Sulfur as a Partial Replacement for Asphalt in Pavement

FOUAD M. BAYOMY AND SAFWAN A. KHEDR

A full-scale experiment on introducing sulfur as a partial replacement for asphalt in road-paving mixtures was conducted in Kuwait. Laboratory and field testing programs were designed and carried out to analyze and investigate the results of this experiment. The optimum sulfur percentage in the sulfur-asphalt binder and the optimum binder content were established for the investigated mixtures at various curing ages. These mixtures were used in constructing two sections, each 0.67-mi long, of the driving lane of a main road. The first one, considered a control section, was constructed using the conventional asphalt concrete mixture. The second was the test section in which the sulfur-asphalt mixture was used in the entire pavement structure. The sulfur-asphalt mixture was found to significantly reduce rutting on the road. This was established in both field and laboratory investigations. Laboratory-aged samples showed longer fatigue life (indirect tensile stress control fatigue test). Inclusion of sulfur in the mixture was also shown to improve Marshall stability, indirect tensile strength, and the rate at which strength was gained during curing. On the other hand, including sulfur made the mixture more susceptible to loss of stability on immersion in water and to having a lower resilient modulus at higher temperatures (above 95°F). Field Dynaflect measurements showed higher deflections for the road test section than for the control section.

Interest in using sulfur in flexible pavement mixtures usually stems from one or both of two considerations: economy and improvement in road mixture characteristics. The first consideration reflects the availability and price of sulfur and asphalt, the percentage of sulfur used in the overall binder, and the optimum binder content of the mixture. The cost of necessary modifications to mixing plants in order to produce the new mixture is relatively minimal because of recent improvements in mixing techniques.

The second consideration, improvement in characteristics of mixtures that contain sulfur as a partial replacement for asphalt (SAPRA), needs more investigation in general and in individual projects. This is because of the different experiences and conclusions reported in the literature, particularly in regard to durability and fatigue resistance of SAPRA mixtures.

Many researchers [e.g., Gallaway and Epps *(1)*] have consistently reported that SAPRA road mixtures possess higher Marshall stability than do conventional mixtures and that this improvement becomes more noticeable with age. However, another study *(2)* reported lower Marshall stability for a SAPRA mixture after 2 years compared with a corresponding conventional mixture. A similar situation obtains for changes in the measured resilient modulus caused by using SAPRA mixtures. Meyer et al. *(3)* and Fromm and Kennepohl *(4)* separately measured higher resilient moduli for SAPRA mixtures with less susceptibility to loss of stiffness at higher temperatures. However, this was not observed by others *(5)*.

Research findings about temperature- and fatigue-related cracking also differ. Many field studies reported slightly higher susceptibility of SAPRA mixtures to cracking [e.g., Munoz *(6)*] because of the increased brittleness of these mixtures caused by the presence of sulfur. Other studies [e.g., Kennedy et al. *(7)* and Meyer et al. *(3)*] reported better fatigue life expectancy for the SAPRA pavements on the basis of laboratory fatigue tests.

These differences in conclusions among various research efforts may be attributed to factors related to the technique of sulfur inclusion in the mixture, mix design considerations, types of materials, environmental conditions, and testing and evaluation procedures and criteria.

The SAPRA road mixtures were found, almost unanimously, to be less susceptible to rutting. This advantage provided by SAPRA is especially important where heavy slow-moving wheel loads prevail in warm climatic conditions.

A pilot project was constructed in Kuwait to test SAPRA application. A laboratory testing and design program was conducted, complemented by a follow-up field testing and evaluation plan, to investigate the performance of the introduced mixture. The project consisted of two 0.62-mi sections of a driving lane on a major six-lane highway. The first 0.62-mi section was constructed as a control section using conventional asphalt concrete. SAPRA mixtures were used in the construction of all pavement layers in the other 0.62-mi test section of the driving lane. The pavement structure was the same in both sections. It consisted of a 1.6-in. wearing surface (Type III), a 2.4-in. binder course (Type II), a 3.9-in. base course (Type I), and a 3.9-in. sand mix subbase course conforming to the Kuwait ministry of public works specifications *(8)*.

The purpose of this paper is to present the results of the laboratory and field research conducted on this project.

EXPERIMENTAL PROGRAM

The experimental program can be divided into two phases, laboratory and field. The laboratory phase was conducted in two stages. The first stage included preliminary studies to establish mix design and procedure and thus determine optimal mixing technique, optimum sulfur percentage in binder, and optimum binder content. Marshall mix design and stability were used as the comparison criteria. Marshall stability tests were run on samples after curing (setting) periods of 1, 3, and

F. M. Bayomy, Civil Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran 31261, Saudi Arabia. S. A. Khedr, Transportation Research Center, The University of Kansas, Lawrence, Kans. 66044; current address: Qatar University, P.O. Box 2713, Doha, Qatar.

10 days. Asphalt cement of 60/70 penetration and 99 percent pure sulfur were used in the mix with crushed limestone aggregate gradation (Type III) as shown in Figure 1. Liquid sulfur, at 280°F, was thoroughly premixed with asphalt, at 300°F, for 30 sec to form sulfur-extended asphalt binder. This binder was then mixed with preheated aggregate, at 320°F, for another 30 sec. This method of preparing SAPRA mixtures was used in both the field and the laboratory.

In the second stage the experimental performance of the SAPRA binder and SAPRA concrete mixture was compared with that of asphalt cement and conventional asphalt concrete, respectively. The following laboratory tests were performed:

1. Penetration (ASTM D 5), viscosity (ASTM D 2171), and softening point (ASTM D 2398). These tests were run for sulfur-to-asphalt ratios of 0/100, 15/85, 30/70, 40/60, and 50/50 at 1, 3, 10, 30, and 90 days of age.
2. Effect of water submersion on strength of SAPRA mixtures (ASTM D 1075). Two sulfur-to-asphalt ratios, 0/100 and 40/60, were used for mixture preparation. At each ratio, three aggregate fillers were used: 7 percent limestone filler (LF), 6 percent LF plus 1 percent hydrated lime (HL), and 7 percent LF plus 2 percent portland cement (PC) premixed with aggregate. Adding 1 percent HL or 2 percent PC, or both, improved mix resistance to water damage *(9)*. These additives were used to study their effect in the presence of sulfur.
3. Fatigue life tests on laboratory-prepared samples. Samples, 4 in. in diameter by 2.5 in. thick, were prepared of mixtures with sulfur-to-asphalt ratios of 0/100, 15/85, and 40/60 and tested after 3, 7, and 30 days of curing. They were tested under 1-Hz haversinusoidal dynamic indirect tensile stress until failure.
4. Laboratory creep tests on multilayered cores obtained from the field. Deformation measurements were made separately for each layer. These tests were performed at room temperature (77°F).
5. Laboratory resilient modulus tests on multilayered cores obtained from the field. Deformation measurements were made for single pavement layers in the cores. These tests were run at various temperatures in the range of 77°F to 131°F and under haversinusoidal dynamic load at frequencies of 1 and 8 Hz.

Details of test procedures for fatigue, creep, and resilient modulus are given elsewhere *(9, 10)*.

Field experimentation and measurements involved

1. Field rutting measurements at two intersections in the test lane, one on the control section and the other on the section in which SAPRA mixtures had been used. The measurements were taken 1 year after the road was opened to traffic.
2. Dynaflect deflection measurements during the year after construction; pavement surface temperature varied from 41°F to 131°F.

ANALYSIS AND DISCUSSION OF DATA

Rheology of SAPRA Binder

The standard penetration test results (Table 1) did not show a distinct trend of variation in the penetration values with sulfur-

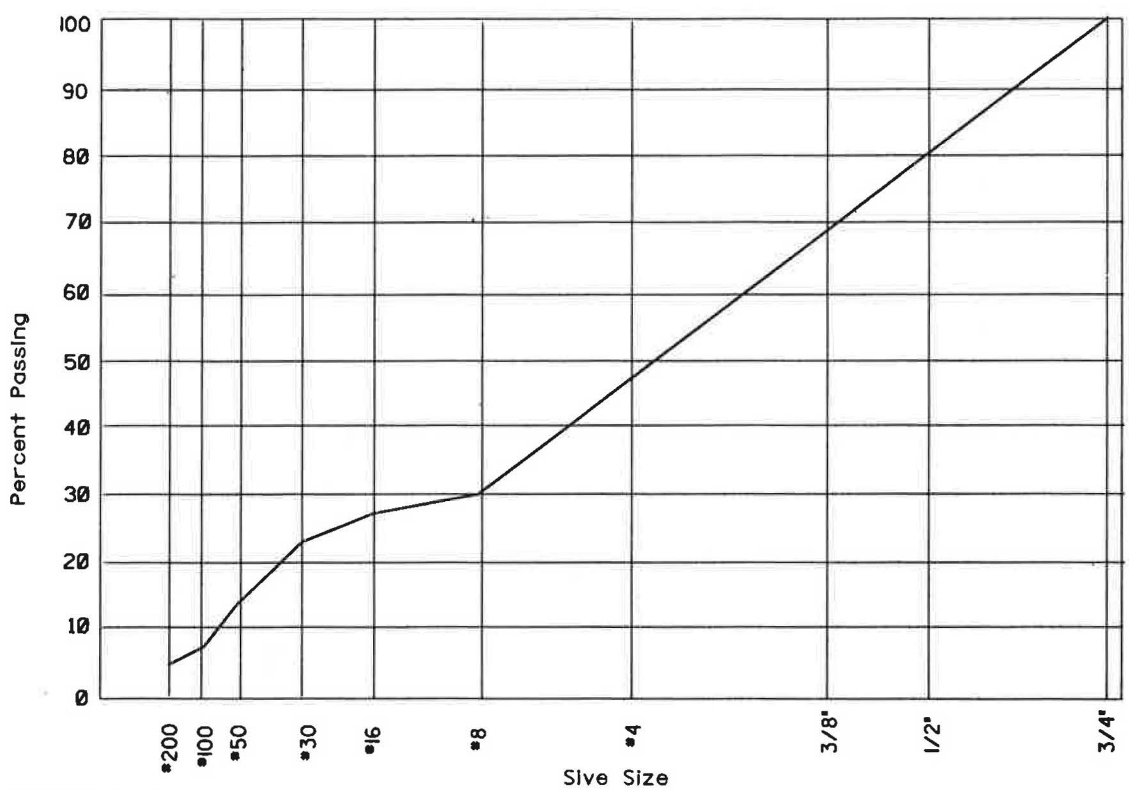

FIGURE 1 Aggregate gradation for surface course (Type III).

TABLE 1 STANDARD PENETRATION TEST RESULTS

S/A Ratio	Age 1 Day	3 Days	10 Days	1 Month	3 Months
0/100	60	53	53	52	33
15/85	81	90	70	56	60
30/70	51	56	75	82	41
40/60	65	55	109	97	91
50/50	61	72	106	89	61

to-asphalt (S/A) ratio or binder age. This might be because it was not practically possible to obtain a homogeneous binder mix at the standard test temperature of 77°F. At high temperatures, the free sulfur globules settled with time and formed sulfur crystals during cooling; this created an inhomogeneous binder. In that case, the measured penetration value normally was not reproducible and depended on the existence of sulfur crystals at or near the penetration needle. Therefore the results were inconclusive and the penetration test, in its standard format, is neither indicative of nor suitable for the needed comparison.

The viscosity tests were run at 140°F. The results are shown in Figure 2. The inclusion of sulfur decreased the binder's viscosity until the dissolving point of sulfur was reached; beyond that point viscosity was higher for higher S/A ratios. The dissolving point of sulfur is the maximum percentage of sulfur that dissolves in asphalt cement. In the present study it was an S/A ratio of approximately 20/80. Sulfur added beyond this ratio existed in the SAPRA binder in the form of free sulfur globules. Similar results have been reported by other researchers *(11)*.

Results of softening point tests are given in Table 2. The results showed that SAPRA binders had lower softening points than did pure asphalt cement. However, it appeared that the S/A ratio did not significantly affect the amount of decrease in the softening point.

TABLE 2 SOFTENING POINT TEST RESULTS

S/A Ratio	Age 1 Day	3 Days	10 Days	1 Month
0/100	55	55	53	57
15/85	48	49	50	50
30/70	57	52	50	50
40/60	50	51	47	50
50/50	55	51	51	49

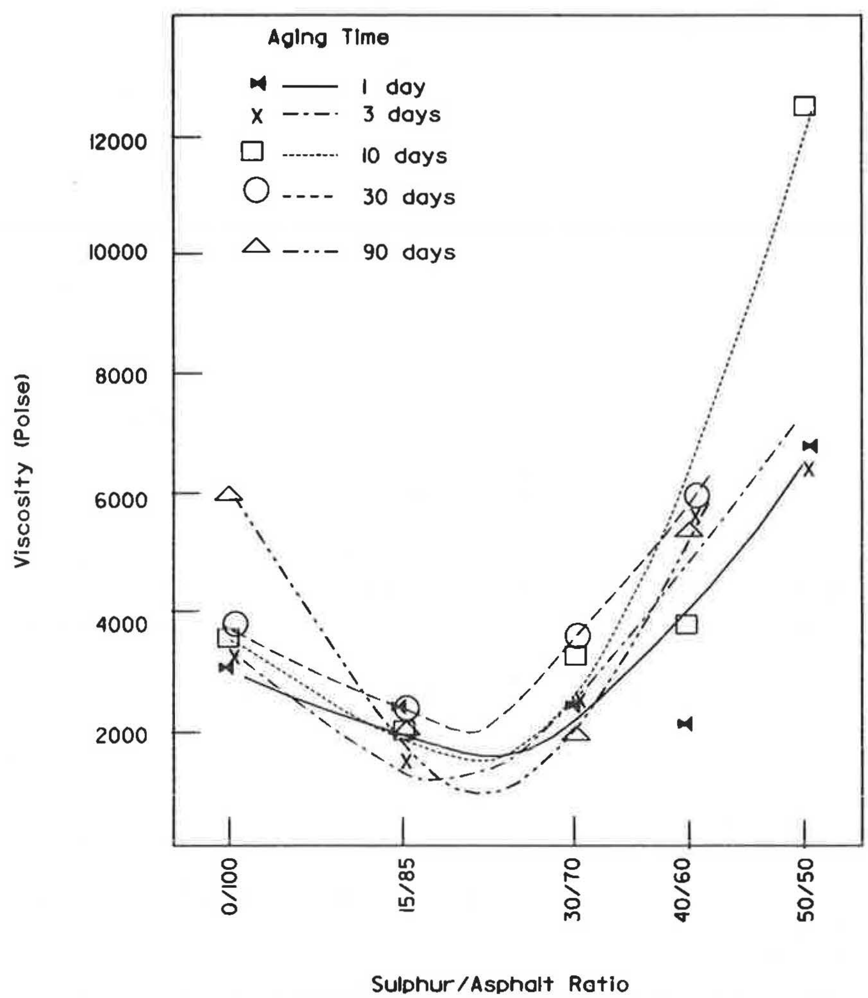

FIGURE 2 Viscosity of SAPRA binder at 140°F.

TABLE 3 SUMMARY OF MARSHALL MIX DESIGN FOR DIFFERENT S/A RATIOS

Mix Property	Curing Time (days)	S/A Ratio 15/85	30/70	40/60	50/50
Optimum binder content (% by weight)	1	5.3	5.5	5.8	6.0
	3	5.2	5.4	5.7	5.7
	10	5.1	5.2	5.6	5.6
Marshall stability (lb)	1	2,100	2,650	3,000	4,700
	3	2,500	2,650	4,000	4,900
	10	2,950	3,240	4,300	5,000
Bulk specific gravity	1	2.390	2.413	2.390	2.400
	3	2.395	2.370	2.400	2.378
	10	2.399	2.363	2.390	2.370
Void ratio (%)	1	2.6	2.1	3.2	4.1
	3	2.4	3.9	3.3	4.3
	10	1.8	3.4	3.5	5.2
Flow (0.01 in.)	1	20	17	19	25
	3	22	17	21	22
	10	22	19	24	24

Mixture Design

Table 3 is a summary of the Marshall mix design results for the SAPRA mixtures with S/A ratios of 15/85, 30/70, 40/60, and 50/50, respectively. Figure 3 shows a typical set of curves obtained for the 15/85 S/A ratio. In recognition of the importance of the effect of curing time *(5)*, the design curves were obtained at 1, 3, and 10 days. Optimum values of mix design parameters after 1 day are shown in Figure 4. The following observations were made about the mix design results (Table 3):

- The optimum binder content for maximum Marshall sta-

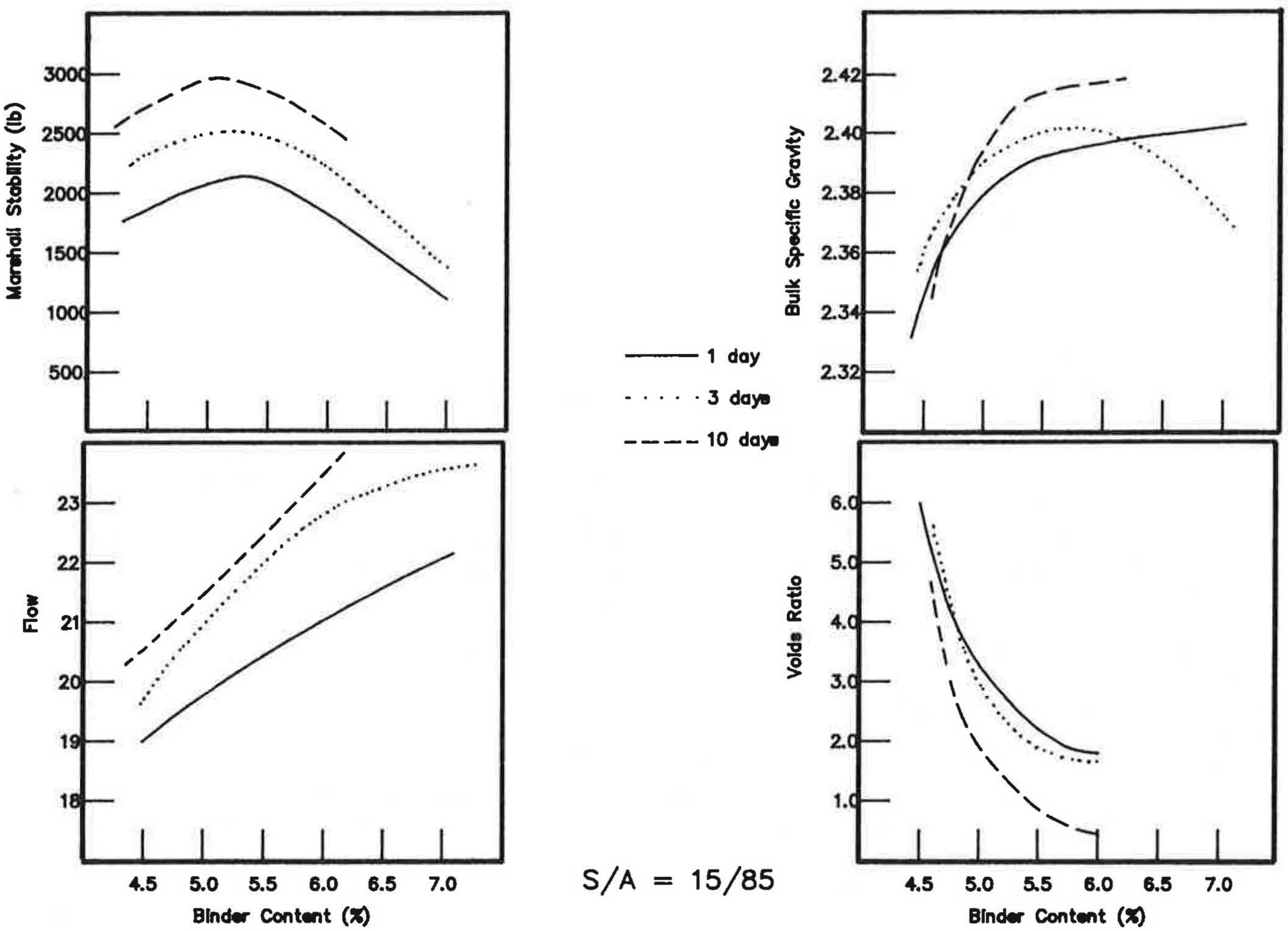

FIGURE 3 Marshall mix design curves for S/A = 15/85.

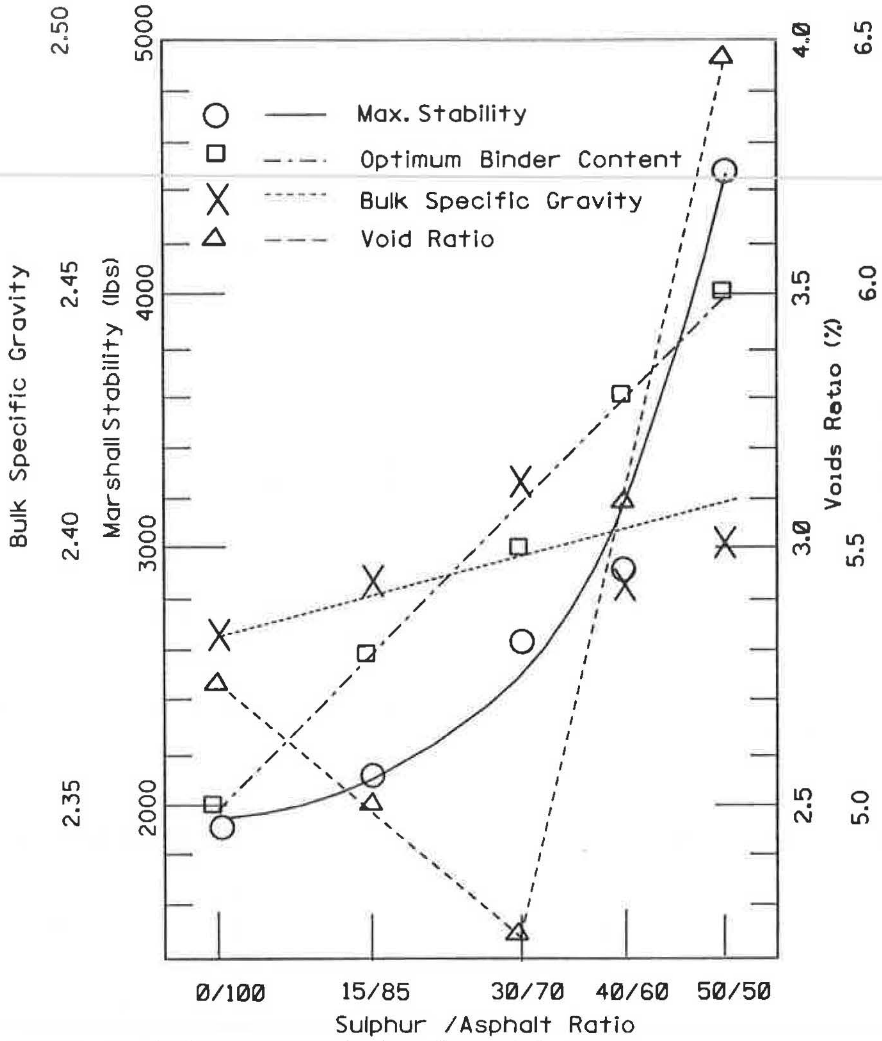

FIGURE 4 Optimum values of mix design at 1 day.

bility was higher for higher S/A ratios (Figure 4). It increased from 5 percent for a ratio of 0/100 to 6.0 percent for a 50/50 ratio. However, the optimum binder content tended to be lower than Marshall mix design might require for more aged SAPRA mixtures.

- The 1-day maximum Marshall stability values increased with increasing S/A ratio. These values also increased with the age of the SAPRA mixtures for all S/A ratios investigated. The rate of this increase, however, was different for various ratios; the highest rate was observed at 40/60.
- The flow of the samples appeared to increase when the S/A ratio was above 30/70. The SAPRA mixture with S/A = 15/85 showed lower flow values. The relationship between flow and binder content, however, did not appear to maintain a particular trend for various S/A ratios or mixture ages.
- There was no discernible trend of variation in the bulk specific gravity or in the voids ratio with age of the mixture.
- There was a different trend of variation in the values of the void ratio, at 1-day optimum binder contents, below and above S/A = 30/70 (Figure 4). Although it was lower up to S/A = 30/70, it shows a shift with significant increase above this ratio. This might indicate higher susceptibility of the SAPRA mixture, with an S/A ratio above 30/70, to rutting. On the other hand, this could be offset by the stiffness contributed by the increased sulfur content of the mixture.

Indirect tensile strength was measured on samples prepared at optimum corresponding binder contents for S/A ratios of 0/100, 15/85, and 40/60. The samples were tested under a load applied parallel to and along a vertical diametral plane that produced a tensile stress perpendicular to the direction of the applied load plane. This tensile stress ultimately caused the specimen to fail by splitting along the vertical diameter. Tensile strength (S) was computed as

$$S = 2P/\pi Dt \tag{1}$$

where

P = vertical load at failure,
t = thickness of the sample, and
D = diameter of the sample.

The results of the test are shown in Figure 5. Indirect tensile strength increased with increase in the S/A ratio.

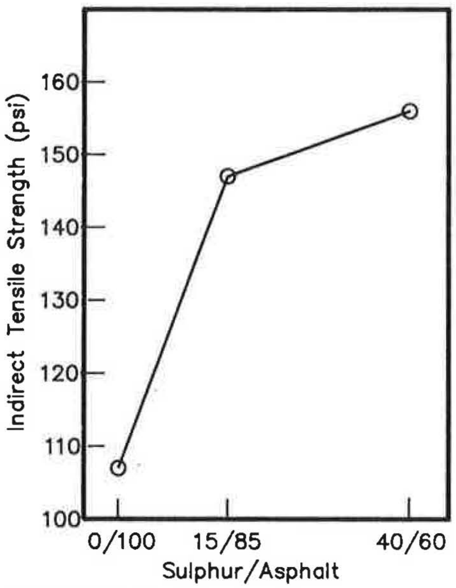

FIGURE 5 Indirect tensile strength of SAPRA mixtures.

Effect of Submersion in Water

Sample groups to be subjected to the standard test for the effect of water on cohesion of compacted bituminous mixtures (ASTM D 1075) were prepared with binder content of 5.8 percent for an S/A ratio of 40/60. The results are shown in Figure 6. The following observations were made:

- The cement-treated mixture provided the highest dry and wet compressive strength, followed by the hydrated lime–treated mixture.
- The index of retained strength (*IRS*) defined as

$$IRS, \% = (C2/C1) \times 100 \qquad (2)$$

where $C1$ is compressive strength of dry specimen and $C2$ is compressive strength of immersed specimen. *IRS* is higher for the cement-treated mixture (83 percent) and for the hydrated lime–treated mixture (82 percent) than for the untreated mixture (31 percent).

- The SAPRA mixture was more prone to moisture-induced damage than were conventional mixtures. This can be seen in Figure 6. The *IRS*-values for the SAPRA mixture tend to be at the lower side of the corresponding range for conventional mixtures.

Resilient Behavior

Resilient Modulus

The values of resilient modulus were determined for field cores by two methods, creep test (assuming viscoelastic behavior of mixtures) and dynamic loading. The first testing method consistently resulted in lower values for resilient modulus in the range of from 30 to 60 percent compared with the corresponding values produced by the second testing method. Only the

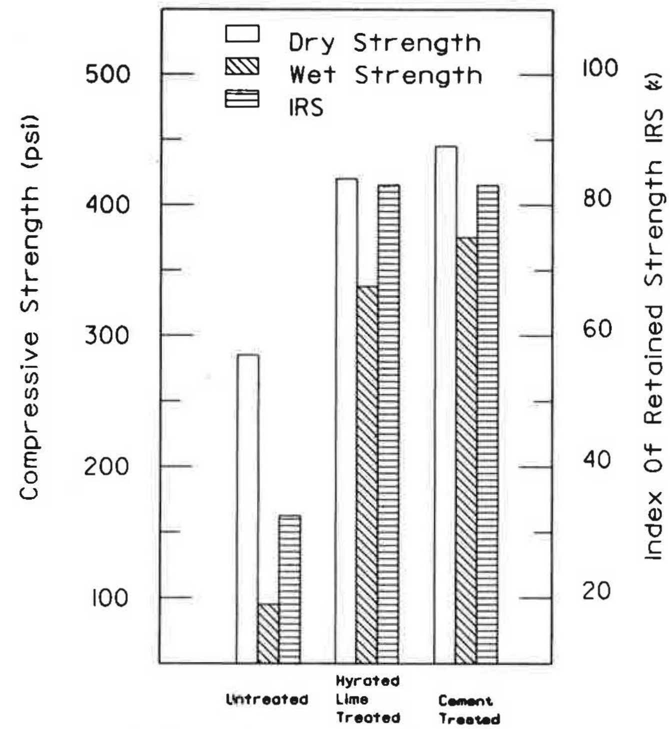

FIGURE 6 Dry and wet compressive strength of SAPRA mixtures (S/A = 40/60).

values of resilient modulus produced by dynamic testing will be discussed further in this paper.

Figures 7–9 facilitate the comparison of the values of resilient modulus of SAPRA and conventional mixtures at two dynamic load frequencies and over a range of road surface temperatures for the surface course (Type III), binder course (Type II), base course (Type I), and sand mix subbase materials, respectively. The following observations can be made:

- The resilient modulus is higher for all SAPRA mixtures than for conventional mixtures for both load frequencies in the low-temperature range of 74°F to 90°F. The only exception was the sand mix in which the SAPRA mixture showed inferior behavior. However, no specific conclusion can be drawn with respect to the sand mix because the available results are only for field cores of sand mix subbase. No laboratory samples of this layer were tested.
- The rates of temperature softening of SAPRA mixtures were higher than those of conventional mixtures. This led to equal or higher values of the resilient modulus for conventional mixtures at higher temperatures. This observation may not agree with previous reports *(4, 7)*. However, it provided an explanation for the behavior of the road mixtures under field Dynaflect testing, which will be discussed in a later section of this paper.

Fatigue Life

Laboratory fatigue tests were performed at 77°F with load control mode under different load intensities. The results are shown in Figure 10 in the form of the stress versus fatigue life

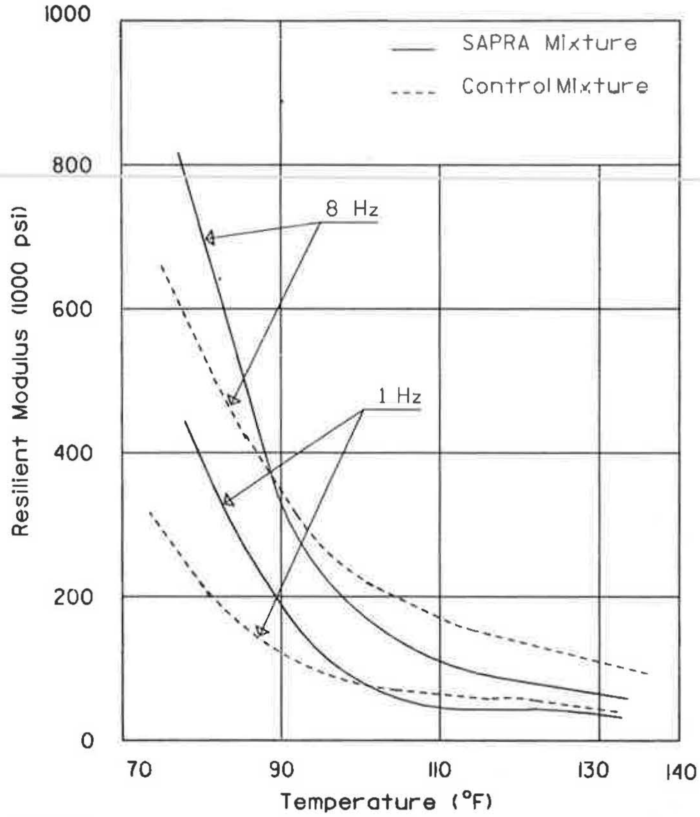

FIGURE 7 Resilient modulus of SAPRA and control mixtures, field cores of surface course.

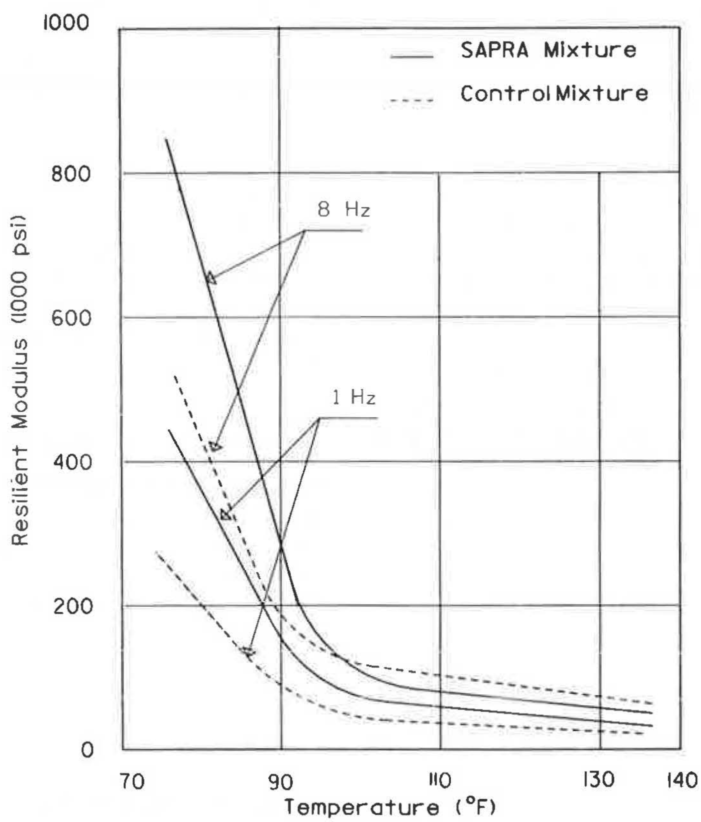

FIGURE 8 Resilient modulus of SAPRA and control mixtures, field cores of binder course.

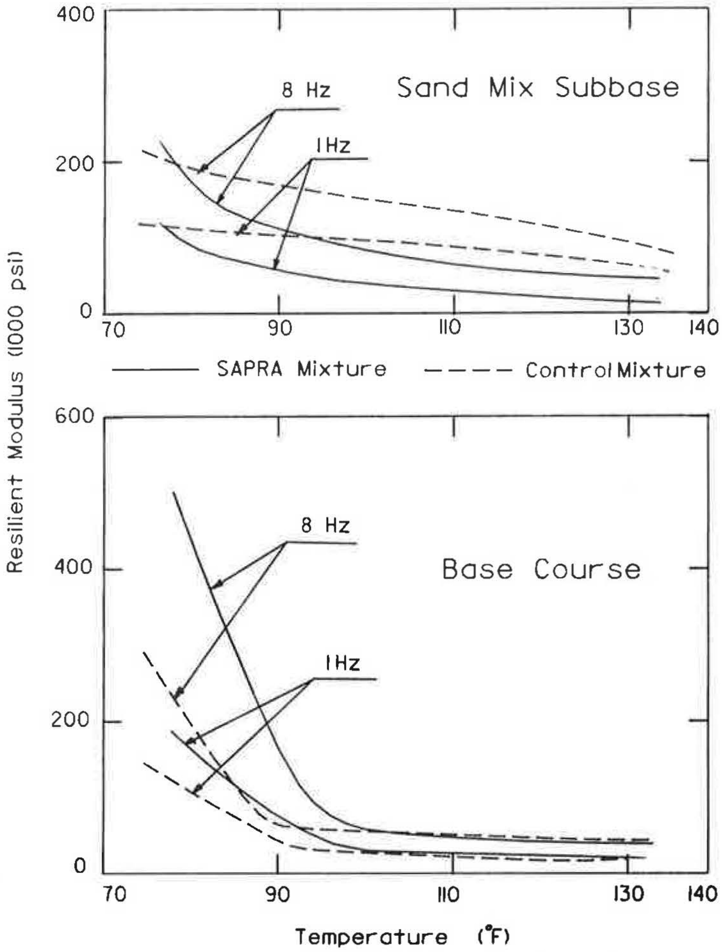

FIGURE 9 Resilient modulus of SAPRA and control mixtures, field cores of base course and subbase sand mix.

relationship (S-N diagram). The following observations can be made:

- Fatigue life increased with curing time. The rate of increase appeared to be variable and to depend on the stress level and percentage of sulfur in the mixture. In general, the rate of increase in fatigue life is higher for the SAPRA mixtures.
- After 3 days of curing, the conventional mix exhibited longer fatigue life than did the SAPRA mixtures. As the curing period was extended, the SAPRA mixtures showed longer fatigue life. The difference was more pronounced at lower stress levels.
- The results appear to suggest that there is an optimum sulfur content at which maximum fatigue life is obtained after a "reasonable" curing period. This might be apparent from the better fatigue life performance of the S/A = 15/85 mixture compared with the S/A = 40/60 mixture.

Field Deflection Measurements

Dynaflect resilient deflection measurements were taken on the test and control sections of the experimental field project. Five deflection geophone readings were taken at the test load ($W1$) and at 12-in. intervals thereof along the deflection basin ($W2$, $W3$, $W4$, and $W5$, respectively). The following deflection parameter definitions are used in presentation of the data:

- Maximum deflection ($W1$) mainly reflects the behavior of the overall pavement structure; higher deflection means weaker pavement.
- Surface curvature index [$SCI = (W1 - W2)$] mainly represents the structural characteristics of the upper portion of the pavement; higher values indicate weaker surface layer or layers.
- Spreadability [$SP = (W1 + W2 + W3 + W4 + W5) \times 100/5\ W1$] is an indicator of the relative stiffness of the pavement components and the load distribution characteristics of the pavement system; higher values (closer to 100 percent) indicate more uniform pavement.

Figure 11 shows the variation in the representative values of the deflection parameters with road surface temperature for both the test and the control sections of the road. Statistical regression analysis led to the following relationships, which represent the test results for the SAPRA test section:

$$\log W1 = -0.4586 + (8.7 \times 10)\ T^2 \qquad R = 0.93 \qquad (3)$$

$$\log (SCI \times 100) = 0.6732 + 0.00022\ T^2 \qquad R = 0.90 \qquad (4)$$

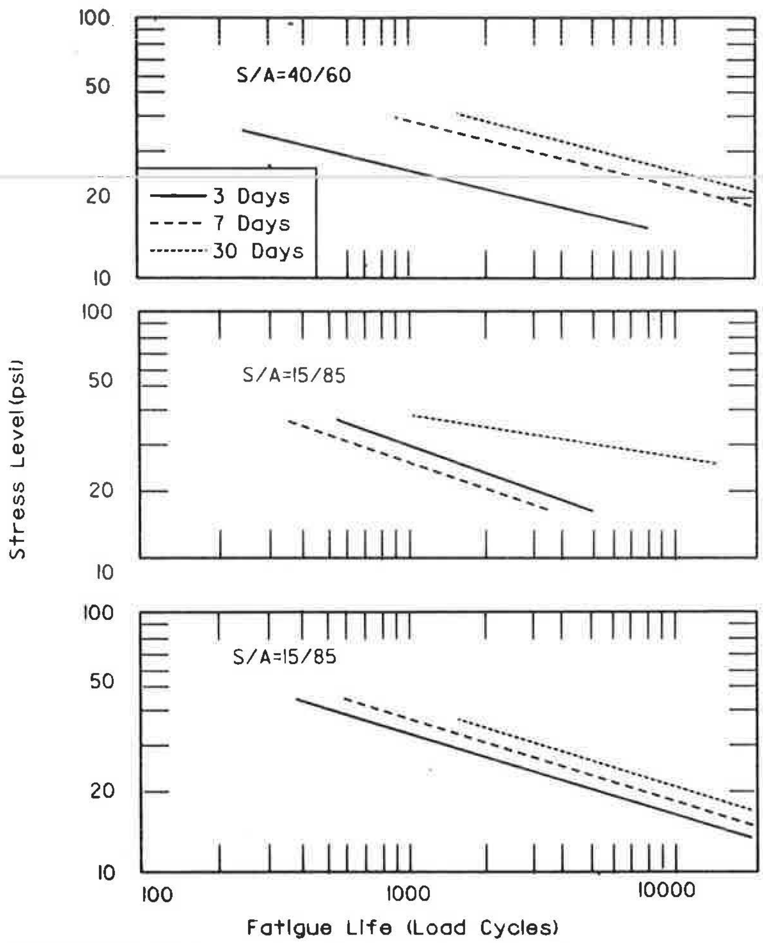

FIGURE 10 Fatigue test results for various S/A ratios.

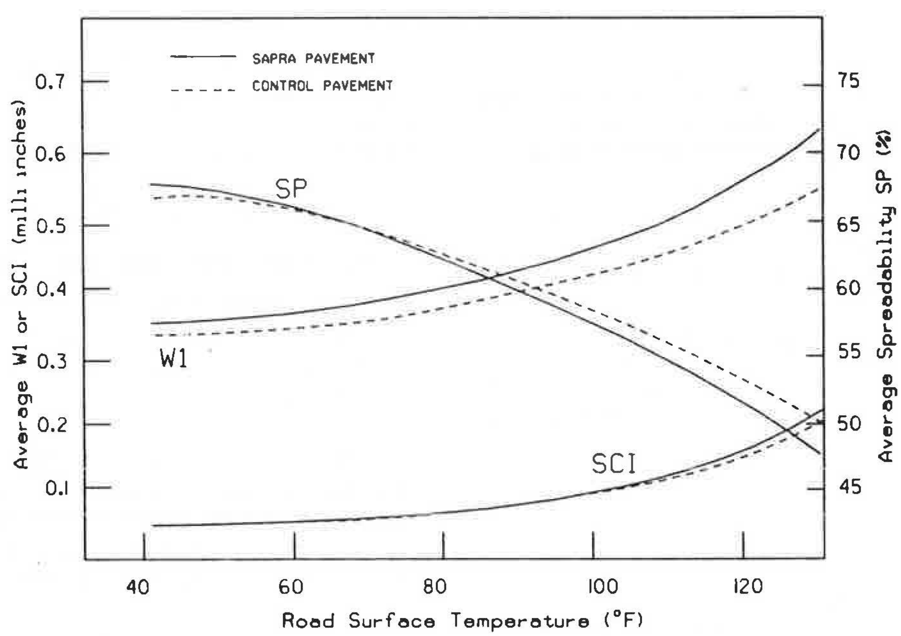

FIGURE 11 Variation of *W*1, *SCI*, and *SP* with road surface temperature.

$$\log SP = 1.8330 - (4.97 \times 10)\, T^2 \qquad R = 0.93 \qquad (5)$$

Those for conventional control sections are

$$\log W1 = -0.4825 + (7.30 \times 10)\, T^2 \qquad R = 0.81 \qquad (6)$$

$$\log (SCI \times 100) = 0.6802 + 0.00021\, T^2 \qquad R = 0.91 \qquad (7)$$

$$\log SP = 1.8278 - (4.31 \times 10)\, T^2 \qquad R = 0.94 \qquad (8)$$

where

T = (5/9) (Tf – 32),
Tf = surface temperature (°F), and
R = statistical correlation coefficient.

The SAPRA test section showed higher deflections ($W1$) than those measured for the control section of the road. This might indicate an overall weaker SAPRA pavement that might result in earlier fatigue cracking in the test section. However, 1 year after construction, this had not happened.

Both sections of the road produced almost identical values of *SCI* except in the high-temperature range in which the SAPRA pavement exhibited higher *SCI* indicating weaker behavior of the surface layer or layers. However, the difference in this range was not considered significant. The lower values of the spreadability *(SP)* of the SAPRA section at high temperature indicated more nonuniformity in that pavement. This might be attributed to the high-temperature softening susceptibility of the subbase sand mix. That is, the poor performance of the subbase, according to the laboratory results, might be a major contributor to the overall inferior performance of the SAPRA pavement.

These observations lead to the conclusion that, with the exception of the sand mix layer, SAPRA mixtures performed almost as well as or insignificantly less well than conventional mixtures from the standpoint of resilient behavior at high temperature. At lower temperature levels, the performance of SAPRA and conventional pavements was virtually the same.

Residual Behavior

Creep Under Static Loads

Table 4 gives the results of a representative creep test in which both SAPRA and conventional mixtures were under the same load at 77°F. The results clearly show superior performance of the SAPRA mixtures. They exhibited between 15 and 48 percent less deformation than did conventional mixtures.

TABLE 4 CREEP STRAINS (10^{-6} in./in.) FOR FIELD CORES (77°F)

Course	SAPRA Mixture	Conventional Mixture
Surface (Type III)	587	1,123
Binder (Type II)	341	403
Base (Type I)	270	511

Permanent Deformation in the Field

Two sites were selected for comparison of permanent deformation, a signalized intersection along the control section and a signalized intersection along the test section of the same driving lane. At intersections the permanent deformation of a pavement surface is the sum of the accumulated static creep due to stopped vehicles and rutting (dynamic creep) due to moving vehicles. The general nature of the static creep and dynamic creep curves is similar *(9)*. However, the mechanism and the material behavior are different in each case. It was practically impossible to differentiate between the two mechanisms in the field measurements. Therefore the objective at this stage of the study was limited to comparing the overall permanent deformation of SAPRA and conventional mixtures.

Figure 12 shows permanent deformation profiles in the left and right wheel track before and partly through the two intersections. It was noticed that the control section had suffered significant permanent deformation whereas the SAPRA test section showed much less deformation. Examination of cored samples from both sections indicated that most of the permanent deformation of the pavement occurred in the binder and base courses, with minor residual deformation in the surface course and minimal change in thickness in the subbase and subgrade layers. In other words, it appeared that most of the permanent deformation of the pavement could be attributed to the bituminous mixtures of the binder and base course layers.

Permanent deformation was considerably higher at the 33-ft spot where the rear wheels of a loaded truck are normally when the truck is stopped at the signalized intersection. Therefore it appeared that static creep might have contributed more to the overall permanent deformation at that spot. The SAPRA pavement showed more resistance to this heavy static loading than did the conventional pavement.

CONCLUSIONS

The following conclusions about SAPRA in flexible pavement, within the limitations and range of the present study, can be drawn.

1. SAPRA pavement projects need individual project study that reflects the particular conditions of the project.
2. SAPRA mixtures were found to have the following advantages over conventional mixtures: (a) lower susceptibility to permanent deformation, (b) higher optimum Marshall stability and a higher rate of stability gain with curing time, (c) higher indirect tensile strength, (d) higher resilient modulus at lower temperatures (73°F to 91°F), (e) longer fatigue life after extended curing time and at the optimum S/A ratio, and (f) equivalent field deflection performance.
3. SAPRA mixtures were found to have the following disadvantages or concerns that need further study: they are (a) more prone to water immersion damage and (b) more susceptible to

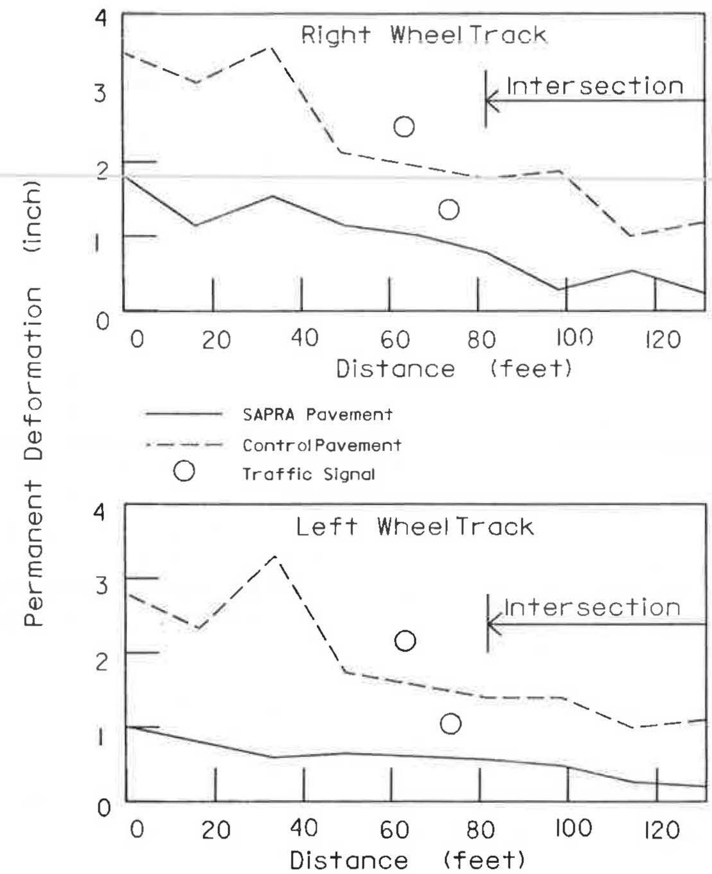

FIGURE 12 Permanent deformation measurements.

loss of resilient strength at higher temperatures. However, this conclusion is based only on tests performed on field cores. More laboratory tests are recommended to reach a firm conclusion.

4. The penetration test in its standard format was unsuitable for investigation of SAPRA binders. Viscosity tests provided better results for identification and comparison of SAPRA binders.

5. The optimum binder content was higher for higher S/A ratios. However, it tends to be less when mix design curves at extended curing periods are considered.

ACKNOWLEDGMENT

Part of this study was conducted as a coordinated project by the Kuwait Road Research Center and the Kuwait Institute of Scientific Research. The authors appreciate the support provided by these organizations, in particular that of A. Al-Abdullah and Z. Abdulrahim. The authors also acknowledge the King Fahd University of Petroleum and Minerals, Saudi Arabia, that allowed its computer facilities to be used.

REFERENCES

1. B. Gallaway and J. Epps. *Compaction of Sulphur Extended Asphalt Paving Mixtures.* FHWA Demonstration Project 54, Sulphur Extended Asphalt. FHWA, U.S. Department of Transportation, 1984.
2. *Sulphur Research and Development.* The Sulphur Institute, Washington, D.C., 1983, Vols. 6 and 7.
3. F. Meyer, E. Hignell, G. Kennepohl, and R. Haas. Temperature Susceptibility Evaluation of Sulfur-Asphalt Mixtures. *Proc., Association of Asphalt Paving Technologist,* Vol. 46, 1977.
4. H. Fromm and G. Kennepohl. Sulphur-Asphaltic Concrete on Three Ontario Test Roads. *Proc., Association of Asphalt Paving Technologists,* Vol. 48, 1979.
5. P. Kandhal. Evaluation of Sulphur Extended Asphalt Binders in Bituminous Paving Mixtures and discussion by B. Gallaway et al. *Proc., Association of Asphalt Paving Technologists,* Vol. 51, 1982.
6. A. Munoz. *Use of Sulphur in Pavements.* Region 6 (Texas), FHWA, U.S. Department of Transportation, 1978.
7. T. Kennedy, R. Haas, P. Smith, G. Kennepohl, and E. Hignell. Engineering Evaluation of Sulphur-Asphalt Mixtures. In *Transportation Research Record 659,* TRB, National Research Council, Washington, D.C., 1977, pp. 12–17.
8. *Specifications for Road Materials and Construction.* Roads and Drainage Department, Ministry of Public Works, Kuwait, 1980.
9. F. M. Bayomy. *Development and Analysis of a Cement Coating Technique: an Approach Towards Distress Minimization and Failure Delay in Flexible Pavements.* Ph.D. dissertation. Ohio State University, Columbus, 1982.
10. M. R. El-Mitini. *Material Characterization for Studying Flexible Pavement Behavior in Fatigue and Permanent Deformation.* Ph.D. dissertation. Ohio State University, Columbus, 1980.
11. J. Muller, B. Cellard, D. Taille, and P. Schneck. Sulphur in Asphalt Paving Mixes. *Proc., IRF Symposium on Sulphur-Asphalt in Pavements,* France, 1981.

Publication of this paper sponsored by Committee on Characteristics of Nonbituminous Components of Bituminous Paving Mixtures.