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Sulphlex Pavement Performance Evaluations from Laboratory Tests

JAMES A. SHERWOOD AND WILLIAM J. KENIS

New types of energy-saving materials are being developed for use in test sections within the U.S. road network. One of these materials, Sulphlex, has recently received a great deal of attention and is being developed as an alternative binder to asphalt and portland cement. Mechanical tests were conducted on specimens of asphalt concrete and Sulphlex 233 mixes. The mechanical tests conducted are those necessary to provide the material characterizations for input to the VESYS structural subsystem. The long-term predicted behavior of Sulphlex pavements was compared with that of conventional asphalt pavements for five different structural designs, on two different subgrades, and for three levels of temperature. A set of design criteria was selected to allow an analysis of the performance of each pavement.

In order to reduce the risk of unsatisfactory pavement performance to an acceptable level, engineers must be able to reliably predict pavement behavior over time. Current methods for predicting such behavior for different types of pavements, environments, and traffic loads are limited to what are known today as rational or, more precisely, mechanistic design procedures. The Federal Highway Administration (FHWA) has developed one such procedure called the VESYS structural subsystem, which predicts the pavement's behavior over time based on the mechanical properties of the layer materials, the anticipated traffic loads, and the local environmental conditions. Mechanistic design procedures are so called because they are in fact developed from the laws of mechanics in which the prescribed actions of forces on bodies of material elements are related to the resulting stress, strain, deformation, and failure of the total pavement structure. The properties of the material elements are determined by subjecting specimens of a given material to a series of laboratory load tests and applying the laws of mechanics for the prescribed geometry and environmental conditions. There are both advantages and disadvantages associated with mechanistic-type procedures. One of the most important advantages is that such procedures permit the use of completely new materials and/or new types of pavement structures.

Today, many new types of energy-saving materials are being developed, and test sections are being placed within the U.S. road network. For instance, improved technology and the energy crisis have provided the impetus for new binders, some of which are asphalts modified with sulfur (1) and other chemicals to improve their durability and performance. Polymer portland cement concretes (2) and concretes that use super water-reducing agents (3) are also being produced with properties quite different from those of conventional paving types. Recycled pavements conserve materials and, depending on the types, the quantity and quality of additives can be expected to perform as well as high-quality conventionally designed mixtures (4,5). Sulphlex (plasticized sulfur) is another new material that might be made to behave similarly to asphalt or portland cement concrete (6,7).

The purpose of this paper is to evaluate the results of a limited number of laboratory tests conducted by FHWA on Sulphlex and asphalt paving mixtures and to predict the performance of selected structural sections under simulated real-world conditions.

SULPHLEX AS BINDER AND MIX

The primary objectives of an initial FHWA study with Southwest Research Institute were to develop a system to modify sulfur so that it would serve as a binder replacement for asphalt and portland cement and to prepare mixtures of the developed binder with aggregates and measure their properties (6). To be used as a pavement binder, sulfur must be modified to exhibit more plastic characteristics. When elemental sulfur is heated to above its transition temperature of about 320°F and rapidly quenched at 68°F, it exhibits a plastic characteristic; hence, it may be called plasticized sulfur. If the material is allowed to return to room temperature, it quickly hardens and brittle sulfur crystals are formed; such a physical change does not lend itself to practical application in the preparation of binders for highway paving. The intent in this study was the conversion of sulfur to a plastic through a chemical reaction, a mechanical change, or a combination of these so that the resulting material at room temperature might have viscosity, penetration, and other characteristics similar to those of asphalt. During the course of the study, more than 450 different formulations were prepared by using combinations of 80 different modifiers. The most promising binders were selected to be evaluated for their behavior when mixed with a select aggregate. The results of laboratory tests conducted on

Table 1. Mix properties.

Mix Property	AC-20 (wt. %)		Sulphlex 233 (wt. %)		
	6.4	6	10.3	6	9
Air voids (%)	3.1	4.0	3.0	11.0	5.0
Stability (lb)	2600	2625	1850	1375	1880
Flow (0.01 in)	12.0	10.0	15.0	9.5	12.0
Voids in mineral aggregate (VMA) (%)	17.0	17.1	18.6	20.0	19.1
VMA filled (%)	83.5	77.5	84.0	42.5	72.5

both the Sulphlex binders and their mixes have been given elsewhere (6).

Further investigations of the behavior of Sulphlex 233 (a binder possessing intermediate properties) were undertaken by the Materials Division of FHWA's Office of Research (7). The objectives of this study were as follows:

1. To develop mixture design methods and establish mix design criteria for flexible Sulphlex paving mixtures and
2. To examine the chemical properties and behavior of Sulphlex binders that affect the engineering performance of the binders and their safe use in construction.

Work continued at FHWA through the efforts of the Pavement Systems Group of the Structures and Applied Mechanics Division. This effort is discussed in detail in this paper with the objective of predicting the in-service behavior of Sulphlex as compared with that of asphalt concrete pavement sections.

MATERIAL PROPERTIES

In order to determine the feasibility of using Sulphlex as a paving material, it is necessary that two different series of laboratory tests be conducted. The first series are those tests dealing with mix design, and the second series are those dealing with the mechanical properties used to predict the integrity of the materials when subjected to traffic loads in pavement structures. Each series, as applied to Sulphlex 233 mixes and AC-20 mixes, is discussed below.

Mix Design Tests

Two mix design methods were used to evaluate Sulphlex 233 mixes: the Marshall test (AASHTO T245) and the immersion-compression test (AASHTO T165). The aggregate used was a 3/8-in top-size trap rock (diabase) from Chantilly, Virginia, that had the gradation and other characteristics given by Leutz and Harrigan (7). The temperature-viscosity curves for Sulphlex 233 and AC-20 have also been given by Leutz and Harrigan (7). The Marshall test results (2) are summarized below:

Marshall Criterion	Optimum Weight Percent	
	AC-20	Sulphlex 233
Maximum density	6.9	11.4
Maximum stability	6.3	10.0
4 percent air voids	6.1	9.6
Avg	6.4	10.3

The mix properties at the optimum binder contents for the Marshall criteria and at the binder contents used for the test series are given in Table 1.

Results of the immersion-compression test series given elsewhere (7) suggested that the 9 percent by weight Sulphlex mix would require an antistripping agent. All Sulphlex mix specimens tested contained 1 percent hydrated lime as the antistripping agent.

The series of tests discussed above suggest that Sulphlex might be a practical paving material, based on stability and durability, provided an antistripping agent is used.

Mechanical Tests

The series of tests discussed here were performed specifically to provide input to the VESYS structural design subsystem. In VESYS three basic mechanical properties are required (8):

1. Relaxation (elastic) modulus or creep compliance: the elastic or viscoelastic parameters necessary for solutions to problems of stress-strain or deflection boundary values in a layered pavement system,
2. Fatigue properties: the coefficient and exponent of the fatigue equation for use in Miner's law to predict the occurrence of fatigue cracking in a layered pavement system, and
3. Permanent deformation properties: coefficient and exponent of the permanent deformation equation for use in the accumulative permanent deformation law to predict rutting of a layered pavement system.

Beam and cylindrical specimens were prepared in accordance with procedures defined in ASTM D3202 and ASTM D3496, respectively. The levels of Sulphlex binder evaluated were on an equal weight and volume basis by using 6 weight percent AC-20 as a control in comparison with 6 and 9 weight percent Sulphlex 233.

The beam specimens as molded were sawed in half, which yielded specimens approximately 1.70 in deep, 3.25 in wide, and 15 in long. A total of 54 beam specimens were available for test.

Preliminary testing, on trial 4x8-in cylinders without caps, showed that the strains on opposite sides were nearly the same. For this reason, the cylindrical specimens were tested as received, i.e., without capping. A total of 27 cylindrical specimens were available for testing.

Equipment

Equipment for testing beams in fatigue and cylindrical specimens for modulus and permanent deformation properties is described. The equipment developed for fatigue testing consisted of a non-servo-air arrangement capable of testing up to six beam fatigue specimens at one time. Six Bellofram arrangements were fabricated on a steel channel in a temperature-controlled chamber. Based on the work of Barksdale (9), five 1-in thick pieces of 50-durometer rubber (20 in long by 4 in wide) glued together and simply supported over a 10-in span provided an elastic foundation for each specimen (the modulus of reaction for this system was 448 pci at 70°F when loaded with a 1.25-in-diameter steel disk). The rubber was used to minimize permanent strains to simulate resilient responses associated in fatigue-type failures. Load was applied to a specimen that rested on the rubber at midspan through a 3x1.25-in steel bar. Load frequency in the form of square-wave pulses was controlled by an electronic pulsing circuit that operated a four-way solenoid valve for applying and releasing pressure (10). Figure 1 shows the FHWA multiple fatigue-testing system developed for this study. Dynamic strains in the lower fibers of the beams were measured by a 2-in active strain gage glued to the side of the beam at the center and near the bottom. A three-dummy bridge arrangement completed the circuit, and strains were recorded on oscillographs.

The equipment used to test cylindrical specimens was a servohydraulic system contained in a temperature-controlled cabinet. Measurements of vertical strain were made by two linear variable differential transformers (LVDTs) on opposite sides of the specimens. Vertical strain from each LVDT plus the load were recorded on oscillographs. Load was applied by a steel disk 4 in in diameter through a ball-bearing interface. Figure 2 is a photograph of the system to test cylinders by static and dynamic compressive loads at various temperatures.

Test Procedures

The beam and cylindrical specimens were tested at three temperatures: 40, 75, and 90°F. In the fatigue tests, different levels of constant dynamic load were applied to the beams so as to induce different peak-to-peak underside tensile strains. In this manner, various fatigue lives could be attained. Load duration was set at 0.1 s with a 0.9-s rest period. The beam specimens were placed on the rubber with strain gage attached and allowed to reach test temperature.

Cylinders were brought to test temperature with LVDTs mounted. Typically, three 5-min creep tests were run at the specified load to condition the specimen. Then a 1000-s creep test was run, which served as a basis for the creep compliances presented in this report. In the creep tests the load was applied in a quick ramp fashion, with full load in 0.01 s. On rebound of the 1000-s creep test, the repeated-load tests were conducted, usually for at least 100 000 cycles. Haversine load pulses were applied once per second with a duration of 0.1 s. A 2-psi preload was used throughout all tests to keep the load disk and specimen in contact. Figure 3 shows a typical load history used to test cylindrical specimens. The cylinders were tested at 10, 20, 30, and 50 psi load levels, depending on temperature.

Laboratory Test Results

In the beam fatigue tests, dynamic and permanent tensile strains near the bottom were recorded versus the number of repetitions to failure. Compressive strains with time were measured in the sustained-load tests on cylindrical specimens. In the repeated-load tests on cylindrical specimens, the

Figure 1. FHWA multiple fatigue-testing apparatus.

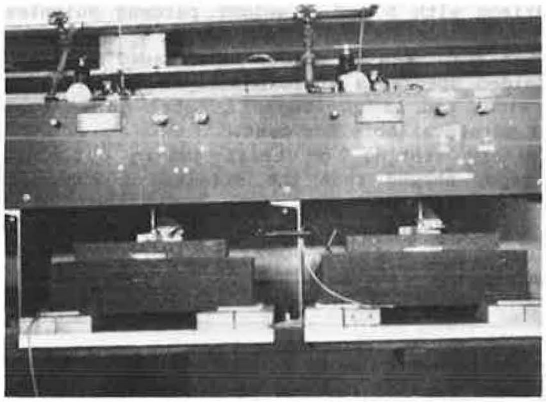


Figure 2. Equipment for compression testing of cylinders.

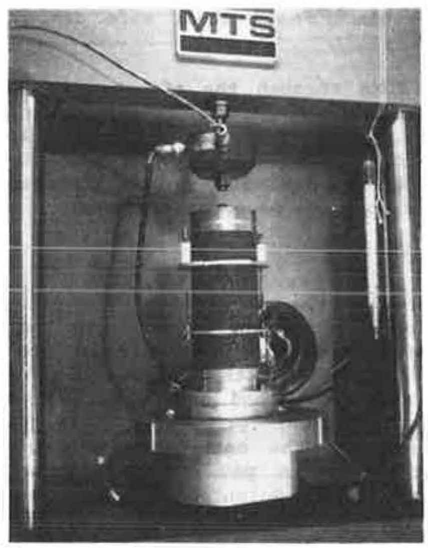
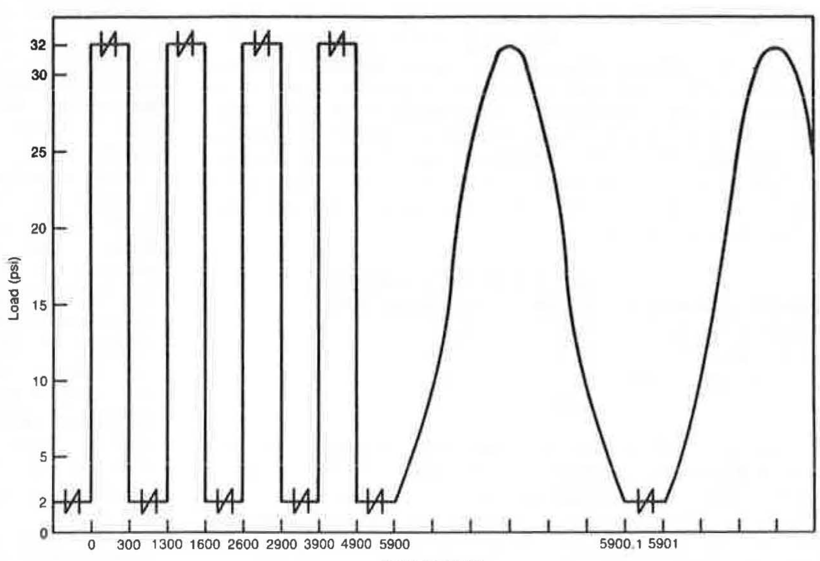


Figure 3. Typical loading for testing cylindrical specimens.



dynamic and permanent compressive strains were recorded versus load repetitions.

Fatigue Properties of Beams

The peak-to-peak or dynamic strain (e) for each specimen was measured at the 2000th repetition, since this was typically the minimum value that lasted until the failure stage. This value for each beam was plotted versus the number of loads to failure (the only exception was whether the beam was in the failure stage prior to 2000 repetitions, in which case the minimum strain was plotted). The results of the fatigue tests are shown in Figures 4-6. There is a clear separation between the Sulphlex and asphalt fatigue lives at each temperature. The fatigue coefficient K_1 and exponent K_2 representing each curve are given in Table 2. Definition of the fatigue equation is given as follows:

$$N_f = K_1 (1/e)^{K_2} \quad (1)$$

where

N_f = number of cycles to failure,
e = peak-to-peak dynamic strain experienced at underside of beam,
K_2 = absolute value of inverse of slope of fatigue line,
$K_1 = N_0 e_0^{K_2}$, and
N_0, e_0 = number of repetitions and strain at the vertical reference axis.

Note that at a given strain level, the asphalt mix possesses the greatest resistance to fatigue, whereas the 6 percent Sulphlex possesses the least. Conclusions regarding field fatigue behavior should not be drawn from these determinations, since the interactions of layer moduli and thickness play an important role in the design process.

Figure 4. Fatigue tests at 40° F.

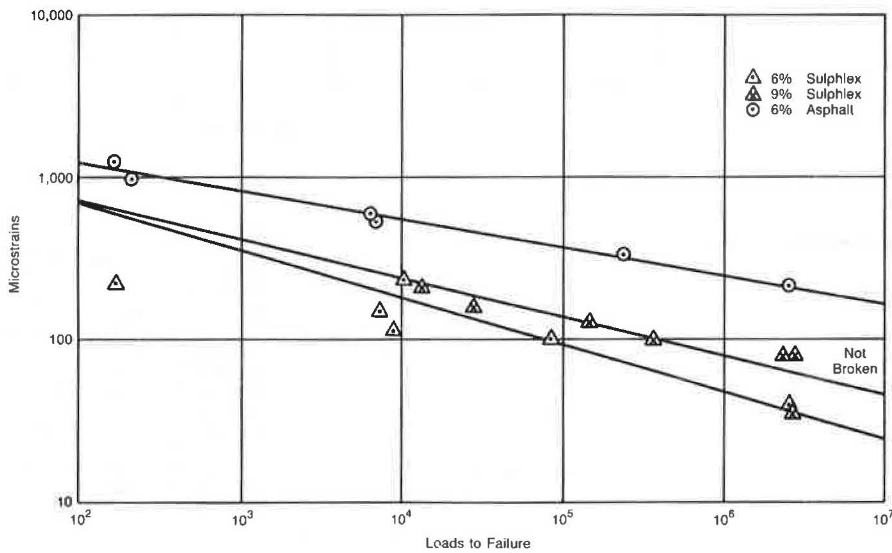
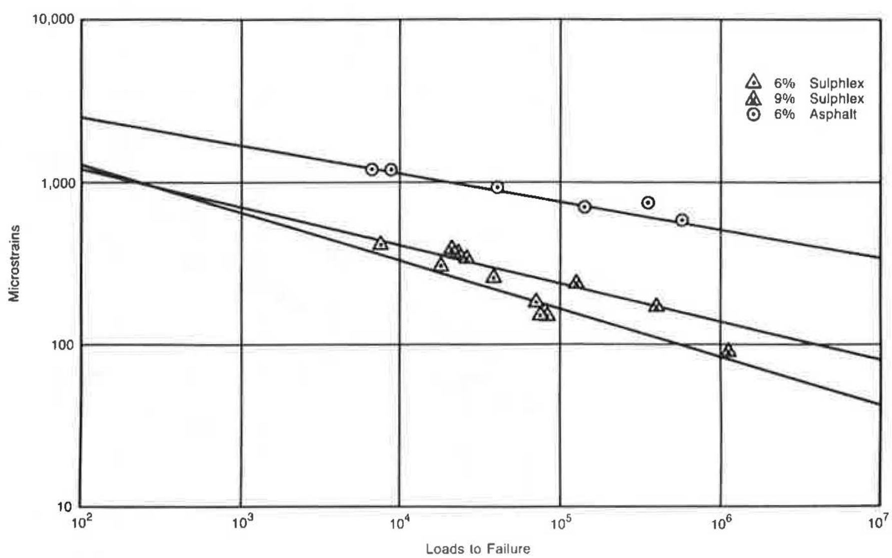


Figure 5. Fatigue tests at 75° F.



Creep Properties of Cylinders

Creep compliance is defined as follows:

$$D(t) = e(t)/\sigma \qquad (2)$$

where σ is the applied sustained compressive stress and e(t) is the resulting time-dependent strain.

Creep compliance curves are given in Figures 7-9 for each mix at the three different temperatures.

Figure 6. Fatigue tests at 90° F.

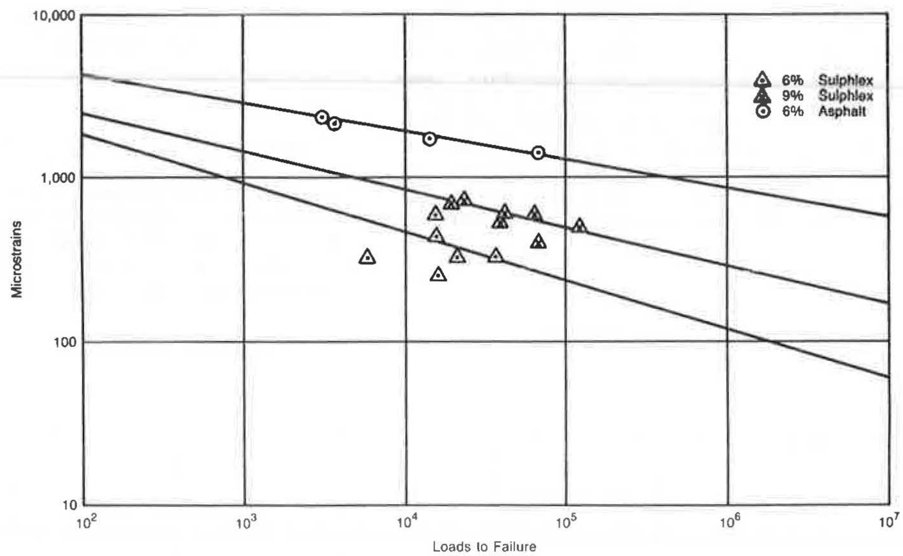


Table 2. Surface materials characterization.

Binder	Temperature (°F)	Fatigue		Permanent Deformation		Modulus (psi)
		K_1	K_2	GNU	ALPHA	
6 percent Sulphlex	40	1.92×10^{-9}	3.39	0	1	3 000 000
	75	1.49×10^{-8}	3.39	0.032	0.63	1 250 000
	90	4.91×10^{-8}	3.39	0.09	0.76	430 000
9 percent Sulphlex	40	5.08×10^{-12}	4.22	0.035	0.45	5 000 000
	75	4.57×10^{-11}	4.22	0.0236	0.51	1 100 000
	90	9.00×10^{-10}	4.22	0.139	0.57	348 000
6 percent asphalt	40	5.77×10^{-16}	5.92	0.038	0.54	1 730 000
	75	3.75×10^{-14}	5.92	0.057	0.72	337 000
	90	8.56×10^{-13}	5.92	0.111	0.58	124 000

Figure 7. Creep compliance, 6 percent Sulphlex.

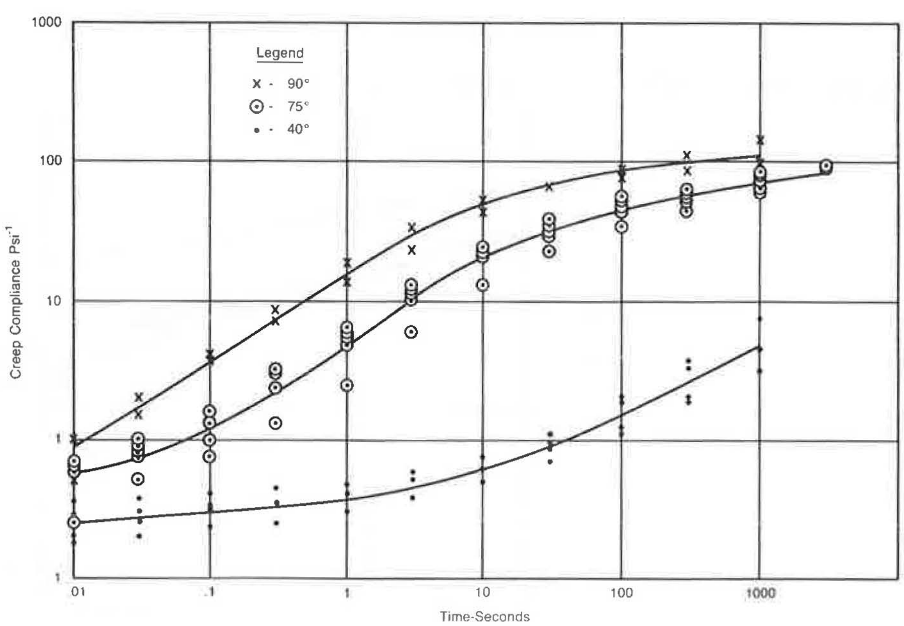


Figure 8. Creep compliance, 9 percent Sulphlex.

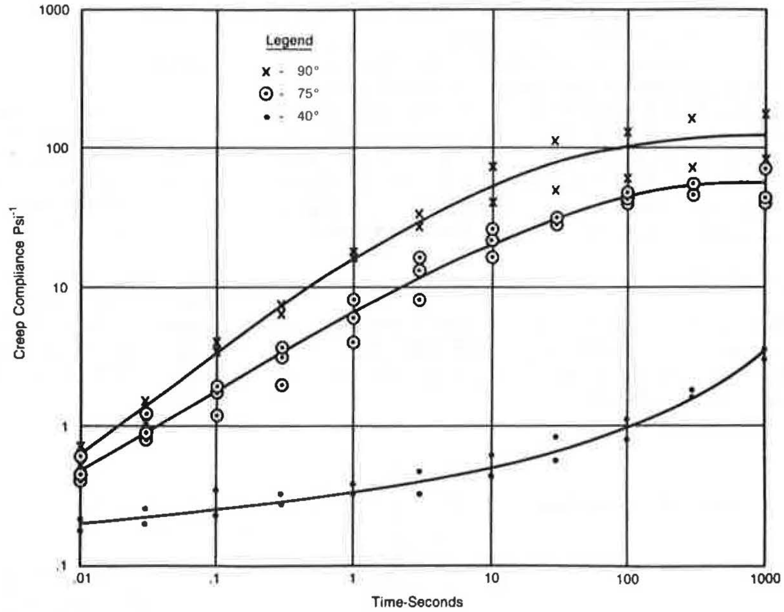
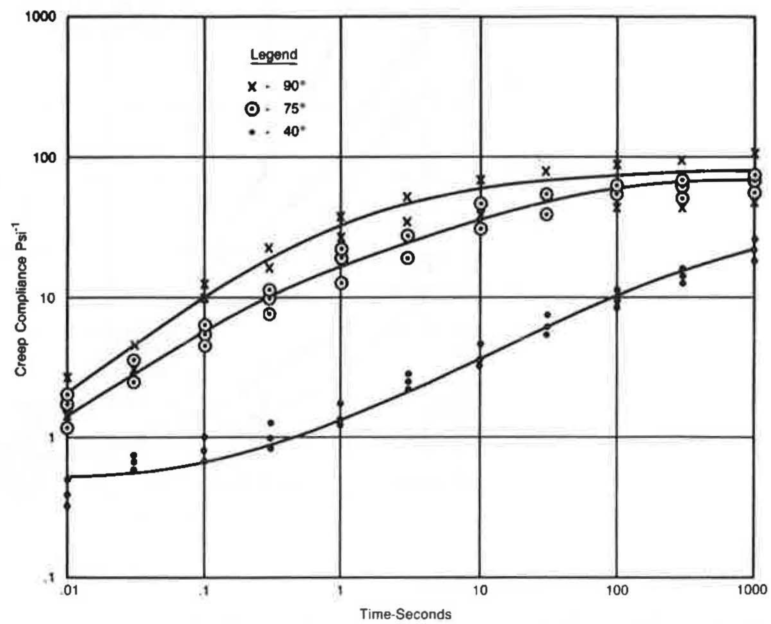


Figure 9. Creep compliance, 6 percent asphalt.



At all temperatures, the mixes are dependent on loading time. In general, the asphalt mix at a given temperature has higher creep compliances (lower moduli) at low loading times. In physical terms, this would mean that under moving traffic, Sulphlex would be the more desirable paving material, i.e., it would have the higher modulus. However, under stationary traffic, Sulphlex would exhibit continued creep and may not be so desirable. There is very little difference between the creep curves for 6 percent and 9 percent Sulphlex.

Modulus Properties

Three different measures of this property are reported:

$|E^*|$ = magnitude of the complex modulus (dynamic modulus) measured at the 200th repetition in the permanent deformation tests,

$E(0.03)$ = relaxation modulus taken as the inverse of the creep compliance measured at 0.03 s of the creep compliance curve, and

M_r = resilient modulus as obtained by using the Schmidt device for 0.1-s loading time (2).

The resilient modulus was obtained from an FHWA report (2). Averages for $|E^*|$ and M_r are given in Figure 10 for each mix, from which it is clear that the Sulphlex mixes exhibit predominantly higher modulus values than the asphalt mixes at all temperatures. The M_r tests (Schmidt) yielded moduli for 6 percent Sulphlex just slightly greater than those for 9 percent Sulphlex; however, the dynamic tests yielded significantly higher moduli for 9 percent Sulphlex at the lower temperatures.

The relaxation and dynamic moduli were determined on specimens aged up to 35 days, whereas the M_r tests were run on specimens aged up to 75 days; thus no significant aging susceptibility is evident. Figure 10 depicts significant temperature susceptibility (9 percent Sulphlex exhibits the greatest).

Permanent Deformation Properties

Based on the assumed linear relationship between the permanent strain per pulse (e_p) and the number of load repetitions (N) on a log-log plot, the following equation may be stated:

$$e_p = e_\mu N^{-\alpha} \quad (3)$$

where

- e = dynamic strain measured at the 200th repetition,
- α = 1 - slope(s), and
- μ = (Is/e), where I is the permanent strain after the first repetition (intercept on log-log plot).

To determine the permanent deformation properties ALPHA (α) and GNU (μ) for the three mixes, repeated-load tests were conducted at seven combinations of temperature and stress: 40°F (30 and 50 psi); 75°F (10, 20, and 30 psi); and 90°F (10 and 30 psi).

Figure 10. Effect of temperature on modulus.

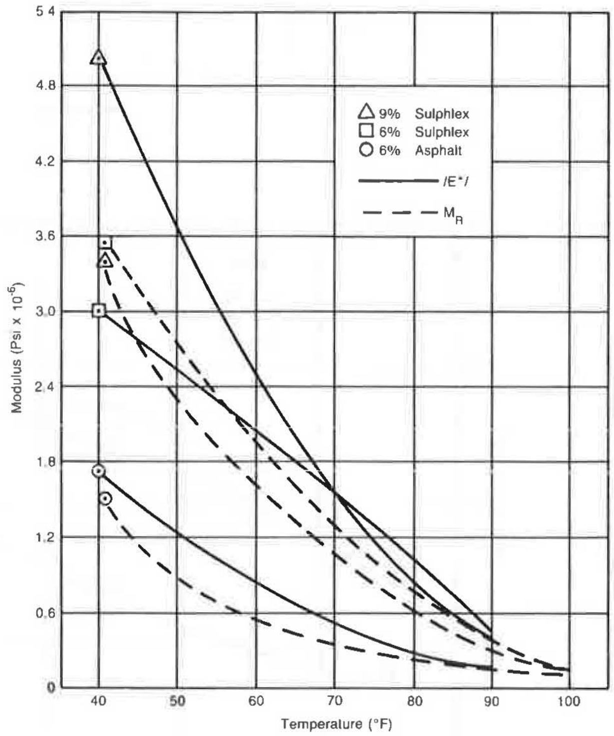
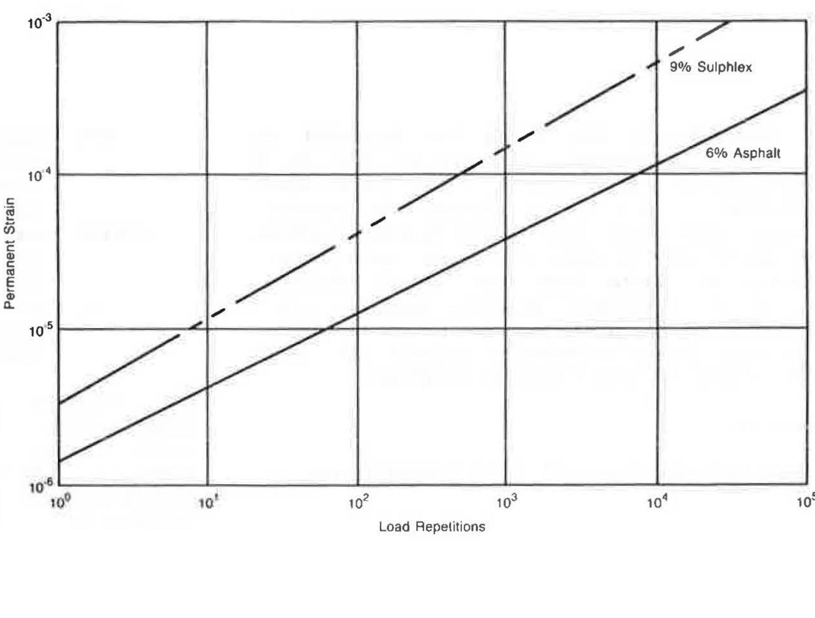


Figure 11. Permanent deformation tests at 40° F.



Straight lines on log-log paper of accumulated strain versus N were fitted to the data to define the slope and the intercept. Dynamic strains were measured at the 200th repetition. These numbers were used to calculate GNU and ALPHA in accordance with Equation 3. The permanent deformation properties reported in Table 2 for each binder at the three temperatures are averages of those found at the stress levels tested. These average values were used to plot accumulated strain versus N as shown in Figures 11-13. The dynamic strains (e) used to define these lines were computed for each binder and temperature by using the moduli reported in Table 2 and a stress level of 30 psi.

Six percent Sulphlex experienced the least permanent strain at all temperatures. At 40°F, 6 percent Sulphlex showed no permanent strain before 10 000 repetitions. Sudden periodic increments of accumulated deformation that took place after 10 000 repetitions could possibly be attributed to slippage within the mix instead of plastic flow. Thus, no line is shown in Figure 10 (dynamic tests at 40°F) for 6 percent Sulphlex.

VESYS DESIGN FACTORIAL

The VESYS III-A structural subsystem was used as an analysis method to predict the performance of the three mixes; the properties were tested at the three temperatures given in Table 2. Five structural designs, given in Table 3, were analyzed on a weak and a strong subgrade. The properties of the three base courses are representative of crushed-stone, cement-treated, and cement-concrete materials. The weak subgrade represents clay at 23 percent moisture content (5 ksi), and the strong subgrade represents the same clay at 16 percent moisture (45 ksi). The total factorial consisted of 90 separate analyses. The subgrade properties, load magnitude, traffic rate, and all other data input to the analysis were the same as for the design example in Chapter 6 of the VESYS User's Manual (8).

To evaluate the damage predictions, design criteria over eight years of service (6.6 million axles) were set as follows:

1. Maintain the fatigue damage index below 1 and
2. Maintain rut depth less than 0.60 in.

Figure 12. Permanent deformation tests at 75° F.

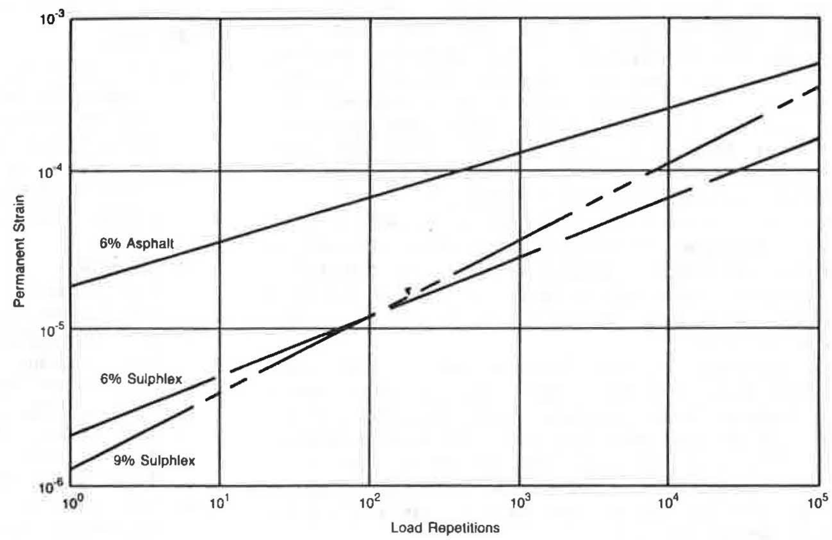


Figure 13. Permanent deformation tests at 90° F.

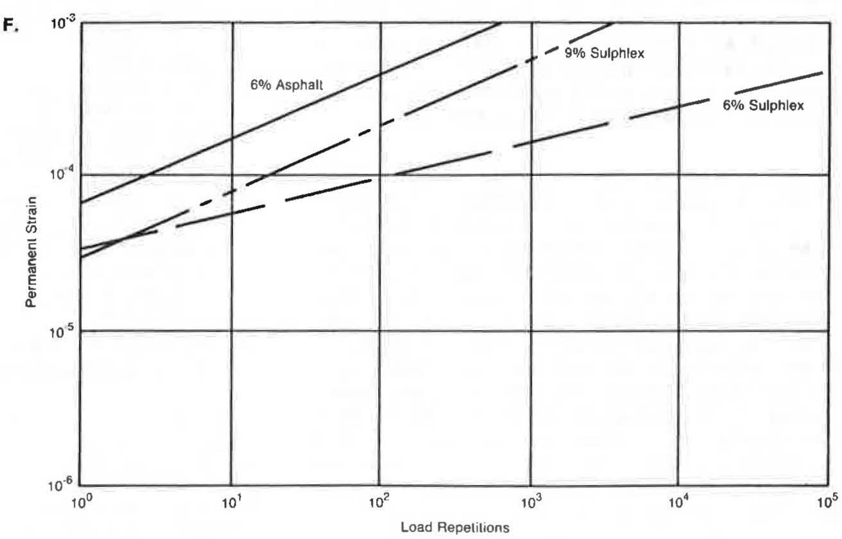


Table 3. Pavement structures for VESYS design factorial.

Pavement Property	Structural Design 1	2	3	4	5
Surface thickness (in)	6	3.5	6	3.5	2
Base thickness (in)	8	18	8	18	12
Base modulus (ksi)	59	59	350	350	1000
Base GNU	0.055	0.055	0	0	0
Base ALPHA	0.73	0.73	1	1	1

Table 4. Evaluation of VESYS design factorial.

		Structural Design[a]									
		1		2		3		4		5	
Binder	Design Criterion	W	S	W	S	W	S	W	S	W	S
6 percent asphalt	Fatigue	*	*	*	*	*	*	*	*	*	*
	Rutting	–	*	–	*	–	*	*	*	*	*
9 percent Sulphlex	Fatigue	–	–	–	–	*	*	*	*	*	*
	Rutting	–	*	–	*	–	*	*	*	*	*
6 percent Sulphlex	Fatigue	–	–	–	–	–	–	–	–	*	*
	Rutting	*	*	*	*	*	*	*	*	*	*

[a]W = weak subgrade; S = strong subgrade. * = satisfies criterion; – = does not meet criterion.

The acceptable designs based on these criteria are indicated in Table 4. A particular design was considered unacceptable if it did not meet the criteria at all temperatures. All pavement designs evaluated with a 6 percent asphalt concrete surface course satisfy the fatigue-cracking criterion (it should also be mentioned that these same pavement designs meet this criterion for 19 years and 20.5 million axles). Designs 1, 2, and 3, however, do not satisfy rutting on the weak subgrade.

The 9 percent Sulphlex designs 3, 4, and 5 satisfy the fatigue criterion; however, design 3 experiences excessive rutting on the wet subgrade. The 9 percent Sulphlex designs 1 and 2 satisfy rutting on the strong subgrade but do not meet the fatigue criterion.

All 6 percent Sulphlex designs satisfy the rutting criterion; however, only design 5 reduces tensile strains in the surface layer sufficiently to maintain the damage index below 1. At high temperatures on the weak subgrade for design 5, the surfaces are always in compression and the tensile stress at the bottom of the base is only 83 psi, thus eliminating fatigue.

An economic evaluation would be required to determine the best alternative design. This would involve comparing the total cost of the acceptable pavements. As an example, a maintenance policy could be adopted to smooth surfaces and to apply a thin overlay to pavement design 2 (3.5-in surface). Such a maintenance policy would restore ride quality and still meet the fatigue-cracking criterion.

CONCLUSIONS

The goal of this research is to provide guidance on Sulphlex pavement design for preliminary construction experiments. In conclusion, 6 percent Sulphlex exhibited the best rutting performance but had the least resistance to fatigue cracking, and 9 percent Sulphlex was similar to asphalt-concrete rutting but had worse fatigue performance. Because the fatigue criterion for the Sulphlex sample pavements analyzed was seldom satisfied, it is recommended that pavement design minimize tensile strains in this material by using thin surfaces over a stiff base course. The sample design procedure presented could serve as a basis on which the state could conduct their own analyses for local materials, traffic, and environment. Each designer should generate feasible alternatives and select the most desirable one by predicting distress and evaluating the economic impacts of construction plus maintenance.

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