1987

(2)

Structural Response of Foamed-Asphalt–Sand Mixtures in Hot Environments

AMIR F. BISSADA

This research project was conducted to investigate the ability of foamed asphalt to stabilize local marginal sand aggregates for use as base or subbase pavement materials. The variables measured were intended to give indications of the quality of performance of these mixtures as well as aid in the development of design procedures for the use of foamed asphalt as a stabilizing agent under the relatively high temperature conditions in the Arabian Gulf. Quantitative information is given about the effects on mixture response of significant factors such as sand type and gradation, quality and quantity of the fine fraction, asphalt grade and its percentage, moisture content, and curing condition. Both moisture and temperature susceptibilities of foamed-asphalt mixes were found to be significantly reduced by the addition of limestone powder to modify the fine fraction of sand. Structural response of foamed-asphalt mixes was compared with that of other hot-asphalt–sand mixes commonly used as base material in Kuwait. It appears that properly designed foamed-sphalt–sand mixes have a structural thickness that corresponds to that of hot asphalt and much less susceptibility to permanent deformations under traffic loads in hot environments.

An adequate procedure for designing foamed-asphalt–sand pavement materials cannot be developed unless the effects of all of the factors that affect mixture performance are thoroughly evaluated and clearly understood. A variety of mix design and evaluation procedures for foamed-asphalt materials has been and is being used in a number of countries (*1–7*). This variety has led to difficulties in correlating and assessing results obtained in different environments. Therefore the initial step in developing a procedure for designing mixtures was to conduct a comprehensive laboratory study to obtain quantitative information about the effects of the properties of available materials and local environmental conditions on mixture response.

The study of foamed-asphalt stabilization of local sands was initiated in Kuwait because (a) there is a lack or limited supply of good-quality coarse aggregates and an abundance of poorly graded sands that are unsuitable for use as a base layer material and (b) asphalt base layers are subjected locally to service temperatures that vary from a minimum of 15°C to a maximum of 55°C (*8*). Within this range of service temperatures, these layers were found to be more susceptible to deformation failure than to fatigue cracking (*9*).

This work has two objectives. The first is to determine the significant factors that affect the structural response of foamed-asphalt mixtures compared with corresponding hot-asphalt plant mixtures. Factors such as moisture and temperature susceptibilities and elastic and creep behavior were considered. The second objective is to evaluate the potential of foamed-asphalt–sand mixtures as a structural base or subbase at relatively high local service temperatures and to compute equivalent thicknesses of these layers on the basis of their ability to dissipate vertical compressive subgrade stresses.

EXPERIMENTAL PROCEDURE

Three grades of asphalt, classified as AC-20, AC-2.5, and a vacuum asphalt residue (VAR) with a penetration of 310, were used in this experiment. These asphalts were tested for penetration, softening point, viscosity, and specific gravity. The apparent viscosity was determined using a rotor viscometer at different shear rates and at temperatures ranging from 60°C to 165°C. The results of these tests are given in Table 1. The foaming characteristics of the three asphalt grades were investigated in terms of their foam expansion ratio and foam half-life under variable foaming temperatures and water contents. In general, the VAR with the lowest viscosity was found to possess the highest expansion ratio and half-life values at all foaming temperatures and water contents considered (Figure 1).

Two major types of locally available sands were used in this study, natural desert sand (S-2) and blow sand (S-3). In addition to these two sands, a third type of sand commonly used in hot-plant asphalt mixtures (S-1) was also considered for use. S-1 consists of natural desert sand, crusher waste aggregate, and limestone powder in a ratio of 46:46:8 by weight. The gradation, specific gravity, AASHTO T99 dry density, and optimum moisture content of the three selected sand aggregates are given in Table 2.

A foamed plant laboratory unit built by Ultra-Tec, Inc., was

TABLE 1 PROPERTIES OF ASPHALTS USED

	Asphalt Grade		
Property	AC-20	AC-2.5	VAR
Penetration at 25°C (0.1 mm)	67	135	310
Softening point (°C)	51	45	36
Viscosity (mPa/sec) at			
60°C	2.8×10^5	3.5×10^4	5.0×10^3
135°C	5.2×10^2	2.4×10^2	1.5×10^2
150°C	3.0×10^2	1.4×10^2	0.9×10^2
165°C	1.2×10^2	0.8×10^2	0.5×10^2
Specific gravity	1.030	1.010	1.005

Civil Engineering Department, Kuwait University, P.O. Box 5969, Kuwait.

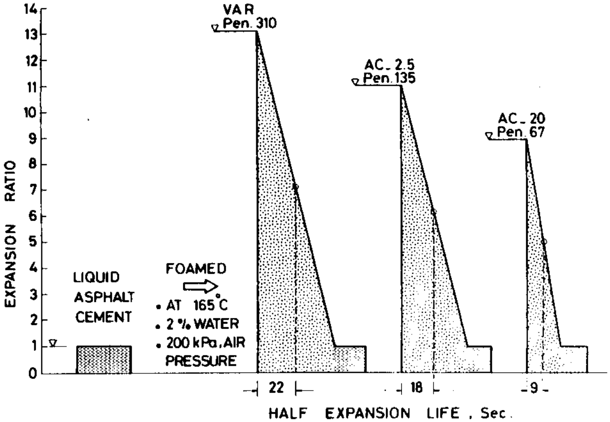

FIGURE 1 Expansion ratio and half-life of foamed asphalts.

used to produce the asphalt mixtures investigated. The electrically powered plant unit contains a foaming device that receives precise measurements of water and hot asphalt and converts them to an asphalt foam that is mixed in a paddle mixer. The plant mixes 7 kg per batch, which is enough to prepare six standard Marshall molds at once. The mixing period in the paddle mixer was 1 min after the foamed asphalt was added. Then the mixture was hand mixed in the pan for approximately 1 min.

The test specimens were molded within 45 min after the mixing operation was completed. Marshall specimens of all foamed mixes were compacted using a mechanically operated compaction hammer according to ASTM D 1559. Compacting was done at room temperature; 50 blows were applied on each side of the specimen. Specimens were carefully extruded from their molds and weighed immediately after compaction. To determine the effect of loss in moisture content, specimens were weighed periodically during curing.

TABLE 2 PHYSICAL PROPERTIES OF SANDS

Property	S-1	S-2	S-3
Gradation particle size (mm) (% passing)			
5	100	100	100
2	93	98	100
1	80	89	100
0.5	55	62	96
0.2	26	12	52
0.1	14	4	27
0.75	8	2	8
Atterberg limit	–	–	–
Bulk specific gravity	2.604	2.612	2.595
Standard proctor dry density (t/m^3)	2.062	1.915	1.736
Optimum moisture content (%)	9.4	7.8	12.0

NOTE: Dash = not provided.

Three different laboratory curing conditions, based on climatic regions of the Arab Gulf, were considered: (a) in air at room temperature (23°C), (b) in a humidity chamber (23°C and 100 percent humidity), and (c) in an oven at 40°C. The first and second curing conditions were supposed to simulate local dry and humid low-temperature seasons, respectively. The third represents the local dry temperate condition.

Foamed-asphalt mixtures were characterized by the Marshall method following ASTM D 1559 except that mechanical compaction was used to apply 50 blows on each side of the specimen at room temperature. The percentage of air voids in the compacted specimens was determined according to ASTM D 3203. Marshall specimens were conditioned according to ASTM D 1075, and moisture damage was determined by using the ratio of the Marshall stability of conditioned specimens to the Marshall stability of dry specimens.

Indirect tensile strength is determined by testing the specimen of standard Marshall size diametrically at a constant rate of 51 mm/min *(10)* for the purpose of evaluating both the moisture and the temperature susceptibility of the foamed-asphalt–sand mixtures.

The apparatus used for measuring creep stiffness was a Freundl type of loading system *(11)*. The frame load and the upper platen preloaded the specimen with 0.01 N/mm^{-2} for 1 min. The constant stress applied to the specimen was 0.10 N/mm^{-2} for 60 min.

Specimens of Marshall standard size were coated with paraffin before being immersed in a 40°C water bath for 1 hr to give them a uniform temperature before testing. The paraffin coating has the effect of avoiding any possible moisture damage to the specimens before and during testing.

A nondestructive resilient modulus (M_R) test was carried out by applying a pulsing load of 0.10-sec duration across one diameter of the cylindrical specimen while the resultant elastic response across the opposite diameter was measured *(12)*. An electrohydraulic apparatus was used to apply the selected pat-

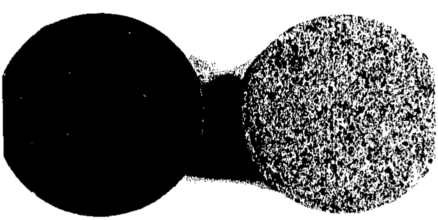

FIGURE 2 Hot-asphalt *(left)* and foamed-asphalt *(right)* specimens.

tern of dynamic loading. Temperature was controlled within 1/2°C using a thermally controlled cabin.

CHARACTERISTICS OF MIX DESIGN

Effect of Asphalt Foaming Properties

All of the foamed-asphalt–sand mixtures looked like moist sand with no visible asphalt color right after cold mixing. However, the compacted specimens after the first curing hours got darker in color, and most of the fine particles were coated with less than 0.50 mm of asphalt. Because of the partial asphalt coating, all foamed-asphalt cold mixes are lighter in color than are corresponding hot-asphalt mixes, as shown in Figure 2.

The effects of foam ratio and half-life on the stability of the foamed-asphalt mixtures were detectable. Foamed-asphalt mixes made with AC-20 with an expansion ratio of 9 and a half-life of 8 sec gave the lowest stability values of any of the mixes considered in this experiment. It was observed that foamed asphalt AC-20 did not have good mixing properties with the sands used in this study. Problems such as stickiness and lumping were encountered with this mix but were not observed in other mixes made with AC-2.5 and VAR with relatively high values of expansion ratios and half-lives. Visual examination of the foamed mixtures revealed that the VAR with the lowest viscosity exhibited the best aggregate particle coating and the most uniform dark color. Mixtures that contained AC-20 were light in color, and no asphalt was visible in those that contained 4.5 percent asphalt. Increasing the asphalt content to 6.5 percent resulted in the appearance of several balls of uncombined asphalt.

The effect of asphalt viscosity at 165°C on Marshall stability of foamed mixtures made with sand S-1 is shown in Figure 3. Foamed mixtures that contained VAR of viscosity 0.5×10^2 mPa/sec at 165°C showed higher stability values than did corresponding mixtures with AC-2.5 and AC-20 of viscosities 0.8×10^2 and 1.2×10^2 mPa/sec, respectively, at 165°C.

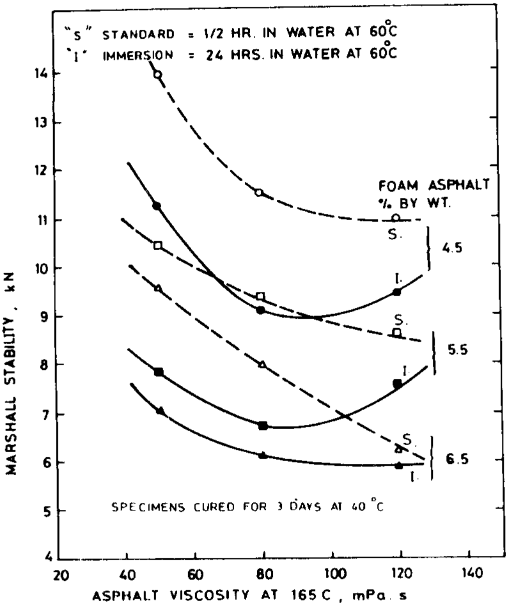

FIGURE 3 Effect of asphalt viscosity on Marshall stability.

After 3 days of curing at 40°C all tested foamed-asphalt specimens had higher Marshall stability values than did corresponding hot-asphalt specimens at lower asphalt contents (Table 3). Maximum stability of foamed-asphalt specimens was found to be at 1.5 to 2.0 percent less asphalt content than that for corresponding hot-asphalt specimens (Figure 4).

The partial asphalt coating in foamed-asphalt mixtures promoted the frictional shear component and resulted in higher air voids and lower measured flow values compared with those for corresponding hot-asphalt mixtures. These values for all tested foamed-asphalt specimens were not significantly affected by either the asphalt content within the range of variation considered or the viscosity of the asphalt cement used.

Effects of Sand Gradation and Particle Shape

Marshall test results for the three sands with grade AC-2.5 asphalt are given in Table 4. Improving the gradation, increasing the percentage of fines (less than 0.075 mm), and using crushed sand particles included in sand S-1 have resulted in significant improvements in Marshall properties before and after water immersion. Standard and immersed Marshall stability values for S-1 foamed-asphalt mixes ranged from 8.0 to 11.5 kN and from 5.1 to 9.2 kN, respectively. These stability values were higher than those obtained for S-2 and S-3 foamed-asphalt mixes.

Foamed-asphalt specimens made from natural desert sand (S-2) had a low stability value and did not withstand the moisture conditioning test. The S-3 blow sand, which includes about 8 percent natural fines of silica dust (less than 0.075 mm), produced foamed mixes of standard Marshall stability ranging from 3.4 to 5.8 kN. The relatively high values of air voids (25 to 30 percent) were related to the poor gradation of this type of sand. All foamed-asphalt specimens prepared from S-3 sand had low immersion stability values and some of these specimens collapsed before testing.

TABLE 3 MARSHALL PROPERTIES OF MIXTURES MADE WITH DIFFERENT GRADES OF ASPHALT

Asphalt Content (% by weight of aggregate)	Stability (kN)	Flow (0.1 mm)	Unit Weight (t/m^3)	Air Voids (%)
Hot Mix (AC-20)[a]				
4.5	7.1	24	2.110	13.1
5.0	7.8	24	2.169	9.9
5.5	8.0	26	2.217	7.2
6.0	10.2	30	2.208	6.9
6.5	9.8	30	2.198	6.7
7.0	8.9	33	2.198	6.0
Foam Mix (AC-20)[b]				
4.0	11.7	21	2.033	16.5
4.5	11.0	23	2.028	16.4
5.0	7.4	22	2.018	16.2
5.5	6.4	23	2.017	15.7
6.0	6.4	23	1.995	15.9
6.5	6.6	24	2.000	15.1
Foam Mix (AC-2.5)[c]				
4.0	12.7	25	2.052	15.5
4.5	11.5	25	2.040	15.9
5.0	11.0	24	2.045	15.0
5.5	9.4	25	2.027	15.1
6.0	8.1	26	2.011	15.2
6.5	8.0	28	2.010	14.6
Foam Mix (VAR)[d]				
4.0	13.8	23	2.041	15.5
4.5	14.0	25	2.052	15.4
5.0	12.8	24	2.038	15.3
5.5	10.4	26	2.020	15.4
6.0	9.9	27	2.016	15.0
6.5	9.6	24	2.000	15.1

[a] Viscosity at 165°C = 1.2×10^2 mPa/sec.
[b] Viscosity at 165°C = 1.2×10^2 mPa/sec.
[c] Viscosity at 165°C = 0.8×10^2 mPa/sec.
[d] Viscosity at 165°C = 0.5×10^2 mPa/sec.

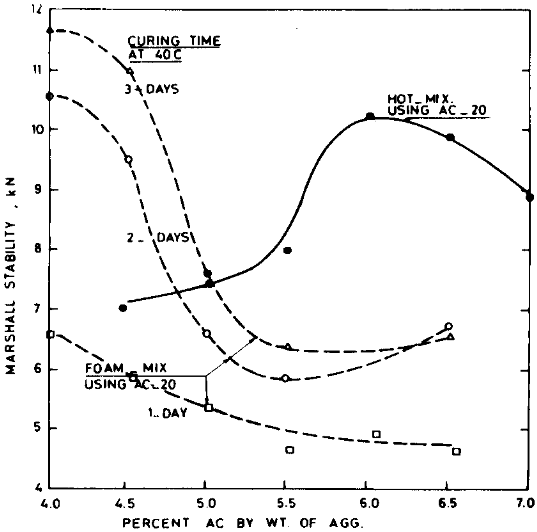

FIGURE 4 Marshall stability versus asphalt content of mixtures made with S-1.

TABLE 4 MARSHALL PROPERTIES OF MIXTURES MADE WITH DIFFERENT SANDS

	Percentage of AC-2.5 by Weight			
Property	3.5	4.5	5.5	6.5
Sand 1[a]				
Standard stability (kN)	9.2	11.5	9.4	8.0
Flow (0.1 mm)	22	25	25	28
Unit weight (t/m^3)	2.020	2.040	2.027	2.010
Air voids (%)	17.9	15.9	15.1	14.6
Immersion stability (kN)	5.1	9.2	6.8	6.2
Sand 2[b]				
Standard stability (kN)	1.7	2.1	1.5	0.9
Flow (0.1 mm)	10	14	12	18
Unit weight (t/m^3)	1.922	1.945	1.932	1.921
Avoid voids (%)	23.5	21.6	21.1	20.6
Immersion stability (kN)	0	0	0.3	0.3
Sand 3[c]				
Standard stability (kN)	3.4	5.8	4.4	3.6
Flow (0.1 mm)	25	28	29	31
Unit weight (t/m^3)	1.720	1.753	1.776	1.729
Air voids (%)	30	27.7	25.6	26.5
Immersion stability (kN)	0	0.4	0.4	0.8

NOTE: Specimens were cured for 3 days at 40°C. Immersion stability was determined after specimens were soaked for 24 hr in 60°C water.

[a] Moisture content: 7.5 percent at mixing, 0.7 to 1.3 percent cured.

[b] Moisture content: 6.4 percent at mixing, 0.7 to 1.3 percent cured.

[c] Moisture content: 9.6 percent at mixing, 2.0 to 2.9 percent cured.

Effect of Mixing Water Content

Figure 5 shows the average values of both Marshall stability (S_M) and indirect tensile strength (S_T) at different water contents for mixtures made with S-2 with 10 percent limestone. Data from this series of tests appear to indicate that the optimum mixing water content was around 9.6 percent by weight of aggregate, which corresponds to about 80 percent of optimum compaction moisture.

Specimens prepared at a moisture content of 40 percent on the dry side of the optimum value were difficult to mix with asphalt. The foamed asphalt was not uniformly distributed and the mix had a spotty appearance. Marshall stability and indirect tensile strength values dropped to about 50 percent of those obtained at the optimum mixing moisture. On the other hand, water content equivalent to 100 percent of the optimum compaction moisture resulted in the initiation of cracks during compaction. Marshall stability and indirect tensile strength decreased to about 70 and 88 percent, respectively, of the values obtained at optimum mixing water content.

The effect of varying the mixing moisture content on the percentage of retained stability and tensile strength after water immersion was found to be negligible. Within the range of mixing moisture contents applied, retained stability and tensile strength ranged from 62 to 82 percent and from 69 to 79 percent, respectively. The lower percentage values are related to the relative decrease in the density of the mix caused by the change in the mixing moisture content.

Effect of Curing Condition

The effect of the three curing conditions on the Marshall stability of the foamed-asphalt mixes and the measurements of loss of moisture are plotted in Figure 6. The following observations resulted from these tests:

- For the three curing conditions investigated, the loss of moisture content measured from the time of molding the specimen is accompanied by an increase in stability values.
- The highest rate of gain in stability was measured for 40°C oven curing and achieved a maximum value after 3 days with a moisture content of about 0.5 percent. No significant increase in stability was observed after 3 days.
- Curing in the humidity chamber resulted in the lowest rate of gain in stability; after 14 days, only 50 percent of the maximum attainable stability was achieved.
- Maximum stability values were measured for specimens cured for 21 days in air at room temperature. These stability values were equivalent to those measured for specimens oven cured for 3 days at 40°C.

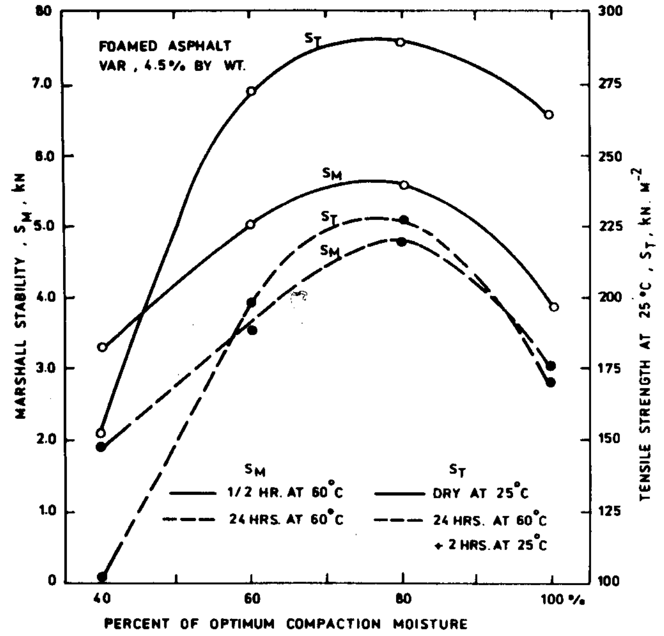

FIGURE 5 Effect of mixing water content on Marshall stability and tensile strength.

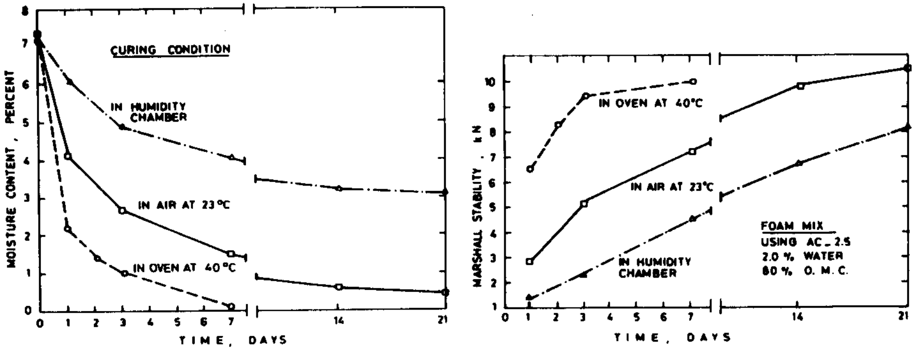

FIGURE 6 Moisture content and corresponding stability under different curing conditions.

- Examination of the data revealed no constant relationship between the loss of moisture and the consequent gain in strength under the three different curing conditions. It appears that, in addition to the effect of moisture loss, other factors such as the aging of the asphalt binder might contribute to the increase in stability of foamed mixes.
- The relations between moisture content and strength, which are related to the three curing conditions, can be used to evaluate foamed-asphalt mixes both at early-cure to determine when a road can be opened to traffic and at ultimate-cure to determine the whole service life of the foamed-asphalt layer.

Moisture Susceptibility

Moisture conditioning of test specimens that contained S-2 with different contents of fine additives resulted in a saturation

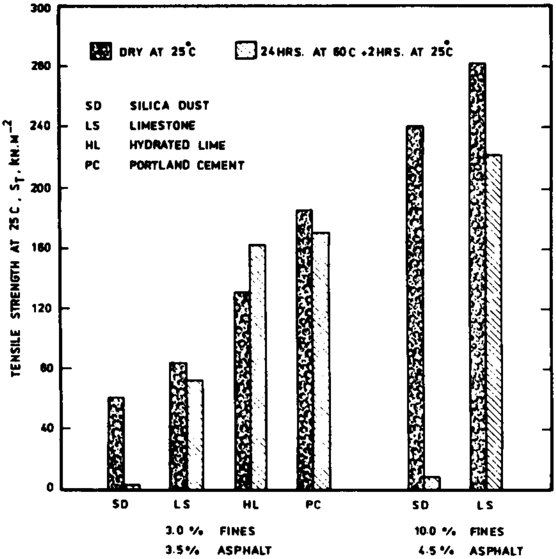

FIGURE 7 Tensile strength of mixes with different fine additives.

percentage that ranged from 40 to 60. This value was established by determining the percentage of air voids in the cured test specimen that were occupied by water after the specimen had been submerged statically in water at 60°C for 24 hr.

The silica dust is nonplastic fines normally found in natural desert sands. Such fines contributed little to improving the resistance of foamed-asphalt mixes to moisture damage. Increasing the amount of fines from 0 to 15 percent by weight of sand resulted in a maximum increase of 20 percent in retained Marshall stability. Many specimens did not withstand the moisture conditioning tests. However, the use of limestone filler (5 and 10 percent by weight of sand) resulted in retained stability values of 83 and 88 percent, respectively. Increasing the limestone filler content to 15 percent did not result in any further improvement in resistance to moisture damage.

Figure 7 shows the results of the indirect tensile tests carried out on foamed-asphalt mixes that contained S-2 with four different types of fines (minus 0.075 mm): silica dust, limestone powder, hydrated lime, and portland cement. The fines content and the asphalt content of all of these mixes were 3.0 percent and 3.5 percent by weight of dry sand, respectively. The mix that contained 3.0 percent portland cement showed the highest tensile strength values before and after moisture conditioning. Foamed-asphalt mixes that contained 3.0 percent hydrated lime had the highest percentage of retained tensile strength. Mixes with portland cement and limestone filler showed percentage-retained tensile strength values of 92 and 85, respectively. As expected, specimens that contained silica dust collapsed after moisture conditioning.

These fine additives modify the sand fines by increasing the fractions of minus 0.075 mm required to produce a stable asphalt mortar. On the other hand, the interaction of the bitumen acids with carbonate surfaces, like those of hydrated lime, portland cement, and limestone powder, results in the formation of calcium salts that are not expected to be water soluble *(13)*. This interaction could be responsible for a strong adhesive bond if these fine additives are added to the sand in a slurry.

The effect of asphalt content on Marshall stability values before and after moisture conditioning has been compared with that for corresponding hot-asphalt mixes that have the same filler content. Figure 8 shows that, at the optimum asphalt content, foamed-asphalt mixes show higher percentages of retained stability after immersion than do hot mixes. Although, in the hot-asphalt mixes, almost all aggregate particles are asphalt coated, which normally produces higher resistance to moisture damage, it appears that there exists a strong adhesive bond if the limestone filler in the foamed-asphalt mixes is added to the sand in the presence of water.

Temperature Susceptibility

Figure 9 shows the effect of increasing the percentage of fines in S-2 on the increase in tensile strength of the foamed-asphalt mixtures tested at temperatures ranging from 25°C to 50°C. The temperature susceptibility of a foamed-asphalt mixture containing 10 percent limestone powder and 4.0 percent 310-pen asphalt was compared with that of corresponding hot-asphalt–sand mixes and the results were plotted on a semilog graph (Figure 10). Both hot sand-asphalt mixtures that contained the harder asphalt grade (AC-20) and the softer asphalt grade (VAR) showed no significant difference in their slope values $\Delta \log S_T$ versus T°C within the range of test tempera-

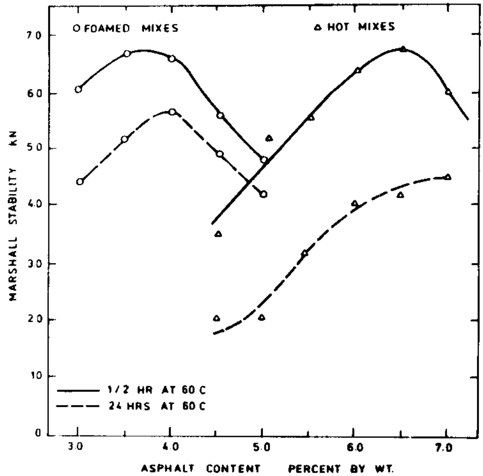

FIGURE 8 Loss in stability after immersion test (S-2 with 10 percent limestone powder).

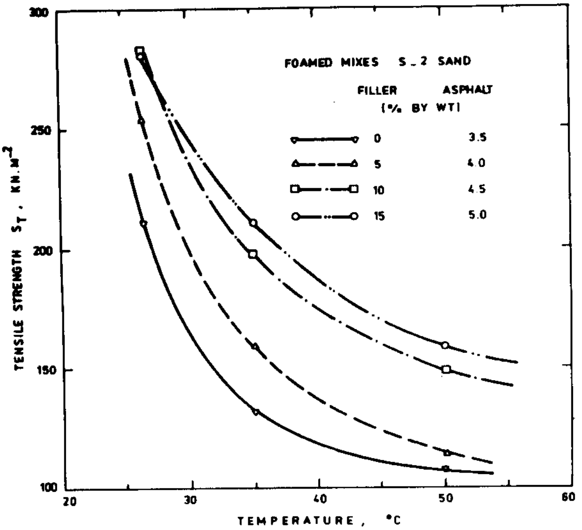

FIGURE 9 Tensile strength versus temperature (S-2 with different limestone filler contents).

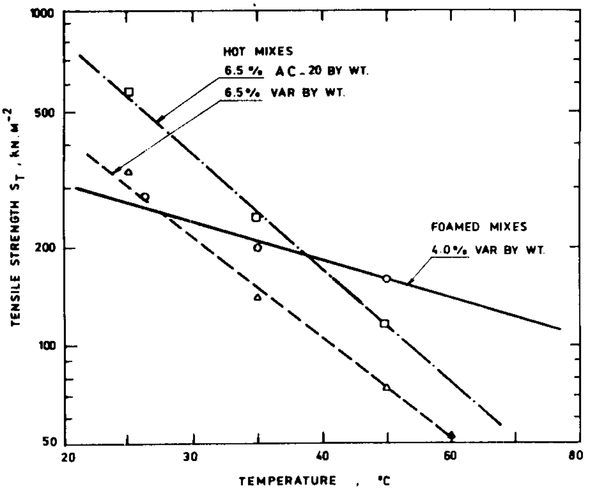

FIGURE 10 Log S_T–T°C relationship for foamed- and hot-asphalt mixes.

tures. A much smaller slope value was measured for the foamed-asphalt mix. The low-temperature susceptibility of the foamed-asphalt mixes is related to the high internal friction between the sand particles, which is due to the relatively low asphalt content.

Figure 11 shows measured resilient modulus (M_R) versus temperature for the foamed-asphalt mixtures and other hot-asphalt mixtures commonly used in Kuwait. The initial and final M_R-values of foamed mixtures were determined after curing at room temperature for 1 day and 21 days, respectively. Although the initial moduli of the foamed-asphalt mixtures over the whole range of test temperatures were quite low, the final moduli after 21 days were found to be about three times higher than the initial ones. At temperatures of 30°C and above, final M_R-values of foamed-asphalt mixtures were found to be equal to or higher than those of commonly used hot sand-asphalt mixtures.

Creep Deformation

Figure 12 shows that the stiffness value (σ/ε_t) during the creep test (60 min) increases as the percentage of fines in sand increases. On the other hand, the rate of decrease in stiffness with time was found to increase with the increase of fines content. Foamed-asphalt mix with 15 percent fines showed a rate of decrease in stiffness four times higher than that for a mix with no fines added. The effect of variations in optimum asphalt content of ±0.5 percent by weight on creep strain was also investigated. Figure 13 shows the results of this study. For all foamed mixtures the trend of increase in creep strain with the increase in asphalt content was obvious. However, there was no detectable difference in the effect of changes in asphalt content on the rate of change in creep strain.

Figure 14 shows that foamed-asphalt mixes that contained 5 percent and more fines had higher stiffness values than did hot-asphalt mixes. Stiffness of foamed-asphalt mixes containing 10 and 15 percent fines was about two- and fourfold higher, respectively, than that of hot-asphalt mixes. The complete coating of the whole sand structure with the asphalt mortar in the hot-asphalt mixes could be responsible for the relatively low resistance of these mixtures to creep deformation.

Stiffness of the mix (S_{mix}) as a function of stiffness of the asphalt used (S_A) in a log-log scale is shown in Figure 15. This presentation of the creep deformation characteristic has the advantage that the relative influence of a number of variables

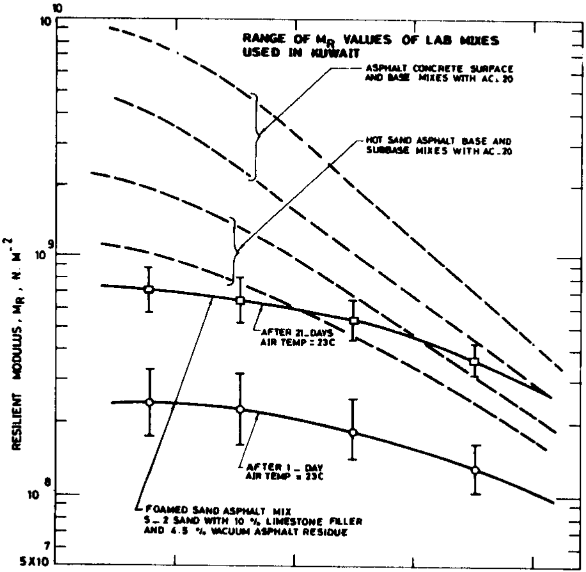

FIGURE 11 Resilient modulus versus temperature.

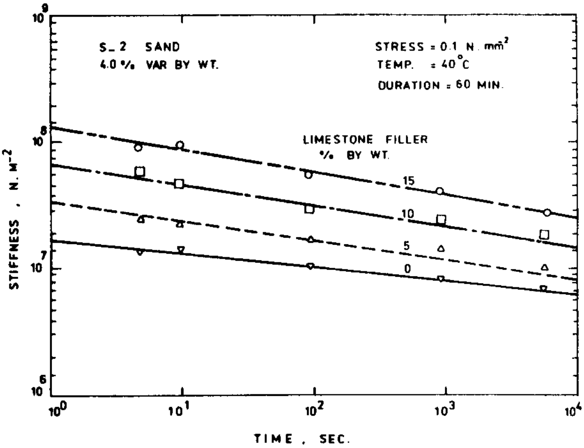

FIGURE 12 Creep stiffness for mixes with different fines contents.

can be quantified because permanent deformation is directly proportional to the reciprocal value of S_{mix} *(14)*. The stiffness of asphalt (S_A) is dependent on loading time, temperature, and asphalt properties and was determined using Van der Poel's nomograph *(15)*.

Figure 15 shows that the slope (q) of the log S_{mix} versus log S_A is equal to 0.08 and 0.18 for the foamed- and hot-asphalt mixtures, respectively. The higher the value of q, the more susceptible will be the mix to permanent deformation. This means that foamed-asphalt mixtures are less susceptible than corresponding hot-asphalt mixtures to permanent deformation. This is related to the improved low-stiffness properties of the foamed-asphalt mixture and to its relatively low asphalt content.

STRUCTURAL EVALUATION

The foamed-asphalt mixtures were evaluated in terms of their ability to perform as a pavement base or subbase layer. The structural evaluation was based on the results of tests carried

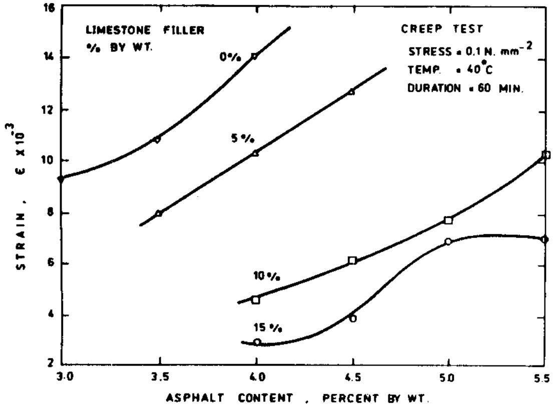

FIGURE 13 Creep strain versus asphalt content.

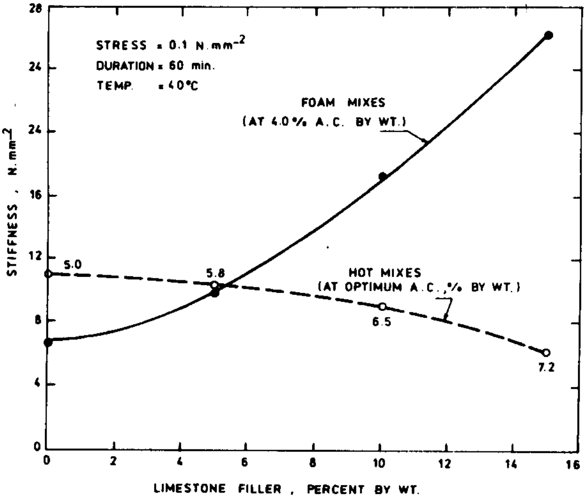

FIGURE 14 Creep stiffness of foamed- and hot-asphalt mixes.

out on mixtures at optimum percentages of foamed asphalt. Resilient modulus data for the range of local pavement temperatures were used to characterize these materials in a layered elastic model of the pavement system. The BISAR multilayered elastic computer program *(16)* and the DAMA computer program *(17)*, which analyze the pavement structure by cumulative damage techniques, were used for this purpose.

There are three criteria that affect the potential of asphalt pavement material as a structural base or subbase layer: (a) distribution of vertical stresses on the subgrade, (b) resistance to permanent deformation, and (c) fatigue life characteristics. The fatigue potential of the foamed-asphalt mixtures was found to be well below that of AASHO asphalt mixtures *(7)*. Foamed-asphalt mixtures have mechanical characteristics that fall between those of a granular structure and an asphalt-coated one. Therefore it may not be realistic to evaluate the fatigue potential of the foamed-asphalt mixtures in comparison with that of hot-asphalt mixtures. Moreover, fatigue cracking of asphalt base layers at high service pavement temperatures proved not to be the controlling criterion for pavement design life *(9)*. In this case, only subgrade deformation and resistance to permanent deformation in the pavement structural system were considered.

Thickness Equivalency

Thickness equivalencies for foamed-asphalt S-2 mixtures with 10 percent limestone powder and 4.5 percent (by weight) 310-

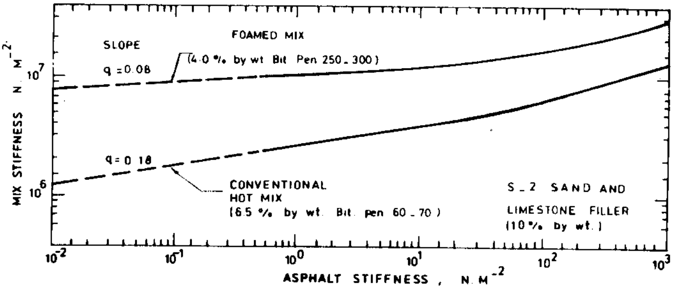

FIGURE 15 Log S_{mix}–Log S_A relationship for foamed- and hot-asphalt mixes.

pen asphalt were calculated on the basis of subgrade deformation damage. The relative ability of the foamed-asphalt layer to distribute vertical stresses and thus reduce critical subgrade strains or subgrade deformations was assessed and compared with that of other materials commonly used in pavement structures in Kuwait.

Two pavement systems were considered in this study. Pavement 1 is representative of a typical structure for a low-volume road [1,200 standard axle load (SAL) or 80 kN per month] in which the foamed-asphalt material is used as a base layer laid directly on the subgrade soil and overlaid with an asphalt concrete surface course 50 mm thick. Pavement 2 represents a medium-traffic volume road (12,000 SAL or 80 kN per month) in which the foamed-asphalt material is used as a subbase layer overlaid with 130-mm-thick base and surface courses of asphalt concrete. The thickness of the foamed-asphalt layer in both pavement systems varied between 80 and 180 mm. For each thickness the structural equivalency with hot plant asphalt concrete, hot sand-asphalt, and sand-gravel was determined. The procedure followed for computing the thickness equivalencies based on equal design lives is shown in Figure 16.

Monthly variation in temperature in Kuwait was used to account for the effect of temperature on moduli of asphalt pavement layers. For the sand-gravel materials the elastic mod-

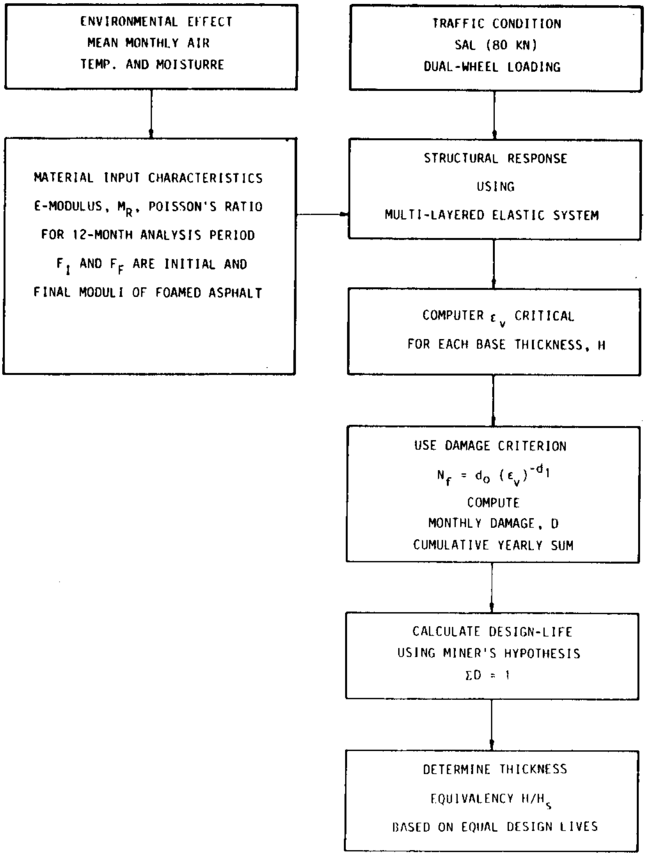

FIGURE 16 Procedure for determining thickness equivalency ratios based on subgrade deformation damage.

ulus is known to be stress dependent and is usually expressed as

$$E = K_1(\sigma_3)^{K_2} \quad (1)$$

where K_1 and K_2 are regression constants related to material type and physical properties and σ_3 is the minor principal stress (N/mm^{-2}). An indirect predictive equation, which was developed at the University of Maryland *(18)*, was used to account for the stress dependency in a simple manner.

Foamed-asphalt mixtures, like hot-asphalt mixtures, have modulus values that strongly depend on temperature. However, moduli of foamed asphalts differ in that they also are dependent on the degree of cure (loss of water). Thus, at any given temperature, the modulus will vary from some initial value (E_i) to the final modulus value (E_f) in a specified curing time. Analytically, this modulus relationship can be defined by *(19)*

$$T_{T,t} = E_{T,f} - (E_{T,f} - E_{T,i})\,(RF)_t \quad (2)$$

where

$E_{T,t}$ = modulus at temperature T and time t (N/mm^{-2}),
$E_{T,f}$ = final modulus at temperature T (N/mm^{-2}),
$E_{T,i}$ = initial modulus at temperature T(°C), and
$(RF)_t$ = reduction factor for cure at time t
= $e^{bt} = (1 - f_c)$

where

b = constant determined by the total cure period (t_c);
t = time at which RF is required (months); and
f_c = specified degree of cure, assumed to be 0.95.

The final modulus of foamed-asphalt specimens was achieved after curing outside the molds in air at 23°C for 21 days. Under field conditions, if it happened that the foamed-asphalt layer was overlaid with an asphalt concrete layer directly after construction, final modulus would be much delayed by the low degree of curing. In this analysis a total curing time of 6 months was assumed in order to achieve the final modulus value (Figure 17).

Figure 18 shows the thickness equivalencies of the foamed-asphalt layers in both pavement systems based on the subgrade damage criterion. That thickness equivalencies are a function of the geometrics of the pavement cross section and the stress distribution in the pavement system is indicated in Figure 18. Using the foamed-asphalt material as a base layer in Pavement 1 has resulted in average thickness equivalencies of 1.62, 1.00, and 0.77 compared with asphalt concrete, hot sand-asphalt, and sand-gravel base materials, respectively. However, in Pavement 2, foamed-asphalt subbase layers had average thickness equivalencies of 1.51, 0.97, and 0.60 compared with asphalt concrete, hot sand-asphalt, and sand-gravel materials, respectively.

Figure 19 shows the distribution of monthly damage to the four different subbase materials in Pavement 2 with equivalent layer thicknesses. Traffic is expected to start immediately after construction in July. The relatively high damage units for the foamed asphalt during the first 2 months of curing are obvious. During the next 4 months of curing, the foamed asphalt exhibits about the same amount of damage as was computed for a sand-gravel layer of equivalent thickness. From May through September, when pavement service temperatures are highest, foamed asphalt exhibited less damage than did hot sand-asphalt and asphalt concrete layers of equivalent thickness.

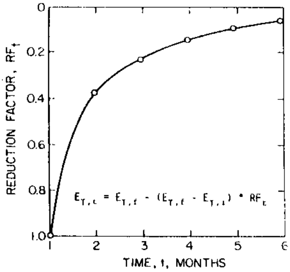

FIGURE 17 ***E*-modulus reduction factor versus curing time.**

Prediction of Permanent Deformation

The permanent deformation predicted within the foamed-asphalt layer was compared with that in an equivalent hot-asphalt layer for Pavements 1 and 2. With the predetermined thickness layer equivalency equal to 1.00, a thickness of 120 mm of foamed-asphalt base and subbase layer was considered. For the two candidate constructions, the permanent deformation was estimated according to the procedure outlined in the Shell Method *(20)*. There are eight steps to be followed in this procedure; the relevant quantities obtained in each step are given in Table 5.

Replacing hot-asphalt mix with foamed-asphalt mix has led to a reduction in the predicted permanent deformation from 8.30 to 5.40 mm for the base layer of Pavement 1 and from 8.25 to 4.20 mm for the subbase layer of Pavement 2. The replacement of hot-asphalt mix with a foamed-asphalt mix has resulted in a reduction in the predicted rut depth ranging from 35 to 50 percent during the whole service life of the pavement.

This analysis did not include the additional permanent deformation that may occur during curing of the foamed-asphalt layer if traffic is expected to use the road immediately after construction.

A lower asphalt grade was used in the foamed-asphalt mix than was used in the hot-asphalt mix. The reduction that occurred in the predicted permanent deformation could be related to the improved low stiffness properties of foamed-asphalt mixes at high service temperatures.

CONCLUSIONS

The foamed-asphalt process is specially suited to stabilizing locally available sands that contain a fines fraction (less than

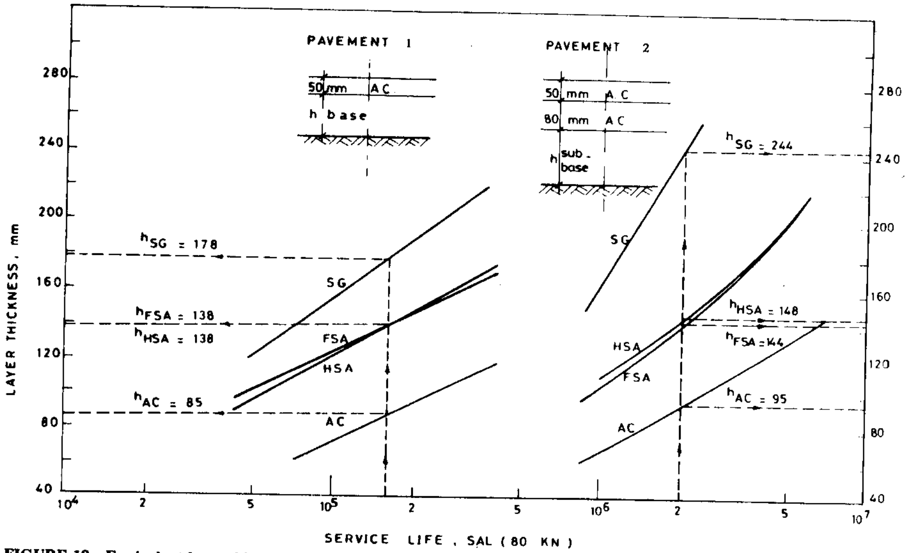

FIGURE 18 Equivalent layer thicknesses for different base and subbase pavement materials.

0.075 mm) at levels of 5 percent and above. The bitumen is concentrated in the finer fraction and forms a discontinuous random matrix of a cohesive asphalt mortar. This discontinuous nature of the foamed-asphalt binding mechanism of the sand aggregate results in mixtures that are much less temperature susceptible than are equivalent hot-asphalt plant mixtures.

The quality of sand is also important in determining its suitability for stabilization by foamed asphalt. The type and quality of fines are mainly responsible for the degree of moisture sensitivity of the foamed-asphalt mixtures. Coating sand particles with limestone powder in a slurry form initiates a subsequent bonding of the asphalt with the limestone surface rather than the surface of the original sand particles. This is quite similar to the effect of hydrated lime in improving the resistance of asphalt mixtures to moisture damage.

The effectiveness of the foaming process was found to be more pronounced at pavement service temperatures above 30°C. Foamed-asphalt mixes have higher tensile strength and resilient modulus values than those for corresponding hot-asphalt mixtures over the range of elevated service pavement temperatures.

Measured against the criterion of subgrade deformation

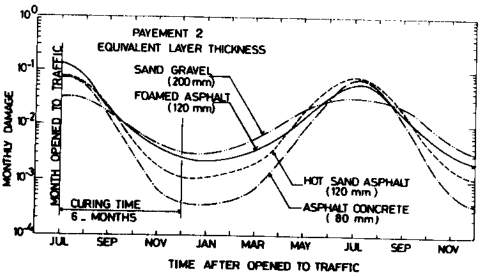

FIGURE 19 Distribution of monthly damage to different subbase pavement materials for Pavement 2.

TABLE 5 PREDICTION OF PERMANENT DEFORMATION AT MAAT = 31°C

Pavement System	$Visc_{eff}$ (N-sec/m²)	T_{eff} (°C)	Creep Curve Slope (q)	E-Modulus (N/m²)	W	$S_{bit,visc}$ (N/m²)	S_{mix} (N/m²)	Z	C_m	Δh (mm)
1[a]										
FSA	1.0×10^3	42	0.08	4.3×10^8	1.6×10^7	9.0×10^{-3}	8.0×10^6	0.3	2.0	5.40
HSA	2.0×10^4	42	0.18	3.8×10^8	4.5×10^5	6.6×10^6	4.2×10^6	0.3	1.6	8.30
2[b]										
FSA	1.5×10^3	40.8	0.08	4.5×10^8	1.6×10^8	1.4×10^{-3}	6.8×10^6	0.2	2.0	4.20
HSA	2.3×10^4	40.8	0.18	4.1×10^8	4.5×10^6	7.6×10^{-1}	2.8×10^6	0.2	1.6	8.25

NOTE: FSA = foamed sand-asphalt mixes, 4.0 percent by weight 310-pen bitumen; HSA = hot sand-asphalt mixes, 6.5 percent by weight 67-pen bitumen.
[a] SAL = 2.2×10^5.
[b] SAL = 2.2×10^6.

damage, foamed-asphalt base and subbase layers under the assumed local curing conditions are superior to unbound materials such as sand-gravel mix. At the local prevailing temperatures (MAAT = 31°C) foamed-asphalt mixes are structurally equivalent to corresponding hot sand-asphalt mixes. This indicates that, because of significant cost savings, sand stabilization with foamed asphalt could be an attractive alternative to either conventional hot-asphalt mixes or granular base materials.

At the local high pavement temperatures, cured foamed-asphalt base layers showed higher resistance to permanent deformations than did corresponding hot-asphalt layers. This is related partly to the improved low stiffness properties of the foamed mixes and partly to the relatively low asphalt content.

ACKNOWLEDGMENT

This paper was prepared as a part of Research Project 83-08-01 sponsored by the Kuwait Foundation of the Advancement of Sciences. The cooperation and assistance received from the Civil Engineering Department at Kuwait University are gratefully acknowledged.

REFERENCES

1. P. J. Ruckel et al. FOAMIX Asphalt Advances. *Symposium on Asphalt Pavement Construction: New Materials and Techniques.* Special Technical Publication 724. ASTM, Philadelphia, Pa., Dec. 1979, pp. 93–109.
2. S. M. Acott and P. A. Myburgh. Design and Performance Study of Sand Bases Treated with Foamed Asphalt. In *Transportation Research Record 898*, TRB, National Research Council, Washington, D.C., 1982, pp. 290–296.
3. F. Abel and C. R. Hines. *Base Stabilization with Foamed Asphalt.* Report CDOH-SMB-R-79. Colorado Division of Highways, Denver, June 1979.
4. P. J. Ruckel, S. M. Acott, and R. H. Bowering. Foamed Asphalt Paving Mixtures: Preparation of Design Mixes and Treatment of Test Specimens. In *Transportation Research Record 911*, TRB, National Research Council, Washington, D.C., 1982, pp. 88–95.
5. R. H. Bowering and C. L. Martin. Foamed Bitumen Production and Application of Mixtures Evaluation and Performance of Pavements. *Proc., Association of Asphalt Paving Technologists*, Vol. 45, 1976, pp. 453–477.
6. D. Y. Lee. Treating Marginal Aggregates and Soils with Foamed Asphalt. *Proc., Association of Asphalt Paving Technologists*, Vol. 50, 1981, pp. 211–150.
7. D. N. Little, J. W. Button, and J. A. Epps. Structural Properties of Laboratory Mixtures Containing Foamed Asphalt and Marginal Aggregates. In *Transportation Research Record 911*, TRB, National Research Council, Washington, D.C., 1982, pp. 104–113.
8. A. F. Bissada. Asphalt Pavement Temperatures Related to Kuwait Climate. In *Highway Research Record 404*, HRB, National Research Council, Washington, D.C., 1972, pp. 71–85.
9. A. F. Bissada, S. K. Hamdani, and H. R. Guirguis. Design Criteria of Asphalt Pavement Structures at High Service Temperatures. *Proc., Fifth International Conference on the Structural Design of Asphalt Pavements*, Delft, The Netherlands, 1982, pp. 142–155.
10. T. W. Kennedy. Characterization of Asphalt Pavement Materials Using the Indirect Tensile Test. *Proc., Association of Asphalt Paving Technologists*, Vol. 46, 1977.
11. E. Dettilster and P. J. Van De Loo. The Creep Test: Influence of Test Parameters. *International Collequium on Plastic Deformability of Bituminous Mixes*, Federal Institute of Technology, Zurich, Switzerland, Sept. 1977.
12. R. J. Schmidt. A Practical Method for Measuring the Resilient Modulus of Asphalt-Treated Mixes. In *Highway Research Record 404*, HRB, National Research Council, Washington, D.C., 1972, pp. 22–29.
13. J. A. Scott. Discussion: Symposium on Antistripping Additives in Paving Mixtures. *Proc., Association of Asphalt Paving Technologists*, Vol. 51, 1982, pp. 346–362.
14. P. J. Van De Loo. The Creep Test: A Key Tool in Asphalt Mix Design and in the Prediction of Pavement Rutting. *Proc., Association of Asphalt Paving Technologists*, Vol. 47, 1978, pp. 522–554.
15. F. Bonnaure, G. Gest, A. Gravois, and P. Uge. A New Method of Predicting the Stiffness of Asphalt Paving Mixtures. *Proc., Association of Asphalt Paving Technologists*, Vol. 46, 1977, pp. 64–100.
16. *BISAR Multilayered Elastic Computer Program.* Shell International Petroleum Company, Ltd., London, England, 1978.
17. *DAMA Computer Program.* The Asphalt Institute, College Park, Md., 1983.
18. B. E. Smith and M. W. Witczak. Equivalent Granular Base Moduli: Prediction. *Transportation Engineering Journal*, ASCE, 1981.
19. L. E. Santucci. Thickness Design Procedure for Asphalt and Emulsified Asphalt Mixes. *Proc., 4th International Conference on Structural Design of Asphalt Pavements*, Ann Arbor, Mich., Vol. 1, 1977.
20. *Shell Pavement Design Manual.* Shell International Petroleum Company, Ltd., London, England, 1978.

Publication of this paper sponsored by Committee on Characteristics of Bituminous Paving Mixtures To Meet Structural Requirements.