1985

3

of asphalt at temperatures that are near those of the pavement. There is a second extrapolation that should not be forgotten when trying to understand pavement conditions: the variation in viscosity at different levels of stress. Asphalts become more non-Newtonian as the temperature of measurement is reduced to ambient. Asphalts vary in their non-Newtonian effects but some vary by a factor of 40 between the low stresses at which viscosities are usually measured in the laboratory and the high stresses found in pavement under traffic. The interpretation of test results can often be greatly simplified if not only the scatter due to temperature extrapolation but also the scatter due to stress extrapolation can be eliminated or reduced.

---

*Koppers Company, Inc.
2701 Koppers Building
Pittsburgh, Pa. 15219

Publication of this paper sponsored by Committee on Characteristics of Bituminous Materials.

Innovations in Oklahoma Foamix Design Procedures

HAZEM A. SAKR and PHILLIP G. MANKE

ABSTRACT

Little attempt has been made in Oklahoma to investigate foamed asphalt mixes or to take advantage of these mixes for road construction purposes. To demonstrate the efficacy and applicability of this type of asphalt mix, a study of factors that affect fine aggregate-foamed asphalt mixtures formulated from materials indigenous to the state was undertaken. In addition to verifying the effects of the amount of fines (percentage of aggregate material passing the No. 200 sieve), mixing moisture content, asphalt content, and curing condition on foamix properties as reported by previous investigators, this study introduced two unique investigative concepts: (a) the use of an aggregate's "particle index" along with the percentage passing the No. 200 sieve to predict its performance in a foamix and (b) the use of a multilinear regression model or equation for determining the optimum premolding moisture content for a foamix. Although only a part of the original investigation, these two aspects of the study are considered directly applicable to foamix mix design procedures. The "particle index" (a measure of angularity and surface texture of aggregate particles) proved to be an excellent indicator of the suitability of marginal quality aggregates for foamixing. By using the predictive multilinear regression equation, the optimum premolding moisture content for a foamix can be ascertained without extensive laboratory testing.

A foamed asphalt mix has been defined as a mixture of wet unheated aggregates and asphalt cement mixed while the asphalt is in a foamed state. These mixes normally produce fairly stiff, stable mortar-type material in which the asphalt is concentrated primarily in the finer fraction of the aggregate, especially the fine sand and silt fraction (1-6). The selective ability of foamed asphalt to coat the fines and form a mortar between the larger aggregate particles creates a new type of asphalt-aggregate structure that is different from other asphalt mixtures.

INTRODUCTION

Some factors have proved to significantly affect the quality and properties of foamed asphalt mixtures both in the laboratory and as finished pavement layers in the field. These factors can be summarized from the literature as follows:

Aggregate Quality

A minimum of 3 to 5 percent passing the No. 200 sieve is considered a basic requirement to get a promising foamed asphalt mixture (1,3,7-9). Lee (3) suggested an upper limit of the percentage passing the No. 200 sieve in the range of 35 to 40 percent.

Mixing Moisture Content

Csanyi's original work and recent studies in Australia and the United States (3,10-13) have pointed out the need for mixing water in the soil aggregate before addition of the foamed asphalt. This mixing water is needed to moisten the material so that any agglomerations can be broken up and the larger particles uniformly distributed through the mix. It also envelopes and separates the fine particles with thin layers of moisture that provide channels through which the foamed asphalt can penetrate to coat these particles (7).

In the literature, the amount of water required for a foamed asphalt mix was considered an important factor by all investigators. Csanyi suggested that the proper amount of water for any mix might be determined by a few trial batches. In recent work in Australia, Bowering (14) suggested that the optimum mixing water content should be the "fluff point," the moisture content at which the soil aggregate has its maximum bulk volume. Use of the fluff point as the mixing moisture content was also recommended by Brennan et al. (4) and by Little et al. (15). Lee (3) found that optimum mixing moisture content varied with the gradation of aggregate (particularly the percentage passing the No. 200 sieve) and ranged from 65 to 85 percent of a soil's optimum moisture content as determined by standard AASHTO test. The term "total fluid content," defined as the mixing water plus foamed asphalt in a mix, has recently been proposed (9). It was suggested that the total fluid content might be equal to the standard optimum moisture content to achieve maximum compaction of the soil-aggregate mixture.

Asphalt Content

As with any asphalt-aggregate mix, the structural properties of foamed asphalt mixtures are dependent on the level of asphalt content. In a study in Australia (1), it was found that mixes made with foamed asphalt and with asphalt emulsion had similar properties up to an asphalt content level of 1.5 percent by dry weight of aggregate. Above this level of asphalt content the foamixes displayed improved structural properties.

Curing Condition

Although foamed asphalt cold mixes do not have the curing problems associated with cutback or asphalt emulsion mixes (16,17), the curing condition must be considered in the mix design and evaluation. Experience has indicated that cold wet foamed asphalt mixes tend to improve with age, traffic, and temperature (6). These conditions contribute to the removal of moisture from the compacted mix.

In addition to these factors, the effect of aggregate particle angularity and surface texture was introduced in this study. This was done using the "particle index" of the aggregates. The particle index value is a quantitative measure of the aggregate shape and surface texture characteristics.

The research effort was directed primarily toward the investigation of the properties of fine aggregate-foamed asphalt mixtures made from materials indigenous to Oklahoma. The major incentives for this work were to develop a foamix design procedure applicable to such materials and to demonstrate the efficacy of this type of mixture as an alternative to the more conventional emulsion and hot mixes presently used throughout the state.

RESEARCH APPROACH

Materials

Asphalt Cement

This investigation of foamed asphalt mixes was limited to the use of an 85-100 penetration paving grade asphalt cement. This grade of asphalt cement is commonly used in asphalt pavement construction in Oklahoma and is specifically required by the Oklahoma Department of Transportation in all plant mix bituminous bases and surface course mixes (18). Because a recent investigation found no appreciable differences in the stabilities of foamed asphalt mixes made with different grades of asphalt cement (3), it appeared that this was a valid decision and would not restrict the applicability of the research results.

Aggregates

Both wind- and water-borne deposits of fine aggregate materials are readily available throughout most areas of Oklahoma. However, certain physical properties of fine aggregates, such as gradation, particle angularity, and surface texture, were thought to affect the suitability of an aggregate for good mixing with foamed asphalt and influence the stability and other properties of compacted mixtures. The aggregates selected should encompass a range of these physical properties to allow determination of the significance of the respective characteristic.

This presented some difficulty because tests on a large number of samples from a variety of sources in central Oklahoma indicated little difference in gradation or angularity of particles. Ultimately, it was decided to select a naturally occurring sand, a processed sand from a screening and washing operation, and a fine aggregate material from a crushing operation. Two additional fine aggregate mixtures were then manufactured by crushing and blending these basic materials to obtain the desired range of properties.

Thus five fine aggregate materials were used in the various aspects of this study. These materials were

1. Sand (N-1). A very fine, silicious, silty sand from alluvium deposits along the North Canadian River in Canadian County. This sand was obtained at a foamix plant site northwest of Yukon, Oklahoma. (Note that alpha-numeric characters are used to identify each of the respective fine aggregate materials.)
2. Washed sand (S-1). A clean, relatively coarse, reddish-brown sand produced from a screening and washing operation at a gravel pit northeast of Asher, Oklahoma. This pit is located in the Maud conglomerate of the Wellington-Admire geologic unit (19) in Pottawatomie County. The conglomerate deposits consist of a fairly homogenous mixture of chert particles ranging in gradation from fine sand to cobbles.
3. Screenings (C-1). Crushed limestone screenings from a quarry and crusher operation northeast of Drumright, Oklahoma. The quarry is located in the Lecompton geologic unit (19) in Creek County. This unit consists of gray thin-bedded to massive lime-

stone that is hard and dense. The individual particles of this crushed material had a relatively high degree of angularity and a rough surface texture.

4. Blended sand (B-1). A mixture of fine sand (N-1) and washed sand (S-1) blended in a one-to-one ratio by weight. The twofold objective of using this blended fine aggregate was to see if the addition of fines would improve the workability and the properties of the coarse sand foamixes and, at the same time, whether the addition of coarser material would enhance the properties of the foamixes made from the finer sand.

5. Crushed sand (C-2). Pit run chert gravel from an Asher, Oklahoma, pit was crushed in a small jaw crusher. The material was then passed through a 3/8-in. (10-mm) sieve to remove the coarser particles. This produced a fine aggregate that has a degree of angularity higher than the N-1, S-1, and B-1 materials.

The general characteristics of the five aggregates are given in Table 1 and shown in Figures 1 and 2.

TABLE 1 Physical Properties of Fine Aggregates

Characteristic	ASTM Test	Test Values for Aggregates N-1	S-1	B-1	C-1	C-2
Sieve analysis	C136	See Figure 1			See Figure 2	
Optimum moisture content (%)	D698	11.0	11.3	10.0	9.8	10.1
Specific gravity	C128	2.43	2.41	2.42	2.6	2.41
Plasticity index (%)	D424	NP	NP	NP	NP	NP
Particle index	D3398[a]	5.3	6.3	5.8	15.5	12.9
Fluff point[b] (%)		7.5	7.6	4.0	4.6	5.5

[a] Modified test, as suggested in the standard procedure for fine sieve fractions.
[b] Nonstandard test procedure.

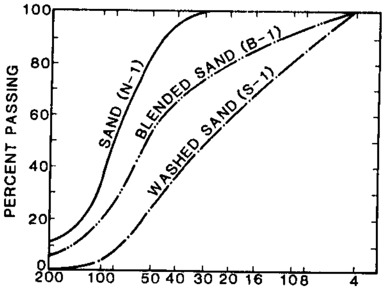

FIGURE 1 Gradation of aggregates N-1, S-1, and B-1.

Equipment

Mixing

Foamed asphalt was produced using a laboratory foamix asphalt dispenser obtained from Conoco, Inc. This dispenser unit was built in the Technical Service Laboratory of Conoco's facilities in Ponca City, Oklahoma, and was designed to simulate foamed asphalt produced in commercial mixing units. A three-speed Hobart C-100 orbital food mixer equipped with a flat beater type agitator was used to blend the foamed asphalt with the respective fine aggregates.

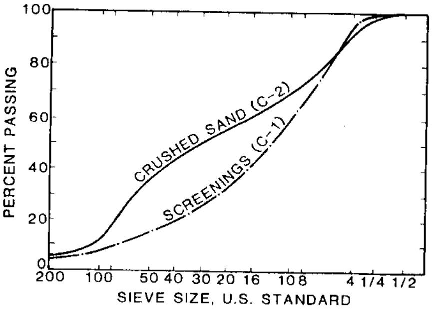

FIGURE 2 Gradation of aggregates C-1 and C-2.

Molding

Mechanical gyratory-shear molding equipment was used for molding the foamed asphalt-aggregate mixtures into test specimens 4.0 in. (102 mm) in diameter and 2.0 in. (51 mm) high. This equipment conveys a gyratory-shearing action to asphalt-aggregate mixtures in a mold at low initial pressure to achieve optimal orientation of the particles. During compaction the platen of this compactor rotates and the specially designed mold imparts a rocking type of shearing action to the compressed mixture in the mold (20).

Testing

Standard Marshall testing equipment, as described in ASTM D1559, was used with the exceptions that the ring dynamometer was replaced by a 10,000 lb (4.45×10^4 N) capacity load cell and a strip chart recorder was employed to record directly the stability and flow values of the foamix test specimens. The use of gyratory-shear compacted 2.0-in. (51-mm) high specimens to obtain Marshall stability values was a time-saving compromise relative to the overall objectives of the investigation and the foamix properties studied.

Testing Program

The testing program relating moisture content, particle index, and percentage of fines of the aggregates to the properties of foamixes was divided into two tasks. The first task was to study the effect of premolding moisture content on the relative strength of the foamed asphalt-aggregate blends as measured by the compacted dry density of the foamixes. Four dry batches of each aggregate (enough to mold at least nine specimens per batch) were prepared. The moisture contents of the four dry batches of aggregate were adjusted to 50, 65, 80, and 95 percent, respectively, of the optimum value as determined from the ASTM D698 test procedure. Each of the wet aggregate batches was then divided into three equal portions and each portion was mixed with a different level of foamed asphalt cement ranging from 2.0 to

5.5 percent by dry weight of aggregate. Specimens were compacted using the gyratory-shear compactor to produce three specimens at each level of foamed asphalt cement content for each of the four levels of premolding moisture content. The height of each specimen was determined in the mold and the specimen was then dried to constant weight in an oven. The dry density of each specimen was determined and the relation between molding moisture content and foamix dry density was plotted. The optimum premolding moisture content for each aggregate at each of the three levels of foamed asphalt content was determined as the moisture content at which maximum dry density was obtained.

The second task was to ascertain the effects of the percentage of material passing the No. 200 sieve and aggregate angularity and surface texture on the Marshall stability values of compacted foamed asphalt mixtures made from the respective aggregates. Also, these stability values were compared with those of hot asphalt mixes made using the same aggregates and asphalt cement.

Batches of the five aggregates, (N-1, B-1, S-1, C-1, and S-2) were adjusted to their optimum premolding moisture content, as found from the first study, before they were mixed with foamed asphalt at four different levels. Triplicate specimens were molded and cured in mold for 24 hr at room temperature followed by out-of-mold curing for 72.0 hr at 105°F (40°C). Similar batches of the same five aggregates were hot mixed with the asphalt cement at three levels of asphalt content, 3.0, 4.0, and 5.0 percent by dry weight of aggregate, and molded using the gyratory-shear compactor. Both foamed asphalt and hot asphalt mixed specimens were tested for Marshall stability at temperatures of 77°F (25°C) and 105°F (40°C).

RESULTS AND DISCUSSION

Premolding Moisture Content

The optimum premolding moisture content can be defined as the moisture content of the foamed asphalt-aggregate mixture at which the maximum density of the compacted mixture is obtained using any method of compaction. In this case, gyratory-shear compaction was used. The Statistical Analysis System (SAS) computer program (22) was used to develop a multilinear regression model relating the premolding moisture content of the foamix and the influencing variables. It was thought that the variables that might affect the premolding moisture content were the aggregate optimum moisture content, the percentage of material passing the No. 200 sieve, the percentage of asphalt cement content, and the fluff point. The following model form was used to develop a relationship between the foamix premolding moisture content and these variables:

$$MMC = \beta_0 + \beta_1(OMC) + \beta_2(PF) + \beta_3(FP) + \beta_4(AC) \qquad (1)$$

where

MCC = foamix optimum premolding moisture content, percentage by dry weight of aggregate;
OMC = aggregate optimum moisture content, percentage by dry weight of aggregate (ASTM D698);
PF = percentage of material passing the No. 200 sieve;
FP = fluff point, moisture content at maximum bulk volume, percentage by dry weight of aggregate;
AC = asphalt content, percentage by dry weight of aggregate; and
$\beta_0, \beta_1, \beta_2, \beta_3, \beta_4$ = regression constants.

A stepwise regression technique provided by SAS was employed to develop the best representative model. The following model has a coefficient of determination (R^2) of 97.7 percent and observed significance level values less than 0.001 for all regression constants.

$$MMC = 8.92 + 1.48(OMC) + 0.40(PF) - 0.39(AC) \qquad (2)$$

The relation given by Equation 2 suggests that, for a given aggregate used in a foamix, the higher the asphalt content the lower the premolding moisture content. It should be noticed that the fluff point (FP) does not appear as an independent variable in the equation. When the fluff point was included, the effect of aggregate optimum moisture content was distorted (i.e., the observed significance level of the regression constant β_1 was higher than any significance level commonly used). When the fluff point was neglected, the stepwise regression analysis resulted in Equation 2. Similar results were obtained when the optimum moisture content, instead of the fluff point, was not included. The dependency of these two variables (FP and OMC) on each other indicated a direct association between their values. However, for the purpose of developing the model, the fluff point was excluded because the procedure for the determination of this variable was not a standard test method.

Table 2 gives the premolding moisture content (MMC) values determined experimentally and the values computed by Equation 2. No apparent differences between the determined and the computed values are observed.

TABLE 2 Determined and Computed Premolding Moisture Contents for Foamixes

Aggregate	Asphalt Content (%)	MMC (% dry aggregate weight)		Computed MMC as Percentage of OMC
		Experimental	Computed	
N-1	3.00	10.80	10.76	98.0
	3.75	10.50	10.47	95.0
	4.50	10.15	10.18	92.5
	5.25	9.85	9.85	89.5
B-1	3.00	6.75	7.08	71.0
	4.00	6.25	6.70	67.0
	5.00	5.75	6.30	63.0
S-1	3.00	6.75	6.85	61.0
	4.00	6.50	6.45	57.7
	5.00	6.15	6.07	53.7
C-1	2.50	6.75	6.50	66.3
	4.00	6.35	5.97	60.4
	5.50	5.70	5.35	54.6
C-2	3.00	6.80	6.83	67.8
	4.00	6.50	6.44	63.8
	5.00	6.20	6.06	60.0

The optimum mixing moisture content (i.e., the moisture content of a fine aggregate required to achieve the best or most uniform distribution of foamed asphalt in the mix) was higher than the premolding moisture content of the mixture for all but one of the five aggregates evaluated in this study. The exception was the coarse aggregate S-1 for which good distribution of the foamed asphalt could not be obtained at either higher or lower moisture contents. This suggests that there is an interaction between the optimum mixing moisture content of an aggregate and the amount of material passing No. 200

sieve contained in the aggregate. It also substantiates the selective ability of foamed asphalt for coating the wet fines found by previous investigators (1,3,9).

Therefore the optimum mixing moisture content can also be defined as the moisture content required to reach the best distribution of wet fines in an aggregate batch before it is mixed with foamed asphalt. The larger the percentage of fines (material passing No. 200 sieve) in the aggregate, the higher the potential for improved distribution of asphalt cement in the mix with increased moisture content. However, compacting a foamixture at its optimum mixing moisture content may result in lower density and strength values. Although oven drying of the mixtures in the laboratory (aeration in the field) could be used to bring the mixes to their desired premolding moisture content (MMC) before compaction, this was considered excessively time consuming and not warranted for the aggregates being studied. Because the optimum mixing moisture contents of the fine aggregates in this study were only 10 to 20 percent higher than the premolding moisture contents, the premolding moisture contents were employed for both mixing and molding. Peripheral test results indicated that little or no change in foamix properties resulted. Use of this technique will greatly reduce the laboratory time required for design of a foamix.

Aggregate Particle Index and Percentage of Fines

Four different factorial experiments were designed to statistically analyze the data obtained from the Marshall stability tests. Two of these factorial experiments (one for foamixes and the other for hot mixes) were used to study the influence of particle index on the Marshall stability of the asphalt-treated aggregates. The other two factorial experiments studied the effect of the percentage of fines (material passing the No. 200 sieve) on the stability of foamixes and hot mixes.

The SAS computer program was used to conduct tests for evidence of real differences in the observed values. The results of these tests indicated the observed significance level and acceptance or rejection of the null hypothesis (no difference) on the basis of a customary significance level of 0.05.

Particle Index

Marshall stabilities of molded specimens of foamixes made from aggregates (B-1, C-2, and C-1) with respective particle index values of 5.8, 12.9, and 15.5 and nearly the same percentage of fines (4.7 to 5.9 percent) were analyzed in a 3 x 4 x 2 completely randomized design factorial experiment. The first factor in the experiment consisted of the three levels of particle index. Asphalt contents of 2.5, 3.5, 4.5, and 5.5 percent by dry weight of aggregate comprised the second factor, and testing temperatures of 77°F and 105°F (25°C and 40°C) represented the third factor.

The analysis of variance of this experiment showed that the null hypothesis of no differences between mean stabilities was rejected. The values of the observed significance levels were less than 0.0001 for all main effects as well as for all interactions between factors. These significant interactions indicate that the factors under consideration (i.e., particle index, percentage of asphalt content, and testing temperature) are not independent of each other and that conclusions related to differences in stabilities at different levels of particle index should be based on individual combinations of percentage of asphalt content and testing temperature. The Tukey's w-procedure (22) was used for judging the significance of differences between paired stability means based on a significance level of 0.05.

Table 3 gives the results of these pairwise comparisons between the three levels of particle index at different asphalt content-testing temperature combinations. The Marshall stabilities of the foamixes versus the percentage of asphalt content for the three levels of particle index at each of the two testing temperatures are shown in Figure 3. Foamixes with higher particle index values tend to produce higher Marshall stabilities, at the same percentage of asphalt content and testing temperature. The only case that deviated from this general trend was the combination of 5.5 percent asphalt content and 77°F (25°C) testing temperature for mixes C-1 and C-2. The Marshall stability of the foamix C-2, with a particle index of 12.9, was slightly higher than that of foamix C-1, which had a particle index of 15.5.

This deviation is considered minor because both

TABLE 3 Multiple Comparisons of Mean Stabilities for Paired Levels of Particle Index (foamixes)

Testing Temperature	Asphalt Content (%)	Sign of Paired Means Difference and Results of Test of Significance of Real Difference		
		$M_{C-1} - M_{C-2}$[a]	$M_{C-1} - M_{B-1}$	$M_{C-2} - M_{B-1}$
77°F	2.5	(+) Significant[b]	(+) Significant	(+) Significant
	3.5	(+) Significant	(+) Significant	(+) Significant
	4.5	(+) Nonsignificant[b]	(+) Significant	(+) Significant
	5.5	(–) Nonsignificant	(+) Significant	(+) Significant
105°F	2.5	(+) Significant	(+) Significant	(+) Significant
	3.5	(+) Significant	(+) Significant	(+) Significant
	4.5	(+) Significant	(+) Significant	(+) Significant
	5.5	(+) Significant	(+) Significant	(+) Significant

[a] M_{C-1} etc. is mean stability value for foamix C-1.
[b] Level of significance $\alpha = 0.05$.

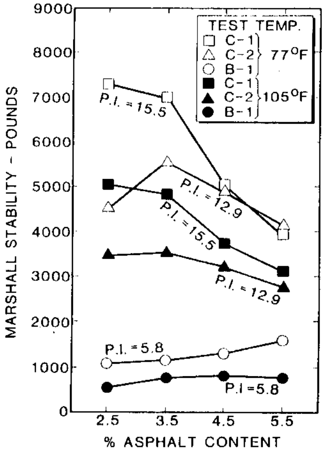

FIGURE 3 Effect of particle index value (P.I.) on Marshall stability of foamixes.

foamixes (C-1 and C-2) have relatively high particle index values and, at the 77°F (25°C) test temperature, the difference between mean stabilities (M_{C-1} and M_{C-2}) of the two mixes are nonsignificant for asphalt contents of 4.5 and 5.5 percent (see Table 3). This implies that the stabilities of these two foamixes were statistically equal at these combinations of particle index, asphalt content, and test temperature.

Also, it is widely accepted by other investigators (1,3) that foamed asphalt has the ability to mix with and selectively coat the fines (material passing the No. 200 sieve) contained in an aggregate. The fine material functions as a filler for the asphalt in the mix and this filled asphalt forms a mortar between the larger aggregate particles. These mineral fines serve to drastically increase the viscosity of the asphalt binder, which provides increased strength to the compacted mixture. When the amount of asphalt is in excess of that needed to blend with the fines in a foamix, quantities of more or less pure asphalt are present in the mixture. This unblended lower viscosity asphalt acts more as a lubricant than as a binding agent and will tend to reduce the strength or stability of the mix.

Because the asphalt content at which the highest stability of foamix C-1 is achieved is 1 percent less than that for the highest stability of foamix C-2 at a test temperature of 77°F (25°C), it is likely that, at 5.5 percent asphalt content, the excess unblended asphalt in foamix C-1 was enough to reduce the Marshall stability below that of foamix C-2, overcoming the relative effect of a higher particle index.

A second factorial experiment was designed to study the effect of particle index on the Marshall stability of compacted hot mixes made with the same aggregates used in the foamixes (i.e., aggregates B-1, C-2, and C-1). This experiment was similar to that for the foamixes with the exception that the levels of asphalt content were 3.0, 4.0, and 5.0 percent. An F-test from the analysis of variance showed the significance of all treatments' main effects as well as interactions between temperature and asphalt content and between temperature and particle index.

Figure 4 shows the relationship between Marshall stability and the percentage of asphalt content at different levels of particle index and testing temperature for the hot mixes. In general, the Marshall stabilities for the respective combinations are considerably lower for the hot mixes than for the foamixes within a similar range of asphalt contents. It is also evident from Figure 4 that stabilities of the hot mixes, at all levels of particle index, are higher when measured at 77°F (25°C). This, no doubt, is a reflection of decreased viscosity in the asphalt binder at the higher test temperature. The results given in Table 4 indicate that the differences between mean stabilities at paired levels of particle index are only significant in 4 of 18 combinations of particle index, asphalt content, and testing temperature. This suggests that, within the limits of this study, the stabilities of the compacted hot mixed aggregates are more dependent on testing temperature than on the level of the aggregate's particle index. This propensity is different from that of the foamixes for which the aggregate's particle index is the predominant factor influencing stability.

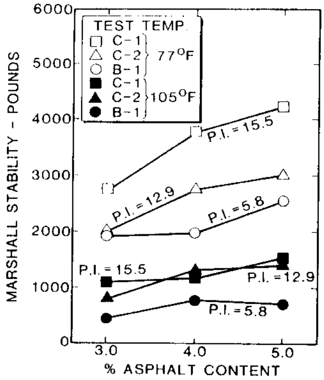

FIGURE 4 Effect of particle index value (P.I.) on Marshall stability of hot mixes

Percentage of Fines

To determine the effect of the percentage of fines (material passing the No. 200 sieve) on the Marshall stability of compacted foamixes and hot mixes, aggregates S-1, B-1, and N-1 were used. These three aggregates had roughly the same particle index values, ranging from 5.3 to 6.3, and contained, respectively, 0.5, 6.0, and 11.4 percent (by dry weight of aggregate) material passing the No. 200 sieve.

The relationship between Marshall stability and percentage of asphalt content at different percentage levels of fines and testing temperature for the foamixes and hot mixes are shown in Figures 5 and 6. Figure 5 suggests that at a given test temperature the higher the percentage of fines in a foamix the

TABLE 4 Multiple Comparisons of Mean Stabilities for Paired Levels of Particle Index (hot mixes)

Testing Temperature	Asphalt Content (%)	Sign of Paired Means Difference and Results of Test of Significance of Real Difference		
		$M_{C-1} - M_{C-2}$[a]	$M_{C-1} - M_{B-1}$	$M_{C-2} - M_{B-1}$
77°F	3.0	(+) Nonsignificant[b]	(+) Nonsignificant	(+) Nonsignificant
	4.0	(+) Nonsignificant	(+) Nonsignificant	(+) Nonsignificant
	5.0	(+) Significant[b]	(+) Significant	(+) Significant
105°F	3.0	(+) Nonsignificant	(+) Significant	(+) Significant
	4.0	(+) Nonsignificant	(+) Nonsignificant	(+) Nonsignificant
	5.0	(+) Nonsignificant	(+) Nonsignificant	(+) Nonsignificant

[a] M_{C-1} etc. is mean stability value for hot mix C-1.
[b] Level of significance $\hat{\alpha} = 0.05$.

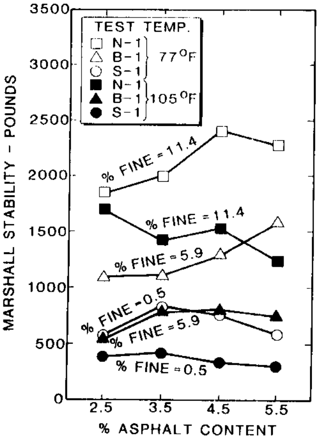

FIGURE 5 Effect of percent fines on Marshall stability of foamixes.

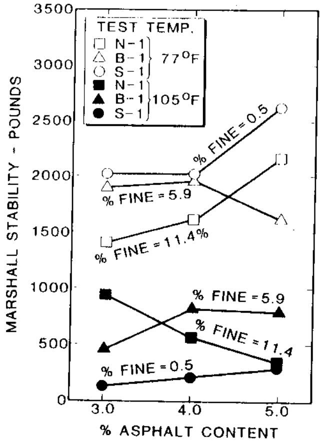

FIGURE 6 Effect of percent fines on Marshall stability of hot mixes.

higher the Marshall stability value at any level of asphalt content. For example, at a testing temperature of 77°F (25°C), the Marshall stability values of specimens made from foamix N-1, with 11.4 percent fines, are higher than are those of specimens made from foamix B-1, with 6.0 percent fines. Also, the Marshall stability values of specimens made from foamix S-1, with 0.5 percent fines, are lower than those of B-1 and N-1. This trend also applies at a testing temperature of 105°F. Figure 6 shows the dominating influence of the testing temperature on the Marshall stability values of hot mixes. The Marshall stabilities of specimens made from hot mixes (N-1, B-1, and S-1) determined at the testing temperature of 77°F (25°C) are higher than those determined at the testing temperature of 105°F (40°C). Furthermore, at a testing temperature of 77°F (25°C), the Marshall stability values of specimens made from hot mix S-1, with 0.5 percent fines, are higher than those for hot mixes N-1 and B-1. This is most probably due to the better asphalt coatings on the particles of aggregate S-1, which had the smallest total amount of surface area compared with the other two aggregates.

The analysis of variance of the effect of percentage of fines on the stability values of compacted specimens from foamixes and hot mixes implied conclusions similar to those obtained for the particle index analysis discussed previously. All main effects and interactions between treatment levels for the foamixes were significant at a significance level of 0.05. For the hot mixes, only the three-factor interaction was not significant. Therefore multiple comparisons between mean stabilities of paired levels of percentage of fines at all combinations of asphalt content and testing temperature were computed using the Tukey's w-procedure. Tables 5 and 6 give the results of the multiple comparisons for foamixes and hot mixes, respectively.

The results of multiple comparisons of the foamixes indicate that the differences between mean stability values of every paired level of percentage

TABLE 5 Multiple Comparisons of Mean Stabilities for Paired Levels of Percentage Fines (foamixes)

Testing Temperature	Asphalt Content (%)	Sign of Paired Means Difference and Results of Test of Significance of Real Difference		
		$M_{N-1} - M_{B-1}$[a]	$M_{N-1} - M_{S-1}$	$M_{B-1} - M_{S-1}$
77°F	2.5	(+) Significant	(+) Significant	(+) Significant
	3.5	(+) Significant[b]	(+) Significant	(+) Significant
	4.5	(+) Significant	(+) Significant	(+) Significant
	5.5	(+) Significant	(+) Significant	(+) Significant
105°F	2.5	(+) Significant	(+) Significant	(+) Significant
	3.5	(+) Significant	(+) Significant	(+) Nonsignificant
	4.5	(+) Significant	(+) Significant	(+) Significant
	5.5	(+) Significant	(+) Significant	(+) Significant

[a] M_{N-1} etc. is mean stability value for foamix N-1.
[b] Level of significance $\alpha = 0.05$.

TABLE 6 Multiple Comparisons of Mean Stabilities for Paired Levels of Percentage Fines (hot mixes)

Testing Temperature	Asphalt Content (%)	Sign of Paired Means Difference and Results of Test of Significance of Real Difference		
		$M_{N-1} - M_{B-1}$[a]	$M_{N-1} - M_{S-1}$	$M_{B-1} - M_{S-1}$
77°F	3.0	(−) Nonsignificant[b]	(−) Nonsignificant	(−) Nonsignificant
	4.0	(−) Nonsignificant	(−) Nonsignificant	(−) Nonsignificant
	5.0	(+) Nonsignificant	(−) Nonsignificant	(−) Nonsignificant
105°F	3.0	(+) Significant[b]	(+) Significant	(+) Significant
	4.0	(−) Nonsignificant	(+) Nonsignificant	(+) Significant
	5.0	(−) Nonsignificant	(+) Nonsignificant	(+) Nonsignificant

[a] M_{N-1} etc. is mean stability value for hot mix N-1.
[b] Level of significance $\alpha = 0.05$.

of fines are significant at all combinations of asphalt content and test temperature. Furthermore, all differences have positive signs (i.e., the mean stabilities for specimens made from foamix N-1, with 11.4 percent fines, are significantly higher than those for specimens made from foamixes B-1 and S-1, with 6.0 and 0.5 percent fines, respectively). Also, the mean stabilities of specimens made from foamix B-1 are significantly higher than those of specimens made from foamix S-1. Therefore a larger percentage of materials passing the No. 200 sieve in a foamix would result in a higher Marshall stability value.

For hot mixes the differences between mean stabilities of paired levels of the percentage of fines factor were nonsignificant for all levels of asphalt content at a testing temperature of 77°F (25°C). The prevailing negative signs in the upper half of Table 6 support the data illustrated in Figure 6; however, these differences are not statistically significant. At a testing temperature of 105°F (40°C), the positive signs of differences between mean stability values dominate (i.e., the Marshall stabilities of compacted specimens from hot mixes made from aggregates with higher percentages of fines are greater than those made from aggregates with lower percentages of fines).

In general, it is evident that the stability values of specimens made from hot mixes tend to be more dependent on the testing temperature than on the constituting aggregate properties. In preparing a hot mix, the hot materials are blended until individual aggregate particles are coated with a thin film of asphalt. When compacted, these asphalt films form a surface or point of contact bond between the particles that is sensitive to temperature changes. The structure of a foamix differs from that of a hot mix in that it is somewhat similar to that of a portland cement concrete. The asphalt cement, while in the foam condition, blends predominantly with the fine materials forming a black strong mortar that fills the voids between larger aggregate particles. This mortar or filled asphalt is less susceptible to temperature change and stronger than plain asphalt cement. This kind of structure in a foamix provides a greater mechanical interlock of the larger particles. Therefore the angularity and surface texture of the aggregate play a more dominant role in the stability of a foamix.

CONCLUSIONS

On the basis of this study and of materials studied the following conclusions are drawn:

1. Foamed asphalt is an effective binder for stabilizing and improving the qualities of indige-

nous fine aggregates for use in road construction in Oklahoma.

2. The particle index (a measure of angularity and surface texture of aggregate particles) is an excellent parameter or indicator of the suitability of fine aggregates for foamixing.

3. Compacted foamixes made with aggregates that have particle index values greater than 10 had significantly higher Marshall stability values at test temperatures of 77°F (25°C) and 105°F (40°C).

4. The amount of fines contained in a fine aggregate greatly influences the quality and properties of the foamix produced. A minimum of 4.0 percent fines is needed for good distribution of the foamed asphalt during mixing and increased stability of the compacted mix.

5. The optimum premolding moisture content for a foamix is a function of the aggregate's optimum moisture content, the percentage of fines in the aggregate, and the percentage asphalt content in the mix. This moisture content can be determined from a predictive equation without extensive preliminary laboratory testing.

ACKNOWLEDGMENT

The work described in this paper forms part of a research program sponsored by the School of Civil Engineering at Oklahoma State University. The authors wish to thank Barbara Vick for her help in typing this paper.

REFERENCES

1. R.M. 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.
2. S.M. Acott. Sand Stabilization Using Foamed Bitumen. Presented at the Third Conference on Asphalt Pavements for South Africa, Durban, 1979, pp. 155-172.
3. D.Y. Lee. Treating Marginal Aggregates and Soils with Foamed Asphalt. Proc., Association of Asphalt Paving Technologists, Vol. 50, 1981, pp. 211-250.
4. M. Brennan, M. Tia, A. Altschaeff, and L.E. Wood. Laboratory Investigation on the Use of Foamed Asphalt for Recycled Bituminous Pavements. In Transportation Research Record 911, TRB, National Research Council, Washington, D.C., 1983, pp. 80-88.
5. R. Szczepaniak. Foamed Asphalt Soil Stabilization-Mix Design and Associated Studies. Technical Report 73-1. Mobil Oil of Australia, Melbourne South, 1973.
6. A.R. Clarke. Foamed Asphalt of Crushed Rock Pavements. Report 76.3. Mobil Oil of Australia, Melbourne South, 1976.
7. L.H. Csanyi. Bituminous Mixes Prepared with Foamed Asphalt. Bulletin 189. Iowa Engineering Experiment Station, Ames, 1960.
8. J. Mosey and R.A. Welke. Use of In Situ Foamed Asphalt in Michigan. Presented at 61st Annual Meeting of the Transportation Research Board, Washington, D.C., 1982.
9. L.H. Franco, L.E. Wood, and A.G. Altschaeff. Laboratory Mix Design Procedure for Foamed Asphalt Mixtures. Indiana Department of Highways, Indianapolis, 1982.
10. P.J. Ruckel, S.M. Acott, and R.H. Bowering. Foamed-Asphalt Paving Mixture: Preparation of Design Mixes and Treatment of Test Specimens. In Transportation Research Record 911, TRB, National Research Council, Washington, D.C., 1983, pp. 88-96.
11. R.H. Bowering. Soil Stabilization with Foamed Bitumen. Highway Engineering in Australia, 1971.
12. Foamed Bitumen--Cold Dustless Mixtures. Technical Bulletin 5. Mobil Oil of Australia, Melbourne South, 1973.
13. R.H. Bowering and D.T. Currie. Experience with Some Bitumen Treated Pavement Materials in Australia. Presented at IRF VII World Congress, 1973.
14. R.H. Bowering. Upgrading Marginal Roadbuilding Materials with Foamed Asphalt. Highway Engineering in Australia, Mobil Oil Australia, Melbourne South, 1970.
15. D.H. Little, J.W. Bulton, and J.A. Epps. Structural Properties of Laboratory Mixtures of Foamed Asphalt and Marginal Aggregates. In Transportation Research Record 911, TRB, National Research Council, Washington, D.C., 1983, pp. 104-113.
16. L.H. Csanyi. Foamed Asphalt in Bituminous Paving Mixtures. Bull. 160. HRB, National Research Council, Washington, D.C., 1957, pp. 108-122.
17. R.M. Nady and L.H. Csanyi. Use of Foamed Asphalt in Soil Stabilization. Proc., Highway Research Board, National Research Council, Washington, D.C., 1958, pp. 452-467.
18. Standard Specifications for Highway Construction. Oklahoma State Highway Commission, Oklahoma Department of Transportation, Section 708, 1976.
19. Engineering Classification of Geologic Materials and Related Soils. Oklahoma Research Project 61-01-1. Research and Development Division, Oklahoma Highway Department, Oklahoma City, 1967.
20. Compacting Hveem Gyratory Test Specimen, Part II. Test Method Tex.-206-F. Materials and Tests Division, Texas State Highway Department, Austin, 1976.
21. A User's Guide to the Statistical Analysis System. Department of Statistics, North Carolina State University, Raleigh, Aug. 1972.
22. R.G.D. Steel and J.H. Torrie. Principles and Procedures of Statistics, 2nd ed. McGraw Hill Book Co., New York, 1980.

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