retained Marshall stability of all emulsion mixtures after vacuum saturation was 80 percent, whereas the average for asphalt-concrete specimens was about 90 percent.

CONCLUSIONS

Based on the preceding experimental investigation, the following conclusions are derived.

1. Curing increases the Marshall stability at room temperature, the tensile strength, the tensile stiffness, and the resilient modulus of the mixture. Curing decreases the amount of moisture retained in the mixture and consequently the bulk specific gravity decreases. The air voids, on the other hand, are increased by curing.
2. The Marshall stability decreased when the asphalt residue content was increased from 2.5 to 4 percent, especially for oven-cured specimens. In addition, Hveem stability at room temperature, Hveem resistance, tensile strength, tensile stiffness, and resilient-modulus values decrease by increasing the residue content. The amount of air voids dropped from 7.4 to 5.3 percent when the residue content increased from 3.25 to 4 percent by weight of dry aggregate.
3. The emulsion mixture is sensitive to temperature. High test temperatures cause hair cracks to develop early during the test before complete failure for both indirect-tensile and resilient-modulus tests. Low tensile strength, tensile stiffness, and resilient-modulus values are obtained at high temperatures.
4. A general reduction in Marshall stability at room temperatures is observed after vacuum saturation. Other mixture properties are not largely affected by vacuum saturation. The amount of moisture absorption did not exceed 2.5 percent by weight of dry aggregate during the vacuum-saturation process.
5. Portland cement increases the Marshall stability at room temperature, especially at early curing ages and for mixtures with low emulsion contents. Also, portland cement increases the moisture retained in the mix, decreases its bulk specific gravity, and increases its resistance to water damage.
6. Emulsified asphalt mixes resulted in bulk specific gravities close to those of asphalt-concrete mixes with similar contents of asphalt residue. Large values of Marshall stability at 22°C were obtained for asphalt-concrete specimens as compared with emulsion-mix specimens. Neither oven-cured emulsion mixes nor asphalt-concrete mixes were greatly affected by vacuum saturation.

ACKNOWLEDGEMENT

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The contents of this paper reflect our views, and we are responsible for the facts and accuracy of the data.

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Stabilization of Silt: A Case Study for Low-Volume Roads in Saudi Arabia

GALAL A. ALI AND ABDEL-FATTAH A. YOUSSEF

Although there is generally a reasonable justification for using lime stabilization for clays and cement or bitumen for sandy soils, no such generalization exists for silts. The range of the applicability of several stabilization techniques to silts is investigated. The main objective of the investigation was to determine the type and quantity of stabilizer(s) suitable for silty soils, which dominate the surface geology of Saudi Arabia. A soil-cement-bitumen model that results in the best mixture performance is presented, and optimum additive percentages are suggested. A physicochemical explanation for such performance is provided. The analysis is based on experimental results obtained from compaction, California bearing ratio, unconfined compression, and modified Marshall tests. It is shown that modification of the silt with 2-3 percent cement followed by stabilization with about 4 percent bitumen gives overall a satisfactory mixture. Such a mixture may be used in the construction of low-volume, low-cost roads or as a subgrade material for paved roads. The proposed mix design is more favorable from the standpoint of strength, durability, and economics than bitumen or cement stabilization, the use of which would require at least 7 and 8 percent, respectively, as minimum stabilizer contents.

During the past decade, the Saudi Arabia Ministry of Communications (MOC) constructed more than 20 000 km of low-volume roads in accordance with the national policy for social and economic development. These low-cost or "agricultural" roads serve thousands of rural communities. In addition, some 30 000 km of paved highways are in use or under construction for which costly borrow materials are being used for the subgrade or subbase.

The MOC is placing increasing emphasis on the development and standardization of the design and construction procedures suitable for local conditions. The fact that Saudi Arabia is one of the major oil-producing countries made bitumen a potential candidate for stabilization investigation and subsequent use in the construction and improvement of low-volume roads.

The surface geology of Saudi Arabia indicates that silts are encountered in many parts of the country (1), as illustrated by the gradation envelopes shown in Figure 1. Thus, this research had the objective of determining the type and quantity of suitable stabilizer(s) applicable to silty soils.

Researchers have extensively investigated soil stabilization with respect to improvements in performance characteristics such as strength, volume stability, and durability (2,3). The economic significance of stabilized earth roads has been verified (4).

There is, in general, reasonable justification to use lime stabilization for clays and cement or bitumen for sands (5-7). No such generalization exists for silts; successful application of polymers to stabilize sandy and silty soils requires special treatment of the stabilizing material (8).

Nevertheless, any soil in question must be subjected to experimental analyses before the appropriate stabilizer can be predicted. Thus, in order to develop a suitable stabilization technique, it was necessary to study the applicability of some of the existing methods that might be potentially appropriate for the soil in question. Mechanical and cement and bitumen stabilization of silty soils were examined in the first phase of this investigation. Cement-modified, bitumen-stabilized silt was subsequently subjected to several characterization tests.

MATERIALS

The soil profile in the Riyadh area consists of 1-4 m of silty soils underlain by a deep layer of weathered rock. Samples obtained from different locations showed minor variations in plasticity and percentage passing the 0.074-mm sieve. Thus, a representative sample was used in this study. The average grain-size distribution curve of the soils is shown in Figure 2. The corresponding pertinent properties and classifications are summarized below:

Property	Percentage
Natural moisture content	2.2
Liquid limit	23.2
Plastic limit	18.5
Plasticity index	4.7

System	Classification
AASHTO	A-4(7)
Unified	ML
FAA	E-6

The gravel used for mechanical stabilization was of the type passing the 9.52-mm sieve and retained on the 4.76-mm sieve. For soil mixtures, sand passing the 4.76-mm sieve and retained on the 0.074-mm sieve was used.

In the soil-cement, ordinary portland cement was applied, while for bitumen stabilization of the silt, medium-curing cutback (MC-1) that satisfied American Society for Testing and Materials specifications was used.

APPLICABILITY OF STABILIZATION METHODS

Mechanical Stabilization

Mechanical stabilization calls for the combination of coarse- and fine-grained materials. Usually the coarse fraction is predominant for optimum density and strength, constituting about 75 percent (5). However, density, strength, and stability will decrease as the fines occupy more space and the coarse particles lose interlocking (9).

Figure 3 shows that the addition of gravel or sand to silt resulted in a relative increase of maximum dry density (MDD) and reduction of optimum moisture content (OMC) without reaching peak values. It was concluded that mechanical stabilization was not suitable for the silty soil investigated.

Soil-Cement

When the cement content in the silt was varied from 0 to 10 percent by weight of the dry soil, dry density decreased as shown in Figure 4a. Comparison was made with the behavior of other typical soils (10). Figure 4b shows that, in the case of sand, dry density continuously increased whereas the sandy clay had density characteristics between those of silt and sand. Changes in OMC due to the addition of cement are also observed, the maximum ranges being about 0.5, 2, and 9 percent, respectively, in sand, silt, and clay.

Bitumen Stabilization

An approximate value for the bitumen content was estimated from Equation 1, which is applicable to fine-grained soils (4):

$$P = 2.75 + 0.064d \quad (1)$$

where P is the bitumen content (percentage of dry soil weight) and d is the percentage of particles passing the 0.074-mm sieve.

Equation 1 assumes that the bitumen content is determined primarily by the percentage of particles smaller than 0.074 mm. An estimated value of 7 percent bitumen by weight of dry soil was used in the preliminary testing program (no curing). Compaction test results, unconfined compressive strength (UCS) values, California bearing ratios (CBRs), and Marshall stabilities are summarized in Table 1. Table 1 also gives the corresponding values for silt, soil-cement, and soil-cement-bitumen. For soil-cement and soil-cement-bitumen, 3 percent cement was used. The results indicate that stabilization of silt with bitumen decreased density, strength, CBR, water absorption, and swell.

The response of the silty soil to cement stabilization is seen from this table to be more favorable than the response to bitumen for some properties. Addition of cement also improved the soil gradation by reducing the amount passing the 0.074-mm sieve (Figure 2). Addition of bitumen to cement-treated soil improved all properties.

BITUMEN STABILIZATION OF CEMENT-MODIFIED SILT

The favorable results obtained from the preliminary tests with soil-cement-bitumen mixtures led us to seek a physicochemical explanation for the behavior of cement-modified bitumen-stabilized silt (CMBSS) in the presence of moisture.

Physicochemical Mechanism

Bitumen stabilization of cement-treated soils and aggregates has been limited to emulsified asphalts (11). George (12) reported that addition of 1.0-1.50 percent cement enhanced the soaked stability of sand-emulsion. The effect of the addition of bitumen to cement-modified soil, and the consequent behavior of the end "product", can be understood if the mechanisms of cement-soil and bitumen-soil are studied. When bitumen is added to moist fine-grain-

Figure 1. Gradation envelopes across mountain and desert in Saudi Arabia.

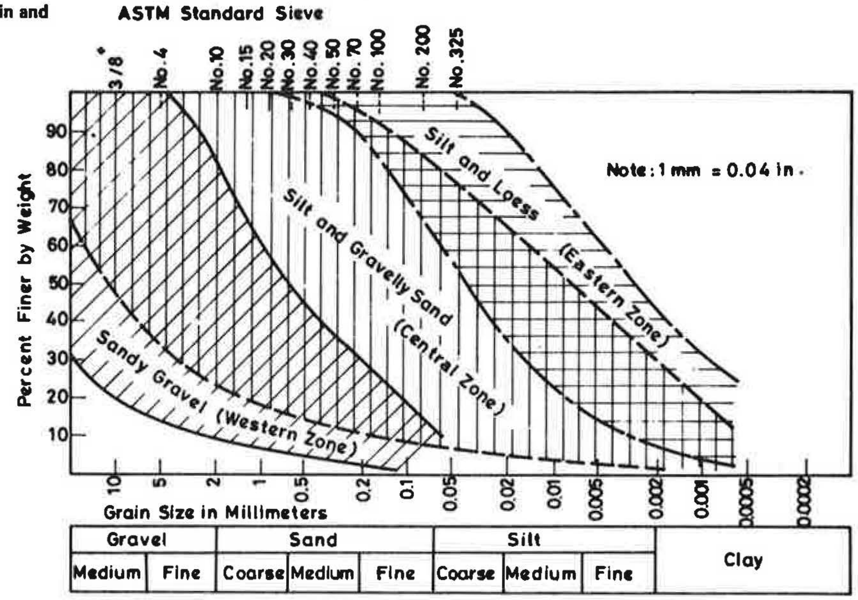
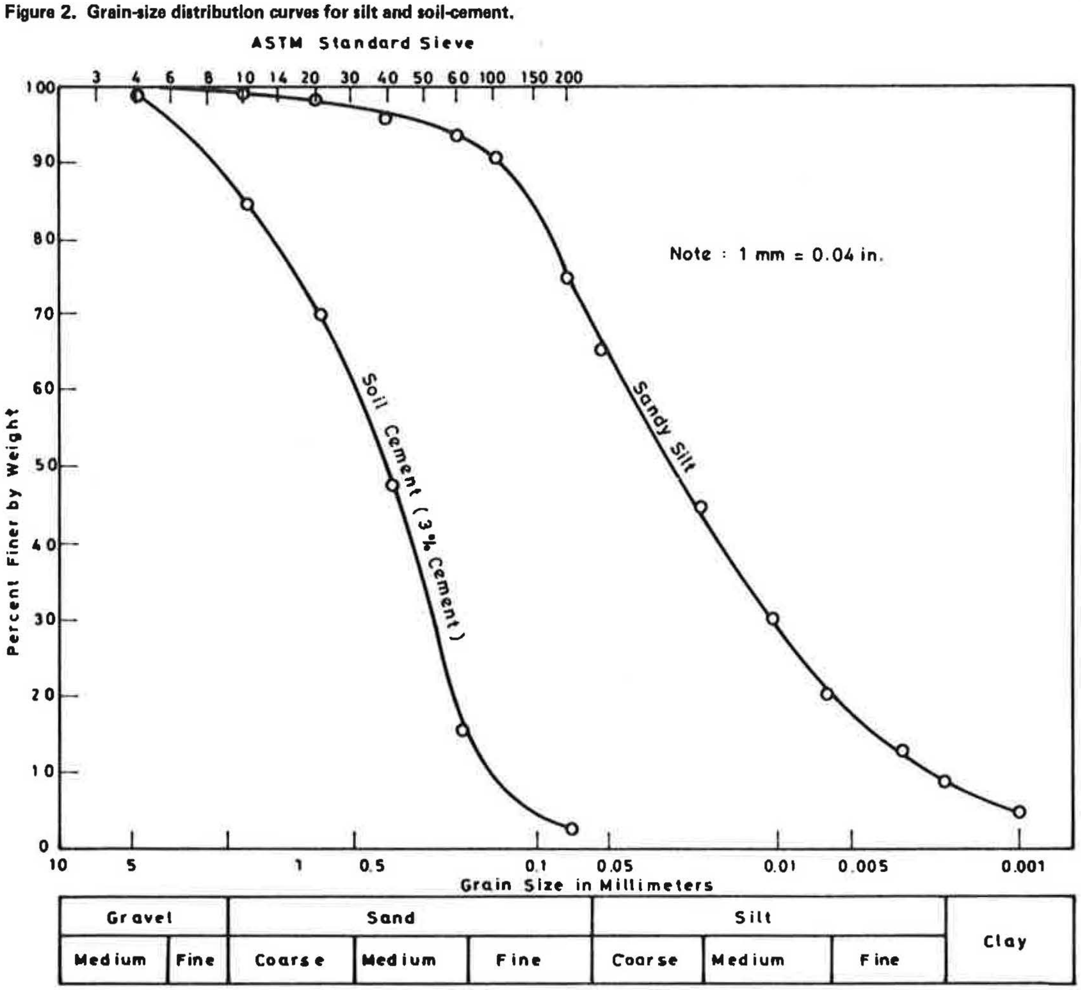


Figure 2. Grain-size distribution curves for silt and soil-cement.



ed soil, its role is to waterproof the soil by coating the particles. The strength gained by compaction will thus be preserved.

Water is essential to soil stabilization by bitumen since the degree of dispersion of asphalt in the soil mass depends on the amount of water present during mixing. However, the adhesion of bitumen to the surface of mineral particles already coated with water is small. Addition of a little calcium hydroxide to water reduces the interfacial energy of the bitumen-water interface to less than one-sixth (13). This energy reduction causes easier displacement of water by bitumen and hence better coating of aggregates by the binder.

The above discussion explains the most frequent use of hydrated lime as an additive to promote coating of wet soil mixtures by bitumen.

The calcium hydroxide needed in bitumen stabilization to assist coating can be obtained indirectly by using cement modifier. When hydration occurs on the addition of water, 75 percent of the portland cement undergoes the following two transformations (14):

$$2(3CaO{\cdot}SiO_2) + 6H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2 \qquad (2)$$

$$2(2CaO{\cdot}SiO_2) + 4H_2O \rightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + Ca(OH)_2 \qquad (3)$$

Thus, the hydration of cement results in lime and tobermorite gel. The latter is basically responsible for binding soil particles and providing strength. When bitumen is added, the hydrated lime will enhance further bonding of the particles and their agglomerates. Figure 5 shows the proposed physicochemical interactions and the resulting beneficial effects. A postulated model is shown in Figure 6. The mechanism of bonding and filling spaces accounts for reduction in swelling and water absorption in silty soils in addition to preserving strength, as will be shown by the experimental results of this investigation.

TEST RESULTS, ANALYSIS, AND DISCUSSION

Estimation of Bitumen Content for CMBSS

The amount of bitumen required to stabilize cement-modified silt is much less than that estimated by

Figure 3. Effects of sand and aggregate contents on compaction of silt.

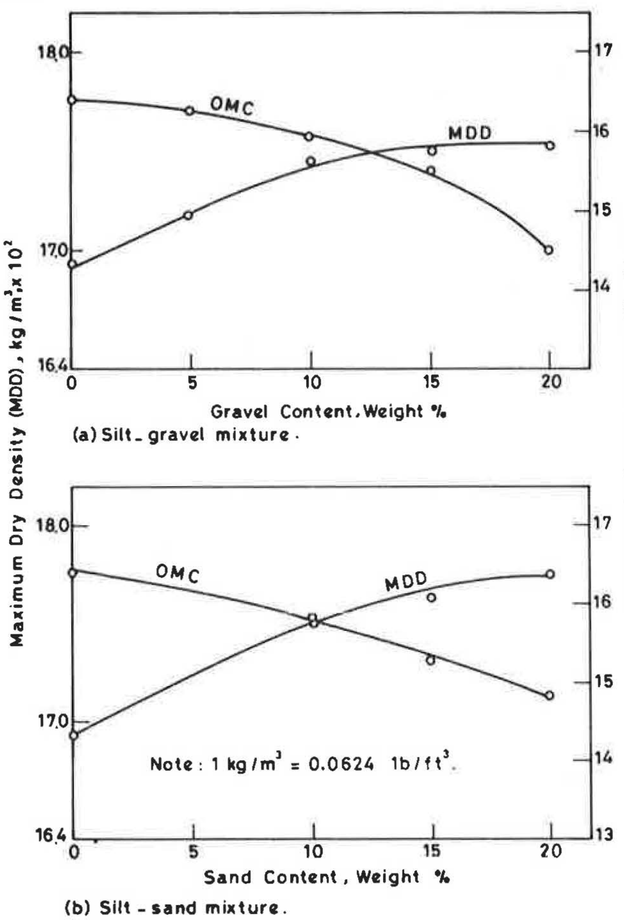


Figure 4. Effects of cement content on compaction characteristics of soils.

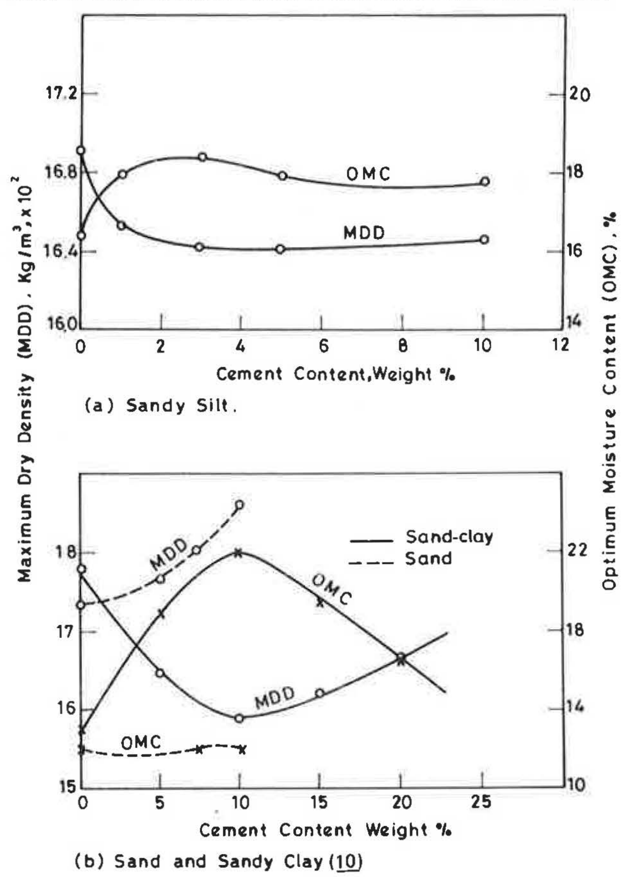


Table 1. Characteristics of untreated and stabilized soil.

Material	Content (%) Cement	Content (%) Bitumen	Dry Density (kg/m^3)	Moisture Content (%)	UCS (MPa)	CBR (%)	Absorption (%)	Swell (%)	Marshall Stability (kN)
Soil	0	0	1693	16.4	0.22	4.5	1.72	0.51	-
Soil-bitumen	0	7	1648	15.6	0.15	2.2	0.68	0	4.1
Soil-cement	3	0	1643	18.4	0.24	28.0	0.57	0.16	-
Soil-cement-bitumen	3	7	1673	15.0	0.26	19.3	0.55	0	9.24

using Equation 1. The amount can be calculated from the modified equation:

$$P = 2.75 + 0.064(d - x) \qquad (4)$$

where x is the reduction in the percentage of fine particles passing the 0.074-mm sieve due to cement modification and (d - x) is the percentage of fine particles passing the 0.074-mm sieve after cement modification. Equation 4 is being further developed in the continuation of this research.

The quantity of bitumen obtained by using Equation 4 should be increased by about 20 percent since some of the cemented particles will be broken up during compaction. Thus, by using the gradation curve of Figure 2 (cement-modified silt) in conjunction with Equation 4, the design bitumen content (P) was predicted to be 3.68 percent. The corresponding value estimated by using the following more detailed empirical formula (5) was 2.54 percent:

$$P = 0.015a + 0.02b + 0.03c + 0.09d \qquad (5)$$

where

a = percentage retained on the 2-mm sieve,
b = percentage passing the 2-mm sieve and retained on the 0.42-mm sieve,
c = percentage passing the 0.42-mm sieve and retained on the 0.074-mm sieve, and
d = percentage passing the 0.074-mm sieve.

Figure 5. Effects of cement modification on particles coated by bitumen.

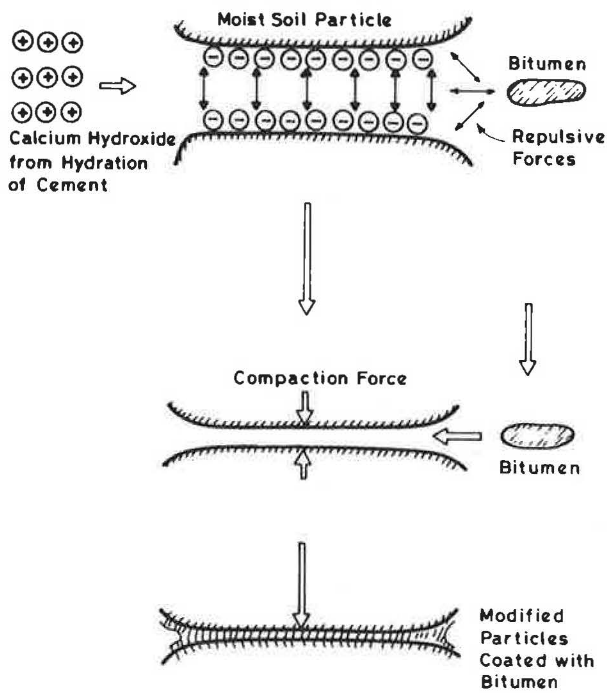
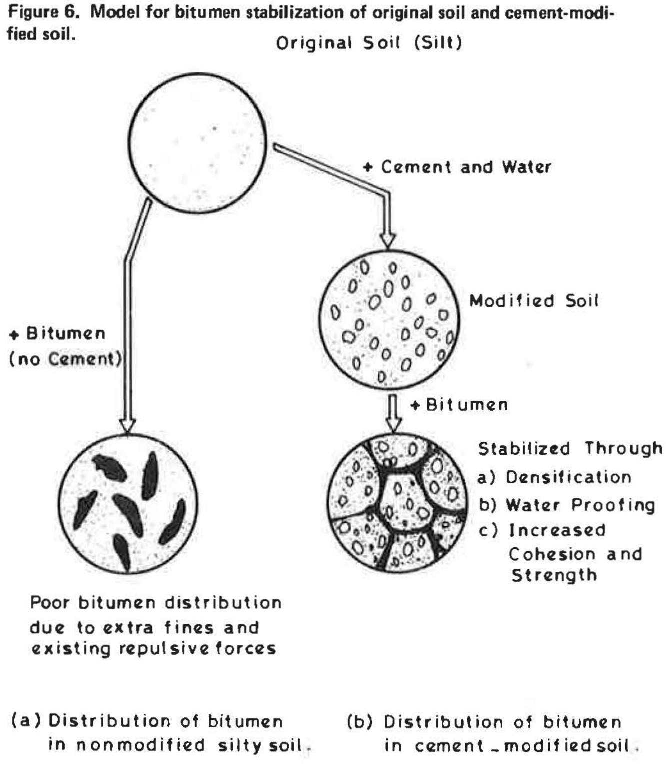


Figure 6. Model for bitumen stabilization of original soil and cement-modified soil.



Methods of Testing

The scope of testing included varying cement and bitumen contents. Test methods were standard Proctor compaction, UCS, Marshall stability, and CBR.

Air-dried soil was pulverized, blended with the appropriate amount of cement, and first mixed with the optimum moisture content and then with bitumen by hand. Unconfined compression tests were performed after one day and seven days with appropriate curing. Early curing studies of cement-modified soil stabilization with asphalt emulsion have been reported in the literature (15).

Marshall stability tests were conducted after soaking for half an hour and for loss of stability after 24-h soaking, both at room temperature (22°-26°C). Unconfined-soaked moisture absorption (USMA) was determined from the Marshall samples. CBR tests were conducted on specimens soaked for four days. Confined-soaked moisture absorption (CSMA) and percentage of swell were calculated.

Compaction and Strength

Figure 7 shows the compaction test results for different mix compositions. Superimposed on the figure is the compaction curve for the untreated soil. Adding cement reduced density and increased optimum liquid content (moisture + bitumen). This indicates that silts do not respond favorably to stabilization by cement alone without additives. The grain-size distribution curve of soil-cement (Figure 2) is similar to that of sands; the nonfilling of the voids thus generated is probably responsible for reducing density. The addition of up to 4 percent bitumen reduced density for all cement contents. Increases in optimum density above that of the untreated soil were observed at 8 percent bitumen content. However, this does not necessarily indicate improvements of other properties, such as strength and stability.

The unconfined compression test results and the corresponding dry densities are shown in Figure 8. The strength curves show that the rate of increase in UCS is largest at 2-3 percent cement. Optimal values are observed to be at cutback bitumen content of 4 percent. Increasing liquid bitumen required additional cement to give higher strength. Figure 8 also shows the effect of curing. The positive response of the soil to the combined cement-bitumen interaction is easily distinguishable. The results of this investigation illustrate that cement modification of silt for cutback stabilization is more ef-

Figure 7. Compaction characteristics of cement-modified soil-bitumen mixtures.

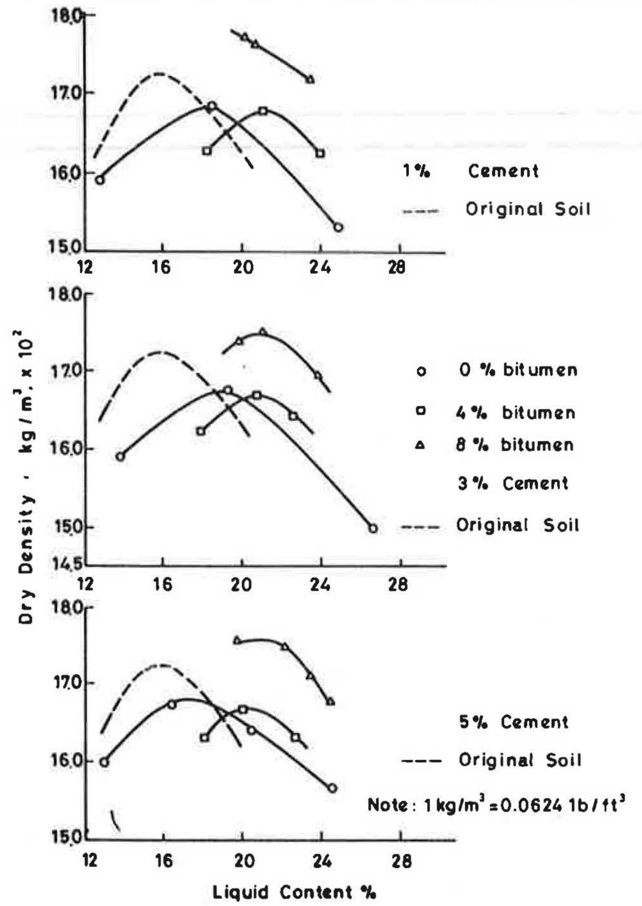
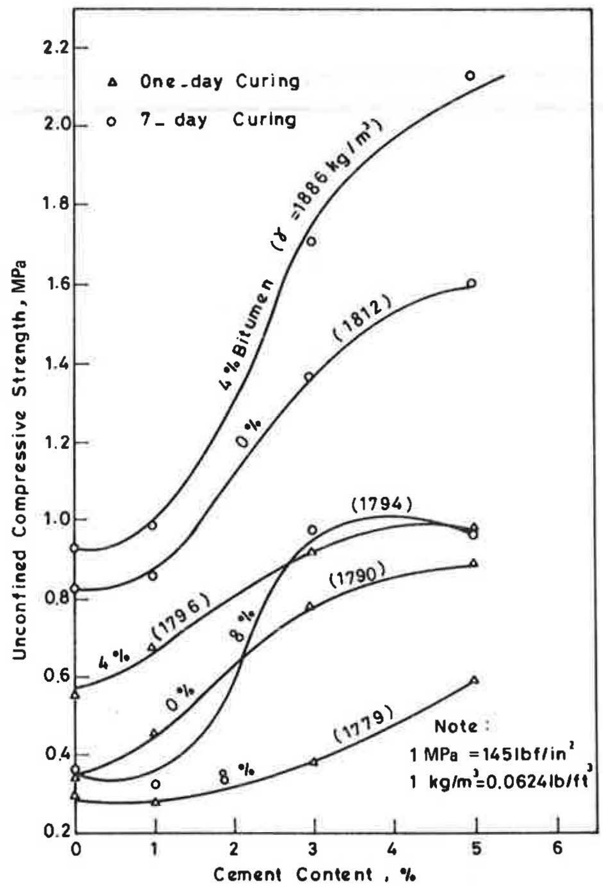


Figure 8. Effects of curing and addition of bitumen on UCS of cement-modified silt.



fective than previous techniques using chemical additives.

Stability and CBR

The Marshall stability and CBR results for the soil-cement-bitumen mixtures are summarized, respectively, in Figures 9 and 10. The high stability values are attributed to the evaporation of some of the fluid (bitumen and water) during the seven-day air curing of the Marshall specimens. In general, both stability and CBR of the cement-modified soil increased with the addition of bitumen, attained optimum values at about 4 percent bitumen, and then decreased. However, the addition of bitumen to the soil or to the soil mixed with 1 percent cement continuously decreased CBR, which indicates that 1 percent cement was not sufficient to modify the silt for bitumen stabilization. This is further illustrated by the Marshall samples containing 1 percent cement, which completely collapsed when soaked for one day.

The relatively high stability and CBR values obtained for mixtures with $\geq$3 percent cement, and the decrease in the rate of increase with increasing addition of cement beyond this value, suggest that 3 percent cement can be used for silt modification. Information in the literature (4) indicates that the addition of 5-7.5 percent emulsion and 3-5 percent cement improved the strength of fine-grained soils.

Water Absorption and Swell

The waterproofing effect of bitumen is illustrated in Figure 11. In both Marshall (USMA) and CBR (CSMA) tests, a reduction in the percentage of water absorbed is observed as bitumen content increases.

It has been suggested that maximum permissible moisture absorption from stability test specimens should not exceed 7-8.5 percent (5,12). Figure 11a shows that even at 2 percent bitumen the mixture satisfies this requirement when soaked for shorter periods. However, for 24-h soaking the absorption requirement is satisifed only at higher bitumen content (4-5 percent). This is attributed to the nature of the test, in which water absorption was allowed from all surfaces of the specimens.

The untreated soil had a swell of 0.51 percent under a surcharge weight of 44.5 N (10 lbf). In general, a maximum of 5-6 percent free swell is allowed in bitumen-stabilized soils. Soil modification by cement reduced swell to about 37 percent; the addition of 4 percent thereafter eliminated swell. As more bitumen was added (8 percent), more voids were filled, the mixture became less stable, and deformation occurred (negative swell).

DESIGN CONSIDERATIONS

The foregoing discussion focused on estimating design values of cement and bitumen contents required for silt stabilization. For satisfactory performance, consideration was given to strength as measured by UCS and CBR, Marshall stability, and durability as evaluated by water absorption and loss in stability. The modifier and stabilizer ranges

Figure 9. Effects of bitumen and cement on Marshall stability.

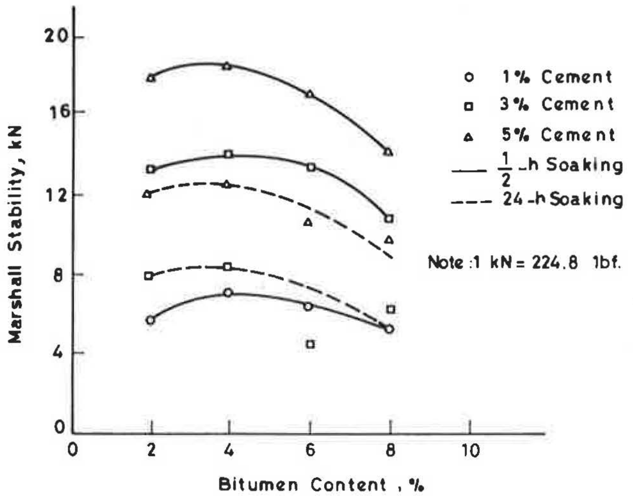
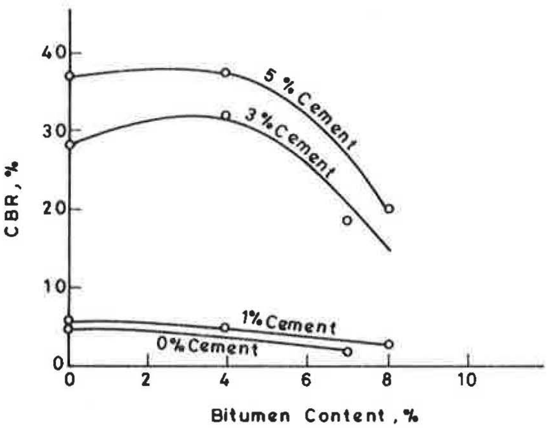


Figure 10. Variation of CBR with cement and bitumen contents.

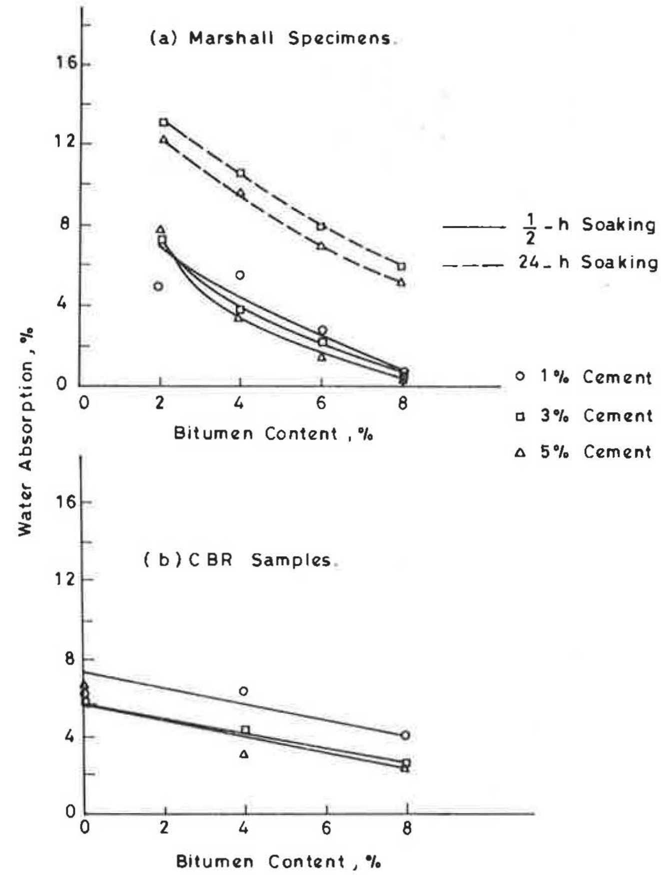


necessary to satisfy the above design factors are summarized below:

Factor	Modifier and Stabilizer Content (%) Cement	Bitumen
Strength		
CBR	3	4
UCS	2-3	4
Marshall stability	3	3-5
Durability		
Loss of stability	3	3-4
Water absorption	3	4-5

The quantitative design bitumen and cement contents determined in this study seem to be practical and economical. The experimentally determined value for the bitumen content compares favorably with that computed from Equation 4. Prediction of the amount of cement required for modification of silt is under consideration. Cement stabilization of A-4 soils requires 8-12 percent (16); in soil-bitumen 7-9 percent asphalt would be needed (5). The silt treatment suggested in this paper may be applied to the top layer of low-volume, low-cost agricultural roads or to the subgrade of paved highways. A minimum value of 25 percent is required for subgrade CBR by the MOC specifications. This is rarely satisfied by the natural soils in situ.

Figure 11. Effects of cement and bitumen on water absorption of stabilized silt.



CONCLUSIONS

The purpose of this paper was to determine a method of stabilization suitable for Saudi Arabia silt and to establish design criteria applicable to low-volume roads. Based on the results and analyses of test data and within the scope of this investigation, the following conclusions and suggestions can be made:

1. Adding economical quantities (3-5 percent) of bitumen and/or cement to silt does not improve the density of the mixture. About 8 percent bitumen content results in a density increase.
2. Significant increases in the strength of CMBSS are expected if the cement content is in the range of 2-3 percent and the amount of cutback bitumen is about 4 percent. Curing plays a positive role in producing the gain in strength.
3. When silt is modified with about 3 or more percent cement and then stabilized with about 3-5 percent cutback bitumen, optimum values of Marshall stability and CBR are obtained.
4. For bitumen-stabilized, cement-modified silt to keep water absorption within acceptable limits and hence retain stability, the cement content must be more than 1 percent and the bitumen content about 4-5 percent.
5. Bitumen is capable of stabilizing cement-modified A-4 silt. The amounts of cement and MC-1 bitumen suggested for modification and stabilization are, respectively, 2-3 and 4 percent.

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Design and Performance Study of Sand Bases Treated with Foamed Asphalt

S.M. ACOTT AND P.A. MYBURGH

The objective was to provide guidelines on the design of sands treated with foamed asphalt. The study included an evaluation of foam properties and a range of sand types. The foam-treated mixtures were characterized by index-type tests and by more fundamental procedures. The design asphalt content was selected as the lowest level at which the mix complied with a minimum Rt value of 70 at 40°C. All other engineering tests were conducted at the design asphalt content. To complement the laboratory work, two roads were constructed and then monitored over a five-year period by various field test procedures. Emphasis was placed on upgrading locally available materials by using low asphalt contents and selecting relatively light pavement designs. All experimental sections consisted of a thin surfacing and a 150-mm foam-treated layer on natural subgrade. From the field investigations, vane-shear and dynamic-cone-penetrometer values were found to be good indicators of shear strength, and limiting values are proposed to prevent distortion. For low-strength mixtures the critical parameter was the time period to develop this minimum required stability. From an analysis of deflection data, the foam-treated layer was considered adequate to protect the natural subgrade for the relatively light design traffic. In conclusion, this study has shown that properly designed sands treated with foamed asphalt can be used with confidence for low-volume roads provided that attention is given to the use of appropriate curing techniques, engineering test procedures, and the adoption of realistic limiting strength values.

An essential requirement for the construction of a low-cost, low-volume road is the need to make greater use of local available construction materials. In areas where sand forms the existing bush track or where there are nearby reserves, foamed-asphalt stabilization becomes a very attractive proposition since small quantities of asphalt can significantly increase the shear strength.

This paper is a summary of a field and laboratory investigation, conducted over a five-year period, in which the overall objective was to provide information on construction techniques and material specification and to formulate mix and structural design guidelines for foam-treated materials. The research approach was to determine the properties of the foamed asphalt and a wide range of natural sands and to then characterize the treated mix by using both index-type values and more-fundamental parameters. From a literature review and from discussion with various engineers, the stabilometer and vane-shear tests were selected as methods that would be most suited for evaluating these mix types in a routine laboratory environment. The stabilometer had also been used previously by Bowering and Martin (1), among others, for the evaluation of foam-treated materials. To complement these tests, the laboratory was equipped with a repeated-load indirect-tensile apparatus to measure the resilient modulus. Indirect tensile strength and static elastic modulus were evaluated by equipment at the National Institute for Transport and Road Research, and data are