabilized asphalt emulsions (with varying mixing water content), and (5) amine-stabilized emulsions (with varying mixing water contents). It will be noted that all the points fall within a band roughly defined by the equation:

$$S = (500 \pm 220) e^{-0.25V}$$

where S = compressive strength psi.

V = volatiles content, percent by weight

Furthermore, each basic type of asphalt stabilization occupies a characteristic zone within this band, with soap-stabilized asphalt emulsions at the lower end, and with amine-stabilized emulsions, antistripping additive-containing cutbacks, and chemical modifiers for cutbacks occupying increasingly higher zones. This correlation is presumably applicable only to M-21 soil, although it is anticipated that a comparable relationship will be found for any specific soil.

It is thus apparent that "chemical modifiers" for asphalt, exemplified by P_2O_5 and the isocyanates, have the greatest beneficial effect on asphalt stabilization, with selected antistripping additives running a not-too-close second. Amine-stabilized emulsions (particularly those stabilized with lauryl or octadecylamine) yield strengths somewhat superior to those of plain asphalt cutbacks, and show far better performance than that of soap-stabilized emulsions, with which they properly should be compared.

CONCLUSIONS

The results of this work (employing a single soil) lead to the following conclusions:

1. Modification of asphalt cutbacks with reactive chemical compounds such as P_2O_5 or toluene- or diphenylmethane-diisocyanate (at concentrations of 10 percent on the asphalt or below) significantly improves cutback stabilization of fine-grained soils, as measured by elevation of compressive strength after 7 days' water immersion. P_2O_5 also markedly accelerates the development of water resistance of stabilized soil during drying and/or curing.

2. Incorporation of trace quantities (1 percent on asphalt) of selected antistripping agents (specifically, lauryl amine and octadecylamine) with cutback-stabilized soil causes a substantial improvement in rewet strength and reduction in water absorption. In some cases (e.g., with lauryl amine) pretreatment of the soil with the free amine in aqueous dispersion gives better results than other means of incorporation; in others (e.g., with octadecylamine) solution of the amine acetate in the cutback appears more desirable. It is believed that the method of incorporation which insures most uniform distribution of the additive through the soil is the most effective. Many antistripping additives which are useful with coarse aggregate appear to be actually detrimental in fine-grained soil.

3. Stabilization of a clayey silt with asphalt emulsions gives generally less satisfactory results than cutback stabilization. Emulsions employing fatty amines as emulsifiers are, however, far superior to the more common soap-stabilized emulsions, and in many cases give water resistance comparable with cutbacks containing antistripping additives. Amine-stabilized emulsions give substantially better results when mixed with soil at high water contents, and hence may be preferable to cutbacks where high soil-water contents are found in the field.

4. There is, for all forms of asphalt stabilization described above, a general correlation between rewet strength and volatiles content of the specimen at time of test. From this correlation, it has been deduced that asphalt, irrespective of its method of incorporation with soil or its chemical alteration, functions primarily as a waterproofing agent for soil, the various additives and improved methods of incorporation merely enhancing its characteristic waterproofing ability.

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