With respect to the type of stabilized road requiring the addition of pulverized clay, several new pieces of equipment are now available and it is definitely sensed that an economical method of preparing the clay off the subgrade and so freeing the operation from weather interference, will do much toward reducing the cost and time of construction This problem is being attacked

To carry on the program and adhere to the "low cost" road idea, we must obtain low construction costs It appears at present that the most efficient equipment will not be inexpensive but yet this equipment on worthwhile projects will materially reduce unit costs and improve quality Therefore, it is urged for the sake of the contractors that jobs of sufficient length be let so it may be possible to invest in equipment which will not only allow for low construction costs, but for completeness in the shortest possible time

I am sure you will find the manufacturers ready to cooperate to their fullest ability in an effort to keep down these costs and it is essential to both manufacturers and the contractors to develop as much uniformity as possible in the specifications and methods used

Mr F T Sheets, *Portland Cement Association* It is only natural that as a consulting engineer and Director of the development department of the Portland Cement Association I am interested in the possibilities of road soil stabilization by the utilization of portland cement The South Carolina Highway Department pioneered in this matter and some of the work that they have done in the last year or two is reported in the current issue of the Engineering News-Record Their work has since been extended to some further field experimentation this year We of the Portland Cement Association are naturally vitally interested in these possibilities and are making a thorough-going research in our own development laboratories in Chicago We have secured soil samples representative of the entire range of soils occurring in the various parts of the United States and, utilizing as best we can the fundamental principles of soil physics and chemistry, we are making a thorough exploration of the possibilities In this work we are getting at the question of durability of the resulting soils by means of cycles of alternate wetting and drying, and alternate freezing and thawing While our results so far have been rather gratifying, we are not making any rash statements or predictions of the ultimate outcome of our laboratory research When we have reached the stage that we feel we have some sound, well authenticated data or information, we shall be very happy to make it available to the Highway Research Board

SOIL STABILIZATION WITH EMULSIFIED ASPHALT

By C L McKesson

Director of Engineering and Research, American Bitumals Company

The purpose of this discussion is to present to the engineering profession the results of studies in soil stabilization over a period of years in a private laboratory, and of construction practices growing out of these studies, not heretofore published except briefly and partially in a paper presented by the writer at the Annual

Convention of the Association of Highway Officials of the North Atlantic States, held in Baltimore, February, 1935.

The subject of soil stabilization is intriguing and engineers have already constructed many successful projects by the methods herein outlined. The utilization of local materials is the objective of every frugal engineer, because greater improved road mileage at lower costs than now prevail must be attained if our vast highway system is to be built up to the condition demanded by the road users. The utilization as surfacing and base, of soils heretofore regarded as being unsuitable even for subgrade, has in many cases been proven not only feasible but most gratifying in low cost.

Figure 1. The beam supporting the men in this photo is a stabilized sundried adobe brick approximately 5″ in thickness and stabilized by methods herein described. The beam was finally broken under a 1150 lb. dead load applied at the center.

Such construction is not haphazard but must be designed, planned and executed with the same thoughtful and careful technical supervision which is given as a matter of course to more expensive types. If so designed and constructed, it is believed that failures will be even less frequent than in high priced pavements.

Stabilized soil is also available as a base for more expensive types where and if expensive types are economically justified, and by the use of stabilized base it is believed that "base failures" can be largely eliminated and thinner pavements safely laid, the saving more than offsetting the cost of the stabilized base.

Successful projects attesting the soundness of soil stabilization have been built under all of the limits of climatic conditions encountered in the United States and some of the projects have gone through several winters.

Cheap quarry waste, clayey pit gravel and similar inexpensive materials are readily converted into good road materials by the methods described. Good materials are improved by having their cementitious binder rendered relatively immune to loss of cohesion by water absorption.

No method or process is "fool-proof" and generally the less expensive types require more engineering skill and care than expensive ones—if the best results are to be obtained.

One of the questions more commonly asked in connection with soil stabilization is, "How thick should it be?" There is no universally applicable answer to this question, any more than to, "How thick should a gravel surface be?", or for that matter any other type of pavement Depth of stabilization will always depend upon climatic conditions, drainage, subsoil, traffic and all of the other conditions which enter into pavement design

Stabilized bases utilize to the fullest extent the naturally cementitious property of the soil This is strikingly illustrated in Figure 1, where an adobe slab, supported at the ends, is carrying a heavy load

The stability tests hereinafter described indicate that stabilized base or surface might perhaps be called a "plastic-solid" because after long exposure to moisture from the subgrade it still retains stability against displacement under tractional forces such as produce corrugations in bituminous pavements, and sufficient flexural strength to give good load distribution to the subgrade, yet is sufficiently flexible to yield slightly under passing loads without breaking as do rigid types

This paper is divided into Part I, in which theory is discussed, Part II, a description of tests and test methods, Part III, devoted to a discussion of design of stabilized mixes, Part IV, relative efficiency of stabilizers and Part V, construction and construction practices with descriptions of some projects already constructed

PART I THEORY OF STABILIZATION WITH EMULSIFIED ASPHALT

Basic Principles

"The General Theory of Soil Stabilization" is clearly and concisely set out in Page 1 of the Committee's Progress Report (1),[1] hereinafter referred to as the Report. For convenience brief quotations from the Report will be included where believed necessary to make this paper complete and readily understandable Soil stabilization with emulsified asphalt will be discussed in the light of the principles outlined in the Report, and of discoveries made in our own laboratories over a period of years, confirmed by many successful soil stabilization projects which were constructed under specifications we have suggested based on research studies

Clay as a binder is capable of developing great cohesive strength It is pointed out in the Report (Page 10) that this can be 19 times as great (in compression) as the strength of an equal proportion of portland cement binder "Adhesives that will furnish films more substantial than moisture alone by permanently destroying the clay and colloidal properties responsible for detrimental volume change in soil mixtures" (Page 11) are necessary for efficient stabilization

Asphalt is a binder known to have adhesiveness and to be a satisfactory cementing medium The Report says, "For a given adhesive and material the thinnest joint gives the greatest strength" (Page 13)

These three fundamental conceptions are the bases of the theory of soil stabilization with emulsified asphalt

Particle Size

Clay particles are extremely small in size, all smaller than 0 005 mm ($\frac{1}{5000}$ in) diameter and a considerable portion smaller than 0 001 mm. The writer can conceive of no other way to produce a thin film of pure asphalt on such minute particles than by the use of asphalt in an emulsion properly manufactured for soil stabilization

[1] Numbers in parentheses refer to list of references at end

Emulsified Asphalt as a Stabilizer

In emulsified asphalt the particles of asphalt are as minute as the clay particles They are carried in water as a suspending medium In order to disperse the asphalt particles uniformly among the clay particles, it is necessary to separate the clay particles with water films By adding the emulsified asphalt to this water, the asphalt particles are uniformly distributed As the soil dries the water films decrease in thickness and the tension of the films increases The Committee's Report tells us that the density of such moisture films can be as great as if under a pressure 10,000 atmospheres The asphalt particles are thus brought into contact with the soil particles under great pressure, and are spread in films of almost unimaginable thinness A clay having an average particle size of 0 001 mm would have a minimum surface area of 13,000 sq ft per lb , assuming the clay particles to be spheres Usually a pound of such clay can be stabilized with emulsified asphalt containing 5 cu in of pure asphalt This indicates a film thickness of about 0 0001 mm ($\frac{1}{250{,}000}$ in)

Undoubtedly a portion of the asphalt is absorbed by the clay particles under the great pressures Some idea of the intensity of these film pressures can be understood from the fact that usually only about one-half of the asphalt can be subsequently removed with carbon tetrachloride

It has been found by field and laboratory work that all types of soil can be stabilized with emulsified asphalt, except those containing considerable amounts of mineral salts, *provided sufficient clay is present to act as a binding medium* It has usually been found that grading above the No 200 sieve is unimportant except for economic considerations Soils, to be suitable for stabilization, should contain a minimum of 20 per cent passing the No 200 sieve, by the wet screening method, and should include at least 5 per cent of clay finer than 0 001 mm , in order to secure necessary structural strength due to the cohesive value of the clay

The quantity of emulsified asphalt stabilizer required increases as the particle sizes decrease When soils are found to have high percentages of material finer than No 200 sieve, and where sand, gravel, quarry waste or other granular material is cheap, it is frequently found economical to blend any one of these materials with the soil to reduce the percentage of material finer than No 200 sieve, and thus reduce the amount of stabilizer The grading of the granular material added does not appear to be critical

The quantity of emulsified asphalt required stabilization can be determined and checked by laboratory tests These tests consist of hydrometer analyses for determination of particle size, the absorption test for determining resistance of treated and untreated samples to moisture from capillarity and a stability test made on the specimens after the absorption test

Mechanics of Soil Stability

In Figure 2 is shown a conception of the mechanics of soil stability and the relation of the stability test—hereinafter described—to the measurement of stability in soil

The conception is made easier if we think of all surfacings (and subgrades) as plastics having varying degrees of resistance to displacement A wet clay is probably the best example of maximum plasticity, bituminous concretes of medium plasticity and the so-called rigid pavement types of minimum plasticity.

Figure 2A shows stress concentration which occurs when a load is applied to a surface of indefinite area, as demonstrated by Vokac (2) and Housel (3). Lines of force are at right angles to the tangent of the stress bands at any point. The direction movement tendency is indicated by arrows.

Figure 2B shows typical deformation which occurs in a plastic surfacing which has not enough internal friction and/or cohesion to withstand the stresses imposed on it by the load L.

Figure 2C shows a surfacing in which cohesion and/or frictional resistance is sufficient to prevent shear and the deformation consists of slight depression at (a) under the load and a slight upward bending of the slab at (b) above the normal level (c) some distance from the load—this, of course, assuming a non-rigid subgrade.

Figure 2D is a modified form of the Hubbard-Fields stability or shear test devised by Watts[2] for measuring the resistance of soils, stabilized or unstabilized, to displacement under load.

The possible stress bands as indicated may, without too great a stretch of imagination, be related to those shown in Figure 2A, lines of force being at right angles to the tangent of the stress bands at any point. The horizontal forces are, of course, resisted by the steel shell of the cylinder and the movement of the soil finally occurs through the orifice. In this test the direction of flow of the plastic is downward instead of upward as in Figure 2A. This is indicated by arrows. The resistance to displacement, whether due to frictional resistance of the particles or actual cementitious films, cannot fail to bear a relation to their performance in a surfacing of comparatively large area, as shown in Figure 2A. This can be easily appreciated by considering that clay, saturated by capillarity, usually has a value for L of less than 15 lb. per sq. in. in this test and the same soil, even when not fully stabilized to resist capillarity,

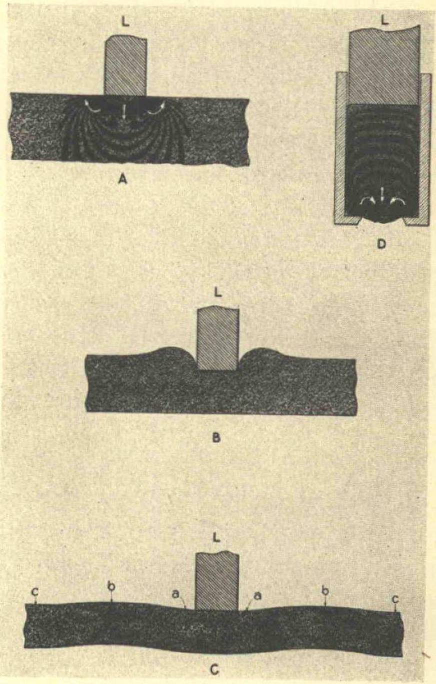


Figure 2. Illustrating Mechanics of Soil Stability

will show a resistance (with the same moisture content) of 300 to 600 lb. per sq. in.

Fully and properly stabilized, the same soil shows great resistance to capillarity and after a month of continuous exposure to free water at the under side, will usually contain only 10 to 20 per cent of the moisture found in untreated soil and a resistance to displacement (in the bottom

[2] V. E. Watts, Research Engineer, American Bitumuls Company, San Francisco, California.

half inch) of 3,000 lb per sq in or more For specific examples see Table III

PART II TEST METHODS

The test methods we have used in soil stabilization are simple. Particle size is of primary importance in designing stabilized mixes and for this the hydrometer method of particle size determination is used, supplemented by screens and sieves for determining percentages of larger particles The hydrometer analyses method has been fully described by Hogentogler and Willis (4)

The determination of the liquid limit and plastic limit of soils is of interest and value in arriving at the amount of water required for thorough mixing of the emulsified asphalt stabilizer These methods are also described by Hogentogler and Willis in the same article (4) The determination of their other soil constants, such as moisture equivalent, shrinkage, etc , appears unnecessary in designing stabilized mixes

In testing stabilized soils absorption by capillarity, and stability after absorption are of utmost importance and special apparatus has been developed for these tests which will be described in detail in the hope that other laboratories will adopt them to the end that test data from different laboratories may be compared and correlated

Preparation of Samples

Samples as received are dried, broken up and passed through a ¼-in. screen The material passing is quartered, and plastic limit, liquid limit, and particle size determinations are made Mixes are made using stabilizer based on the formula given herein, or with various arbitrary percentages in instances where "cut and try" methods are used The soil is then mixed with diluted stabilizer, or first with water and then with stabilizer, until the asphalt is uniformly distributed and the mass is at a consistency between the plastic and liquid limits

The mixed soil is allowed to dry to a stiff moulding consistency and is tamped into 2-in brass moulds 4 in long After further drying, but while still slightly damp, it is compressed—usually under a load of 1,000 lb per sq in —and is then pressed out of the mould and placed in a drying oven or cabinet and maintained at about 140°F until at a constant weight Mixing may be done by hand or with any suitable equipment and the details of the tamping and compacting methods are unimportant because the ultimate compaction and density are obtained by shrinkage during the drying operation

Any method of preparing samples may be employed which will insure uniform, homogeneous specimens, with the asphalt uniformly distributed *Drying*, however is important—both in laboratory work and in field construction The extremely thin films produced in drying are necessary to bring the asphalt into and around the soil particles It has been shown that the efficiency of stabilization is increased as much as 50 per cent by thorough drying In the field, drying is obtained through the combined action of warmth and wind,—and because drying is important, stabilized material should *never be topped off with a wearing surface until thoroughly dried to the bottom*

Absorption Test

The specimens prepared and dried are then ready for the capillarity absorption test

The absorption test is made in a closed cabinet containing pans filled first with a layer of standard Ottawa sand and then a layer of diatomaceous earth covered with blotting paper, with water-feeding apparatus which keeps the water level exactly at the under side of the blotting paper This apparatus is shown in detail in Figure 3

Although the humidity within the cabinet remains very high due to the continuous evaporation of water, the individual specimens are wrapped in cellophane on the sides and covered on top with foil or shallow aluminum cups slightly larger in diameter than the specimen This prevents the escape of any water taken up by capillarity, and is believed to approximate the exposure of any two-inch cylindrical portion of stabilized soil in a pavement where it is exposed to water at the under side, where evaporation is prevented by the surrounding stabilized soil, and where surface evaporation is restrained by surfacing

Because it is not usual or good construction practice to permit ground water to be maintained at the bottom of the pavement, this severe exposure may be considered as an accelerated test

Specimens are usually removed for daily weighings and the period of test may be 7 to 90 days It will be found that the absorption decreases rapidly after the first day, because the capillarity of stabilized soil is very low

Great care must be observed in removing specimens from the blotter to prevent loss of weight in the specimen due to portions adhering to the blotter This is particularly true in the untreated specimens which take up water quickly and become soft and non-cohesive Any portion of the specimen remaining on the blotter must be removed and replaced on the bottom of the specimen before each weighing The necessity for doing this can be avoided by placing a disc of saturated filter paper under the specimen when it is first placed on the blotter and then weighing the specimen with the filter paper each time The weight of the saturated filter paper is of course added to the initial weight of the dry specimen, which weight also includes the cellophane wrapper and the cover

Tests by immersing specimens in water are misleading and not recommended In such tests the absorption depends on the size of voids between particles, water entering from the sides and top under

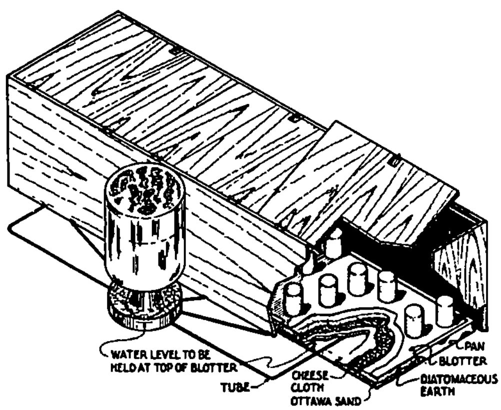


Figure 3. Absorption Test Apparatus

hydrostatic pressure Granular soils, although actually more stable, make a poorer showing when submerged than do denser and finer soils with minute voids Under service conditions only water from capillarity is encountered and the tests should, therefore, be made for absorption by capillarity

Stability Test

Stability against displacement is the objective in stabilization and consequently the stability test is the most important of all tests in stabilization work Absorption is of interest because we know that increases in the thickness of the water films result in decreases in stability and in reduced cohesive strength In Table I of the Committee's Report (1) cohesion for liquid clay is given as 100 lb , and for very stiff clay at 2,000 lb per sq ft

Stability tests are made on the specimens which have been subjected to the absorption tests As the bottom of the specimen, adjacent to the free moisture in the pan, (subgrade) has had the most

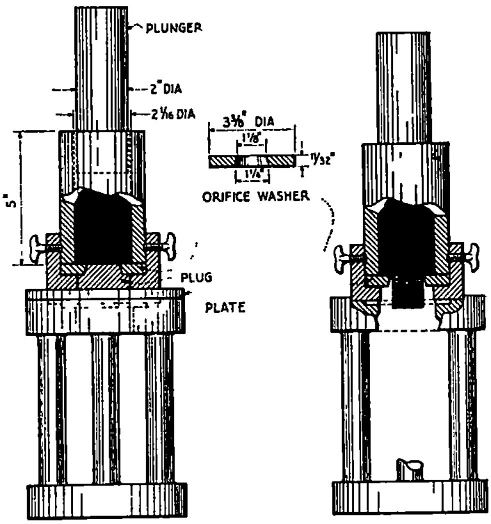


Figure 4 Stability Test Apparatus

severe exposure, stability is determined for successive ½-in strata, beginning at the bottom

For purposes of determining the efficiency of the stabilization, treated and untreated samples are always run simultaneously for absorption and afterward for stability Usually the untreated specimens take up their full moisture content within 24 to 48 hours In the case of finer soils the stability of the bottom ½-in is usually nearly zero and there is little appreciable increase in the upper layers or strata

With stabilized soils the bottom layer always contains some moisture, but usually the stability of the bottom ½-in is very high and successive strata increase greatly in stability

The stability test apparatus consists of a heavy steel cylinder $2\frac{1}{16}$ in in inside diameter and 4 in or more high It is provided with a tool steel orifice plate at the bottom, the orifice having an area of exactly one square inch and beveled downward from the cutting edge A plunger 2 in in diameter and a supporting frame complete the apparatus, which is shown in detail in Figure 4

To make the test the specimen is placed in the cylinder with the orifice plugged The equipment is placed in a compression machine and a total load of approximately three thousand pounds applied to press the specimen down into contact with the sides of the cylinder and the orifice plate The plug is then removed, marks are made at ½-in intervals on the plunger and the load applied at a rate sufficient to move the plunger ½ in per min The load is read as each ½-in mark is reached, and consequently at the completion of the extrusion of each ½-inch stratum

The maximum load applied in making the stability test should usually be about 25,000 pounds (approximately 8,000 pounds per square inch) but if desired this may be increased to about 40,000 as the apparatus is designed to withstand this total load The test is intended to measure resistance to displacement by plastic flow, and a specimen which resists displacement under a load of 8,000 lb per sq in is virtually a solid and may be so regarded Test values beyond this limit are not usually significant as an index of plasticity

In the earlier studies and before the

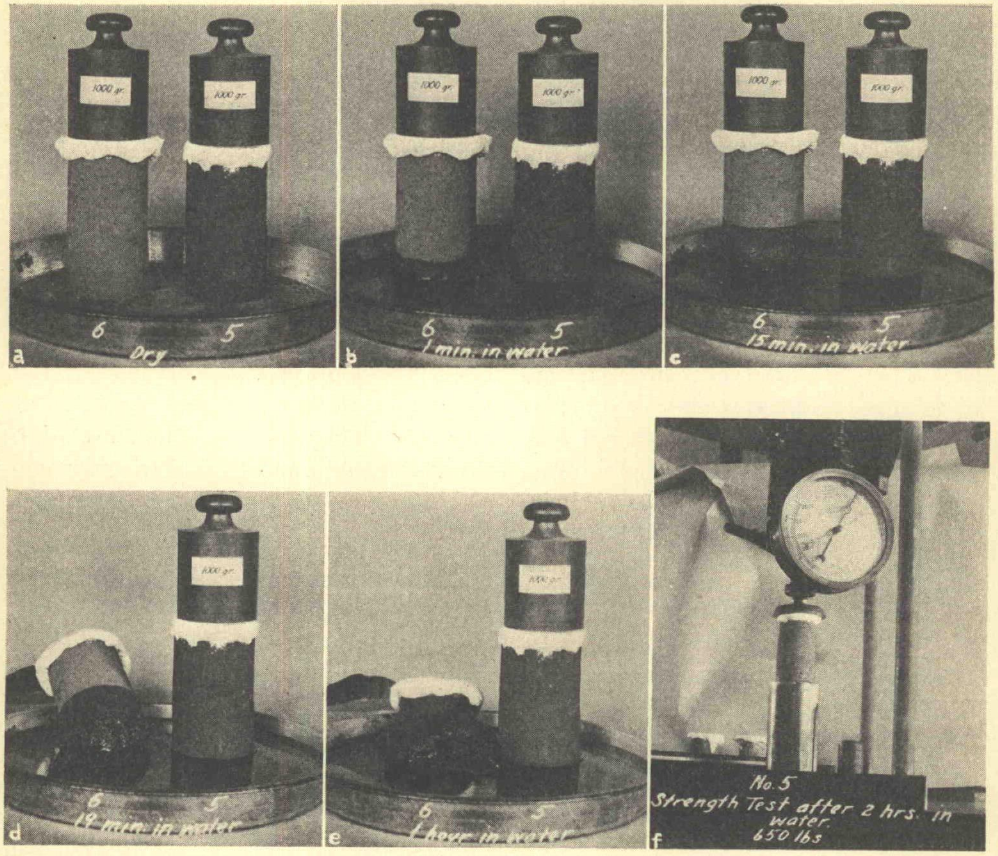


Figure 5

a. Stabilized and unstabilized specimens at the start of the test. No. 5 is stabilized and No. 6 unstabilized.

b. One minute after water was placed in the pan. Note the capillary rise of water in the untreated Specimen No. 6.

c. After 15 minutes water has risen about ⅓ the height in Specimen No. 6. No rise in the stabilized Specimen No. 5.

d. After 19 minutes Specimen No. 6 collapsed under the 1000-gram load.

e. After one hour the untreated Specimen No. 6 is a pile of mud. The stabilized specimen shows no signs of capillary rise of water.

f. After 2 hours the stabilized specimen was removed and tested for compressive strength. A 650-pound load was required to cause failure, just the same as with a duplicate specimen not subjected to the water test.

present absorption and stability tests were developed to measure quantitatively the efficiency of stabilization, moulded and dried specimens were placed in shallow pans containing about $\frac{1}{4}$ in. of water. The time was noted in which untreated specimens collapsed under a weight of 1,000 grams. Treated specimens were allowed to remain in the pans with the lower ends immersed in water for a few days and were then tested for compressive strength and compared with the compressive strength of treated specimens not exposed to water absorption The results of such a test shown in Figure 5, illustrate strikingly the effect of stabilization The soil used in these specimens consisted of 20 per cent yellow clay soil blended with 80 per cent clean concrete sand There are two specimens involved, one stabilized and the other unstabilized The stabilized specimen, numbered 5 in Figure 5, contained 2 per cent of emulsified asphalt stabilizer (1 1 per cent asphalt) The unstabilized specimen is numbered 6 in Figure 5 Both specimens were mixed, compacted and dried under identical conditions The results of the tests are fully explained in the comments accompanying the illustrations in Figure 5

The clay soil portion of the blend used in the test illustrated in Figure 5 had the grading and constants shown in Table I Engineers, in looking over the blend detail, will be struck by the thought that the blend appears to be good subgrade material, but the test results clearly demonstrate the need for stabilization

Typical results of tests by the present absorption and stability methods appear in Table III and elsewhere in this paper.

PART III DESIGN OF STABILIZED BASES

Selection of Soil

While all soils, except those containing considerable amounts of mineral salts (alkali soils), are susceptible to stabilization, the quantity of stabilizer may frequently be reduced and economy effected by adding sand, gravel, quarry waste or any other inexpensive granular material Studies should first be made to determine the cost and efficiency of the stabilization of the natural soil and then of blends, if granular material is available There is usually no economy in adding granular material if the soil does not show more than 30 per cent passing the No 200 sieve (by the wet screening method) Where more fines are present, granular material may be added to reduce the total percentage finer than the No 200 sieve in the blend to not less than 20 or 25 per cent. Inasmuch as the granular material coarser than No 200 sieve is ignored in determining stabilizer requirements, costs may be estimated on the amount of the sta-

TABLE I

YELLOW CLAY

Mechanical Analysis			Soil Constants	
Passing Sieve	Mm	Per cent		
No 10		100	Liquid Limit	46 0
40		98	Plastic Limit	28 4
80		96	Plasticity Index	17 6
200	0 074	90	Field Moisture Equivalent	33 6
	0 05	80	Lineal Shrinkage	7 2
	0 005	45	Shrinkage Limit	13 0
	0 002	33	Shrinkage Ratio	1 92
	0 001	25	Specific Gravity	2 57

bilizer required for the soil finer than No 200 sieve used in the blend

With the yellow clay soil described in Table I and used in the tests shown in Figure 5, 13 per cent of stabilizer would have been required By blending with 80 per cent of clean coarse sand (i e , in a 4 to 1 ratio) the stabilizer requirement for the blend should have been one-fifth of that for the soil alone, or 2 6 per cent Actually, only 2 per cent was used in the tests, but research since that time indicates that 3 per cent of stabilizer should be the minimum for any soil or soil blend to give the best results

An example will be given to show actual economy effected in blending A heavy black adobe soil was available which would have required 13 per cent stabilizer, or 6 gal per sq yd for a 4-in thickness Assuming stabilizer to cost 11 cents per gallon, delivered and applied, the cost for stabilizer would have been 66 cents per square yard Quarry waste was available at 80 cents per ton, delivered A blend of three parts of quarry waste and one part soil reduced the cost for stabilizer to $16\frac{1}{2}$ cents per square yard, and the quarry waste at 80 cents per ton cost 12 cents per square yard, making a total cost for stabilizer and quarry waste of $28\frac{1}{2}$ cents,—a saving of $31\frac{1}{2}$ cents per square yard

TABLE II

STABILIZER REQUIREMENTS

Soil Identification and Lab No	Per cent Pass 200 Mesh	a	b	c	Per cent Stabilizer based on 15% × 200M	Value for K	Per cent Stabilizer using formula K (0 05a + 0 1b + 0 35c)	Per cent Stabilizer Required Based on Stability and Absorption Tests*
		Per cent Passing 200 and retained 0 005 mm	Per cent Passing 0 005 mm and retained 0 001 mm	Per cent Passing 0 001 mm				
2-221 Ariz	71 0	39 0	12 0	20 0	10 70	0 5	5 07	5 00
2-241-11 M F Sandy	27 4	17 4	5 0	5 0	4 10	1 0	3 12	3 00
2-320B† M F Sandy	35 0	22 0	5 0	8 0	5 25	1 0	4 40	4 00
2-241-4 M F Adobe	91 9	41 4	17 5	33 0	13 80	1 0	15 37	14 00
2-320A† M F Adobe	84 0	31 0	22 0	31 0	12 60	1 0	14 60	13 50
2-334 Sandy (Colo)	62 0	42 0	6 0	14 0	9 30	0 7	5 32	5 00
Oakland Adobe	90 0	39 0	21 0	30 0	13 50	0 64	9 40	9 00
S F Soil	54 9	27 9	9 0	18 0	8 25	1 0	8 60	8 30

* A series of tests with varying amounts of Stabilizer indicated these percentages to be the minimum for satisfactory stability

† See Absorption and Stability Tests in Table III

Quantity of Stabilizer Required

Laboratory research and construction have demonstrated that the quantity of stabilizer required can be determined by an empirical formula

$$S = K\ (0\ 05a \text{ plus } 0\ 1b \text{ plus } 0\ 35c)$$

in which S = percentage of stabilizer required, a = percentage of soil passing a No 200 sieve (wet method) and coarser than 0 005 mm , b = percentage of soil between 0 005 mm and 0 001 mm in particle size, c = colloidal clay finer than 0 001 mm particle size, and K = a factor which is constant for any particular type of soil to be treated (For most soils K = 1)

The value of K, which changes in the above formula when the soil type changes, can be determined by trial using the stability and absorption tests to check the efficiency with different quantities of stabilizer, or it can be determined by a simple modified hydrometer test, the details of which are not yet in form for publication While the value for K varies with different soil types, it has been found to remain constant for all soils of the same origin, regardless of grading Table II shows typical soils and their stabilizer requirements Table IV shows the "constants" for three of these soils and serves to illustrate that the amount of stabilizer required is not a function of these soil constants The soil constants in columns 1 and 2 are substantially identical but materially different amounts of stabilizer are required

An approximate method for determining the required amount of emulsified asphalt stabilizer consists of determining the percentage of material which can be washed through a No 200 sieve and basing the amount of stabilizer on this fraction of the soil Frequently an amount of stabilizer equal to 15 per cent of the weight of the No 200 sieve material will be found satisfactory With extremely difficult soils, 20 per cent of the No 200 sieve material may sometimes be required, and with favorable soils, satisfactory stabilization may at times be had with 10 per cent of stabilizer, based on the weight of the No 200 sieve material

Unstabilized soil after a few hours in the absorption test usually shows its maximum absorption and little or no resistance in the stability test The treated samples of the same soil usually show a resistance of 3,000 to 15,000 lb per sq in in the bottom ½-in layer of the specimen, after 7 days in the accelerated absorption test

TABLE III

ADOBE SOIL

Lab No 2-320A

Capillary Absorption Tests

Days	Untreated % Water* Absorbed	Treated with 12 9% Emulsified Asphalt Stabilizer % Water* Absorbed
1	14 0	1 6
2	20 5	2 5
7	30 0	4 3

Stability Tests

Strata	After 7 days Absorption Untreated	After 7 days Absorption Treated
	Load Lbs Sq In	*Load Lbs Sq In*
Bottom		
½"	0	4,900
2nd ½"	0	8,300
3rd ½"	0	18,800
4th ½"	16	25,000

SANDY SOIL

Lab No 2-320B

Capillary Absorption Tests

Days	Untreated % Water* Absorbed	Treated with 4 2% Emulsified Asphalt Stabilizer % Water* Absorbed
1	10 5	0 2
3	11 0	0 5
5	11 5	0 7
7	11 5	0 78
13		1 1

Stability Tests

Strata	After 7 days Absorption Untreated	After 13 days Absorption Treated
	Load Lbs Sq In	*Load Lbs Sq In*
Bottom		
½"	2500	14,000
2nd ½"	2500	17,100
3rd ½"	3150	17,100
4th ½"	4400	17,100

* Absorption based on weight of specimen as previously dried at 140°F

In Table III are shown typical results of absorption and stability tests The two soils selected for this study were a sandy soil and a heavy black clay known in the West as "adobe" and in some other sections as "gumbo" The two soils occurred close together on the same project and are probably of the same origin It will be noted from Table II that K = 1 for both of them Table II also shows the grading of the two samples and the computed and actual stabilizer requirements

The adobe soil, untreated, showed an absorption in two days of 20 5 per cent and 30 0 per cent in 7 days (Table III) This was reduced by the stabilization to 4 3 per cent in 7 days The stability of the untreated specimen ranged from zero in the lower stratum to 16 lb in the fourth stratum, 2 in from the bottom The stabilized specimen of the same soil showed 4,900 lb per sq in resistance to displacement in the lower stratum and 25,000 lb per sq in 2 in above the bottom

The sandy soil, untreated, absorbed 10 5 per cent of water in one day and a total of 11 5 per cent in 7 days By stabilization the absorption in 13 days was reduced to 1 1 per cent The untreated material, after the indicated absorption, shows a resistance to displacement of 2,500 lb per sq in but by stabilization this resistance was increased to 14,000 lb per sq in —in other words, the soil was changed from a plastic to substantially a solid While this particular soil might be adequate in untreated form as a subgrade material it would be unsuitable (without stabilization) as a base for an economically thin wearing surface

Both of the materials as treated are suitable as a base and require only a light wearing surface to protect them from the abrasive action of traffic

The tests shown in Table III are typical of results on many hundreds of soils from all parts of the world which have been studied in our laboratory

It should be borne in mind that in studying the stability results any value above 8,000 lb per sq in indicates the specimen to be more nearly a solid than a plastic substance The significance and importance of the stability test for measuring resistance to displacement is obvious after a study of Figure 2 of this paper, or of Figure 2 of the Report (1) The

TABLE IV

SOIL CONSTANTS AND STABILIZER REQUIREMENTS FOR THREE TYPICAL SOILS

	(1) Oakland Adobe	(2) No 2–241–4 M F Adobe	(3) No 2–241–11 M F Sandy
Liquid Limit	59 0	58 5	—
Plastic Limit	26 6	25 0	—
Plasticity Index	32 4	33 5	—
Field Moisture Equivalent	36 9	33 0	15 1
Lineal Shrinkage	7 5	8 5	0 4
Shrinkage Limit	22 4	12 4	14 4
Shrinkage Ratio	2 15	2 19	1 86
Specific Gravity 77°/77°F	2 35	2 63	2 49
Stabilizer Required	9 0%	14 0%	3 0%

For gradings see Table II

test clearly shows the relative resistance to displacement of stabilized and unstabilized soils It also shows relative values of various stabilizers and of variations in quantity of stabilizer An excess of stabilizer may be almost as detrimental to stability as an insufficient amount and it is important that a reasonably close approach be made to the optimum quantity The optimum quantity is far below the minimum used in bituminous mixes where asphalt is relied upon as the binding medium.

PART IV. EFFICIENCY OF EMULSIFIED ASPHALT STABILIZERS

In the foregoing discussion and tables the quantity of emulsified asphalt stabilizer indicated as necessary to accomplish stabilization is based on the use of a stabilizer of maximum efficiency

The soap types of emulsified asphalt have been used in road building and maintenance for about 25 years Quick-setting emulsified asphalts have come into extensive use in the United States since 1927 Neither of these products are suitable for use in soil stabilization The A. S T. M. Tentative Standard Test Methods and also Specifications for Emulsified Asphalts are all written around the above types of emulsions

To accomplish stabilization the asphalt must be uniformly dispersed throughout the mass of minute soil particles by mixing, and it is obviously necessary that an emulsified asphalt be used which is stable against breakdown during the mixing operation, even in the presence of electrolytes usually present in the soil The demulsibility test (A S T M -D-244T) using 50 mm of 0 1 normal $CaCl_2$ solution, is therefore applicable, but with the requirement that no appreciable break shall be allowable (2 per cent maximum demulsibility should be the limit) A further test, referred to as the cement mixing test, which indicates mixing properties in the presence of electrolytes and of powdered materials is also necessary. This test is made as follows.

Cement Mixing Test

Not more than 5 per cent of the stabilizer shall be broken when subjected to the following mixing test

Fifty grams of portland cement previously sieved through a No 80 sieve shall be placed in a tin having a capacity of approximately 500 cu cm One hundred cubic centimeters of the stabilizer to be tested shall be poured on the cement and stirred with a ½-in steel rod 60 times during one minute One hundred fifty cubic centimeters of distilled water shall then be added and stirring continued for 3 min (at the above rate) Ingredients and apparatus shall be maintained at a temperature of approximately 77°F during mixing Pour the mixture through a tared 14-mesh iron wire sieve, rinsing until wash water is clear Place screen in a tared shallow pan, heat until dry and weigh The weight, in grams, of the material retained on the screen and in the pan is the percentage broken

Quick drying is essential if the asphalt is to remain uniformly distributed while the water is being drawn out of the soil by evaporation and capillarity A dehydration test on the stabilizer has, therefore, been found necessary and is described as follows:

Dehydration at 100°F

The dehydration loss in 96 hours shall not be less than 0 60 when the stabilizer is subjected to the following test

One hundred grams of the stabilizer to be tested shall be placed in a tared pyrex dish, 77 mm in inside diameter by 40 mm in height, having a flat bottom and vertical sides The dish shall be placed in the center of a shallow pan about 5 in in diameter and 50 grams of granular anhydrous calcium chloride shall be spread in the pan so that it surrounds the dish containing the emulsion The entire unit shall then be placed in a constant temperature oven set at 100°F At the end of exactly 96 hours, during which time the sample shall not be disturbed by stirring or excessive movement, the loss of weight of the emulsion shall be determined The dehydration loss shall be expressed as the ratio of loss in this test in 96 hours to loss in the test for "Residue at 163°C "

Soap in any appreciable amount has been found to be detrimental in an emulsified asphalt stabilizer, even though the emulsion may meet the physical tests above specified Tests indicate that 0 75 per cent should be the maximum allowable amount of saponifiable substances (Abraham Method) including saponifiable substances naturally occurring in the asphalt

There are two courses open to a prospective user for the selection of an efficient emulsified asphalt stabilizer,—one is the adoption of a product which has been successfully used over a period of years, making the tests described above and the usual A S T M Test Methods

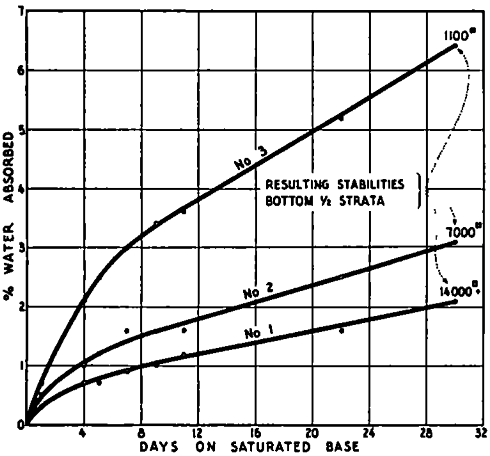


Figure 6. Absorption-Stability Tests on Three Commercial Mixing Emulsions. Soil, Quantity of Emulsion, and Test Conditions Identical. For Physical Characteristics of Emulsions See Table V.

to determine viscosity, percentage of residue, settlement and miscibility, for purposes of identification and check The other is to run absorption and stability tests in addition to the test described, on the stabilizer proposed for use, including at least one of known suitability, preferably using the actual soil to be stabilized. Fortunately this is not burdensome to any road-building department having a good laboratory

The relative efficiency of stabilizers having similar physical properties when determined by the present A S T M. Tentative Test Methods is shown in Figure 6 and in Table V The emulsions involved are all commercial products regularly marketed for use in fine aggre-

TABLE V

PHYSICAL PROPERTIES OF EMULSIFIED ASPHALTS USED AS STABILIZERS*

See Figure 5 for Relative Efficiencies

	Emulsion No 1	Emulsion No 2	Emulsion No 3
Residue	57 6%	60 2%	58 0%
Viscosity	46 0	34 7	19 4
Demulsibility (50 cc)	0 0	5 0	0 0
Cement Test	Passes	Passes	Fails
Dehydration (96 hrs)	0 655	0 281	0 338
pH	11 5	11 6	12 0
Settlement 5 days	—	—	—
Saponifiable (Abraham)	0 41	2 41	1 48

* These are commercial emulsions produced by three manufacturers and sampled from shipments to customers

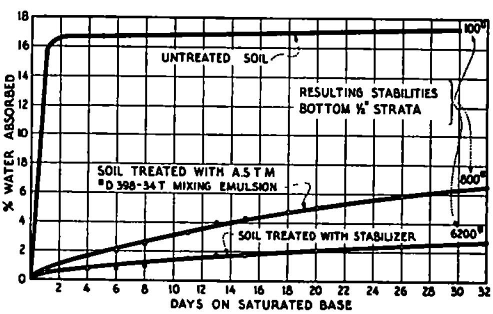


Figure 7. Efficiency of Stabilizer in Comparison With a Standard Emulsion Designed for Other Mixing Work.

gate mixes and meeting test requirements much more rigid than those specified in the A S T M Tentative Standard Specifications (1934) for Mixing Emulsions (Intended for Coarse Aggregate Mixes)

Figure 7 and Table VI show a similar

comparison in stabilization efficiency of an emulsified asphalt especially designed for the purpose (conforming with the requirements recommended in this paper) and an emulsified asphalt meeting the A S T M Tentative Standard Specifications for Emulsified Asphalt for Coarse Aggregate Mixes,—D398-34T (Identical with American Association of State Highway Officials Specifications M-48)

It will be noted that the ordinary mixing emulsion (A S T M D398-34T) is about one-third as efficient as the designed stabilizer, as indicated by capillarity absorption test, and less than one-seventh as efficient when measured by the stability test Table VI also shows the reduced capillarity resulting from proper stabilization treatment,—the untreated sample absorbing 15 6 per cent moisture in 4 days and 1 7 per cent more in the following 28 days, making a total of 17 3 per cent, and the properly stabilized sample showing a steadily diminishing rate of absorption, with a total absorption in 32 days of only 2 7 per cent

TABLE VI

EFFICIENCY OF STABILIZER IN COMPARISON WITH A STANDARD EMULSION DESIGNED FOR OTHER MIXING WORK

Days	Untreated Soil % Water Absorbed	Treated with Emulsified Asphalt A S T M D 398-34T Coarse Agg Mixing Emulsion % Water Absorbed	Treated with Stabilizer % Water Absorbed
1	15 6	0 7	0 4
4	16 6	1 6	0 7
6	16 8	2 0	0 8
8	16 8	2 5	1 0
11	16 9	3 3	1 5
13	16 9	4 0	1 7
15	17 0	4 3	1 7
18	17 0	4 8	2 0
20	17 1	5 1	2 1
26	17 2	5 9	2 4
32	17 3	6 5	2 7

Stability Test—At 32 Days

Strata	Untreated Soil		Treated with Emulsified Asphalt A S T M D 398-34T Coarse Agg Mixing Emulsion		Treated with Stabilizer	
	Total Load Resistance in pounds	% Water in Stratum	Total Load Resistance in pounds	% Water in Stratum	Total Load Resistance in pounds	% Water in Stratum
Bottom ½″	100	18 6	800	15 1	6200	9 2
2nd ½″	100	18 2	1050	12 8	12,200	6 0
3rd ½″	100	19 6	1800	11 7	14,000+*	4 9
4th ½″	100	20 2	3500	10 0	14,000+*	—

* 14,000 lbs was the limit of the apparatus used in these tests
All samples from same soil Treated samples contained equal asphalt content

PART V CONSTRUCTION

Early Stabilization Projects

Emulsified asphalt stabilization projects have been constructed in many States, including Maryland, New Hampshire, Massachusetts, Vermont, Ohio, New Jersey, Virginia, Mississippi, Arkansas, Georgia, California, Oregon and Nevada The earliest of these projects was Beck Road in Alameda County, California, constructed in 1928 On this project 1 to 1 5 in of gravel remaining on the roadway from previous surfacing operations was scarified and mixed with about equal parts of heavy black clay (adobe) subsoil Water was then added and emulsified asphalt was mixed in with spring-tooth harrows and blade graders Nothing was known at that time regarding the comparative effectiveness of emulsified asphalts as stabilizers, or regarding the design of stabilized mixtures as described in the earlier parts of this paper and as now practiced on stabilization projects Those responsible for this early job, and all the engineers who saw the construction under way, had many misgivings regarding its ultimate success Much to their surprise the project was entirely successful and has now carried traffic for seven years with very low maintenance costs There have been no base failures and the money expended for maintenance has consisted principally of a light surface treatment constructed two years later A paper describing this project was delivered by Mr C H Thomas (5), one of the engineers in charge of the work, a few months after its completion

The following year, in 1929, a 4-in stabilized soil landing area was constructed at Clover Field Airport at Santa Monica, California, using substantially the same methods as were developed the previous year This project was also successful and is still in service

The next project, and the most important up to that time was the stabilization of runways at the Glenn Martin Airport in Baltimore, Maryland, in September, 1930 On this project 4 in of yellow clay soil which had no supporting strength in wet weather was stabilized with emulsified asphalt, and was outstandingly successful This stabilized base was used without surfacing for two or three years and now serves as a base for a bituminous wearing surface The success of this project stimulated the research studies described in this paper

On the Glenn Martin Airport work 4 gal of emulsified asphalt were used per square yard of 4-in thickness regardless of changes in soil grading or soil constants Analyses of the soil made since that time show variations in grading which would have justified variations in the quantity of emulsified asphalt, and the result would have been greater efficiency and lower costs The quantity of water used on these earlier jobs was varied as appeared necessary to obtain a plastic mixture It is notable that on the Glenn Martin work heavy rainfall during construction inundated the area and although operations were delayed, the stabilized soil mix was not damaged

The construction equipment and mix methods used on the Glenn Martin project were substantially the same as those used on some of the recent projects, and will be hereinafter described

On all of the projects constructed prior to 1934 the emulsified asphalt used as a stabilizer was far less efficient than that now recommended A knowledge of the fundamental principles has resulted in the development of a much more efficient stabilizer It is believed that for all practical purposes the elements of uncertainty have been removed and that efficiently designed soil stabilization projects of uniform quality and low costs can now supersede the "rule of thumb" methods previously used

Construction Methods

Construction methods and equipment used in soil stabilization work with emulsified asphalt do not differ greatly from those used in other types of construction in which bituminous binders are used The only outstanding difference is that in soil stabilization work considerable quantities of water are required to wet the soil and to dilute the stabilizer The following methods have been and may be used.

1 Hand mixing followed by compaction obtained with a "pugging" or tamping roller of the "sheep's-foot" type
2 Mixing in place with discs, spring-tooth harrows and blade graders
3 Mixing in place with motorized road mixers,—with results approximating those obtained with a pug mill
4 Pre-mixing at a central plant either at the project or at the source of supply when quarry waste or similar material is used

Hand Mixing

No large projects have yet been constructed in the United States in which hand mixing was employed, but the use of hand mixing is now contemplated on a number of W P A projects in which it is believed necessary to utilize the maximum amount of labor

Stabilization as hereinbefore described is also being applied to the manufacture of sun-dried adobe brick for building construction Usually hand mixing is employed in this type of work

Hand mixing methods have been employed in India and the Orient where coolie labor is inexpensive and equipment is scarce

On a project described by Brigadier Haswell (6) the soils were first carefully and intelligently tested by simple methods to determine the quantity of emulsified asphalt stabilizer required The soil was then loosened with hand picks, laid out in squares each with a known stabilizer requirement,—water was applied with a hose, and the emulsified asphalt was distributed from drums Mixing was accomplished with the use of hand hoes and also by having the coolies tramp in it with bare feet This was followed by "pugging" with a hand operated roller, resembling on a small scale the tamping rollers used in this country After mixing had been satisfactorily accomplished the surface was leveled by hand followed by dragging with plank floats During the drying period shrinkage cracks occurred but these were closed by continuous rolling first with a light and then with a heavy roller These interesting construction methods employed by Brigadier Haswell are illustrated in Figure 8

The most important feature of this project, as will be fully appreciated by those who study the printed report referred to in the footnote, is the thoroughness with which the work was planned and the care taken to investigate the soils and to determine the proper bituminous content The project is reported to have been entirely successful in providing a satisfactory landing area for heavy military planes, and to have been unaffected by torrential rainfall following its completion

Mixing in Place Using Harrows, Discs and Blade Graders

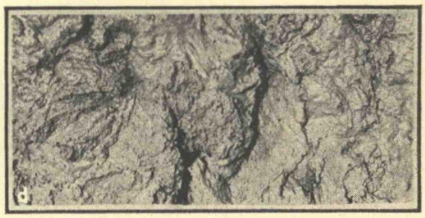
Where blade-graders, discs and spring-tooth harrows are to be used as the mixing equipment, other equipment required will usually consist of water trucks, distributor trucks for stabilizer, a tamping or sheep's-foot roller and a tandem roller A scarifier is also necessary where the surface to be treated has been previously compacted.

The various steps in the construction will be readily apparent from the description of a few typical projects:

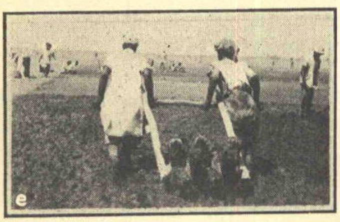
a. Banked Squares to Facilitate Accurate Proportioning

b. Diluted Emulsion Stabilizer Ready for Mixing Operation

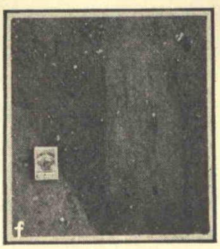
c. Primitive But Effective Mixing Procedure



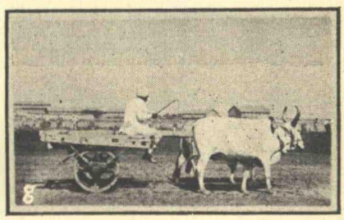
d. Appearance of Completed Mix



e. "Pugging Roller" Aids Drying and Consolidation



f. Tail Skid Barely Marks Completed Surface After Heavy Rain



g. Light Roller Used Prior to Heavy Rolling

Figure 8. Soil Stabilization. Drigh Road Aerodrome, R. A. F. Karachi, India

The Glenn Martin Airport work is typical of projects in which the native soil is used without reducing the clay content by admixture with sand or other inexpensive mineral aggregate. The first stage in this project was the loosening of the existing soil to a depth sufficient to give a 4-inch thickness after final compaction. This was accomplished by the use of disc cultivators.

The next stage would normally have

been the application of water with tank trucks to bring the soil to mixing consistency. On this particular project, as previously mentioned, heavy rainfall made it unnecessary to supply water artificially. 1 gal. per sq. yd. of emulsified asphalt was applied to the wet soil with an ordinary distributor truck, the truck being closely followed by discs to prevent the emulsified asphalt from collecting in pools. This discing constituted the first stage of the mixing operation.

asphalt, making a total of 4 gal., was then applied and disced in. At this stage the soil was probably almost to the liquid limit in moisture content. Heavy rainfall after the final application still further increased the water content.

After mixing operations had been completed, a steel shod sled was used for smoothing and for obtaining partial compaction. As the soil gradually dried out an "A" frame drag was used to still further smooth and compact the surface.

Figure 9. Glenn Martin Airport. The second application of one gallon per square yard of emulsified asphalt being applied. Note the saturated condition of the soil at this stage due to rainfall.

A second application of 1 gal. per sq. yd. of emulsified asphalt was then applied (Figure 9) and followed immediately by discing. The saturated condition of portions of the area at this stage due to heavy rainfall can be seen in Figure 9. After the first two applications of emulsified asphalt had been thoroughly disced into the soil, a third application of 1 gal. per sq. yd. was distributed and the discing operation repeated until the emulsion was uniformly blended with the soil.

The fourth application of emulsified

After this the surface was finally brought approximately to the required cross-section by the use of a metal road plane.

Following the initial compaction and leveling, it was necessary to fill up low spots formed by settlement. The material for filling up these low spots was premixed with emulsion in the proper proportions on an adjacent runway and brought into place with wheel scrapers. It was then spread by hand.

After the stabilized area had partially dried out, the surface was given a preliminary rolling with a 3-wheel roller.

The mixture was still quite plastic at this stage and marked appreciably under the roller. The rolling was continued at intervals until the stabilized runway was sufficiently dried to carry the roller without marking and to support gasoline supply trucks and heavy transport planes of one of the Atlantic Coast lines then using this field as an airport.

Figure 10 shows a 12-ton load passing over the completed runway, without damaging it, about a month after completion and while the section was still slightly plastic because of the high original water content supplied by the rains and cold, wet early winter weather which had continued following completion.

It will be noted that mixing on this project was accomplished entirely with disc cultivators and that the entire 4-in. compacted thickness was completed in one layer and not in "lifts" as is the usual practice now to insure more perfect mixing.

A very good example of soil stabilization work embodying the present ideas with reference to construction is the La Tijera Boulevard job constructed as a research project by the Los Angeles County Highway Department in 1934. On this project three sections were allotted to emulsified asphalt, and several to road oil which was used in various quantities.

This Boulevard is an important artery and the project referred to is about 15 miles from the center of Los Angeles. It is subjected to continuous and heavy traffic. The pavement is 40 ft. wide with an additional 3 ft. on each side sloped upward 3 in. to form a gutter making a total paved width of 46 ft. The natural soil at the site is a fine yellow clay having a high percentage of colloidal material, as is evidenced by Figure 11 showing shrinkage cracks formed during the dry season. Sand was available at a cost of 60 cents per ton delivered and a study of the project indicated that a saving of 10 cents per square yard could be effected by bringing in two parts of sand to be mixed with each one part of the clay soil.

The soil was first scarified to provide approximately one-third of the required

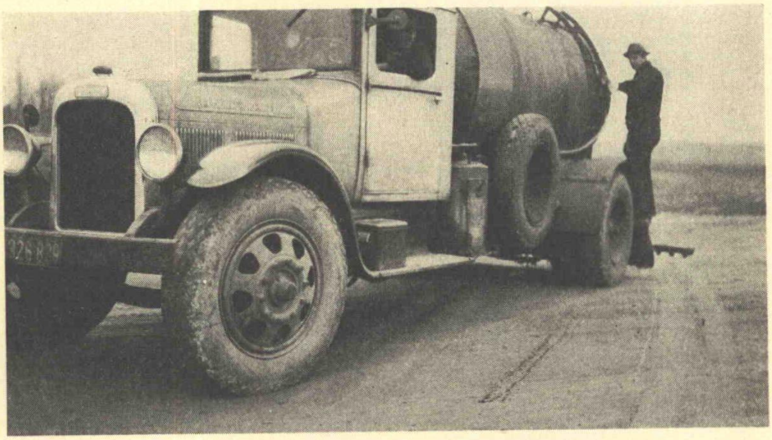


Figure 10. Glenn Martin Airport. A 12-ton load on the completed runway about one month after compaction and before complete dehydration. Although the stabilized surface was only 4 inches thick, no damage resulted under this heavy load.

finished thickness of 4 in. Sand was then distributed over the loosened subsoil in the ratio of about two parts sand to one part soil. Figure 12 shows the work at this stage. The clay and sand were mixed with blade graders (producing a loose thickness of about 5.5 in.), and the blend then moistened with water to slightly less than the plastic limit content.

Figure 11. La Tijera Boulevard, Los Angeles (1934). Shrinkage cracks in yellow clay subsoil utilized in stabilization construction

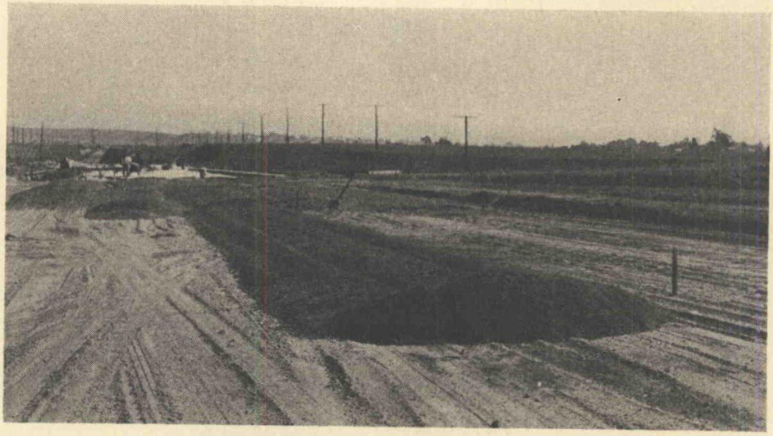


Figure 12. La Tijera Boulevard. Sand being spread for blending with clayey soil prior to stabilization

On the first section of the project it was decided to apply the emulsified asphalt in a 4 to 1 dilution in eight separate applications to insure thorough and uniform dispersion of the stabilizer. The total required quantity of emulsified asphalt was 1.34 gal. per sq. yd.; this amount having been previously determined by laboratory studies as the quantity required to give optimum stability against displacement and absorption. Adding the water in the 4:1 ratio resulted in requiring approximately 7 gal. of diluted emulsion, and this divided into eight applications gave $\frac{7}{8}$ gal. per application.

The soil was bladed to the required cross-section and was then worked in five strips, each being about eight feet wide. In working each outside pair of these 8-ft. strips the material was bladed, in four separate "lifts" per strip, to windrows on the shoulders and on the center strip of the road. Thus about one and one-half inches (loose thickness) was bladed off in each lift. Prior to each movement of the material to the windrow it was given an application of the diluted emulsified asphalt and was disced to effect mixing. Following this stage the material for each strip was bladed back from the windrows and spread, in four lifts as before, each spread receiving an application of diluted stabilizer emulsion and discing and harrowing to perform the mixing. Figure 13 shows the condition of the mix at the time the third lift had been returned to place on the road. After the outside 16 ft. on each side had been thus treated (each being given eight separate applications of the diluted stabilizer) the center 8-ft. strip was treated, but by this time experience had demonstrated that the amount of material (about five and one-half inches loose for a 4-in. compacted thickness) could be handled in two lifts instead of four and also that less water was needed.

The center strip was therefore handled in two lifts with a total of four applications of 2:1 dilution, the total emulsion being 1.34 gal. per sq. yd. as before.

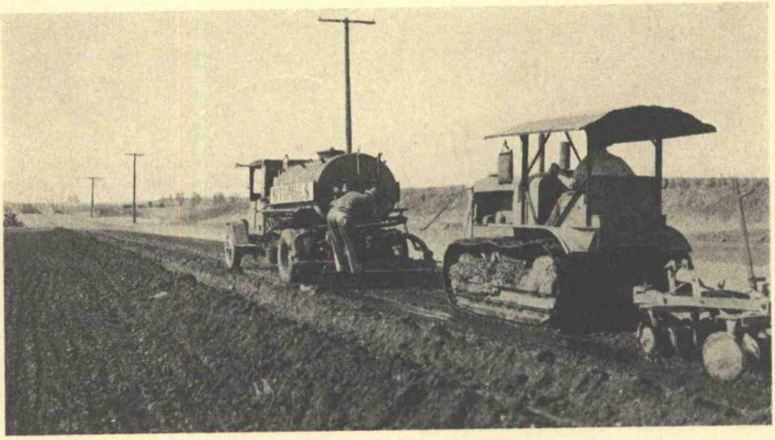


Figure 13. La Tijera Boulevard. Applying stabilizer followed by immediate discing. The next to the last application on an 8-foot strip next to the center strip which has not yet been treated.

The treated soil over the full width of the road was turned several times with a blade grader to insure perfect mixing.

Two other sections of this project were treated with emulsified asphalt stabilizer. The procedure on both of them involved handling in two lifts with a total of four applications of stabilizer instead of four lifts and eight applications. On one section the stabilizer was diluted 2 to 1 and on the other section undiluted stabilizer was used, the soil having been previously wet to a point well beyond the plastic limit.

Reducing the number of applications

and the number of lifts proportionately reduced the cost of construction without reducing the efficiency of the mixing. The only difficulty encountered in the mixing was on the section on which the undiluted stabilizer was applied. Here in spite of the fact that the total moisture content was practically identical, much greater difficulty was encountered in obtaining a uniform dispersion of the asphalt.

After the completion of the mixing operations, as above described, the surface was allowed to dry until it would carry a roller without excessive displacement and it was then given initial rolling. The first section was again rolled after it had dried sufficiently to compact satisfactorily under the roller. At this stage of the construction a rain storm occurred which lasted several days. The last two sections were at the time only partially mixed although the entire quantity of stabilizer had been added. After about four inches of rainfall the end of the storm found the soil mixture undamaged and the work then proceeded to its conclusion. Figure 14 shows sections 2 and 3 after having been graded to the required cross-section subsequent to the storm, at a time when they were almost ready for rolling.

When the sections were completed and allowed to dry thoroughly to the subgrade, a few shrinkage cracks appeared. They were filled by light watering and blading, after which the surface was rolled and given a two-application surface treatment.

The surface treatment used on this job (and on many others similarly constructed) involved first an application of $\frac{1}{4}$ gal. per sq. yd. of quick-setting emulsified asphalt followed immediately by a covering of 25 to 30 pounds of $\frac{3}{4}$-in. to $\frac{1}{4}$-in. rock, the rock being broomed and rolled. There then followed a second application of $\frac{1}{4}$ gal. of the quick-setting emulsified asphalt and a cover of about 12 lb. per sq. yd. of coarse sand broomed into place and then rolled. Figure 15 shows the texture of this surface treatment at the time of completion, and Figure 16 shows the condition after nine

Figure 14. La Tijera Boulevard. Stabilized soil after completion of mixing. Mixed material was bladed out from roadway to form 3-foot V gutters

months of use. During this 9-month interval, including an exceptionally wet winter, no breaks occurred in the base under traffic, and no maintenance was required.

ous distress, apparently due to the road oil being unable to resist displacement by capillarity.

The sections of pavement stabilized with emulsified asphalt are now more than

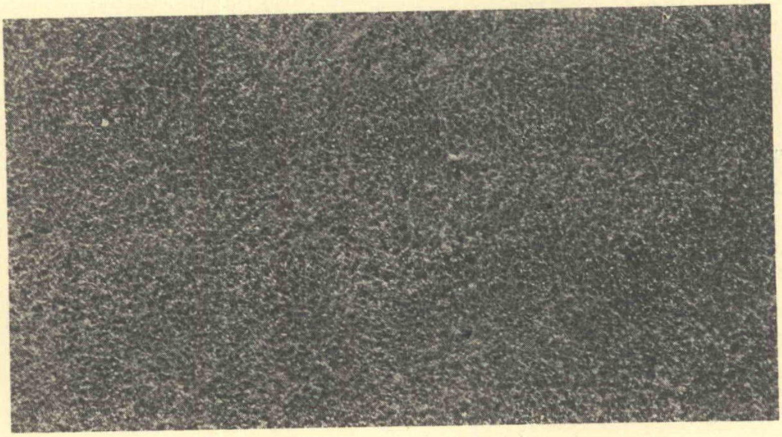


Figure 15. La Tijera Boulevard. Texture of roadway after completion of surface treatment

Figure 16. La Tijera Boulevard. View of same place as Figure No. 14, showing condition after nine months use

The sections of this project adjoining the ones stabilized with emulsified asphalt were treated with road oil (and surfaced as above). Figure 17 shows their condition at the end of the 9-month interval. Although subsoil conditions were identical these oil treated sections suffered seri-

half through their second winter and no breaks or failures have so far developed. That this is an extremely satisfactory showing will be understood when it is known that adjoining boulevards, and cross boulevards, carrying the same traffic are all of concrete, eight inches or more in thickness and are continuously giving trouble due to heaving and movement resulting from unstable subgrade which swells and shrinks excessively as moisture content changes between wet and dry seasons.

The La Tijera Boulevard project was one of the first projects constructed in which the mixture was properly designed both as to water content and emulsified asphalt stabilizer requirements. It was also designed to reduce the amount of stabilizer to a minimum by reducing the clay content to the minimum necessary to give cohesive strength to the stabilized base.

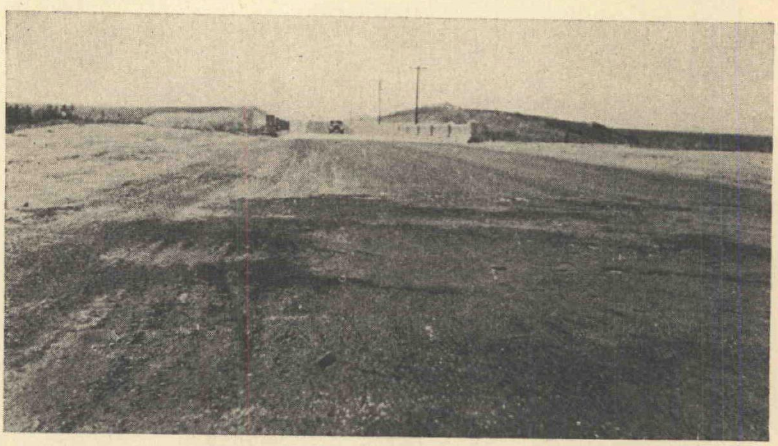


Figure 17. La Tijera Boulevard. Road oil stabilized section adjacent to the emulsified asphalt stabilized section shown in Figure No. 16, after nine months of use. Serious displacement and breaking up is shown.

Mixing in Place With Motorized Road Mixers

Various types of road mixing machines have been used successfully on soil stabilization jobs with emulsified asphalt as a stabilizer. When such equipment is employed the cost of mixing is appreciably less than when blade graders and harrows are used.

Several projects were constructed during the last year using a Gardner mixer. This type of mixer has a revolving spindle studded with mixer blades which turn upward through the material to be mixed and carry the mixture over the top of the spindle, depositing it about 2 ft. in the rear. The spindle revolves approximately two hundred fifty revolutions per minute and the mixing action is rapid and efficient.

Figure 18 shows this mixer in operation on the "Rim of the World" Highway in the San Bernardino mountains of California, this being a portion of the State Highway System. The project had previously been surfaced with a 3-in. bituminous mat but maintenance costs were very high due to frequent subgrade failures. In the photograph the oil mat is shown in a windrow on one side. It was returned from this windrow to the road after the completion of the base stabilization. Snowfall and heavy precipitation keep the subgrade saturated in many places the greater part of the year.

The quantity of stabilizer required for various sections of the project was predetermined by tests in the State Highway Laboratory. Samples of the mix were taken during construction and tested, with results that fully confirmed the correctness of the assumptions made in the design of the mix with respect to optimum resistance to displacement and to absorption.

The construction methods on this project were substantially the same as those employed on the La Tijera project, the principal difference being in the use of the Gardner mixer instead of discs and harrows. The sections were all worked in half widths, with traffic being carried under control on the other half of the roadway. The Gardner mixer made it unnecessary to remove the material from its original location or to windrow it outside of the half width strip.

The subsoil was first scarified, water was added, and diluted emulsified asphalt stabilizer was applied with a truck distributor. The material was then moved in a little on each side with a blade in order to accomodate the width of the mixer, and mixing followed as is shown in Figure 18.

After the required number of applications of diluted stabilizer, each followed by the mixer, the stabilized soil mixture was leveled with a blade grader and allowed to compact under traffic with occasional blading to obtain a uniform surface and to prevent formation of ruts. The quantity of stabilizer was varied with changes in grading of the soil as determined by laboratory and field tests.

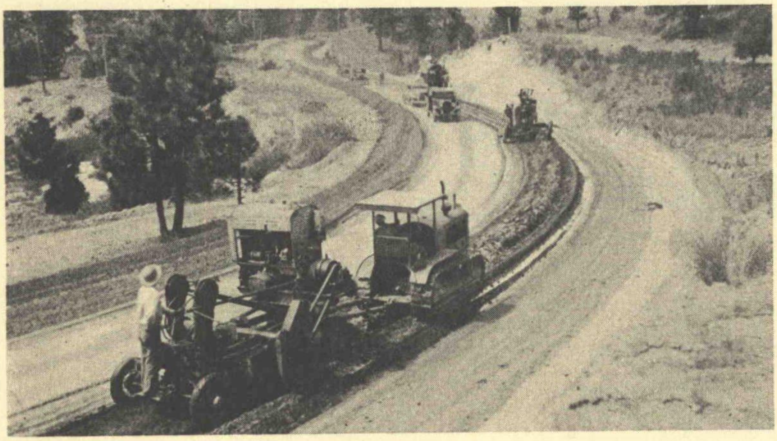


Figure 18. Stabilized base being constructed in half width of the roadway using a mixing machine; traffic using other half of roadway. Oil mat mix was bladed to one side prior to stabilization work.

Figure 19 shows the stabilized soil under process of being compacted by traffic. Figure 20 shows the same section after traffic has completely and uniformly compacted it. This method of compacting is probably the least expensive and most efficient and should be utilized wherever possible.

On some sections a number of weeks elapsed after the stabilized base was open to traffic before the re-laying of the oil mat. During this time the stabilized base carried the traffic without damage although some blading and sprinkling was found desirable to replace material removed by ravelling or abrasion.

Stabilized base does not have the appearance of an asphaltic mixture. It is usually only slightly browner or darker than the natural soil and after drying, usually becomes very hard. Figure 21 is a texture picture of the stabilized subsoil shown in Figure 20 after it had been compacted.

Although stabilized base is hard and has good supporting strength a bituminous surface has always been found necessary to protect it from loss through abrasion. The surfacing should be planned as a part of the project and not left as a maintenance item. This is in agreement with a principle, now being frequently expressed and which was clearly stated by Lang (7), who says, "If a sufficiently firm road bed could be obtained, any thin surface which would not

Figure 19. Project shown in Figure No. 18. Stabilized base was compacted under traffic

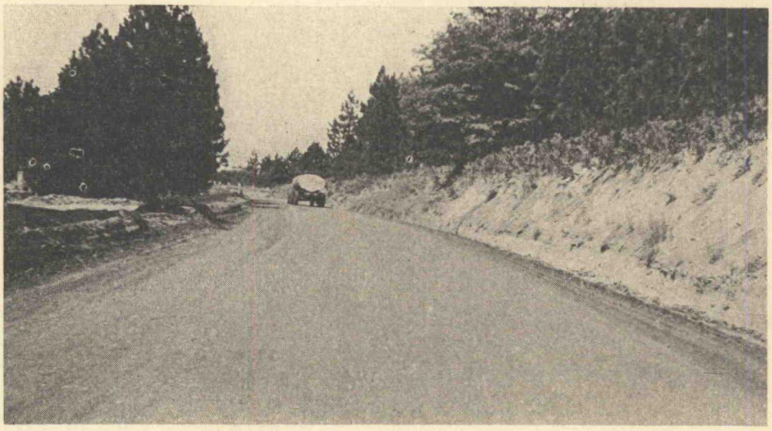


Figure 20. Same as Figure No. 19. Appearance of base after being compacted under traffic

shatter under traffic and which would stand abrasive wear, should be sufficient." On emulsified asphalt stabilization projects constructed to date, a light wearing surface, applied as previously described, has proved entirely adequate regardless of the volume of traffic.

The most recent innovation employed in the construction of stabilized bases consisted of using a mixer of the Gardner type and "fueling it in flight," so to speak, throughout the mixing operation. The project was Yarmouth Avenue in the City of Los Angeles. The soil was a tank trailer and a hose leading from a distributor truck, as is more particularly described below.

The width of the roadway was 20 ft. and as the mixer was able to pick up a 7-ft. strip no windrowing was necessary. The full width was treated in three strips. The full thickness was mixed at one time. The diluted emulsified asphalt stabilizer was applied to the soil through spray bars in front of and above the spindle. It was fed under pressure from a pump mounted on the mixer, supplied from a trailer towed behind which was

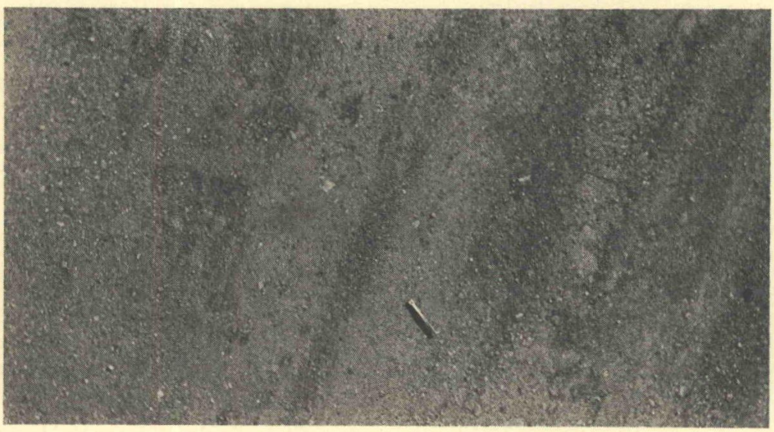


Figure 21. Texture of compacted base shown in Figure No. 19

fine silty clay ranging in stabilizer requirements from 3 to 7 per cent based on particle size determinations and also on stability and absorption tests.

On this project the soil was loosened and pulverized to give a 4-in. finished thickness after treatment. At the beginning of the mixing operations the soil was dust dry and loose and fluffy. All the water required for wetting was applied during the mixing operation, together with the stabilizer, in the form of a 4:1 dilution, this diluted material being fed to the mixer while in motion, using a replenished as needed by tank trucks which drove along side and refilled the trailer truck while in motion. The mixer and trailer were drawn by a caterpillar tractor at a rate of about $\frac{3}{4}$ mile per hour. The mixing "train," consisting of tractor, mixer and trailer, is shown in Figure 22, together with a supply truck (which is shown pumping over into the trailer).

The variation of asphalt content was accomplished by cutting off the spray bars in the mixer on the sections which had previously received sufficient stabilizer and allowing the machine to continue merely as a mixer until another section was reached where additional stabilizer was required. Each strip received a total of five trips of the mixer which gave perfect dispersion of the asphalt (the mixture being at about the plastic limit consistency).

Laboratory research has demonstrated that optimum stability against displacement is usually obtained with less stabilizer than is necessary for optimum stability against absorption, and sometimes the amount required for maximum resistance to absorption results in a very appreciable decrease in resistance to displacement. On the project being discussed the quantity of stabilizer was designed to give the maximum stability against displacement except in the bottom layer (one half inch, more or less) which was enrichened to give maximum stability against absorption. This is believed to be sound and economical practice because the total quantity of stabilizer is much less than if maximum stability against absorption were to be obtained throughout the entire thickness, and the supporting strength greater.

The enrichening of the bottom layer was quickly and inexpensively accomplished by placing a spray bar back of the spindle and spraying diluted stabilizer on the underside of the ribbon of mixed material as it passed through the air from the top of the spindle to the subgrade 2 ft. in the rear, and also by applying stabilizer to the subgrade immediately ahead of the falling mixture.

With the mix methods and equipment used on the Yarmouth Avenue job it is believed that the cost of adding water, stabilizer and mixing, exclusive of subsequent shaping and compacting operations, can be reduced to two or three cents per square yard from previous costs which have ranged from seven to ten cents per square yard. The "train" of equipment has the further advantage that the watering and mixing operations are completed in a minimum of time thus reducing the loss of water by evaporation and materially lessening interference with traffic. There are no windrows along the shoulders to obstruct the flow of traffic, and the road may be worked in half widths without incurring extra ex-

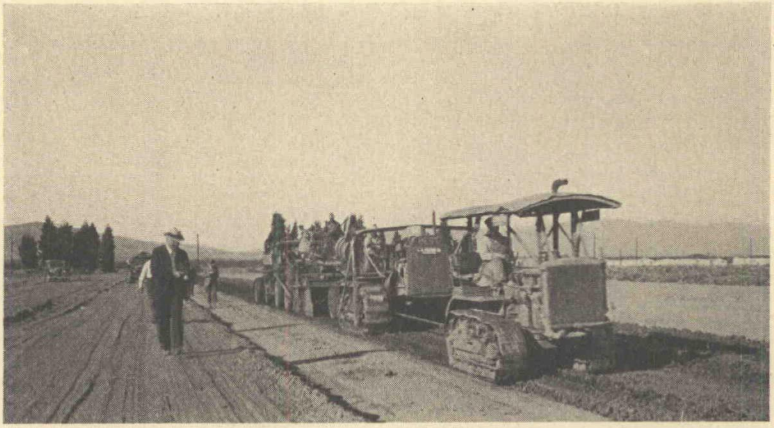


Figure 22. Mixer "train" applying enriching application to under side of stabilized mixture in its last trip

pense. Figure 22 shows the mixer "train" making its last trip over the section while applying the enrichening layer to the bottom of the stabilized base.

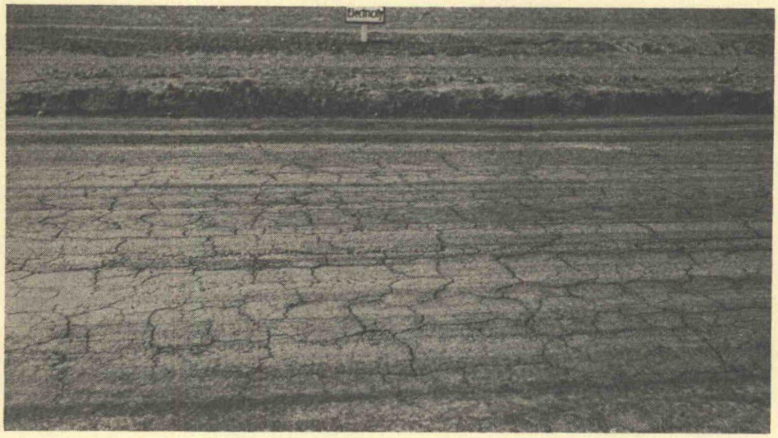


Figure 23. Rolling was not continued during drying period and stabilized base shows many shrinkage cracks which were closed by sprinkling and drag-brooming before construction of wearing surface.

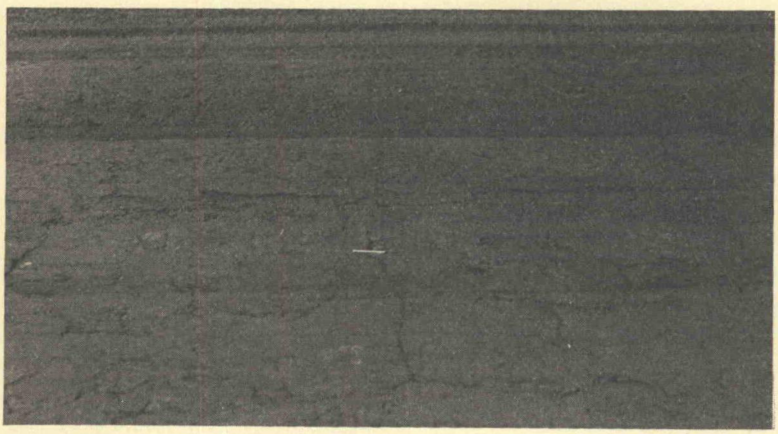


Figure 24. Same as Figure No. 23, with cracks nearly filled and closed

After the mixing operation was completed, the stabilized material was bladed approximately to the cross-section and rolled with a tamping roller to aid in obtaining uniform compaction. Then the base was rolled with a tandem roller and allowed to bake thoroughly in the sunshine. Due to the fact that rolling was not continued during the drying period shrinkage cracks appeared in the base as shown by Figure 23. After the drying was completed down to the subgrade the cracks were filled by sprinkling the surface lightly, then dragging with a heavy broom drag which loosened and deposited sufficient stabilized material to fill the cracks. Figure 24 shows the cracks substantially all filled and the base nearly ready for the construction of a light wearing surface.

The shrinkage during drying results in greater compaction than could be obtained by mechanical means alone. Shrinkage cracks which will occur with clayey soils are not objectionable as they are readily filled after the stabilized base has dried, but these cracks may be largely prevented if rolling at intervals during the drying operation is feasible and economical.

Other types of road mixing equipment similar to the Gardner mixer have been used on soil stabilization work. Any efficient mixer can be used, and any mixer which lifts the material from the subgrade during the mixing operation will permit the enrichment of the bottom layer at the time the mixed material is

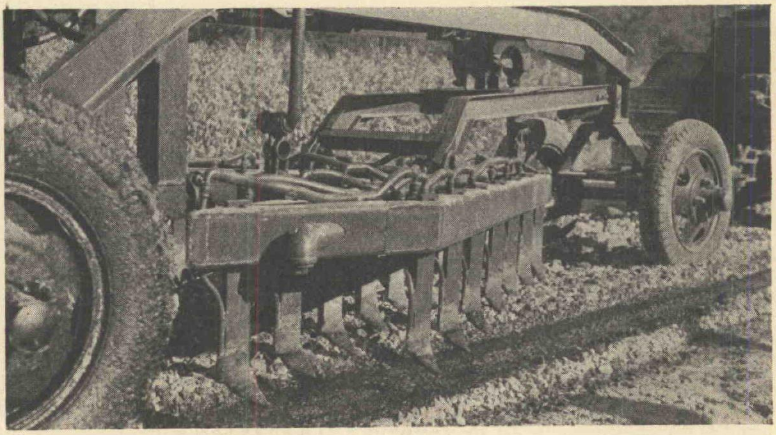


Figure 25. Missouri State Highway Project. A mixer having scarifier teeth, with pipes and nozzles back of them for applying water and stabilizer to the soil

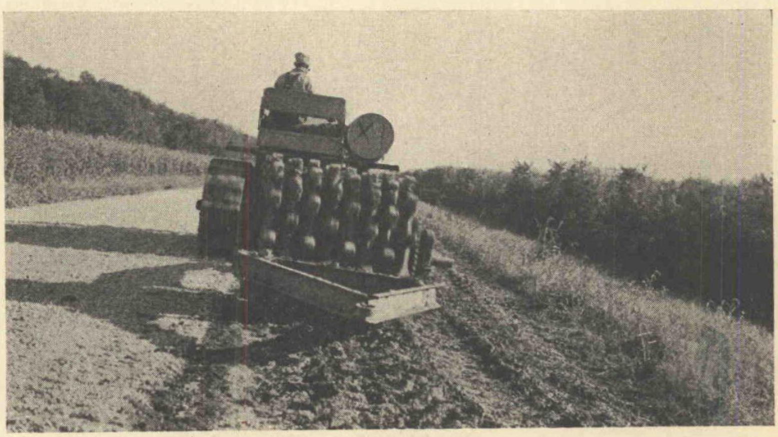


Figure 26. A tamping roller being used to mix and compact stabilized soil

deposited without additional handling. Equipment manufacturers are already developing special equipment for stabilization work.

An interesting departure from the usual type of equipment is illustrated in Figure 25, taken on a project in Missouri. This machine is provided with rows of scarifier teeth with a pipe extending to the subgrade back of each tooth. The water and stabilizer are applied under high pressure through nozzles on these tubes. Following the mixing and application of stabilizer as done by this machine on the project illustrated, further mixing was obtained by the use of a tamping roller shown in Figure 26.

In using the various types of road mixing equipment the length of section laid out for construction is not critical. At first it was assumed that the section had to be mixed and laid quickly before the stabilized mixture could dry, but while this is usually the economical way, it has since been found that the mixes can be re-tempered if necessary after the original mixing, or they can be stored in windrows along the side of the road so as to retard drying between stages of the construction.

Pre-mixing at a Central Plant

This method is particularly adaptable where waste pit-run gravel or other similar materials are to be stabilized. It has been found that such materials can usually be satisfactorily stabilized with 3 per cent of stabilizer due to the relatively low clay content. Three percent is the minimum recommended and such materials should have 15 to 20 per cent finer than the No. 200 sieve including cementitious material necessary to give cohesive strength.

In the pre-mix method of construction, as used on a few jobs to date, the stabilizer and aggregate were mixed in a pug or drum type of mixer at a central mixing plant, either at the source of supply or at the rail head. As no screening, drying, or heating is required the cost of prepara-

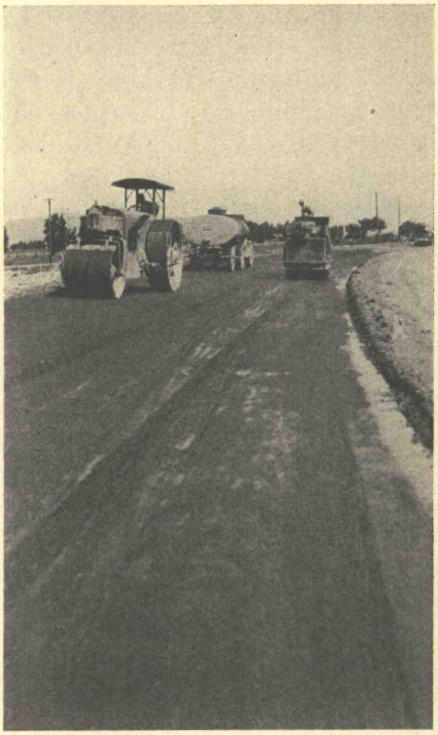


Figure 27. Stabilized base mixture being watered and then rolled until mortar flushed to the surface. A waterproof base of concrete-like hardness resulted.

tion is extremely low. A typical example is the project built by the California Highway Department near Sacramento, during the 1935 season. The mixing was accomplished at the producer's sand and gravel plant. As the plant was not located on the railroad the stabilized mixture was trucked to the railroad and dumped from the truck into gondola cars The material was then transported by rail to the project, unloaded with clam shovels and spread with dump trucks The material was shaped, rolled and compacted with rollers according to the usual practice for crusher run bases.

There is apparently no limit to the distance such a material can be transported as it does not set up in the cars, dehydration being necessary to cause this If shipped long distances a waterproof cover might be necessary to prevent excessive evaporation

Another successful project was constructed by the Nevada State Highway Department at Fernley, Nevada In this case the stabilized aggregate mixture was delivered with trucks and spread to the required cross-section with an Adnun type mixer. Then it was sprinkled and rolled until thoroughly compacted and until the mortar flushed to the surface The result was a base of almost concrete-like hardness, which shed water as perfectly as if heavily bitumenized

It is believed that the utilization of quarry waste and of cheap pit-run aggregate, and the conversion of these materials into high class road building aggregate will open up a field for low cost road construction which will react not only to the benefit of highway builders but to the advantage of the material men as well, inasmuch as most of them now have vast supplies of material on hand which can be converted into an unanticipated asset

CONCLUSION AND ACKNOWLEDGMENTS

The writer has attempted to describe the theory and practice of soil stabilization with emulsified asphalt in the light of present knowledge and experience That this type of construction is economical and efficient has been demonstrated repeatedly over a period of years The theories will undoubtedly be better understood and construction practices rapidly improved and developed by the many engineers in all sections of the country who have been and are planning and constructing stabilization projects

The writer expresses the belief that this new development is of sufficient importance to justify the same careful study and research which highway engineers have given to all other types of construction and out of which has come the present high state of development in highway building

The writer gratefully acknowledges the splendid work of Mr Hogentogler and others mentioned whose writings have been found invaluable Sincere appreciation is also accorded to the engineers whose courage and foresight have made possible the many projects constructed during recent years and also for their helpful and intelligent cooperation which has made possible the present state of development

Credit is also given to Mr V E Watts for his valuable assistance and collaboration throughout these studies, and particularly for his development of the simple but effective special test methods herein described

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