Granulometric and Volumetric Factors In Bituminous Soil Stabilization

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• THE DIFFERENT TYPES of soil-bitumen, the same as other man-made construction materials, were developed empirically before the fundamental scientific factors were recognized and assayed. Respective general specifications still bear the marks of this empirical development. This leads quite often to a misunderstanding of the physical purpose they are supposed to serve and to an all too strict adherence to the letter rather than the meaning of the specifications. The results are structures that not only cost more than they should but also do not represent the optimum in obtainable quality. This situation obviously calls for an analytical approach.

In a man-made construction material two sets of factors are important. One is concerned with the ease or difficulty of making a uniform mixture of the ingredients and of placing, densifying, and finishing this mixture. The other is concerned with the final properties of the structure in which the material is used, the most important of which are resistance to mechanical and weathering forces. Usually a compromise is made between the two sets of requirements, especially early in the development of the art when the available equipment imposes its own limitations on the properties of the final material in the structure. Improvement of equipment and technology moves the limit of compromise towards greater perfection of the material. An excellent illustration of this is the effect which the introduction of vibration has had on concrete technology. To "freeze" early equipment limitations into standard specifications for a construction material is costly and an impediment to progress.

EMPIRICALLY DEVELOPED TYPES

The Highway Research Board Bulletin on "Soil-Bituminous Roads" (*1*) lists the following empirically developed types:

1. Soil-bitumen proper, a waterproofed cohesive soil system.
2. Sand-bitumen, a system in which loose beach, dune, or other sand of similar character is cemented together by bituminous material.
3. Waterproofed granular stabilization, in which the soil material possesses good gradation from coarse to fine constituents, meeting certain high potential density requirements, and is waterproofed by uniform distribution of small amounts of bitumen.
4. Oiled earth, in which the surface of an earth road is made water-resistant by the application of slow or medium curing road oils.

The areas of application of these different types have been circumscribed by certain granulometric and consistency factors. These are given in Table 1. Accordingly, soil-bitumen proper may be made from all H.R.B. Classification soil types except A-1a, A-3, A-2-5, A-2-7, A-5, and A-7. Sand-bitumen can be made of A-3, A-1b, and certain sandy A-2 soils; A-1a, A-1b, and the coarser grained A-2 soils lend themselves to waterproofed granular soil stabilization. This overlapping shows a lack of definition of the empirically developed types of soil bitumen. Furthermore, there are definite discrepancies. If, for sand-bitumen, up to 25 percent of −200 material is allowed only in the case of a narrow gradation of the sand and less than 12 percent for a wide gradation, why is 13 to 30 percent of −200 material allowed in the wide gradation of Type C of waterproofed granular

TABLE 1
TYPES OF SOIL-BITUMEN AND CHARACTERISTICS OF SOILS EMPIRICALLY FOUND SUITABLE FOR THEIR MANUFACTURE

Sieve Analysis	Soil-Bitumen[1], %	Sand-Bitumen, %	Waterproofed Granular Stabilization, %		
			A	B	C
Passing:					
1½ inch			100		
1 inch	[2]		80-100	100	
¾ inch			65-85	80-100	100
No. 4	> 50	100	40-65	50-75	80-100
No. 10			25-50	40-60	60-80
No. 40	35-100		15-30	20-35	30-50
No. 100			10-20	13-23	20-35
No. 200	10-50	< 12; < 25[3,4]	8-12	10-16	13-30
Characteristics of Fraction Passing No. 40 Sieve					
Liquid limit	< 40				
Plasticity index	< 18		< 10; < 15	< 10; < 15	< 10; < 15[5]
Field moisture equiv.		< 20[3]			
Linear shrinkage		< 5[3]			

[1] Proper or general.
[2] Maximum size not larger than 1/3 of layer thickness; if compacted in several layers, not larger than thickness of one layer.
[3] Lower values for wide and higher values for narrow gradation band of sand. If more than 12 percent passes, restrictions are placed as indicated on Field Moisture Equivalent and linear shrinkage.
[4] A certain percentage of —200 or filler material is indirectly required to pass supplementary stability test.
[5] Values between 10 and 15 permitted in certain cases.

soil stabilization? Also, for all soil-bitumen types a certain minimum content in —200 material is either specified directly or implied by the stability test requirements, notwithstanding the fact that numerous successful soil-bitumen constructions have been executed in which the soils contained no —200 material. Obviously, a need exists for a rational reexamination of bituminous soil stabilization.

If the purpose of soil stabilization is to improve the bearing capacity of a soil and/or to maintain it at a certain level, the better the original soil is in this respect the less improvement is needed. The Highway Research Board Subgrade Materials Classification gives a general rating of the quality of soils as subgrade materials based on granulometric and consistency factors. Although this system is of empirical origin, it possesses in its present form a definite theoretical substructure. Also, a very large amount of experimental work performed in the author's laboratory has shown that the group index which is part of the H.R.B. Classification is an excellent indicator of the susceptibility of soils to bituminous and resinous stabilization.

The main stability factor with or without bitumen of the A-1, A-2, and A-3 soils is the friction and interlocking of the granular constituents; the maximum of 35 percent allowed for the A-2 soils makes certain that the silt-clay portion does not effectively interfere with this mechanical stability factor. Admixture of bitumen or of filler material to A-1 and A-3 soils can only have the purpose of supplying cohesion or of decreasing the permeability of the system. Admixture of bitumen to the A-2 soils may be for the purpose of supplementing the natural cohesion, of modifying the water affinity of the —200 material and of lowering the permeability of the system. The importance of the granular bearing skeleton reaches into the group of silt-clay materials to a maximum clay content of about 20 percent (*2*). The exact percentage is a function of the water affinity of the clay fraction. Wherever such a bearing skeleton exists, the amount of bitumen added must be kept sufficiently low not to interfere critically with the continuity of the skeleton. Bituminous stabilization of silt-clay materials with more than 20 percent of clay becomes increasingly a problem of waterproofing that can be solved successfully only by application of surface chemistry.

RATIONAL SYSTEM OF SOIL-BITUMEN TYPES

The methods of bituminous soil stabilization group themselves logically in the following manner:

I. Systems with granular skeleton as main mechanical strength factor either open (without −200 material) or dense (with −200 material).
  (a) Bearing skeleton: coarse aggregate
    1. Bitumen-bound gravel-sand mixtures, open
    2. Waterproofed granular soil stabilization, dense
  (b) Bearing skeleton: sand
    1. Bitumen-bound sand (without −200 material), open
    2. Sand-bitumen (with −200 material), dense

II. Waterproofed silt-clay materials
  (a) Silt component forming or participating in formation of granular bearing skeleton; clay fraction less than 20 percent of the −200 material;
  (b) Systems with predominant clay fraction.

Practical examples of these systems are:

I. (a) 1. Tar-bound river and bank gravels presently employed for base construction in Western Germany.
    2. Bituminous compositions developed by McLeod in Canada.
  (b) 1. Beachhead stabilization methods developed by the author for the U. S. Navy Department (*3*).
    2. Sand-bitumen in Florida and California.

II. (a) Loess soil stabilization in the vicinity of St. Joseph and Washington, Mo.
  (b) Clay soil stabilization in northern Missouri.

GRANULOMETRIC CONSIDERATIONS

Granulometry is concerned with size, shape, and gradation of particles; their arrangement and packing into multi-particulate uncemented or cemented systems; and the physical properties of such systems as influenced by the particulate components. The science of granulometry was founded by Feret in connection with his classical work on hydraulic mortars (*4*). This science has found widest application in the field of concrete proportioning where men like Fuller (*5*), Abrams (*6*), and Rothfuchs (*7*) followed in the footsteps of Feret. However, as Feret already stated, the principles of granulometry are of a geometrical character and are not bound to a particular grain size range. They hold for coarse and fine aggregates, for silt and clay materials, and even for systems in which the effective particles are atoms and molecules, as in liquid melts or in crystalline solids. It is worthwhile, then, to see what the laws of granulometry can tell about bituminous soil stabilization.

It is important to realize that the rules of granulometry as normally applied to mortars and concretes have been developed for mixtures of "workable" consistency. In fact the term and concept "normal consistency" originated from Feret's work. The numerical relationships between maximum density and gradation of granular systems derived by Feret (*4*), Fuller (*5*), and others (*8*) actually hold only for a relatively loose packing of the coarsest component. Narrowly graded material in this condition, which may be achieved by simple pouring with or without rodding, usually has a voids volume of about 50 percent. Many natural deposits of granular materials possess this voids volume, which may almost be considered a natural constant because it also corresponds closely to the average packing of molecules in solid systems. In other words, this is the condition of minimum packing effort, hence of easiest workability. Obviously, for greater packing efforts, such as are now widely used in soil stabilization, and with more effective packing methods, the quantitative

TABLE 2
DENSITY OF SAND FOR DIFFERENT CONDITIONS, MOISTURE CONTENTS, AND PLACEMENT METHODS; AFTER R. FERET

Condition and Placement Method	Water and Air Voids, %
(a) Dry sand poured with scoop into 50-l. measure	45
(b) Sand with increasing moisture content poured as in (a)	45 to 56.7
(c) Dry sand poured into 1-l. measure	44.5
(d) Dry sand poured and shaken into 1-l. measure	35
(e) Water-saturated sand placed into a 1-l. measure	37.5

expressions of the laws of granulometry must be changed correspondingly.

Feret already realized the importance of packing effort and procedure on the density obtained, as is evident from some of his data reproduced in Table 2. Winterkorn (*9*) pointed out the analogies existing between molecular and macromeritic systems (gravel and sand assemblies), especially with respect to the voids volumes at the densest (T_0), melting, and boiling states (see Table 3). According to this concept granular material at its greatest obtainable density corresponds with respect to volume relationships to the solid state of atomic and molecular systems at the absolute zero temperature, whereas at the critical voids ratio the state of the granular material is analogous to that of molecular assemblies at their melting points. For easiest placement of granular systems they must be in the "molten" condition with respect to the volume relationships of the coarsest components. This is the case for mortars and concretes of normal consistency or workability. After setting and hardening of the cementing materials the coarse aggregate has volume relationships corresponding to those of cubical packing. This can give strong systems if the cements themselves furnish good mechanical resistance.

For workable plastic concretes the consequence is the water-cement ratio law of Abrams, which is a specific expression of Feret's more general law. However, for cementing materials that are essentially high-viscosity liquids, such as most bitumens, the granular mixtures must be so designed and so densified that the absolute volumes of the granules that form the bearing skeleton are greater than at the critical voids ratio for these granules taken by themselves. In other words, a well-designed and sufficiently densified bitumen-stabilized granular soil (sand-bitumen, waterproofed granular systems, etc.) must expand if sheared. The greater the expansion the greater is the inherent mechanical stability of the system. This, not gradation, is the most important design criterion for all Type I soil-bitumen systems.

With respect to permanency of this stability it is required that neither exposure to severe moisture condition nor the effect of freezing and thawing, occurring at the place of use of such systems, will result in a decrease of the absolute volume occupied by the bearing skeleton to such an extent that shear can take place without expansion. Whether soil-bitumen systems of Type Ia and b should be endowed with lowest possible water permeability by filling the interstices between

TABLE 3
PHASE-VOLUME RELATIONSHIPS FOR DIFFERENT TYPES OF PACKING AND FOR MAXIMUM DENSITY, MELTING AND BOILING CONDITIONS

Packing	Voids, % Densest or T_0	Melting	Boiling
Rhombohedral	25.9	38.8	47.8
Cubic	47.6	56.7	63.1
Lorenz[1]	53.3	61.4	67.1

[1] Average packing of atoms and molecules in simple solids.

the bearing granules with −200 material of a composition and character to just fill the available pore space at maximum natural moisture content (F.M.E.) depends on the characteristic of the subgrade. The more water-susceptible the stability of the subgrade soil is, the less pervious should be the base. Important aspects of this phase have been treated in previous work (*10*).

PRACTICAL APPLICATIONS

Stabilization of Beach Sand for Military Purposes

It is outside the scope of this paper to describe in detail the application of the previously stated principles to all possible types of soil-bitumen. For purposes of illustration, the design procedure for beach sand stabilization with resinous cementing agents is chosen. It has been found that such systems follow Feret's strength law

$$S = K \left(\frac{C}{1-s} \right)^n \qquad (1)$$

in which

S = compressive strength;
K = essentially the strength of the cement, but influenced by material and packing;
C = absolute volume of the cement;
s = absolute volume of the sand; and
n = constant depending on material and geometrical factors.

Also, it has been found that different sands require satisfaction of their surface adsorption before Feret's law comes into play. The amount needed for this satisfaction is the product of a material's constant a and the absolute voids volume of the densified sand. Table 4 presents a simple practical classification of beach sands, together with characteristic data needed for design. The design for a certain compressive strength is performed in the following steps:

1. Classify the sand in question by means of Table 4.
2. Determine specific gravity and unit weight to which sand can be densified by a vibration method giving results comparable with those obtained in field construction; with these values determine absolute volume of voids by means of Fig. 1.
3. Take representative absorption factor in Table 4 and use to find absorption requirements of sand by means of Fig. 2.
4. Select desired compressive strength and find from Fig. 3 the ratio of cement

TABLE 4
CLASSIFICATION AND CHARACTERISTIC DATA FOR BEACH SANDS

Type of Sand	Average Sp. Gr.	Rodded Unit Weight, lb/cu ft	Factors		
			a	K	n
I. Quartzitic-siliceous:					
(a) Pure quartz, spherical shape such as Ottawa sand	2.5-2.8	100 +	0.035	1,200	1.4
(b) Predominantly siliceous, various shapes, colors grey to yellow	2.5-2.8	100 +	0.075	5,000	2.0
II. Igneous rock fragments:					
(a) Volcanic ashes and cinders	2.3	80	0.100	10,000	3.0
(b) Intermediate	2.3-2.65	80-100	0.088	10,000	3.0
(c) Dense basaltic, rheolitic	2.65 +	100 +	0.075	10,000	3.0
III. Calcareous					
(a) Corals	2.4-2.5	80-100	0.100	7,500	2.5
(b) Shells	2.5	80-100	0.075	3,000	1.75

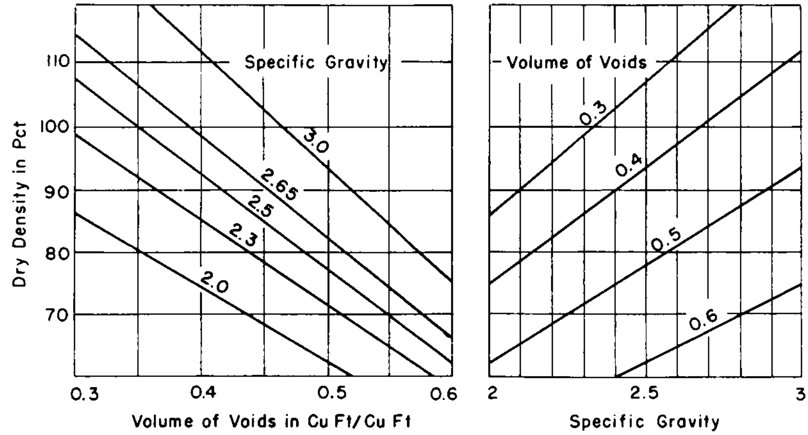

Figure 1. Relation between unit weight, specific gravity, and volume of voids.

to voids volume that gives desired strength for the sand concerned.

5. Read from Fig. 4 the amount of stabilizer required for cement voids ratio determined in Step 4. Add this amount to absorption requirements determined in Step 3. Sum gives total amount of cementing stabilizer required.

This design is for the case where the binder substance forms a strong solid or plastic cement. The particular curves are for compositions containing aniline, furfural, and pentachlorophenol. Even higher *K*-values can be obtained by other formulations based on the aniline-furfural reaction (*11*). Figures 5, 6, and 7 show

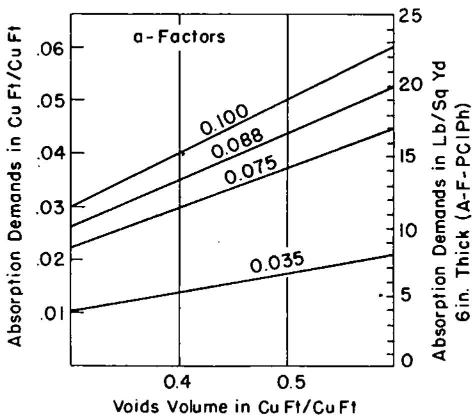

Figure 2. Amount of stabilizer required for absorption demands.

the practical application of this beach stabilization method.

Waterproofing of Silt-Clay Materials

With increasing clay content of these materials surface-chemical factors play an increasingly important role (*12, 13*). These factors and the improvement of bituminous stabilization by various admixtures have been discussed at length in the literature. However, much laboratory and field experience indicates that volume relationships are important even in these systems. On one hand, there exists a minimum amount of bitumen that can be uniformly mixed with a cohesive soil; on the other hand, there are maximum amounts that cannot be exceeded without seriously lowering the mechanical resistance of the soil-bitumen system even in dry state. Obviously, only a portion of the absolute volume not filled with soil solids should be filled with bitumen. For average mineral composition of soils the amount of bitumen to be employed becomes a function of the dry density of the compacted soil system.

Fig. 8 gives a proportioning guide with a suggested range of bitumen content to be used in trial mixtures. The method employed by the author is as follows:

1. Determine optimum moisture content and maximum dry density of soil-water mixtures by use of the Dietert

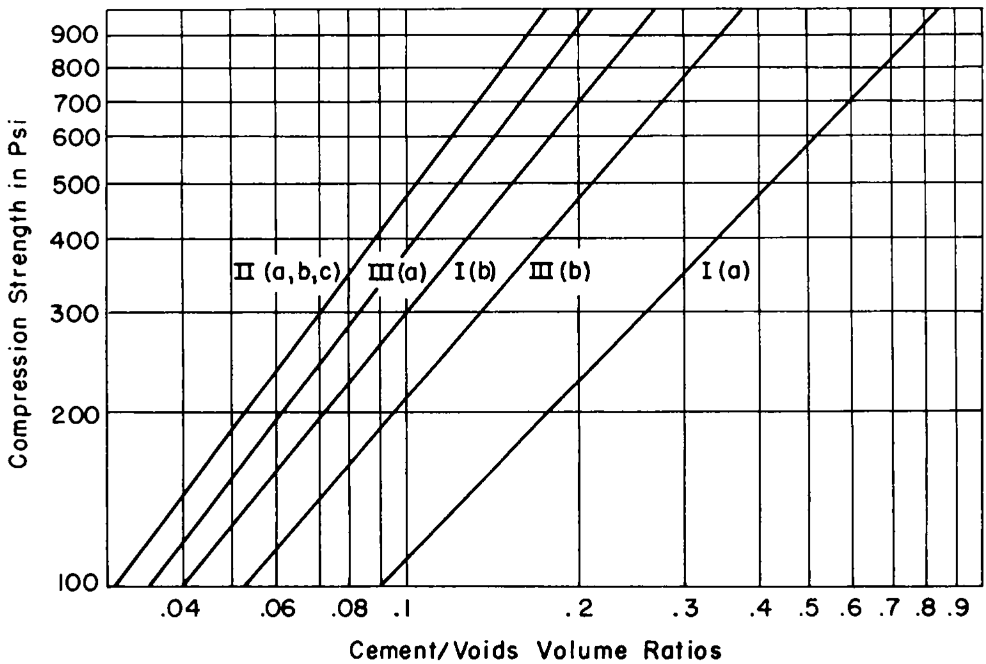

Figure 3. Cement/voids volume ratios for desired compression strength and various sand types.

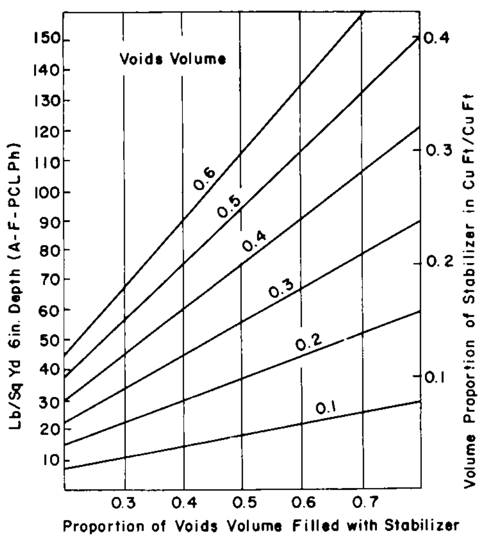

Figure 4. Quantity of stabilizer required for different voids volumes.

compactor, employing 20 blows of the hammer.

2. Make trial mixtures of soil, water, and bitumen containing the latter in three different percentages covering the range given in Fig. 8 for the dry density determined in Step 1 at moisture contents that permit uniform mixing, and using the same compaction method as in Step 1.

3. From the results of Step 2, calculate amounts of materials to make ten 2-in. by 2-in. cylindrical specimens.

4. Air-cure the specimens to constant weight and subsequently immerse five of them in distilled water for seven days. The water should just cover the upper surfaces of the specimens.

5. After seven-days immersion, weigh the wet and also the dry specimens and determine their compressive strengths.

If the wet compressive strength of the soil-bitumen specimens is greater than 75 psi, the mixture is satisfactory for base construction. If several mixtures fulfill this requirement, the composition of the one with the highest wet compressive strength and the smallest ratio between dry and wet strength is chosen. If none of the soil-bitumen specimens

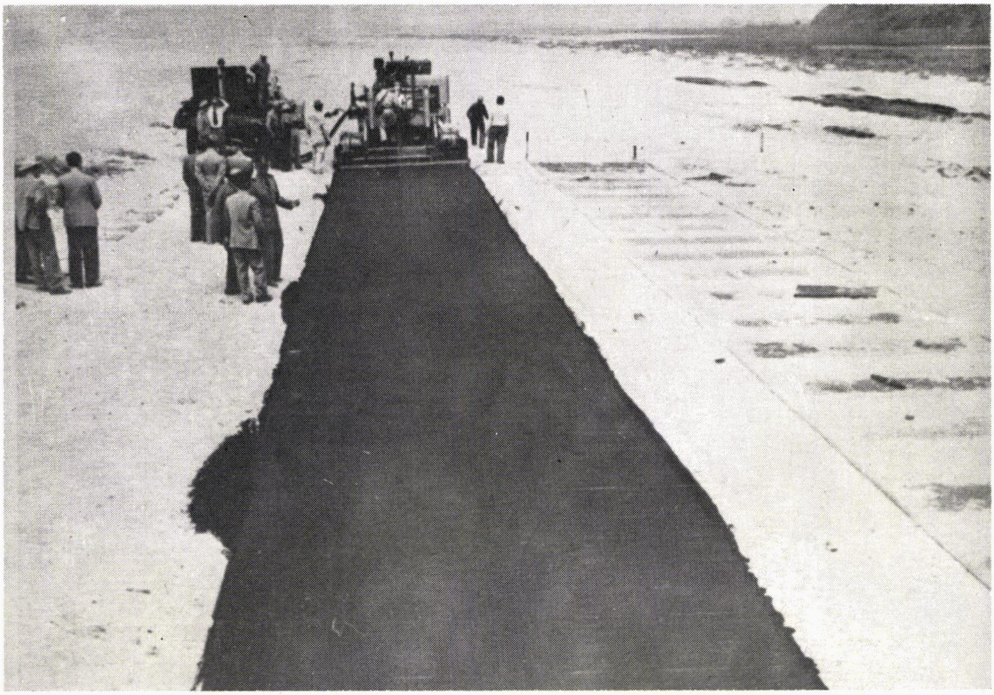

Figure 5. Proportioning guide for bituminous stabilization of cohesive soils.

pass the wet strength requirement, even at the highest bitumen content, tests should be repeated at the highest bitumen content indicated in the proportioning guide with the addition of inorganic or organic admixtures that have been found useful in decreasing the water affinity of soil-bitumen systems.

SUMMARY

The different possible types of soil-bitumen mixtures suitable for base course construction have been discussed and coordinated with the subgrade soil classification system of the Highway Research Board.

The bearing of granulometry and volume relationships on the stability of soil-bitumen systems of various types has been pointed out and ways have been shown for the practical use of the most important principles of granulometry.

This use is illustrated by design methods for stabilized beach sand and for stabilized silt-clay materials.

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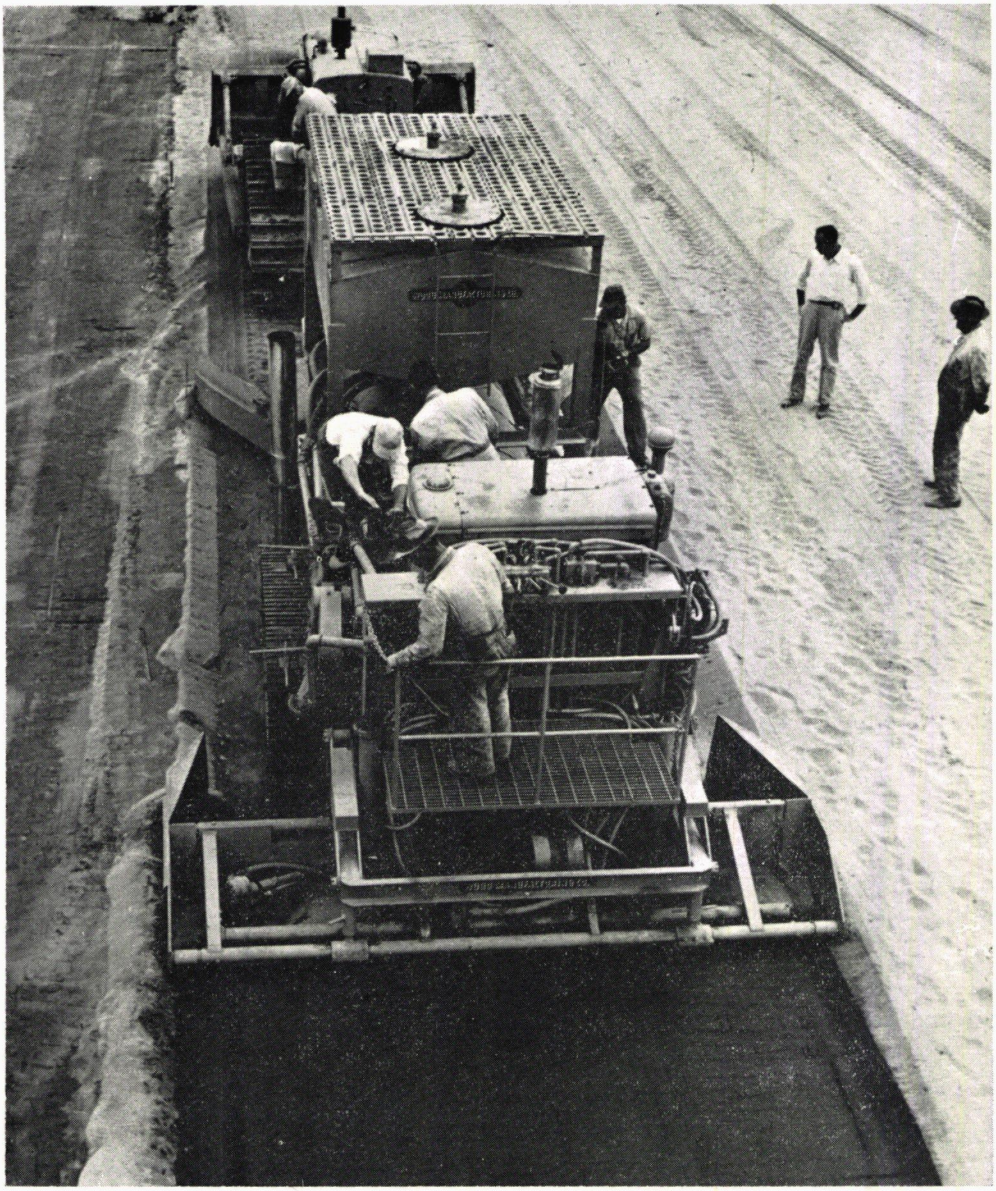

Figure 6. Beach stabilization experiment at Port Hueneme.

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Figure 7. Use of traveling mixer in beach sand stabilization.

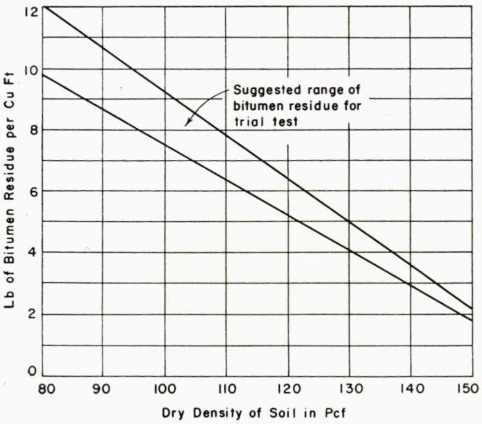

Figure 8. Beach stabilization in Marine Corps maneuvers.

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