FUNDAMENTAL RESEARCH IN BITUMINOUS SOIL STABILIZATION

By V A ENDERSBY

Research Engineer, Shell Development Company

SYNOPSIS

Information now available indicates a possibility of stepping up soil stabilization to a higher class of construction. The term "bituminous soil stabilization" describes a soil-oil-water system in which the cohesive agent is clay, and in which the water content, upon which cohesion is dependent, is controlled by the oil. "Clay" indicates the particle size in which hydraulic cohesion is most fully developed

A definite soil system exists, which changes with the degree and method of mixing, the process passes through an optimum phase during mixing. The importance of water control is shown. There are vital differences in the phase aspects of different mixers.

If a laboratory specimen is cured at high temperature, the waterproofing will be misleadingly high Except where high temperatures are used, the water content tends to reach the same magnitude regardless of curing methods However, the longer the time required, the less the structural damage Short-time capillary absorption is dangerously lement

Liquid oils vary as to viscosity, curing properties, and chemical nature Great variations are possible Different types of oil have different phase effects In an ordinary soil-oil-water system, a large part of the oil is merely mechanically included. An effective alteration results in spreading of oil and displacement of water As oil content is increased, the soil will tolerate more water for the same swell This is also true of improvement in stabilizer. No simple relation exists between water absorption and mechanical stability

The factor of friction is imperfectly represented in compressive strength Friction does not vary to the same extent or in the same direction as cohesion It is indicated that it is possible to improve soil stabilization with liquid oils several-fold by proper relation between oil and water content, phase mixing, proper curing, selection of stabilizer, selection of stabilizer content

For control test procedure Curing should be done in a manner approximating field conditions; exposure to water should be more severe than capillary methods, swell should be regarded as not proportional to loss of bearing power; for the evaluation of bearing power, both friction and cohesion must be taken into account

Although soil stabilization with liquid asphalts has been in use for some years, certain fundamental principles involved have only recently become clear. It can now be said that the practical application of these, to the extent of a possible three or fourfold improvement in the work of the past, is merely a matter of extending investigation to a satisfactory range of soils and stabilizing oils A comparison of data previously shown by Benson and Becker (1),¹ and of new material given herein, with practice, indicates that the results of work done in the past may have

¹ Numbers in parentheses refer to the list of references at the end of the paper

varied 100 per cent or more in quality, even though those doing it were under the impression that methods were uniform.

These facts are of particular importance at the present time, because of the difficult climatic and working conditions under which many roads and airports all over the world have to be constructed; and also because of increasing scarcity of base materials and labor for producing them The information now available indicates a 'strong possibility of stepping up soil stabilization to a higher quality class of construction than it has usually been considered for, and thus releasing a large volume of more expensive materials for critical needs other than bases.

While the data given herewith are described as "fundamental," they are regarded as so in the immediately practical sense.

Some fundamental principles are presented, with illustrations, and this is followed by a soil study of a more detailed and qualitative nature.

Definition of Bituminous Soil Stabilization

The term "bituminous soil stabilization" is often used to cover anything from a clay-bound soil lightly treated with oil, to an oil-bound sand As it has been employed by most of the fundamental investigators of the subject, it describes a soil-oil-water system in which the cohesive agent is clay, and in which the water content, upon which the cohesion is vitally dependent, is controlled by the waterproofing effect of the oil

However, it is impossible to design a mix in which the hydraulic cohesion is unchanged by the addition of oil. Oil is itself a cohesive and a lubricant, as is water, and its introduction into the soil will change the mechanical characteristics to some degree. If the oil becomes the dominant cohesive, the mix is no longer a true soil stabilization in the scientific sense, but is rather a soil mix. In the appended soil study, the characteristics of the 8 per cent oil stabilization tend toward the latter condition.

The Cohesive System in a Soil

Cohesion in a soil is usually ascribed to "clay" In actual fact it is all due to water, and the clay merely indicates the particle size range in which hydraulic cohesion is most fully developed, simply because of the great surface area per unit weight.

The major requirement for producing strong cohesion is to make the film of cohesive agent between two surfaces as thin as possible. This is because the shearing resistance of a viscous film between two solid bodies is inversely proportional to the thickness of the film A film one molecule thick cannot be sheared at all, and such a film of water would be a perfect cohesive, since the power of water to adhere to a mineral surface is enormous. To produce high cohesion in a clay soil, it is then necessary to compact it very closely or to dry it out; the latter process is the more efficient, as we all know from encountering hard "dry" clay of approximately the consistency of brick

The molecular layers of water next to a mineral surface adhere so tightly that they can be driven off only by temperatures practically sufficient to calcine the mineral. Hence such a thing as a chemically dry soil is seldom seen. It is believed by some that these layers exist in a special condition of orientation akin to ice, and have great rigidity.

The lubricant action of water is as important as its cohesive action, because without the proper amount of water, the soil cannot be compacted enough to bring thin films of water into play. A so-called "dry" clay has a very desirable water content to start with, so far as cohesion is concerned; but the surfaces cannot be brought close enough together to make use of it.

On the other hand, a thin film of water is essentially thirsty and tries to add to itself with any available extra water. Thus if a soil is compacted with an excess of water in the voids, the films between surfaces immediately expand and cohesion is lost, the soil swelling again as soon as the load is removed. Thus every soil has an "optimum" water content for maximum compaction, which is usually in excess of the optimum for cohesion. This excess can only be removed by evaporation. Permanent cohesion can thus be sought by keeping the initial water as low as compatible with satisfactory compaction, or by curing the soil after compaction, or both

The problem resides in the fact that, no matter how the thin water film is achieved, it remains thirsty and water must be prevented from reaching it

There are two theories regarding the action of oil in waterproofing the soil One is the "plug" theory which holds that the capillaries are simply plugged with bodies of oil, preventing the water from either entering or leaving. The other is the "intimate mix" theory, under which the individual particles are supposed to be coated with oil. Neither can be considered as covering the whole ground, though the "plug" theory, on a simple statistic basis, must be nearer the truth The mineral surface in a clay is so enormous that no amount of oil ordinarily used can be expected to coat it completely.

Moreover, if such large amounts of oil are used, the soil becomes lubricated by the oil and loses much stability on that account, long before a perfect waterproofing coat is achieved. Because of the high viscosity of the oil, an excess of oil also prevents compaction Thus stabilization does not improve in ratio with the amount of oil used, but begins to decline in quality beyond a certain amount of oil.

On the other hand, the oil plugs exist largely in the form of films partly spread over the particles This is exemplified by the fact that if the oil is treated in such a manner as to promote spreading, the efficiency of the stabilization is increased

Fundamentally it must be borne in mind that the function of the oil is not to produce cohesion; but to protect the hydraulic cohesion The cohesion due to oil is much weaker than the hydraulic cohesion and should never be substituted for it more than necessary

Phase Mixing

As a matter of fact, the action of the oil is not a simple plugging of capillaries A definite soil system exists, which changes its nature with the degree and method of mixing; and so far as waterproofing is concerned, the process passes through an optimum phase during the progression of mixing. The first detailed investigation of this feature, so far as the writer is aware, was published by Benson and Becker in 1942 (1).

Some of the phenomena connected therewith had also been noted by the writer These stages or phases seem to be substantially as follows:

- 1 The oil is distributed through the soil in large masses having little waterproofing value.
- 2 These masses are broken down until a substantial "plugging" action is evident.
- 3 The oil is distributed over aggregations or "cells" of soil particles.
- 4. At first these cells are too large, and the entrance of water into individual cells imperfectly waterproofed breaks down the soil as a whole.
- 5. An optimum condition is reached where the cells are small enough so that failure of individual scattered members is not serious.
- 6 The cells become too small, hence imperfectly waterproofed, because the oil is distributed too thinly.
- 7 A condition approaching "intimate mixing" is reached. In this region some stabilizations continue to improve; others break down completely. In general the stabilizations described by Benson broke down in this region; in general those appended hereto continued to improve. The reasons for the difference are quite complex

The formation of the soil cells is well illustrated in Figure 1, reproduced from Benson's paper.

The facts found both by Benson and the writer show that control of the mixing phases is vital to the best results. In other words, sufficient control of field mixing methods should be maintained, to make sure that optimum waterproofing is being obtained. This has been neglected in the past. Benson has a successful trial road job in operation, which was constructed on this principle.

Some of the mechanical properties of Benson's phase mixes, subsequent to exposure to water, are shown in Figure 2.



Figure 1. Upper, Samples Broken Open. Lower, Samples Sawed Open. (From Benson and Becker, *Proceedings*, Assoc. Asphalt Paving Tech., Vol. 13 (1942).)

The Control of the Soil System

Certain factors involved in adequate control of the soil-oil-water system are as follows:

Water: It is hardly possible to mix oil with dry soil satisfactorily, as the oil will not spread well over a dry mineral unless the mineral is very hot. A water film "lubricates" the oil and promotes its spread. This is a function in addition to

the lubricating action of the water in promoting compaction. There appears to be evidence that the amount of water needed to promote satisfactory distribution of the oil is slightly in excess of that required to promote optimum compaction. Beyond this point, the distribution improves, but compaction and cohesion fall off, and curing becomes difficult. A routine method of selecting the proper water content for a given soil, which involved testing over a wide range of water contents for the sta-



Figure 2. Effect of Variable Asphalt Content. (From Benson and Becker, *Pro*ceedings, A.A.P.T., Vol. 13 (1942).)

bilized soil, would be quite cumbersome, especially as the amount varies somewhat with the amount of oil. Various expedients have been devised to cope with this. Klinger (3) uses an exudation point based on the combined oil and water content which the soil will tolerate when compacted. Benson (1) uses a "fluff point," based on the fact that as water is added, the soil reaches and passes through a condition in which it becomes loose and "fluffy," with a moist appearance. When this condition is passed, it becomes cohesive and "muddy." Benson mixes at the upper fluff point. This method has also been adopted by the writer, and will be illustrated later. The importance of water control is shown in Figure 3, reproduced from Benson These mixes had been immersed in water without curing. If curing is employed, the relationships will change somewhat

Benson regards it as desirable to wet the soil a number of hours before mixing with oil, in order to give the water time to



Figure 3. Variable Moisture Mixtures. (From Benson and Becker, *Proceedings*, A.A.P.T., Vol. 13 (1942).)

infiltrate soil cells and break them down to a satisfactory fineness in mixing The more water employed, the more thoroughly the cells are broken down.

Type of Mixer There are vital differences in the phase aspect of different mixers. This is interesting in view of the fact that mixer types and mixing methods are the most loosely specified points in many proposed routine control methods.

Benson shows some of these differences in Figure 4 Similar effects found by the writer are given in Figure 5 Benson found that satisfactory correlations could be made between laboratory mixers and field methods.



Figure 4. Comparison of Mixer Types. (From Benson and Becker, *Proceedings*, A.A.P.T., Vol. 13 (1942).)



Figure 5. Comparison of Mixer Types

Post-Fabrication Phenomena

The chief problem of laboratory control is to select tests which will conform with what may be expected of the soil under future conditions, for no stabilized soil will remain in the condition in which it is laid down. The status of the oil changes, in that there is a slow continued distribution through the mix, tending in general to improved resistance to water Also, where cutbacks are used, there is considerable stiffening of the oil film, also tending to increased water resistance Stiffness of film is one of the factors causing the oil to resist stripping from the particles by water.

The water content will increase or decrease, or both by turns. An initial de-



Figure 6. Effect of Curing Method on Capillary Absorption. MC-0 Stabilizer



Figure 7. Effect of Curing Method on Absorption by Total Immersion MC-0 Stabilizer.

crease through curing, will give permanent resisting characteristics which an uncured soil will not have. The more thorough the curing, the more marked the resistance. If a laboratory specimen is cured at high temperature, the apparent waterproofing will be misleadingly high This is illustrated in Figures 6 and 7. The specimens shown were cured to constant weight except in humid air, where curing was for one week.

The ultimate water content which may be expected is very important. Except

where high temperatures are used, the water content tends to reach the same magnitude regardless of curing methods or method of exposure to water. However, a strong time element is involved The longer the time required for water to enter the soil, the less the structural damage for a given amount of water (4) On the other hand, the longer the water remains in the soil, the greater the stripping action exerted on the oil The interrelation between absorption of water, swelling of the soil, and mechanical stability, is not only complex but difficult to forecast There is a considerable accumulation of scattered observations indicating that after long periods of time, complete saturation of a base may be reached under most surprising conditions, such as in the desert. Such happenings are due to trapping of capillary water or vapor under pavements. Devising a laboratory absorption method which is satisfactorily correlated with field conditions is probably the most difficult problem of today, in the art of bituminous stabilization The writer has employed total immersion for seven days. This is probably over-severe, almost certainly so for uncured soils. On the other hand, short-time capillary absorption is, in the opinion of the writer, dangerously lenient

Mechanical Tests

The final criterion of the quality of a stabilization is its bearing power under load, after subjection to the maximum exposure to water which may be expected The forces involved in displacement of a pavement base are very complicated, and the correlation with laboratory tests has been insufficiently investigated. This difficulty is not confined to oil-stabilized bases. Most of the empirical tests in use are of the nature of compression or extrusion methods The soil in practice acts in confinement. In compression tests it is less confined, and in extrusion tests more confined, than in practice. Thus the former type will show failure for some materials which serve satisfactorily in practice, and the latter will show marked resistance for some which fail in practice. The triaxial test involves a truly scientific method of analysis of the forces, but is affected by dimensional factors which require correlation. It is correlated to the basic bearing power formula developed from Prandtl's work, and hence has a basis absent from purely empirical methods (2).

Water Absorption, Swell, and Stability

The swelling of a soil is proportional to the water absorbed, but the proportion varies with the soil and type of treatment. The loss of mechanical stability due to water is not, as some tend to think, directly correlated with swell Swell is important of itself, as affecting distortion of road surface and possible failure of rigid pavements, but should be considered in that light principally

Selection of Stabilizing Oils

Liquid oils vary as to viscosity, curing properties, and chemical nature

Very high viscosity is undesirable as making the oil too difficult to mix with the soil. Figure 8, from Benson, illustrates this Deterioration took place upon a change from MC2 to MC3, and failure occurred with MC4. The writer has had similar results, one of which is illustrated in Figure 9, a comparison between MC0 and MC2 oils The writer recommends not over Grade 2 and preferably not over Grade 1 Grade 0 is used in the appended studies

With regard to curing properties, the question is probably more open. Rapidcuring oils may give trouble during any prolonged process of mixing and compacting. Slow-curing oils may not develop sufficient film stiffness On the whole, the preference seems to be for medium-curing oils

Oils differ very much in chemical na-

ture. It is desirable to use oils which have a high affinity for mineral surfaces, and this affinity can be improved by chemical treatment. Cracked oils have it by nature, but are known to have undesirable traits



Figure 8. Effect of Asphalt Viscosity, (From Benson and Becker, *Proceedings*, A.A.P T., Vol. 13 (1942).)



Figure 9. Effect of Asphalt Viscosity

in some other applications, and their use in soil stabilization has been insufficiently investigated. Oils can also be improved by adding agents which stiffen the film upon curing. In general very great variations are possible in stabilizers. This is illustrated in Figure 10 Since little scientific study has previously been made of these differences, it appears that in previous stabilization work, the best results could hardly have been obtained as a rule, unless by accident.

Different type of oils also have different phase effects, as shown in Figure 11.



Figure 10. Water Absorption of a Soil Using Different Stabilizers of the Same Grade. Soil A, Stabilizer 6¹/₂ Per Cent MC-0. Specimens Immersed Without Curing. Sample Weights Approximately 450 G.



Figure 11. Difference in Phase Behavior of a Soil Produced by Adhesive Treatment of Oil. Soil A, 4 Per Cent MC-2 Oil, Pug Mill Mixer.

The Use of Adhesion-Promoting Agents

While a chemical discussion is not in order in this paper, some of the physical principles involved may be of interest

If we place a drop of oil and a drop of water on a mineral surface side by side, the two contend for possession of the surface. Each material tends to spread out because of the attraction of its molecules for the stone, each is restrained by its surface tension, which tends to keep it in spherical form The resultant of these forces decides whether oil or water occupies the stone Improvement of the oil can be effected either by decreasing the surface tension or increasing the affinity for mineral, or both If the affinity of the oil for the stone is high enough, it will displace a water film entirely, once it touches the stone at any point, and vice versa Most normal oils adhere to stone in the presence of water, either because they reached parts of the surface first, or because the water was drawn from between the oil and the stone by evaporation Oils which have a natural ability to force water away from stone are rare. Thus in an ordinary soil-oil-water system, a large part of the oil is merely mechanically included in the mix or precariously attached to the stone surface. (Fig. 12 A, left.) An effective alteration of the oil affinities results in spreading of the oil and displacement of the water. (Fig. 12A, right.) The respective modes of cohesion of particles, and waterproofing, are shown in Figure 12B, and the makeup of the corresponding soil cells, in Figure 12C

Very noticeable differences in the physical action of the mixes appear at once The treated mix offers more resistance in mixing; the oil disappears into the soil more quickly; and upon compaction, the soil will tolerate much more total liquid When without exudation. liquid is squeezed out of the treated mix, it will usually be pure water, while in the case of the normal mix, it will be a mixture of oil, water, and often colloids. The treated mix will cure more rapidly because the oil hodies are under the water films instead of over them.

The resultant differences in the quality of the stabilization will be illustrated, among other matters, in the soil study which follows.

A Soil Study

It was thought that a study of a single soil, incorporating an illustration of the fundamental features heretofore discussed, would be of interest at this point.





The mechanical analysis of the soil used is as follows

Per cent	Hydrometer, mmg	Per cent
83 1	0 062	30 8
64 9	0 043	298
574	0 0153	26 6
49 1	0 0121	23 8
42 0	0 0078	20 3
368	0 0038	169 -
34 4	0 0016	10 7
	Per cent passing 83 1 64 9 57 4 49 1 42 0 36 8 34 4	Per cent Hydrometer, mmg 83 1 0 062 64 9 0 043 57 4 0 0153 49 1 0 0121 42 0 0 0078 36 8 0 0038 34 4 0 0016

The soil is thus approximately 30 per cent clay with a substantial sand skeleton. The Atterburg constants show a high plasticity index and high shrinkage factor.

The test methods used were as follows ·

The soil was mixed with a water content of 8.5 per cent (Benson's "fluff point") and allowed to stand in an airtight container for 17 hours. It was then mixed in a Kitchen-Aid, Model K, for periods of $\frac{1}{2}$, 1, 2, and 5 minutes, and molded into cylinders 2 in. diameter by 4 in. height, under a pressure of 1000 psi., retained for 1 minute. Double plunger was used for compaction. The cylinders were tested immediately, after soaking for 7 days without curing, and after curing for 7 days at room temperature followed by soaking Testing speed was 0.10 in. per minute, and temperature was 77 deg F.

The cylinders were loaded in a triaxial cell at lateral pressures of zero and 20 psi, and the apparent Mohr's Constant of cohesion, (C), and apparent angle of internal friction, (\emptyset) , determined thereby

The basic stabilizing oil was a standard MC0 of normal California type, termed stabilizer 1. Stabilizers 2 and 3 were modifications of stabilizer 1, having the same rheological properties but differing chemically

The relation between water and oil contents in terms of strength is shown in Figure 13. The relation between water content and specific gravity of the compacted material is given in Figure 14.

Taken together, these form an argument for the use of the "fluff point," which gives strength reasonably near the maximum and gives a reasonable approach to maximum density, except in the 8 per

100 Benson's Fluff Point 90 40°(apparent) C + 175 psi - (apparent) Cylinders 2" by 2" 80 Compressive Strength, psi 74 Oil Content 60 50 40 30 20 Water, per cent on oven-dry weight

Figure 13. Water Content and Stability Soil A, 2 Min. Mix, Uncured, Stabilizer 3



Figure 14. Water-Density Relation. Soil A, Stabilizer 3

cent mix, which contains more oil than would normally be used in stabilization. In this case, the total liquid content for maximum density remains fairly constant. It seems that the water should not exceed the "fluff point."

The 8 per cent mix seems to be on the side of a soil mix, rather than a soil stabilization.

The general relationship found between water absorption and swell is shown in Figure 15, including all the variations in oil content and type of stabilizer. It will be noted that swell was substantially proportional to water absorption where the



Figure 15. Water Absorption and Swell. Soil A, All Phases and Stabilizers, All Stabilizers MC-0.

same curing method was used. In general this rule appears to hold good, but the ratio of swell to absorption differs for different soils. Figure 16 shows the detailed relationship for the various treatments, and explains the scattering of points in the general diagram A phase effect is evident in most cases It is seen that as oil content is increased, the soil will tolerate more water for the same swell This is also generally true of improvement in the stabilizer.

No such simple relationship exists between water absorption and mechanical stability (Fig. 17) Here, phase effect and the differences due to stabilizers, are out of proportion to water absorption, and the trends are complex, although it is true as a broad rule that the higher the absorption the lower the stability An attempt to judge stability by absorption, however, would be quite fallacious Swell is a separate but important factor.

The difference in stabilizers is most important, and particularly in relation to phase effects If we assume that normal previous practice is represented by stabilizer 1 at 1-minute mixing, which appears



Figure 16. Water Absorption and Swell. Soil A, MC-0 Stabilizers, Cured 7 Days, Soaked 7 Days

to be reasonable, then a several-fold improvement is obviously possible by combined phase control and improvement of stabilizers The interrelationship between phase, stabilizer, curing methods, and compressive strength, is shown in Figure 18 Characteristic differences in the original



Figure 17. Water Absorption and Compressive Strength Soil A, MC-0 Stabilizers, Cured 7 Days, Soaked 7 Days



Figure 18. Compressive Strength

strengths appear. The phase effect changes with the stabilizer; the strength before absorption decreases with increasing oil content, as originally indicated in Figure 13; but strength after absorption increases with increasing oil content, in reverse order. Using stabilizers 2 and 3, the strength after curing and soaking overlaps the original strength in the early mixing phases where 8 per cent of oil 18 used.

The form of the phase curves differs from most of those of Benson's curves, due to differences in soil, curing and soaking methods, viscosity and type of oil, and mixers

We now come to the problem of relating mechanical stability as tested in the laboratory, to actual bearing power under a pavement. It is obvious that at some point during the various treatments, this soil passes from a condition in which it would not carry a pavement when saturated, unless hydrostatically confined, to an acceptable bearing power.

At which point does this occur?

A comparison of Mohr's constant of cohesion with the compressive strength, shows that the two are closely proportional in this soil However, the factor of friction is imperfectly represented in the compressive strength, but this factor is very important in bearing power, especially in a confined material of low cohesion The results are shown in Figure 20, giving the theoretical bearing powers, and assuming that the pavement restraint is 0 25 psi. over the base It will be observed that the bearing powers are of the order of ten times the compressive strength. The absolute values are exaggerated, because the cylinders were tested to maximum resistance and hence to a higher degree of deformation than would be permissible in a base.

The stabilizer as a waterproofing agent



Figure 19. Formula for Prandtl Bearing Power (Strip Bearing).

The only known formula which includes cohesion, friction, and paving restraint, is that of Prandtl. This has not been sufficiently compared with actual bearing tests to permit advocacy for use in design as yet, though this is a correlation badly needed. However, it is so well based on known phenomena that it may be considered reliable for comparison of bearing powers. This cannot be accomplished by a simple compression test. The formula, with a graph of its constants for convenience, is given in Figure 19. Formidable as it appears in mathematical form, its use with the graph is merely a slide-rule matter of no difficulty, once the angle of friction and Mohr's constant are known.

has two functions: one, preservation of the hydraulic cohesion, and the other, prevention of hydraulic lubrication. Friction does not always vary to the same extent or in the same direction, as cohesion. Thus there are considerable differences in the stability in terms of bearing power, from stability in terms of compressive strength This will be seen upon comparing Figures 18 and 20 A particularly interesting case is that of the 4 per cent mix with stabilizer 3, showing a sharp phase effect due to high friction in the early mixing stages. Stabilizer 3, in general, shows sharper phase effects in bearing power than it does in compressive strength. The differences between the stabilizers continue to show

up sharply, but in the heavily oiled 8 per cent mix, the differences in the cured mix tend to become less No doubt oiling could be carried so far that differences in the oil would be entirely masked by the massive protective effect of the high oil content; but the bearing power would decrease from excessive lubrication.

Of all the variations shown here, one would choose the 6 per cent mix with stabilizer 2 or stabilizer 3, as optimum.



One unquestionable fact emerges from this study: the relative efficiencies of the three stabilizers It appears then, that comparative evaluation of different stabilizers is the easiest part of an investigation, as the differences will show up by almost any means of comparison which involves exposure to moisture. This emphasizes the fact that waterproofing is the major feature of stabilization.

Similarly, comparisons can be made on all points, with more ease than the establishment of absolute values Taking a given soil, it is not hard to develop its best possibilities in terms of optimum mixing methods, optimum water content, optimum oil content, optimum type of stabilizer, etc. For what conditions the combination is good enough, or too good to the point of being uneconomical, is another question.

Points Requiring Development

Perhaps the problem of a reliable method of exposing stabilized samples to water 1s the principal one which is unsolved The method of soaking for a week immediately after fabrication, 1s unquestionably over-severe. Rapid saturation of the base is the worst condition that could possibly occur in a road, and that seldom; while under any but very abnormal conditions, any soil mix will get considerable curing before being heavily exposed to water.

On the other hand, a well-cured mix in a dry climate will often become saturated by entrapment of water over a long period of time.

The indication is that all test mixes should be cured and also that they should be soaked; but that curing should not exceed normal temperatures and should not extend over the period of time that might be normally expected in practice.

It is highly probable that test methods should be varied according to climate and use. For instance, in building an airfield in parts of Alaska and in many tropic regions, it may be necessary to lay down the soil in intervals between rains or even in rain; and to use the field under such weather and drainage conditions that saturation is to be expected before any effective curing can take place In the above soil study there appear some mixes which would probably give satisfaction even under such extreme conditions, though the soil itself is quite adverse.

As to normal construction, there is considerable need for examination of stabilized soil bases, which have been used under pavements over considerable periods of time. There is scattered material available on this, but not enough for recommendation of a test standard

The second great need is for a correlative study of the various compression, shear, extrusion, and bearing tests in use, and actual bearing power. So far, although various of these have been found acceptable by limited groups, no one of them has yet shown such overwhelming evidence of validity as to achieve general acceptance.

Conclusions

1 It is indicated that it is possible to improve soil stabilization with liquid oils several fold over normal previous practice

2. This may be accomplished by attention to

- a. Proper relation between oil and water content
- b The significance of phase mixing.
- c. Proper curing.
- d. Improvement of and/or proper selection of stabilizer.
- e. Proper selection of stabilizer content.

3. The following is indicated as to control test procedure:

- a. Benson's "fluff point" is a simple and adequate guide to proper water content for mixing and compacting.
- b. Curing should be done in a manner approximating field conditions, at temperatures not over normal and for periods of the order of a week.
- c. Exposure to water should be more severe than capillary absorption methods, but if possible should be adapted to climatic and drainage conditions. If a test of maximum severity is desired, total immersion for a week is sufficient
- d Swell of the immersed soil should be regarded as significant because of

its effect on pavement distortions, but should not be regarded as proportional to loss of bearing power.

- e In a given soil, swell is proportional to absorption, but the proportion decreases with effectiveness of the treatment.
- f For evaluating the comparative efficiencies of various treatments in maintaining mechanical stability against water absorption, a compression test is adequate for practical purposes However, it is not adequate for comparing different soils, and the proportion of bearing power to compressive strength may vary considerably in different treatments in the same soil. For the evaluation of bearing power, both friction and cohesion must be taken into account.
- g An adequate picture of the mechanical behavior of the soil seems to require shear tests under variable normal load, such as triaxial tests, from which the Mohr coefficients can de deduced.

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DISCUSSION ON FUNDAMENTAL RESEARCH IN BITUMINOUS SOIL STABILIZATION

PROF. D. P. KRYNINE, Yale University A correction must be introduced into this remarkably clear and interesting paper. The Prandtl formula which is used by Mr. Endersby for the determination of the bearing power of a pavement, cannot be applied in this case. This is because one of Prandtl's assumptions is an indefinitely deep and indefinitely wide mass As used in the paper, the Prandtl formula furnishes exaggerated values of the bearing power.

MR ENDERSBY Professor Krynine's objection to the use of the Prandtl theory for calculating the actual bearing power of a pavement is quite correct, as is the reason given for it

However, it will be noted that the use of it in my paper is for calculating the relative bearing powers of the different mixes, and not their absolute bearing powers.

The relative bearing powers thus found differ from the absolute in that they are affected by the dimensions of the specimen; in this respect they will be higher than the real, on the other hand, I have reason to suppose that the actual bearing powers in a subgrade are augmented by restraints of a greater effectiveness; in fact, some data at hand indicate that in service some of these mixes give a higher bearing power than shown by the Prandtl formula. The question of an actual service correlation is still open and is under investigation, but it is highly probable that a satisfactory one does exist, for the reason that dimensional effects, while they may cause an exaggeration of resistances, do not in general tend to upset the comparison between materials of different bearing powers I have found evidences of good correlation between the Prandtl formula and the measured results of the California Bearing Test, in which the

dimensions have been chosen in such manner as to minimize dimensional effects to a large degree.

I believe that Professor Krynne will agree that no bearing power, shear, or strength formula, used to interpret the results of a laboratory test of any kind, can be applied with mathematical exactitude to "semi-infinite" masses. In this respect neither the Prandtl formula nor its approximate physical synonym, the California Bearing Test, is in any worse position than, for instance, a laboratory compression test used for the designing of a large concrete beam, or a soil shear test used for foundation design.

In my opinion, the Prandtl formula, with the necessary triaxial tests, is not as well suited for routine design work as simpler methods, but for research has the advantage that the internal factors of resistance can be traced by it

MR. C. L. MCKESSON, Butumals Company Were the residual binders in the MC-2 and MC-0 materials used in the consistency tests the same?

MR ENDERSBY Yes.

MR A HOLMES, Standard Oil Development Company In comparing the relative effects to be obtained by water and oil, the author has employed somewhat viscous oils such as asphalt cutbacks which he calls simply oil This does not permit a true picture of the theoretical aspects involved in the use of such two dissimilar liquids as oil and water because of their vastly dissimilar viscosities. In my opinion, a fundamental study such as has been presented, should preferably have considered liquids of the same viscosities, since viscosity largely determines the rate at which the bituminous material will be displaced by water from aggregates, when this can occur

Although the "clay" contributes to the cohesion of soil, with the aid of water, clay is something more than mineral matter sub-divided to within a given particle size range The binding effect of clay is also dependent upon the mineralogical and chemical nature of the material and upon how its properties are influenced by the action of water.

If the cohesion of a soil were solely dependent upon the shearing resistance, in other words the viscosity of the liquid in a soil-liquid mixture, then all such mixtures made with liquids of the same viscosity and compacted to the same dry soil density would have the same strength. Compacted soil-oil mixtures having much greater strengths than those obtained with water, using equal volumes of the liquids for a given weight of dry soil, can be obtained with low viscosity petroleum oils ranging in absolute viscosity from that less than water, such as naphtha, to that greater than water such as gas oil or light lubricating oil This has also been noted for some organic liquids. These observations were made on a silt-clay soil having 65 per cent passing the No 200 sieve, 19 per cent clay and 10 per cent colloids Excess of either oil or water, single or in combination, prevents maximum soil compaction, the difficulty increasing with increase in viscosity of the oil, a fact which the author has noted.

We are in general agreement with the "plug" theory for waterproofing soils in which liquid bitumens more or less completely plug the capillaries of the previously wetted soil The pre-addition of water to a soil is an essential step to obtaining the uniform distribution of the bituminous liquid binder. Experience teaches that there is an optimum combination of water and oil for each soil and even soils which are ordinarily considered as "good" can generally be improved in quality by treating with water and bitumen.

Our experience does not apparently

agree with that of the author to the effect that dry soils cannot be easily mixed with oil, provided the oil is sufficiently low in viscosity. Although water apparently promotes distribution of bituminous liquid binder in a soil, the addition of too great a quantity promotes stripping and resultant loss in the waterproofness of the mixture, an action similar to that on the coarser aggregate of paving mixtures.

The intimateness of the distribution of the water has a marked effect upon the strength of the compacted mixture. Although this is promoted to a certain extent by allowing the well-mixed soil-water mixture to stand overnight, best results are obtained by wetting the soil with excess water and drying to the desired moisture content. Around 25 per cent greater strength can be thus obtained. The same general effect is obtained for soil-water-bitumen mixtures. A simple way to determine the thoroughness of the liquid distribution in a soil-liquid mixture is to rub out a portion on a plate with a knife or spatula and note the streaks, if any.

We are in agreement that curing bituminous soil mixtures at high temperatures gives misleading results on the indicated waterproofing.

From the opinion that "the longer the water remains in the soil, the greater the stripping action exerted on the oil," one might conclude that all bituminous stabilized soil mixtures will ultimately fail, a very discouraging prospect for the stabilized soil constructions in humid locations From this viewpoint, the 7-day water absorption test does not appear to be severe enough, rather than being too severe.

Although petroleum oils differ in their chemical nature, according to our observations they all exhibit approximately the same affinity for any one mineral aggregate, but differ according to whether the aggregate is dry or wet. In the latter case, the adhesivity or affinity is rather small as . a rule, but can be improved by the addition of certain chemicals or wetting agents We have not found that these greatly alter the surface tension of the oils but do lower their interfacial tension towards water and the mineral aggregate as well as the interfacial contact angles with the aggregates in the presence of water. It is these later factors which determine the preferential wetting of the aggregate by water or the treated oils However, such treated oils do not appear to completely displace the water from the water-wetted aggregate.

MR. ENDERSBY: I agree with most of Mr. Holmes' points. My paper is oversimplified in presenting mainly broad considerations.

The differences in clay are as he states, but the binding agent remains water. This could have been brought out in a fuller presentation.

It is also true that different liquids of the same viscosities have different binding powers according to chemical nature The relation between film thickness and shearing strength is a major factor but there are others. This should have been mentioned, but to explore it fully either theoretically or by test is a rather involved problem. For instance it is thought that special viscosity exists in the neighborhood of a surface to which certain liquids adhere. The practical consideration of compaction has the same bearing in either case, as the action of surface forces depends upon the proximity of surfaces also

I am indebted to Mr Holmes for bringing out that such an organic liquid as naphtha will produce greater strength in soil than water I have not so far experimented with such low viscosities, and would be interested to learn whether a theory exists to explain the matter. It occurs to me that several factors may be involved.

On the mixing of oils with dry soils vs. wet soils, my experience would indicate that the wet mixing is easier, given all other conditions equal. The undesirability of too much mixing water is quite true; in addition to the disadvantage mentioned by Mr. Holmes, it retards curing.

I believe it is well recognized that stripping has a time factor, but this does not necessarily mean that all oil stabilizations will ultimately fail, because even in a continuously wet soil, stripping tends to reach a limit, because the stripping properties of the different particles differ and the initial adhesions also differ. In the case of oils having a high affinity for the soil, stripping of the major amount of surface may be zero to begin with, in which case the time factor cancels out.