Long-Term Pavement Performance History of Sulfur-Extended Asphalt Test Roads in Eastern Province of Saudi Arabia

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In 1978 the Metrology, Standards, and Materials Division of the Research Institute at King Fahd University of Petroleum and Minerals (KFUPM/RI) launched an in-house research study on sulfur-asphalt pavement development because sulfur produced in Saudi Arabia was available in abundance and the international price of paving asphalt was soaring because of the energy crisis. Among the various available techniques of substituting asphalt with sulfur, the sulfur-extended asphalt (SEA) paving technology developed by Gulf Canada was considered to be the closest to practical applications. Three SEA test roads were laid in the Eastern Province in cooperation with Gulf Canada and the Ministry of Communication (MOC), Saudi Arabia, as a part of the ongoing road development program of MOC. A sulfur/asphalt ratio of 30/70 by weight was used in Test Road 1 (Kuwait Diversion) and Test Road 3 (KFUPM), whereas a higher percentage of 45/55 was used in Test Road 2 (Abu Hadriyah Expressway). Performance of the three test roads has been monitored from time to time. For each test road, the control section using the normal asphalt concrete has shown a better performance than the SEA sections.

The Pavement Research Group of the Metrology, Standards, and Materials Division of the Research Institute, King Fahd University of Petroleum and Minerals (KFUPM/RI), Dhahran, Saudi Arabia, has been involved in design, construction, and monitoring of pavement conditions of three sulfur-extended asphalt (SEA) test roads as a part of an internal research project on sulfur-asphalt pavement development (PN15002). The project started in 1978 when sulfur produced in the kingdom as a by-product of the gas-gathering plants was available in abundance and was creating a disposal problem. Also, the energy crisis of the 1970s had significantly increased the cost of asphalt on a global market, and laboratory and field trials conducted in the United States and Canada proved sulfur to be a viable substitute for partial replacement of asphalt from both engineering and economic considerations (*1–3*). Of all the sulfur-based paving systems that were developed, the SEA type developed by Gulf Canada is the closest to a commercial application. Therefore, the KFUPM/RI entered into a joint venture with Gulf Canada to develop the SEA pavement technology within the kingdom.

Three full-scale SEA test roads were constructed between 1979 and 1982 as a part of the ongoing road development program of the Ministry of Communications (MOC), Kingdom of Saudi Arabia. The tasks pursued and the laboratory tests conducted to arrive at suitable mix designs have been reported elsewhere by Akili and Dabbagh (*4*), Akili and Uddin (*5*), Akili (*6*), Courval and Akili (*7*), and KFUPM/RI (*8*). Early performance results of the SEA test roads were reported by Akili and Arora (*9*).

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This paper presents the long-term pavement performance history of the SEA test sections and compares their performance with the control sections composed of normal asphalt concrete (AC) specifications. The field data collection included traffic loads, pavement distress, surface roughness, skid resistance, and Benkelman beam and Dynaflect deflections. In addition, a number of cores were extracted periodically from the SEA and control AC sections and tested in the laboratory to evaluate the in situ percent air voids and mechanical properties, such as resilient modulus, split tensile strength, and fatigue resistance. The laboratory tests were performed at varying temperatures to determine the temperature susceptibility of the mixes. The results of the laboratory evaluation were used to interpret the observed pavement condition history of the SEA and control sections.

DESCRIPTION OF SEA TEST ROADS

The three SEA paving projects are located in the Eastern Province of Saudi Arabia near the towns of Dammam and Dhahran and were phased in with the ongoing MOC contracts. Pavement cross sections including sulfur/asphalt ratios used are shown in Figure 1. No substantial changes were introduced in design, materials, or construction procedures as a result of sulfur addition, except for the following:

1. A deliberate reduction in the base course thickness in one of the SEA sections of Test Road 2 to monitor the effect of thinning SEA pavement on performance and pavement life.
2. The addition of 1 percent portland cement to the SEA mix of Test Road 3, partially replacing its fine fraction. This was judged to be an expedient method of keeping the percent loss in a 24-hr Marshall stability within the specified limit.

Materials and Mix Design

The coarse aggregates used in the three paving projects were derived from shallow limestone beds, described at best as average in quality. The fine aggregates were a mixture of quartzitic dune sand and limestone crusher material ranging from about 5000 to 50 μm in diameter. A single asphalt type (60 to 70 pen grade) common to all three test roads was obtained from the Ras Tanura

Refinery. The elemental sulfur added was a commercial grade with a minimum tested purity of 98 percent, a maximum carbon content of 1 percent, and a specific gravity of 1.977 at 23°C.

The Marshall method was used for the SEA mix design for all three test roads, as shown in Figure 2. Sulfur/asphalt (S/A) binders were prepared by blending heated sulfur and asphalt at a temperature of 140 ± 2°C by means of a high shear blender. Marshall briquettes were prepared in the normal manner with 75 blows per face. Table 1 shows the selected Marshall design data for the three test roads. Each result is an average of three separate determinations. The results of the SEA mixes followed the normal pattern except for somewhat higher stability exhibited compared with control samples, particularly at an S/A weight ratio of 45/55 for Test Road 2.

SEA Mix Production and Paving

The SEA mix production of Test Road 1 was accomplished with Société Nationale EIF Aquitane process and equipment. Gulf Canada process and equipment were deployed for the construction of SEA pavements of Test Roads 2 and 3. The two processes are similar in principles and use an add-on unit that blends hot sulfur and asphalt in desired proportions and delivers the blend to the pugmill. Methodology used is shown by a flow diagram in Figure 3. On all three test projects, blending of sulfur and asphalt resulted in homogeneous dispersion of minute sulfur particles in asphalt, as verified by periodic checks under a microscope. The construction steps in terms of transportation, placement, compaction, and quality control of all three SEA pavements were almost the same as those normally followed with conventional asphalt concrete pavements.

PAVEMENT EVALUATION SURVEYS

All three test roads are under periodic monitoring. The evaluation methodology used is shown in Figure 3 and briefly summarized as follows.

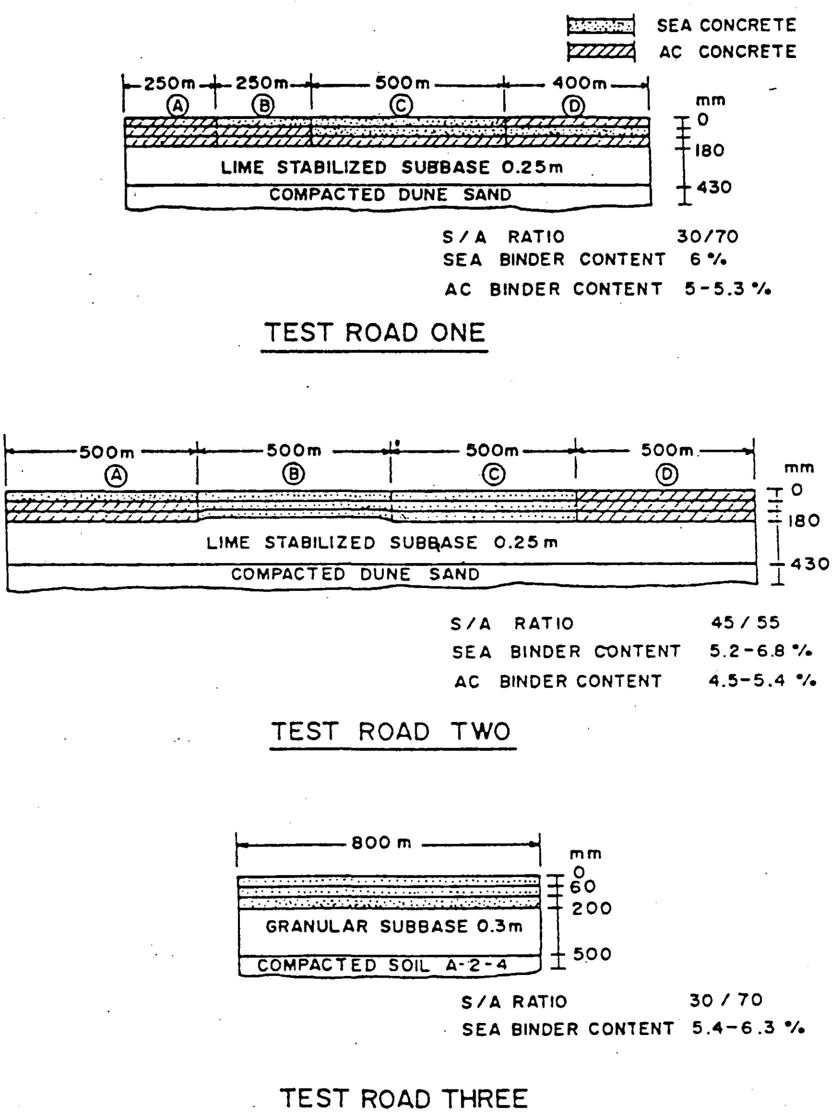

FIGURE 1 Pavement sections for three test roads.

Traffic Counts and Axle Load Survey

Traffic counts were made with manual counters as well as an automatic traffic counter. SEA Test Road 1 has an average daily traffic (ADT) of about 100 with 50 percent trailer truck traffic. Test Road 2 has very heavy traffic with an ADT of about 6,000 and 25 percent trucks. Test Road 3 has an ADT of about 3,000 with 5 percent light trucks. Axle loads of typical trucks operating on SEA Test Road 2 located on Abu Hadriyah Expressway were measured with the Trevor Deakin portable weighbridge designed by the Transport Research Laboratory (TRL), United Kingdom. About 26 to 72 percent of the loaded trucks were found to exceed the legal axle load limits set out by the MOC (*10*). Observed axle loads were converted into equivalent axle load applications of 8.2 tons and found to be about 5.5×10^6 applications per year for the slow lane (*11*).

Pavement Distress Survey

A distress survey for each test road was conducted following the method of pavement rating (PAVER) developed by the U.S. Army Corps of Engineers (*12*). Each SEA test section was divided into a number of sample units of 30-m length covering both lanes for SEA Test Roads 1 and 3. For the Abu Hadriyah Expressway, which was carrying very high traffic, the distress survey was conducted in the slow lane only, which was highly distressed. Severity was measured as low (L), medium (M), or high (H), whereas extent of distress was measured in linear meters or square meters, depending on the distress type as per the procedure of the U.S. Army Corps of Engineers (*12*).

Roughness and Skid Resistance Surveys

Pavement roughness was measured for Test Road 3 using the TRL bump integrator (*13*), which consists of a single-wheeled trailer that is towed on a wheel track at a speed of 32 km/hr. It measures the sum of the downward movements of the wheel relative to the trailer chassis produced by the unevenness in the pavement profile in the longitudinal direction. The integrated downward movement (in centimeters) divided by the distance traveled (in kilometers)

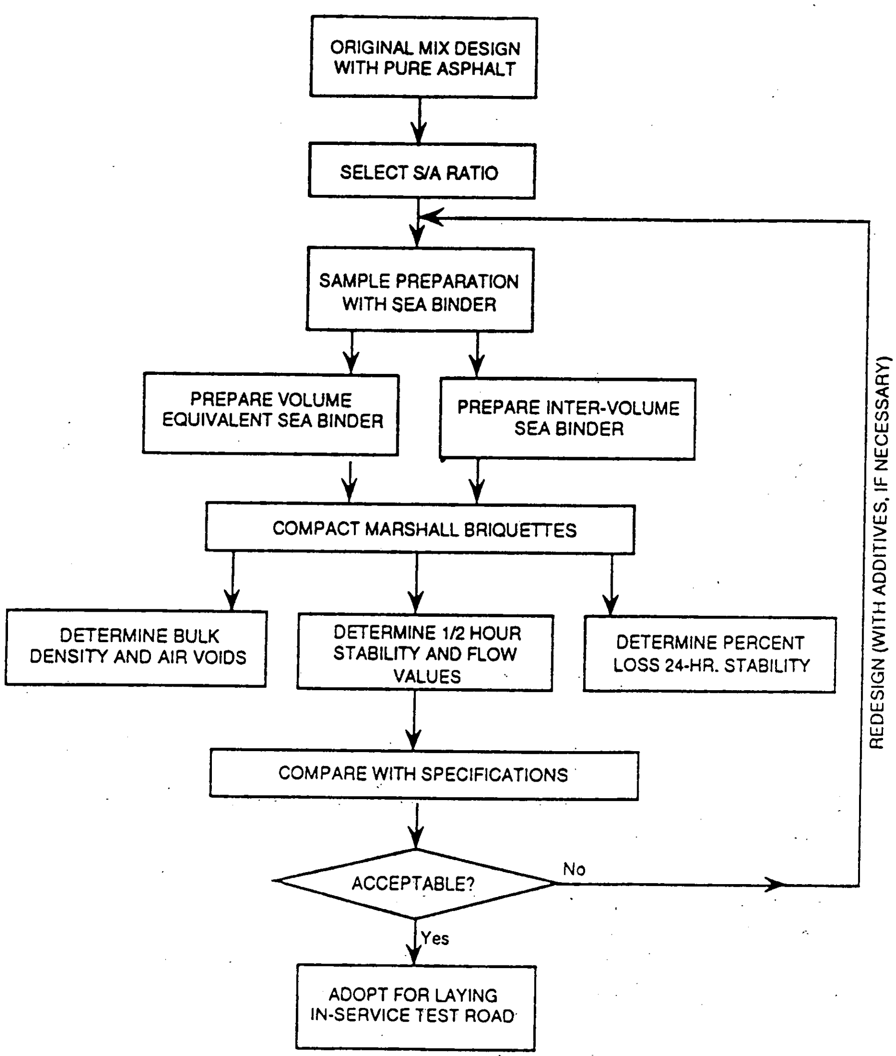

FIGURE 2 Flow chart showing Marshall method for SEA mix design.

gives the roughness of the pavement surface in centimeters per kilometer.

Skid resistance measurements were also made on Test Road 3 using the mu-meter following the procedure recommended by ASTM E670.

Deflection Surveys

Initially, the Benkelman beam rebound deflections (BBD) were measured along the outer wheelpath of the slow lane using the Western Association of State Highway Officials (WASHO) method (*14*). Test points were located 0.9 m from the pavement edge and at 20-m intervals along the entire pavement length. Pavement temperatures were also measured near the deflection points at a depth of 60 mm.

Later on, when Dynaflect was procured, the dynamic deflections were measured on Test Roads 2 and 3 using this equipment. Testing locations were selected at 0.9 m from the pavement edge at 50-m intervals. Pavement temperature was measured occasionally during the tests. The following parameters were computed for each test location from the five geophone deflection readings: Dynaflect maximum deflection (DMD) = D1 (reading of Geophone 1); surface curvature index (SCI) = D1 − D2; and base curvature index (BCI) = D4 − D5.

A significant correlation was observed between DMD and pavement mean temperature (T). On the basis of observed air and pavement temperatures in the Eastern Province of the kingdom, 35°C was selected to represent mean annual pavement temperature for the SEA test roads and the control AC sections. The following relationship was found to represent the temperature adjustment factor (TAF) for DMD at 35°C.

$$\text{TAF} = 1.658 - 0.0184T \quad R^2 = 0.9884, \text{SE} = 0.0138 \tag{1}$$

No adjustment was found necessary for SCI and BCI. By measuring DMD, SCI, and BCI, a qualitative analysis of the structural adequacy of pavement was obtained.

Field Coring and Testing

Field cores of 10-cm diameter were taken from the wheelpaths on the slow lanes of the test roads, initially upon the opening to traffic and later at periodic intervals. The following tests were performed on the cores.

Bulk Specific Gravity and Rice Maximum Specific Gravity and Percent Air Voids

ASTM D2726 and D2041 were used for these tests.

Resilient Modulus

Cores were tested for resilient modulus (M_R) in the split-tensile mode under dynamic loading (ASTM D4123). To determine the temperature susceptibility of SEA mixes, the tests were performed at various temperatures ranging from 5°C to 49°C. The resilient modulus was calculated from the following equation, assuming Poisson's ratio as 0.35.

$$\text{Resilient modulus (MPa)} = 618.3\ P/h \cdot d \tag{2}$$

TABLE 1 Marshall Laboratory Mix Design Data for Three Test Roads

Description	Composition		Bulk Density (g/cc)	Air Voids (%)	Marshall Stability (kN)	Marshall Flow (mm)
	S/A Ratio[a]	% Binder[b]				
Test Road One-Wearing Course	0/100	5.0	2.345	3.5	12.05	1.9
	0/100	6.0	2.371	1.5	8.23	3.0
	30/70	5.25	2.380	3.8	19.95	2.7
	30/70	5.66	2.381	3.2	17.24	2.9
	30/70	6.10	2.394	2.2	9.60	2.5
Test Road Two-Base Course	0/100	4.5	2.341	4.6	18.54	2.1
	0/100	5.0	2.361	4.1	20.55	2.1
	0/100	5.5	2.348	3.9	15.53	2.5
	45/55	4.5	2.365	7.0	26.15	1.3
	45/55	5.2	2.366	6.2	26.28	1.8
Test Road Two-Wearing Course	0/100	5.5	2.385	6.3	15.16	3.8
	0/100	6.0	2.341	4.7	16.45	3.7
	0/100	6.5	2.341	3.2	13.03	3.9
	45/55	5.4	2.359	7.2	16.46	2.1
	45/55	6.0	2.357	6.4	16.29	2.4
	45/55	6.7	2.367	5.4	20.71	3.4
Test Road Three-Base Course	0/100	5.0	2.319	4.7	14.45	2.5
	0/100[c]	5.0	2.327	4.4	12.83	2.7
	30/70[c]	5.4	2.351	4.6	13.23	2.5
	30/70[c]	5.9	2.377	3.0	14.18	2.7
Test Road Three-Wearing Course	0/100	5.3	2.348	3.5	10.98	3.8
	1/100[c]	5.0	2.316	4.7	12.74	3.7
	30/70[c]	5.8	2.365	4.4	11.10	3.5
	30/70[c]	6.2	2.375	3.7	12.04	4.2

[a] *S/A ratio is weight percentage of sulphur and asphalt*
[b] *% binder refers to percentage binder by weight of total mix*
[c] *With one percent Portland cement by weight of aggregate*

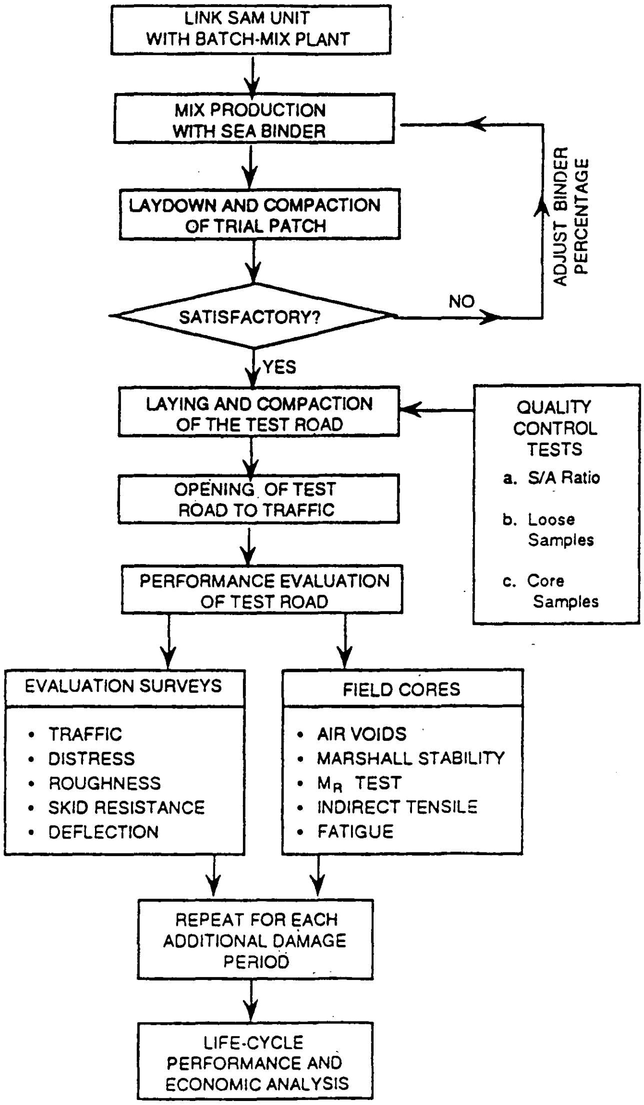

FIGURE 3 Steps involved in construction and evaluation of SEA test roads.

where

P = applied load (kN);
h = thickness of specimen (mm); and
d = recoverable horizontal deformation (mm).

Indirect Tensile Strength

Indirect tensile strength was carried out on a Marshall loading device at a loading rate of 50 mm/min. The load was applied on two opposite generators using stainless steel curved strips. The failure occurred instantaneously along the diametric plane at the maximum load sustained by the specimen. Cores were tested at room temperature and also at a low temperature of 5°C, simulating the local winter conditions when thermal cracking is more likely to occur.

Fatigue Resistance

Cores were tested in the split-tension mode using the dynamic loading equipment required for the M_R test. Initial elastic tensile-strain levels in the range of 55 to 130 μm were applied, and load was held constant until fracture occurred. The number of load repetitions to failure was recorded for each core. The test was performed at 35°C, which represents the mean annual pavement temperature for this region.

DISCUSSION OF RESULTS

Pavement Distress

Pavement distress data were analyzed to determine the most frequently occurring distress types and the pavement condition index (PCI). The PCI is a measure of a pavement's structural integrity and operational condition. Predominant distress types, considered here as those occurring in more than half the number of selected sample units in a section, are listed in Table 2. The SEA sections mostly developed longitudinal/transverse cracking in Test Road 1; alligator cracking and block cracking in Test Road 2; and block cracking and longitudinal/transverse cracking in Test Road 3. Some of these distresses are shown in Figures 4 through 6. On

TABLE 2 Predominant Distress Types Observed in Three Test Roads

Predominant Distress Types	Percentage of Selected Sample Units Showing Predominant Distress Types: Test Road One SEA	Test Road One AC	Test Road Two SEA	Test Road Two AC	Test Road Three SEA	Test Road Three AC
Alligator Cracking	–[a]	–	100	–	–	–
Block Cracking	–	–	80	–	63	–
Longitudinal/ Transverse Cracking	60	100	–	–	63	–
Polished Aggregate	–	–	–	100	–	65

[a] *Not predominant*

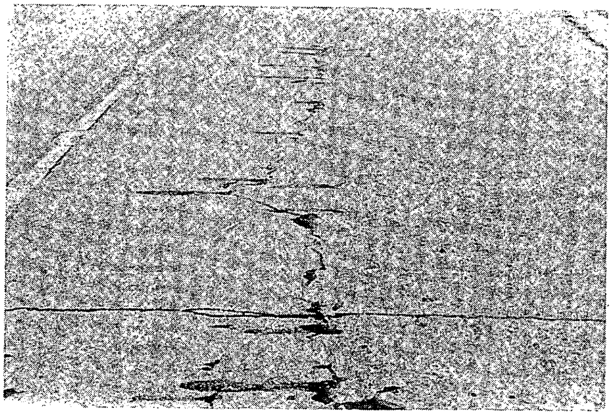

FIGURE 4 Typical longitudinal transverse cracking in SEA section of Test Road 1 (Kuwait diversion).

the control AC sections, the most predominant distress types were found to be longitudinal/transverse cracking and polished aggregate. Although alligator cracking is the load-associated distress and considered to be an indicator of structural deficiency, block cracking and transverse cracks are the climate-associated cracks caused by thermal stresses.

Table 3, which summarizes the pavement evaluation survey results, shows the latest (1993) PCI for each test road. The PCI variation with time for Test Road 3 is shown in Table 4. For each test road, the control section's PCI is higher than that of the corresponding SEA sections. The PCI of the control AC section varies from 85 to 98, indicating a very good to excellent pavement condition. The lowest PCI (41) is found for SEA Section B of Test Road 2, which indicates a fair pavement condition. The other two SEA sections of Test Road 2 are also characterized by lower PCIs compared with those of the SEA sections of Test Roads 1 and 3. Lower PCIs may be attributed to a much higher traffic loading on Test Road 2 and to the reduction in base course thickness in Section B. This is also corroborated by the presence of alligator cracking, which was observed only in the SEA sections of Test Road 2 because this distress type is known to be load-associated distress.

Pavement Roughness and Skid Resistance

Average roughness values of 170 cm/km and 150 cm/km were obtained for Test Road 3 for SEA and control AC sections, respectively, and are considered acceptable for riding quality. Similarly, average wet mu skid numbers of 62 and 73 were obtained for Test Road 3 for 300-m segments of SEA section and control AC section, respectively, which are also considered acceptable.

Pavement Deflection

The 85th-percentile deflection results are summarized in Table 3. Although the criteria used to interpret the deflection results are based on general rules of thumb, nevertheless they do provide relative measures of structural adequacies of the various test sections in question. The following observations were made from Table 3.

1. Benkelman beam deflections indicate lower BBD values for the control AC sections compared with the corresponding SEA sections. According to Lister (*15*), pavement life may be related to Benkelman beam deflection as follows:

$$\text{Life} \propto 1/(\text{deflection})^3 \quad (3)$$

Section B of Test Road 2, having the highest deflection, indicates the lowest life.

2. DMD values for Test Roads 2 and 3 indicate a trend similar to that observed for Benkelman beam deflections. DMD values of Test Road 2 are about 1.5 to 2 times those of Test Road 3, indicating lower structural capacity of Test Road 2. Further, like BBD, the DMD is the highest for SEA Section B of Test Road 2.

3. SCI, which is inversely proportional to the pavement upper-layer elastic modulus, is found to be the highest for Section B of Test Road 2, indicating the lowest elastic modulus of SEA layer for this section. Further, since the SCI of this section is greater than 6.25 μm, according to Teng and Sheffield (*16*), its SEA pavement layer is weak and needs an overlay. Distress survey results confirm this to be the worst section, characterized by the lowest PCI and fair pavement condition. SCI values of other SEA sections of Test Road 2 are also high, being about six to

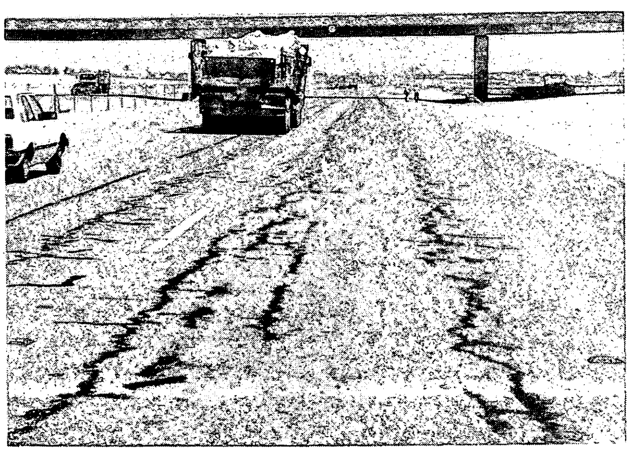

FIGURE 5 Typical alligator cracking in SEA Section B of Test Road 2 (Abu Hadriyah Expressway).

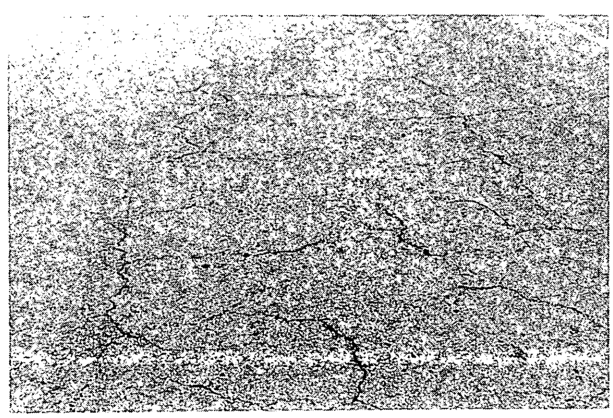

FIGURE 6 Typical block cracking in SEA section of Test Road 3 (KFUPM).

TABLE 3 Summary of Pavement Evaluation Survey Results for Three Test Roads

Item	Test Road One				Test Road Two				Test Road Three	
	AC(A)[a]	SEA(B)	SEA(C)	SEA(D)	SEA(A)	SEA(B)	SEA(C)	AC(D)	SEA	AC
PCI(%)	98	85	89	91	56	41	62	85	80	92
BBD(μm)	294	356	339	313	282	438	334	232	280	186
DMD (μm)	_b	–	–	–	13.72	14.48	11.94	13.21	8.64	6.35
SCI(μm)	–	–	–	–	4.93	9.02	3.86	4.90	0.61	1.68
BCI(μm)	–	–	–	–	1.19	0.66	1.47	1.50	0.48	0.58
Field Cores: Air Voids (%)	4.96	–	7.87[c]	–	–	–	9.28[c]	7.08	3.96	4.92
Field Cores: Resilient Modulus (1000 MPa), Room Temp (23°C)	11.20	–	11.83[c]	–	–	11.66[c]	–	11.35	7.30	5.95
Field Cores: Indirect Tensile Strength (KPa), Low Temp (5°C)	2129	–	1840[c]	–	–	1800[c]	–	–	2005	2263

[a] *AC Section A*
[b] *Not available*
[c] *Average value for SEA sections*

TABLE 4 Variation of Pavement Characteristics with Age for Test Road 3

Characteristics	Test Section	Year					
		1982[a]	1984	1986	1989	1991	1993
PCI (%)	SEA	100	_b	–	85	81	80
	AC	100	–	–	–	95	92
Field Cores: Air Voids (%)	SEA	5.15	4.12	3.96	3.96	–	–
	AC	–	6.50	4.92	6.68	–	–
Field Cores: Resilient Modulus (MPa), Room Temp (23°C)	SEA	2450	5760	7300	9980	–	10500
	AC	–	5110	5950	8860	–	–
Field Cores: Indirect Tensile Strength (KPa), Room Temp (23°C)	SEA	1021	1419	1405	1393		
	AC	–	1625	1732	1809	–	–

[a] *As constructed*
[b] *Not available*

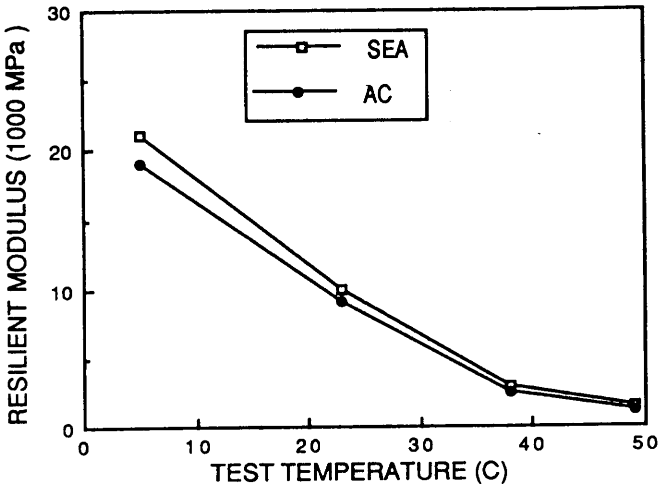

FIGURE 7 Effect of temperature on resilient modulus of field cores extracted from Test Road 3.

eight times those of Test Road 3. This trend may be attributed to load-associated alligator cracking observed in Test Road 2 as discussed earlier and shown in Table 2.

4. BCI values shown in Table 3 are indicators of subgrade strength. According to Teng and Sheffield (*16*), BCI values greater than 3.75 μm indicate a weaker subgrade. Because low BCI values are encountered for both Test Roads 2 and 3, strong subgrade conditions exist for these roads.

Field Core Properties

The average core properties presented in Tables 3 and 4 and Figures 7 and 8 are discussed.

Percent Air Voids

Percent air voids for the three test roads as determined from the cores extracted in 1986 are presented in Table 3. For SEA sections, the air voids range from 3.96 to 9.28 percent, compared with 4.92 to 7.08 percent for the control AC sections. Table 4 shows the percent air void variation with time for Test Road 3. There has been a consistent decrease in air voids for the SEA section, which may be attributed to further densification of the SEA layer under traffic.

Resilient Modulus

M_R values determined at room temperature (23°C) from 1986 cores are presented in Table 3 for the SEA and control AC sections of the three test roads. M_R values for the SEA sections ranged from 7300 to 11 830 MPa and are somewhat higher than those of the corresponding AC sections.

Table 4 shows a gradual increase in M_R values with age for SEA and AC sections of Test Road 3, which may be attributed to the combined effect of hardening of the binder and densification of the mix under traffic.

The effect of temperature on M_R studied on the 1989 cores from Test Road 3 is shown in Figure 7. As expected, M_R decreased with an increase in test temperature. The decrease is more significant in the temperature range of 5°C to 38°C and much less significant in the range of 38°C to 49°C. The above figure also shows that the temperature susceptibility of M_R is approximately similar in magnitude for both the SEA and AC mixes. In fact, the SEA cores showed somewhat higher stiffness at a low temperature of 5°C and almost similar stiffness at a high temperature of 38°C. These values are contrary to the requirement of an ideal mix, which should show less stiffness at low temperature to avoid cracking and an increased stiffness at high temperature to avoid rutting.

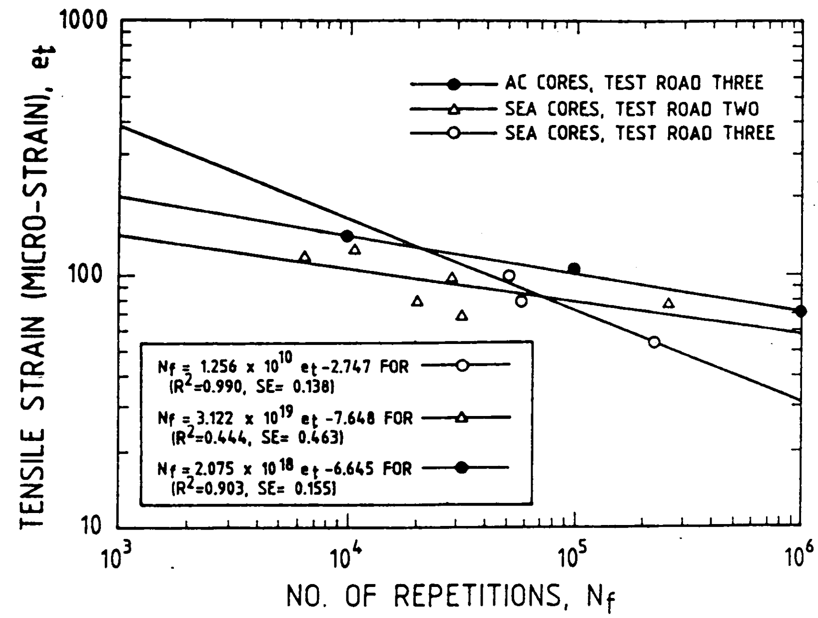

FIGURE 8 Fatigue resistance at a test temperature of 35°C.

Indirect Tensile Strength

Table 4 shows a variation in indirect tensile strength of cores taken from Test Road 3 during the period 1982 to 1989, as tested at room temperature (23°C). An increase in strength with age was noticed, particularly in the initial years after construction. Further, the SEA cores have shown somewhat lower tensile strength than the control AC cores. Low temperature (5°C) results, summarized in Table 3, also indicate lower tensile strength (by 11.4 to 13.5 percent) for SEA cores, which explains the greater extent of thermal cracking, in terms of block cracking and transverse cracking, observed in the SEA test sections in field.

Fatigue Resistance

Figure 8 shows the fatigue resistance of SEA and AC cores of Test Roads 2 and 3. For tensile strains of about 100 μm as expected under heavy traffic loads, the fatigue resistance of SEA cores is found to be lower than that of the AC cores. This explains the reason for early fatigue carcking in the form of alligator cracking observed in the SEA sections of Test Road 2.

CONCLUSIONS

Following are the major interim conclusions drawn from the pavement performance evaluation surveys of the three SEA test roads conducted to date. The evaluation surveys will continue until final conclusions are made on the life-cycle performance and economic viability of SEA pavement technology in Saudi Arabia.

1. The most predominant distress manifestations in the SEA test sections are the load-associated alligator cracking and the climate-associated block cracking and transverse cracking. Greater incidence of cracking is observed in the SEA sections than in the control AC sections.

2. The pavement distress condition rating characterized by PCI shows a lower rating for the SEA sections. SEA Section B of Test Road 2 on Abu Hadriyah Expressway has the lowest PCI of 41, indicating a fair pavement condition and an urgent need for an overlay. For this section, the SEA base course thickness was deliberately reduced by 20 percent to verify whether thickness reduction was possible with SEA pavement.

3. Roughness and skid resistance surveys conducted for Test Road 3 show acceptable values for both the SEA and control AC sections.

4. Dynaflect deflection surveys of Test Roads 2 and 3 show low BCI values in the range of 0.48 to 1.50 μm, indicating strong subgrade support conditions for the test roads. The very high SCI of 9.02 μm observed for Section B of Test Road 2 indicates a deteriorated condition of the SEA pavement layer of this section. This is also corroborated by the pavement distress survey that yielded the lowest PCI for this section.

5. Laboratory characterization of field cores extracted from SEA and control AC sections reveal lower indirect tensile strength and lower fatigue resistance of SEA cores. Lower tensile strength may be the cause of block cracking and transverse cracking observed in the SEA sections of the three test roads. Similarly, lower fatigue resistance may be the cause of alligator cracking observed in the SEA sections of the heavily trafficked Test Road 2.

ACKNOWLEDGMENTS

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