INFLUENCE OF PROCESSING PROCEDURES ON STRENGTH OF SAND STABILIZED WITH CATIONIC BITUMEN EMULSION

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This is the first of 2 papers that describe a laboratory study of the factors affecting the shear strength of a uniformly graded sand stabilized with cationic bitumen emulsion. Triaxial tests have been used to ascertain the effects of emulsion content on the cohesion and angle of shearing resistance of stabilized sand. Unconfined compression tests were used to investigate the influence of the viscosity of the base bitumen and also the effect of varying the initial moisture content of the sand. The addition of fillers of various types such as cement, hydrated lime, crushed limestone, and fine sand has been experimented with, and their influence on shear strength has been determined. A study of the effect (on strength) of changing the order of addition of ingredients during mixing is described. The effect of aging on the unconfined compressive strength of stabilized sand is reported.

•IN MANY AREAS of the world, particularly in underdeveloped countries, there is a shortage of natural materials suitable for road construction. In such locations, some form of in situ soil stabilization can often provide an alternative means of construction especially suitable where the intensity of traffic is low. Cement is the most commonly used stabilizing agent; but in the case of fine uniformly graded and rounded sand, often found in arid or semi-arid areas, cement stabilization has not been a particularly successful solution.

Some success has been achieved in stabilizing sands with bituminous binders. A useful bibliography on bitumen stabilization has been published by the Road Research Laboratory (1). This paper is concerned with the use of cationic emulsion for stabilizing medium to finely graded sand, which normally would be difficult to treat.

Two main categories of emulsion exist. The first is the more commonly used "anionic" emulsion, the development of which took place in the 1930's. The other, more recently developed, is "cationic" emulsion, which was first prepared in Europe and has been used on a commercial scale in the United States since 1958 (2, 3). An investigation of the effects of the variables of manufacture on its properties was carried out by Sauterey et al. (4); information on cationic emulsifiers has been published by Armour Hess Chemicals, Ltd. (5).

There was a paucity of information on the properties of sand-cationic emulsion mixes, and the authors considered that it would be useful to carry out a laboratory study of these so that the information would be available to assist highway engineers concerned with mix design, field processing, and curing. Full-scale field tests will doubtless be necessary before reliable specifications can be written, but at least the number of areas of ignorance has been reduced. Two papers will describe the results of this work. This is the first and is concerned with the effects of mixing proportions, mixing process, compaction, and curing on the strength of sand-cationic emulsion mixes.

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Siliceous aggregates have negatively charged surfaces; therefore, cationic emulsions adhere to the great majority of construction aggregates much more readily than anionic emulsions do. This means that bitumen deposited on aggregate surfaces will tend to adhere and will resist being stripped off in the presence of water. This superior adhesion property is the chief advantage of using cationic rather than anionic emulsion and accounts for the superior rewet strength and water absorption properties of soils stabilized with cationic emulsions. Also, because of their affinity to aggregate surfaces, cationic emulsions unlike anionic do not break primarily because of a loss of water and, therefore, do not depend on the slow evaporation of water. Consequently, on breaking, some strength is developed immediately, although this may not be very great. They can, therefore, be used on wet and cool aggregates as well as on dry warm surfaces.

One disadvantage of cationic emulsion compared with anionic is that the mixing stability tends to be low, i.e., the emulsion "breaks" after only a brief period of mixing. This breaking time may be controlled to some extent by selecting various proportions and types of emulsifier; but if the correct selection of these is not made, then inadequate coating will result and the ultimate strength of the mix will be impaired.

CATIONIC EMULSIONS USED

The viscosity of an emulsion starts to rise rapidly when its bitumen content is increased by more than 60 percent (5); hence, all the emulsions used in the investigation had bitumen contents within the range 56 to 64 percent.

Some emulsions were made up with Shell Mexphalt bitumen having a viscosity grade of 190 to 210 penetration and with a cationic emulsifier known as Redicote E11 (6), abbreviated RE11. Initial aggregate coating tests proved that 0.4 percent emulsifier was required to make the emulsion stable enough for adequate coating during mixing. Other emulsions using bitumen with viscosities 90 to 110 and 60 to 70 penetration required 0.6 and 0.75 percent respectively of emulsifier to ensure adequate mixing stability. Generally, mixing stability was improved by keeping the pH values only slightly acidic.

Two other types of emulsion were used. A 90 to 110 penetration bitumen was emulsified with 1.09 percent Duomeen Tallow (5), abbreviated DT and supplied by Armour Hess Chemicals, Ltd. The other type of emulsion, referred to as Lion, was prepared by Lion Emulsions, Ltd. Two such emulsions were used, one having 60 to 70 penetration and the other 40 to 50 penetration bitumen. The properties of these emulsions are given in Table 1.

PROPERTIES OF SAND CHOSEN FOR INVESTIGATION

It was desired to carry out the study by using a sand similar to many naturally occurring sands, which would be difficult to stabilize. Leighton Buzzard sand having the fairly uniform grading shown in Figure 1 was used. Its properties are given in Table 2.

TABLE 1
PROPERTIES OF EMULSIONS USED

Emulsifier		Viscosity (penetration)	Emulsion Viscosity (deg Engler)	Bitumen Content (percent)			pH	Typical Residue on No. 100 Sieve (percent)
Type	Percent			Specified	Measured	At Top of Container After 9 Months		
E11	0.4	190 to 210	15	64	61	1.5	5.7	0.25
	0.4	90 to 110	15	64	60	2.5	5.7	0.25
	0.6	90 to 110	15	64	60	5	5.7	0.25
	0.75	60 to 70	15	58	57	—	4.9	0.25
DT[a]	1.09	90 to 110	15	64	61	58.3	—	0.25
Lion	—	60 to 70	5.4	56	55	39	—	0.05
	—	40 to 50	5.4	56	55	—	—	0.05

[a]Formulation in parts by weight of emulsion was 0.13 percent Duomeen T, 0.13 percent Arquad T50, 0.13 percent Ethoduomeen T/13, and 0.7 percent conc. HCl.

EFFECT OF EMULSION CONTENT ON STRENGTH OF STABILIZED SAND

Because the shear strength of sand is due entirely to its frictional properties, its strength is a function of its porosity and the confining stresses to which it is subjected. The addition of bitumen as a binder has the effect of giving unconfined sand some cohesive strength; but, in general, it also reduces the angle of shearing resistance. Different proportions of bitumen in sand will result in varying values of cohesion and angles of shearing resistance, but it is important to realize that the strength exhibited by stabilized sand may also be influenced by the numerous variables, both natural and man-made (Fig. 2).

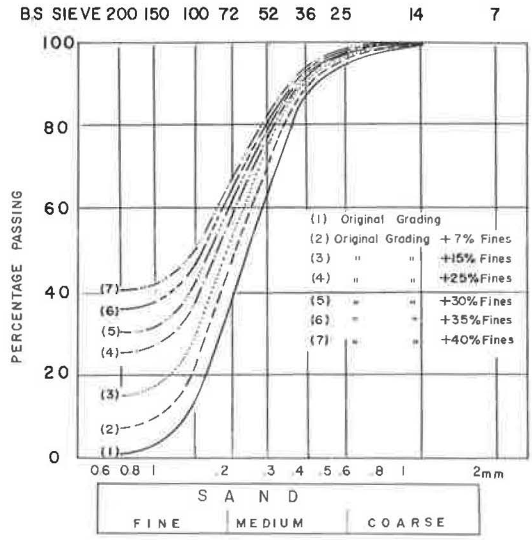

Figure 1. Grading of sand used in the investigation.

For a given sand, stabilized with a particular percentage weight of emulsion, the strength actually measured can vary significantly with type of test used to measure strength; rate of loading; efficiency of mixing; density to which the material is compacted; moisture content; confining stresses to which the specimen is subjected; temperature at which it is mixed, cured, and tested; and age of the specimen.

Because mixes containing different emulsion contents have their strength changed by different amounts by these variables, the optimum emulsion content for one set of conditions is generally different from that for another set of conditions. This is also true of other bituminous-bound materials (8, 9). Hence, it is not possible to think in terms of there being an "optimum" emulsion content to give maximum shear strength, unless most of these conditions are also specified. Further, the emulsion content that gives maximum shear strength under a defined set of conditions will, in general, not be the content at which the highest dry density can be achieved by a given amount of compactive effort. Nor will the specimen having the highest strength necessarily have the greatest stiffness. It is also true that the mix that gives the highest strength may not be the least permeable or may not have the greatest resistance to absorption to water.

TABLE 2

PROPERTIES OF LEIGHTON BUZZARD SAND USED IN STUDY

Property	Amount
Chemical	
Silica, percent	98.81
Alumina, percent	0.35
Other metal oxides, percent	0.54
Ignition loss, percent	0.20
Total	99.90
Physical	
Maximum dry density (B.S. 1377), pcf	101.5
Optimum moisture content (B.S. 1377), percent	10.5
Surface area, cm^2/gram	119.5
Specific gravity	2.65
Angularity (7)	1.1
Sphericity	0.82
Minimum porosity (at 0 percent moisture content), percent	31.3
Uniformity coefficient	1.95
Internal porosity, percent	0.4 to 1.4

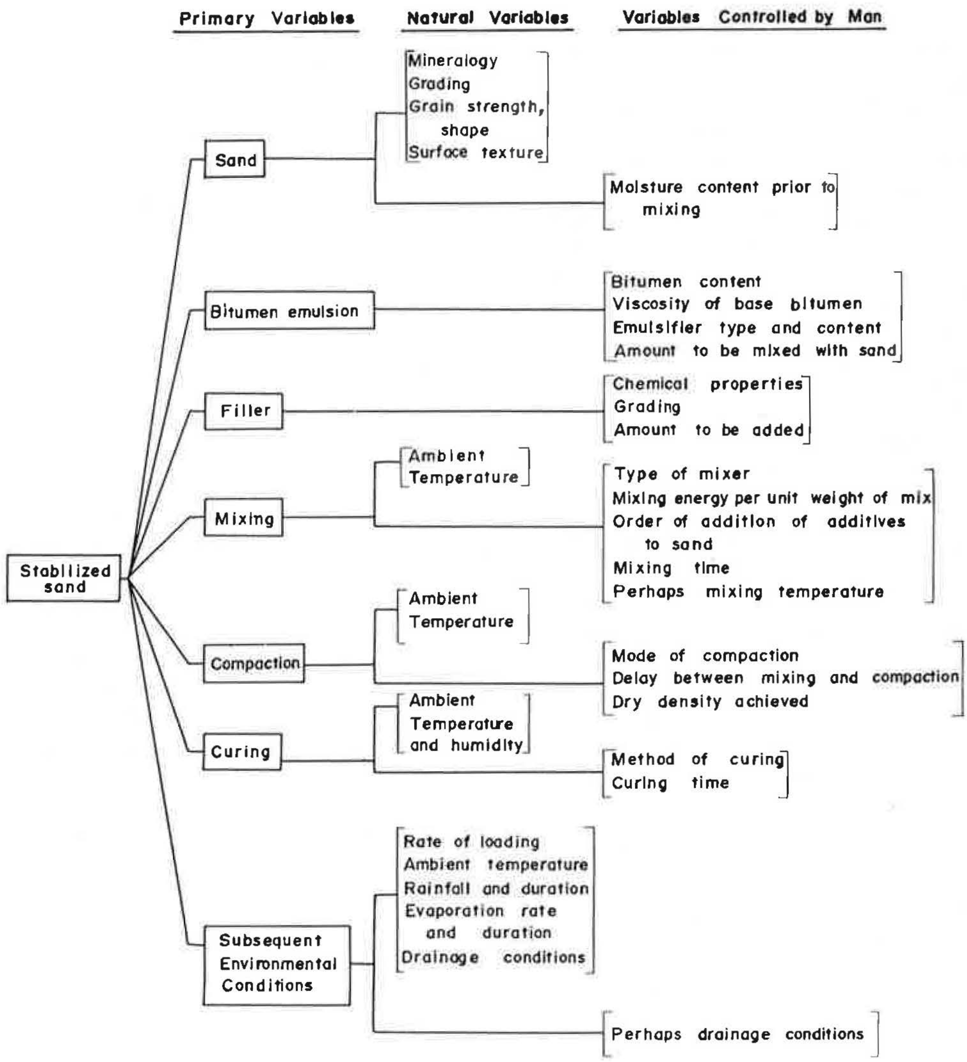

Figure 2. Variables affecting stability of sand stabilized with cationic emulsion.

The influence of emulsion content on shear strength was investigated by carrying out conventional undrained triaxial tests on 4 by 2 in. diameter air-dried specimens. Varying cell pressures (between 0 and 60 psi) were applied to identical specimens so that the apparent cohesion, C_u, and the angle of shearing resistance, ϕ_u, could be determined. All specimens were deformed at a constant rate of strain of 1.1 percent per minute under constant temperature conditions (18 C).

Several batches containing different emulsion and water contents were mixed. Two types of emulsion were used: RE11 with 60 to 70 penetration and Lion with 40 to 50 penetration. Specimens containing 3, 6, 9, and 13 percent RE11 emulsion with respectively 5, 4, 3.5, and 3 percent additional water were made. Other specimens containing 3, 5, and 7 percent Lion emulsion with respectively 3, 3, and 2 percent additional water were also made. The proportions of additional water used approximated those found from previous experiments to give the highest unconfined compressive strengths. All specimens were given standard mixing and compaction as described in the Appendix. Curing consisted of 7 days air-drying, after which the specimens were tested.

The shapes of the stress-strain curves were similar for all specimens in that the maximum deviator stress and the strain at failure increased with increasing cell pressure (in all cases). Typical Mohr circles for 3 percent RE11 are shown in Figure 3. The failure envelopes were very close to straight lines, although they tended to be slightly concave downward. For the purpose of determining C_u and ϕ_u, the straight line that best fitted the results (usually touching the Mohr circles for $\sigma_3 = 20$ and 40 psi) was taken, as shown in Figure 4. The resulting values of C_u and ϕ_u are shown in Figure 5.

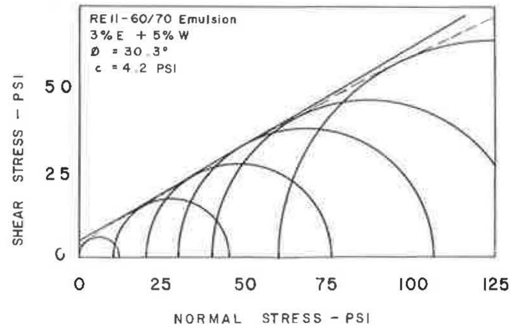

Figure 3. Typical Mohr circles for sand-emulsion mixes.

These show that addition of emulsion to sand has the simultaneous effect of increasing the cohesive strength and reducing the frictional resistance. For the particular conditions of test, maximum cohesion was developed when the bitumen content was about 4 to 5½ percent (7 to 10 percent emulsion). The angle of shearing resistance fell linearly with bitumen content (9).

Some of the tests were carried out with Lion emulsion that had a more viscous base bitumen than the RE11. These specimens yielded a higher cohesive strength as one might have expected, but the angles of shearing resistance measured were apparently unaffected by the type of emulsion used. Lees (9) has also reported that ϕ_u is independent of bitumen viscosity in other types of bituminous mixes.

The results suggest that small percentages of bitumen impart cohesive strength without preventing contacts being formed between sand grains, which are necessary to mobilize frictional resistance. As the proportion of bitumen is increased, the effects are (a) to improve particle coating and increase the area of bitumen that has to be sheared and (b) to increase the VMA and, therefore, reduce the degree of particle interlock and the shearing resistance normally mobilized in dilating the sand. When the bitumen content exceeds the optimum for that set of conditions, the bitumen will tend to act as a lubricant separating the sand particles.

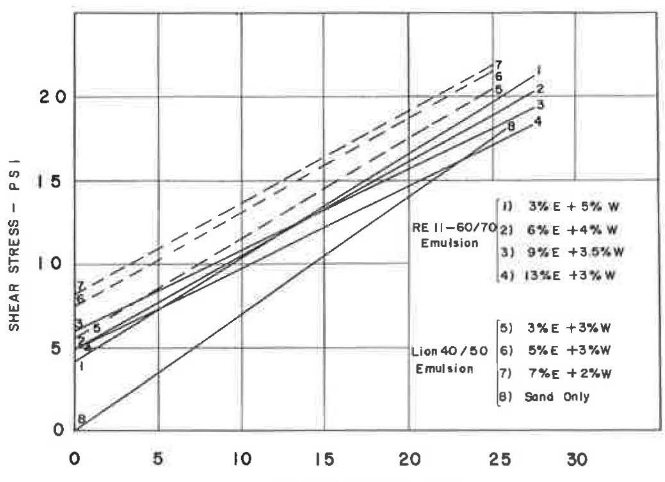

Figure 4. Mohr envelopes for various emulsion contents.

EFFECT OF INITIAL MOISTURE CONTENT OF SAND

From the literature, it can be concluded that the presence of moisture in a soil prior to the addition of emulsion aids the processing of sand bitumen mixes generally in the following ways: It facilitates mixing and distribution of binder; it provides sufficient liquid in the mix to bring it closer to optimum for compaction; and it hydrates any chemically active filler that may be present.

While the presence of moisture may delay the breaking of stable anionic emulsion and the adherence of the bitumen to the surfaces of sand particles, cationic emulsions are not so affected, owing to the preferential absorption of bitumen to negatively charged surfaces.

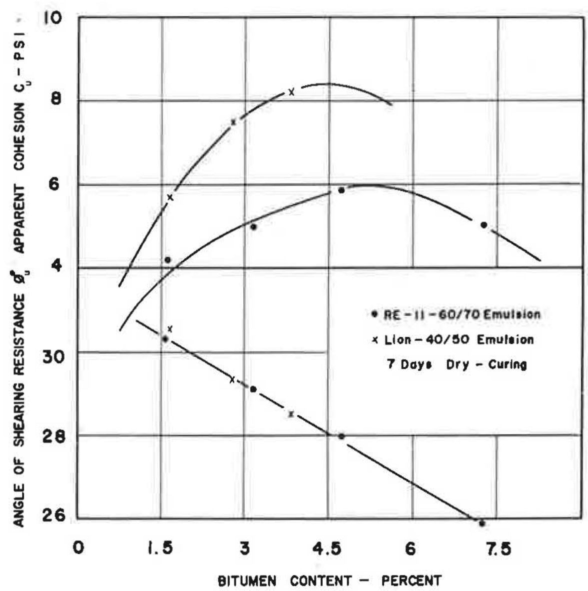

Figure 5. Effect of bitumen content on cohesion and angle of shearing resistance.

The effect of the initial moisture content on the unconfined compression strength of sand emulsion mixes was investigated by testing specimens in sets of three, each set being made up with sand having a different initial moisture content. Results were obtained by using emulsion contents of 3 and 5 percent (Lion with 40 to 50 penetration bitumen). All samples were given the same standard vibration compaction and cured for 7 days in air-dry conditions. The results of these tests, shown in Figure 6, indicated that there was an optimum initial moisture content (3 percent) that gave the highest unconfined compressive strength.

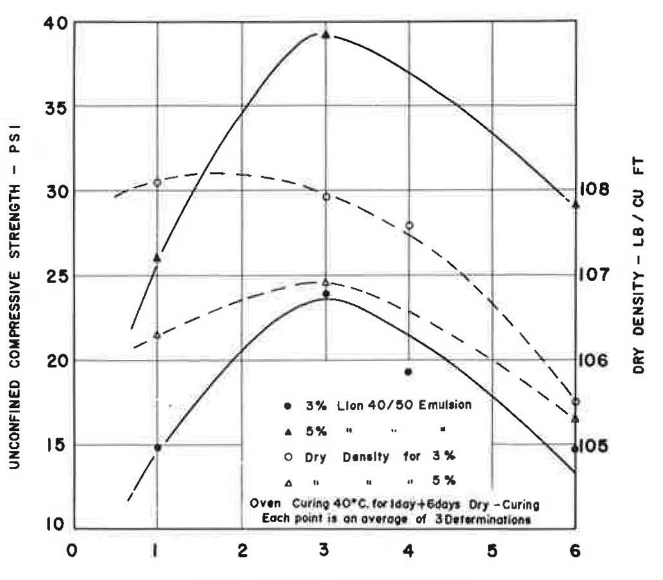

Figure 6. Effect of initial moisture content on strength.

For both emulsion contents, the dry density achieved by compaction was only marginally affected by increasing the initial moisture content from 1 to 3 percent, but the compressive strength increased significantly presumably because of improved distribution of bitumen and coating of the particles. However, it may be seen that, when the initial moisture content was more than 3 percent, the dry density achieved was deleteriously affected and there was a concomitant reduction in strength. It was noted that specimens having an initial moisture content of more than 3 percent became very "spongy" and soft during compaction.

The results of these tests prove that as much water should be present as will not deleteriously affect efficient compaction. If sand is dry, water should either be added to the sand prior to mixing it with emulsion or be added to the emulsion, thus decreasing its viscosity and increasing its mixing stability.

EFFECT OF EMULSION TYPE AND BITUMEN VISCOSITY

A perfunctory investigation was carried out to observe the influence of the viscosity of the emulsion base bitumen on the strength of the stabilized sand and to ascertain whether the type of emulsion affected strength.

Specimens were made up for unconfined compression tests by using varying proportions of different emulsions. The standard mixing and compaction procedure was used, but curing consisted of storing specimens for 7 days in a sealed condition at laboratory temperature.

The results of these tests, shown in Figure 7, reflect the very low strengths typical of specimens that have not been allowed to dry out during curing. It is clear that the emulsions having the lowest base bitumen penetrations or highest bitumen viscosity gave the highest strength. The optimum emulsion content that yielded the highest strength in each case was not the same. The reason for this was not investigated, but differences in emulsion properties such as the stability and the emulsion viscosity suggest that they are responsible.

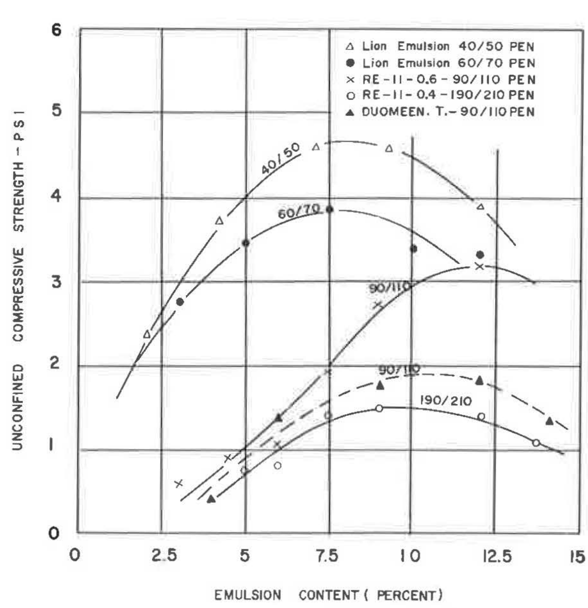

Figure 7. Effect of type of emulsion and viscosity of base bitumen on strength.

EFFECT OF ADDITION OF FILLER

The sand used for the experiments described was uniformly graded and had a relatively low stability compared with materials containing a wider range of particle sizes. It is well known that the addition of fines to a uniformly graded material will have the effect of increasing its mechanical stability. The increase in strength is accentuated if the fines are pozzolanic. This fact is well shown by the results of unconfined compression tests carried out on sand stabilized by addition of filler only. Figure 8 shows how the strength was significantly increased by addition of either cement, hydrated lime, or crushed limestone passing the No. 200 B.S. sieve. The results shown were for specimens mixed with 9 percent water, vibration-compacted to the same density (within practical limits), and wet-cured for 7 days before being tested.

Other sand-filler-emulsion mixes having 9 and 12 percent DT emulsion with 5 and 10 percent hydrated lime and 7 and 12.5 percent crushed limestone dust were made. Standard compaction was applied, and the specimens were tested after 7 days wet-curing. The results of these tests are shown in Figure 9.

As one might have expected from the results shown in Figure 8, mixes containing the higher proportions of filler gave the highest strength. By comparing Figure 8 with Figure 9, it is evident that for samples containing a high filler content the emulsion contributed nothing to the strength. For those containing low amounts of filler, the emulsion increased the strength significantly. Figure 9 might lead one to suppose that there is an optimum emulsion content of about 9 percent giving highest strength, but this is unlikely to be true for specimens of a different age or for specimens cured in a dry instead of a wet condition.

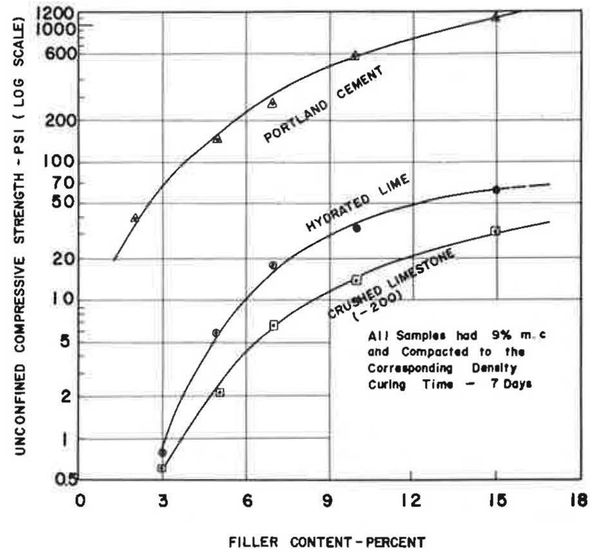

Figure 8. Effect of filler type and content on unconfined compressive strength of sand.

EFFECT OF GRADING OF SAND

A comprehensive study of the effects of grading would alone require a long-term investigation. However, by varying the content of sand passing a No. 200 B.S. sieve, it was possible to study the grading variable that probably has the major influence on engineering properties.

A number of samples of sand were made up to the various gradings shown in Figure 1 by adding various percentages of fine Leighton Buzzard sand passing through a No. 200 sieve. These various samples were stabilized with both 9 and 12 percent DT emulsion, the specimens being prepared, cured, and tested in exactly the same way as described earlier.

Addition of fines had an effect similar to that of the addition of fillers in that it increased strength as shown in Figure 10. However, the strengths resulting from addition of fines were appreciably lower than those achieved by fillers, presumably because of the chemically less active nature of the fines.

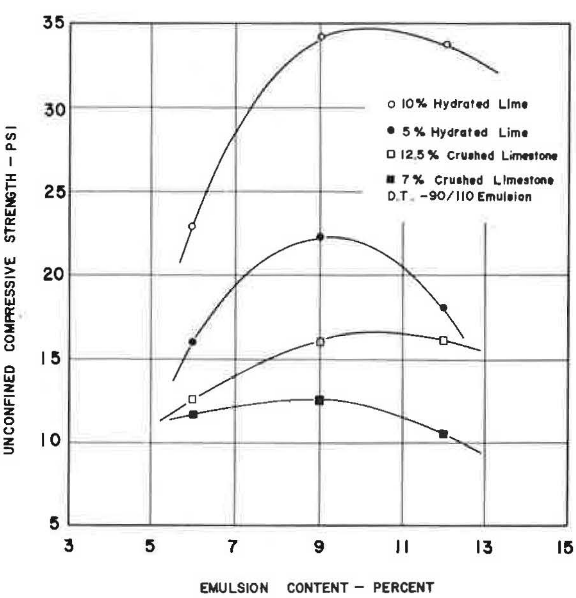

Figure 9. Effect of filler and emulsion on strength.

EFFECT OF CEMENT AND EMULSION ON COMPACTION

Compaction tests were carried out in turn on (a) sand with water, (b) sand plus 10 percent cement with water, (c) sand plus 10 percent cement with various emulsion contents, (d) sand with various emulsion contents, and (e) sand plus various emulsion contents with water.

All materials were mixed in a ½-cu ft paddle mixer. The ingredients were added to the mixer in the following order: sand, distilled water, cement filler, and emulsion. (Experiments on mixing procedure, which were run subsequently, showed that filler should have been added after the emulsion in order to give the highest strength.)

The Kango hammer described in the Appendix fitted with a 4-in. nominal diameter piston was used to compact the material into a standard AASHO mold. Two minutes of vibration were given to each of the 3 layers.

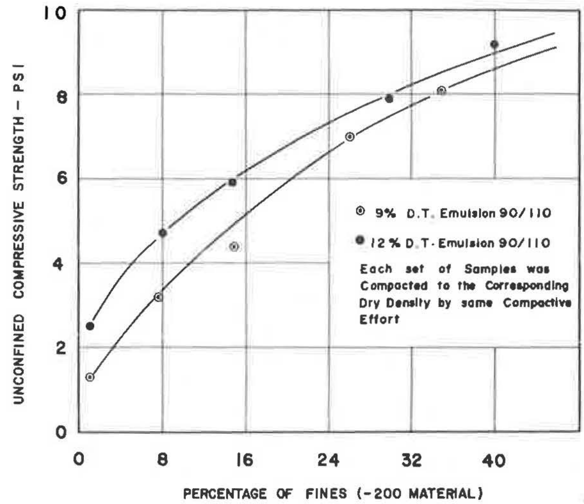

Figure 10. Effect of fines on compressive strength of emulsion stabilized sand.

The results of these tests are shown in Figures 11 and 12. Figure 11 shows the typical compaction curve for sand with its double optima at 0 and 9 percent moisture contents. The addition of cement only to the sand had the effect of increasing the dry density by an almost constant amount over the range of moisture contents tested.

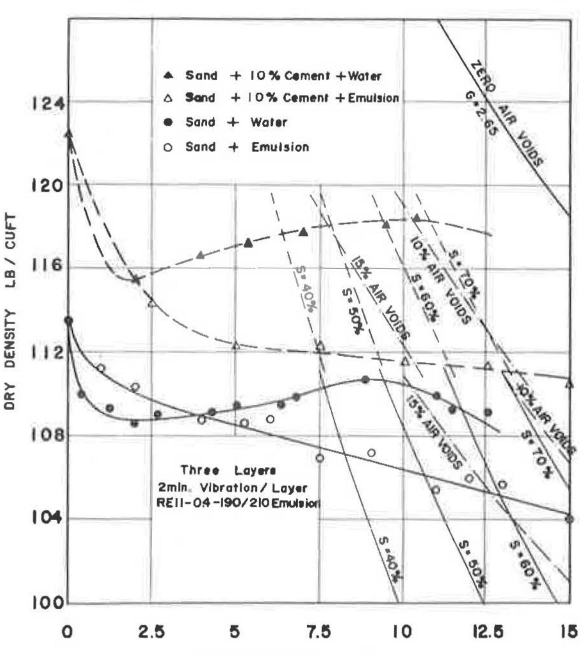

Figure 11. Results of vibrational compaction tests on sand and stabilized sand.

Emulsion had the effect of reducing the dry density, and this fell with further increases in the emulsion content so that there did not appear to be an optimum emulsion content to give maximum dry density. Addition of cement as well as emulsion again increased the density, as one might have expected.

The tests in which both emulsion (RE11 with 60 to 70 penetration) and water contents were varied showed that the addition of emulsion had the effect of decreasing the optimum water content but increasing the optimum liquid content (Fig. 12). Addition of emulsion, however, had the effect of reducing the dry density so that the percentage of air voids at the maximum dry density obtained for each emulsion content only decreased slightly. For practical purposes, it could be assumed to remain constant at about 17 percent air voids.

EFFECT ON STRENGTH AND STIFFNESS

Two series of tests were completed: The first examined the ef-

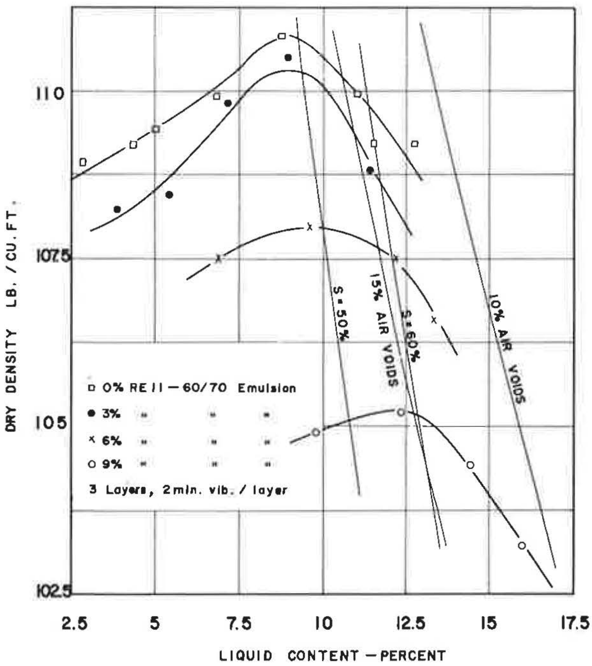

Figure 12. Effect of liquid content on the vibration compaction characteristics of sand-emulsion mixes.

fects of emulsion content with and without 10 percent cement filler added, while the second studied the effect of adding 10 percent cement and emulsion to sand, having varying initial moisture contents. All specimens were compacted by the standard equipment described in the Appendix, but compaction was adjusted so that specimens would have dry densities corresponding to the liquid and cement contents shown in Figure 11. Where the moisture content was adjusted, the dry densities to which materials were compacted were interpolated from the density curve for sand plus cement plus water and sand plus cement plus emulsion shown in Figure 11. All specimens were wet-cured before being tested in unconfined compression.

Figure 13 shows the results of the first series of tests. The effect of addition of cement is obvious, and it is clear that the cement was acting much more as a stabilizing agent than as a filler. The sand containing emulsion without a cement filler had a strength of only a few pounds per square inch.

Figure 14 shows that, for different emulsion contents, different quantities of water had to be added to give maximum strength, and the optimum liquid content increased with increase in emulsion content.

It was evident that the presence of emulsion only contributed to the strength of the sand-cement mix when the moisture content was low and that emulsion added to mixtures having adequate water for hydration of the cement had a marked detrimental effect on strength. Addition of emulsion also resulted in a concomitant reduction in stiffness as measured by the slopes of the stress-strain graphs obtained.

From this, it may at first sight be concluded that, if it is economical to use cement as a filler, it would be better to stabilize the sand with cement rather than to add emulsion. This would be true if unconfined compressive strength were the only criterion for satisfactory stabilization. However, a sand-cement mix is very stiff and, when laid on a relatively flexible sand subgrade, may well fail in tension when loaded. According to Burmister's analysis of a 2-layer elastic system, if the top layer is very

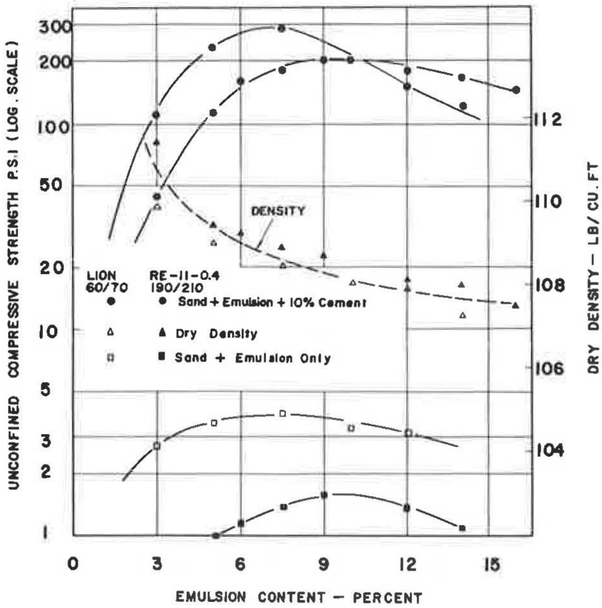

Figure 13. Effect of emulsion content on the compaction and strength of stabilized sand and sand-cement.

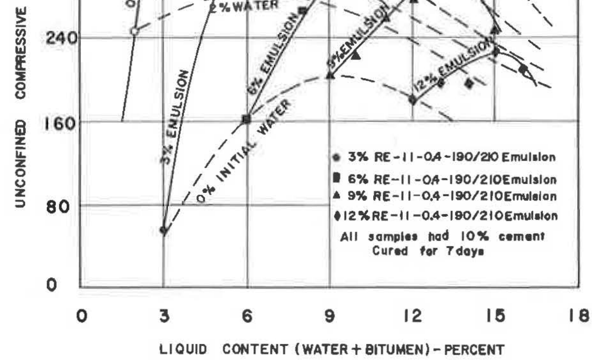

Figure 14. Effect of moisture and emulsion content on 7-day strength of cement-emulsion stabilized sand.

stiff relative to the subgrade, it is subjected to high tensile stresses on the interface between the 2 layers. If the stiffness of the top layer is reduced, the effect is to reduce the tensile stress in the material at the expense of a small increase of shear stress in the subgrade. Although the stiffness or modulus of deformation of a cement-stabilized sand may be of the order of 10^5 to 5×10^5 psi, the modulus of bitumen-stabilized sand is of a lower order around 10^4 to 10^5 psi, depending on the density, bitumen, and water content. Hence, although soil cement has a high compressive strength, it may fail in tension while a more flexible material with a lower compressive strength may well survive under the same loading conditions.

EFFECT OF MIXING PROCEDURES

A study was made of the effect on the 7-day compressive strength first of the mixing time and second of the order of addition of ingredients during mixing. In both cases Lion emulsion with 60 to 70 penetration was used. In the first study, 3 different liquid contents were selected: 6 and 9 percent emulsion with no water and 6 percent with 3 percent water. All batches (having a constant weight of sand) contained 2 percent cement that was first mixed dry with the sand before addition of emulsion and water. The batches were all mixed in a food mixer set at constant speed. The effect of mixing times varying between 7.5 and 240 seconds were studied. After mixing, specimens were prepared, each being compacted to the same density. After curing under sealed conditions for 7 days, specimens were tested in unconfined compression. All mixes increased in strength during the initial stages of mixing. They then reached a maximum strength from which they fell slightly as the mixing time was extended. The specimens with 9 percent liquid content reached their peak strength after only 15 seconds of mixing, while the mixture with only 6 percent emulsion required an optimum period of 30 seconds. It was apparent that mixing times in excess of optimum resulted in slight stripping, but the loss of strength was not great.

To investigate the mixing order, i.e., the order in which the ingredients should be fed into the mixer, 8 different combinations were studied (the letters S, E, W, and F denote sand, emulsion, water, and filler respectively and are arranged to represent the order of addition): SFEW, SFWE, SEWF, SEFW, SWFE, SWEF, SF/EW, and SW/F/EW. These 8 batches each containing the 7.5 percent Lion emulsion, 2.5 percent water, and 5 percent cement filler were mixed in a ½-cu ft concrete mixer for a total period of 1.5 minutes. The individual ingredients were added to the sand one at a time at intervals of about 10 seconds. All specimens were then compacted to the same density and cured for 7 days in a sealed condition before being tested. The results of the unconfined compression tests obtained for each of the 8 orders of mixing are shown for comparison in Figure 15. Each strength plotted represents the average from 4 tests. This demonstrates the important difference that the order of addition can make to the strength of otherwise identical mixes.

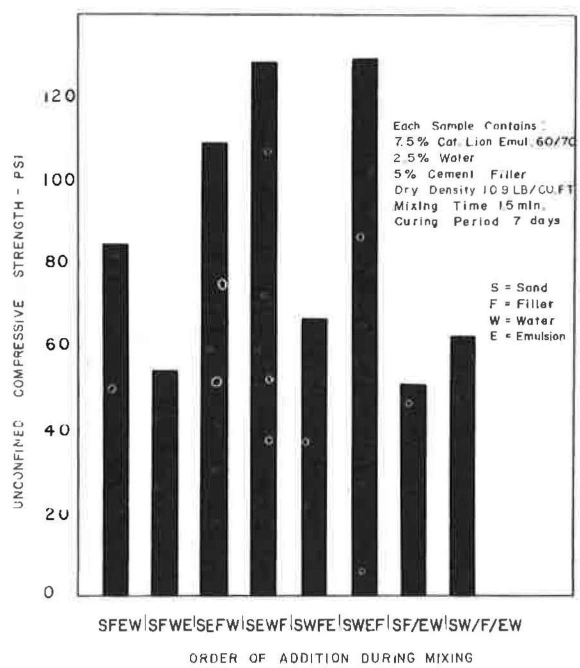

Figure 15. Effect on strength of the order of addition of ingredients during mixing.

It will be noted that the highest strengths were obtained by adding the filler last, while the lowest strengths were obtained by adding the cement filler first to dry sand. Presumably, the reason for this phenomenon is that, when the cement is added last, the bitumen has a chance to adhere to the surfaces of the sand particles before the cement is added. When the emulsion is added to a sand cement mix, the greater affinity of bitumen for the finer particles might result in poor coating of the sand.

CURING

During the initial stages of the investigation, specimens were compression-tested after being cured under sealed conditions for a period of 7 days at laboratory temperature. The strengths of these specimens were found to be very low, and it was appreciated that, when no active filler such as cement was to be added, a more appropriate method of curing would be to allow the specimens to dry out before testing. Similar conditions of air-drying would probably be more prevalent on construction sites than would soaked or sealed conditions.

A study of the effect of curing time was carried out by using specimens stabilized only with 6, 9, and 13 percent of RE11 emulsion with 60 to 70 penetration mixed with additional water contents of 4, 3.5, and 3 percent respectively. Compacted specimens were air-cured for periods varying between 1 and 12 weeks. Figure 16 shows their unconfined compressive strength plotted against bitumen content for different ages.

The interesting point to note is that, whereas at 7 days there appeared to be an optimum bitumen content of 5 percent, after 2 weeks the specimens with 7.4 percent bitumen had increased in strength more than those with lower bitumen contents, and the optimum bitumen content appeared to have increased. Hence, within the range of economic proportions of emulsion, the more emulsion that is added the higher the long term strength is likely to be under conditions of dry-curing.

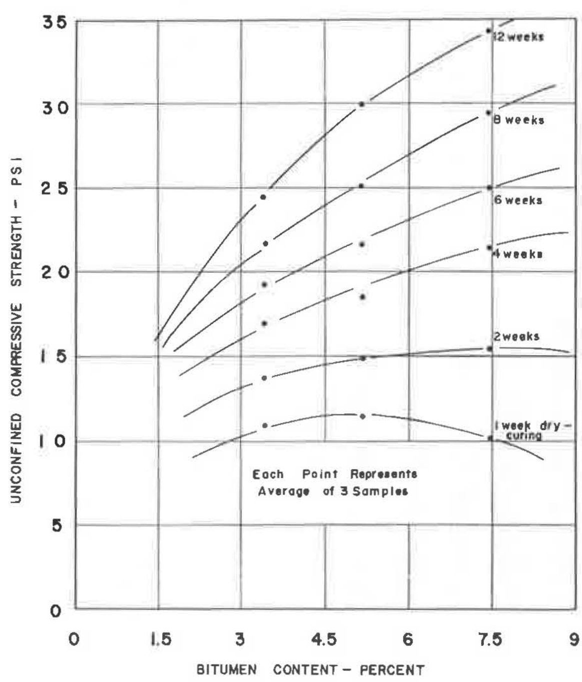

Figure 16. Effect of curing period on strength of emulsion stabilized soil.

CONCLUSIONS

When specimens of cationic emulsion-stabilized sand were triaxially tested after 7 days of dry-curing, an emulsion content in the range from 7 to 10 percent gave the highest cohesion, C_u. The angle of shearing resistance, ϕ_u, of the sand was reduced in proportion to the percentage of emulsion added but was independent of the viscosity of the base bitumen.

The presence of some water in the sand had the effect of increasing the ultimate 7-day strength of air-dried stabilized specimens. It was shown that as much water should be present during mixing as will not deleteriously affect compaction.

The unconfined compressive strength of sand-emulsion mixes was shown to be greatest when the emulsion was made with the lowest penetration grade of base bitumen.

The addition of filler to the uniformly graded sand had the effect of increasing the dry density achieved by a given amount of compactive effort and improved the mechanical stability of the sand. Cement filler greatly increased the compressive strength of sand-cement-emulsion mixes and was clearly acting more as a stabilizing agent than as a filler. These mixes, however, combined high strength without the accompanying brittleness of cement-stabilized material.

Other fillers such as hydrated lime, crushed limestone dust, and sand fines were effective in increasing strength, though to a lesser degree. This is supported by shear strength measurements in the field by Marais (10) who showed that sand-filler-emulsion mixes had strengths considerably higher than mixes lacking filler. It is recommended that, in circumstances where uniformly graded sand is to be stabilized with emulsion, a filler should be added if economically possible.

When a filler was added to a mix, it was demonstrated that the order in which ingredients were added affected the ultimate strength of the material. The highest strength is obtained by always adding the filler last after the other ingredients have been given a preliminary mix.

The compressive strength of emulsion-stabilized sand was shown to significantly increase with age. Tests on specimens cured for 3 months in air-dry conditions showed that (within the limit of economic proportions of emulsion) the more emulsion used, the higher the strength was.

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Appendix

STANDARD PROCEDURE USED FOR SAMPLE PREPARATION

Mixing was carried out either in a ½-cu ft, 500-watt, pan type of concrete mixer (for large batches) or in a 150-watt Sunbeam food mixer. A known weight of oven-dry sand was fed to the mixer, and then water (if any), emulsion, and filler were added. Mixing was continued until no better coating could be achieved. Unless otherwise specified, 2-in. wide by 4-in. high split molds similar to those described in B.S. 1924 were used. The only difference was that an inner liner of cardboard or perspex tube was used, so that a 2-in. diameter specimen enclosed in a protective cover could be extruded from the mold. This prevented disintegration of the specimens during extrusion.

Compaction was by means of a vibrating Kango type L hammer with a 2-in. nominal diameter plunger. The hammer weighs 15 lb, has 400-watt power, and has a frequency of 2,100 cycles/minute. The standard procedure was to apply 20 seconds of vibration to each of the 3 equal layers. For some experiments, however, as explained earlier, the amount of compaction was adjusted by trial and error to produce a specimen of a required density.

During compaction, the remaining mix was covered to prevent loss by evaporation. On completion of compaction, the nuts clamping the molds were slackened, and the liner tubes containing the samples were extracted. When specimens were wet-cured, the lining tubes were sealed top and bottom and stored for 7 days at 18 C. Before testing, the liners were split down the side and the samples released intact.

Where specimens were dry-cured, they were ejected from perspex liners out of which they were more easily released than from standard split molds. The specimens were then left to cure by exposure to the laboratory atmosphere for 7 days, after which they were weighed, measured, and tested.