BENEFICIAL USE OF SULPHUR IN SULPHUR-ASPHALT PAVEMENTS

Final Report

Texas A&M Research Project - RF 983 - 1B

Volume I of III

Evaluation of Sand-Asphalt-Sulphur Mixtures Under Repetitive Loading Conditions

Prepared for

U. S. Department of the Interior - Bureau of Mines

and

The Sulphur Institute

by

Texas A&M Research Foundation
College Station, Texas 77843

August 1974

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1.0 Introduction and Summary

1.1 Purpose

The purpose of this study is to evaluate selective sand-asphalt-sulphur mixture designs under repetitive loading conditions. It is also the purpose of this program to provide a responsible and readily available source of technical information and recommended procedures for use in research, education and engineering construction of pavements which use asphalt and sulphur as binders.

1.2 Scope and Objectives

The long-range objectives of this study are to exploit the available technology and evaluate the potential of sand-asphalt-sulphur (S-A-S). The program as proposed consists of three tasks.

Task I - Laboratory Evaluations and Theoretical Analysis of S-A-S Mixtures Under Repeated Loads.

Task II - Update of Literature and Patent Review Generated Under Phase 1-A.

Task III - Update of User's Manuals Prepared During Phase 1-A.

These three tasks are being conducted concurrently, and the results achieved, to date, are reported herein.

1.3 Background

Shell Canada Limited is currently developing a sulphur-asphalt-sand paving material called "Thermopave". The techniques developed and the results of actual field tests were reported in a series of technical papers by Deme et al [1-4]. A study under the joint sponsorship of the Bureau of Mines and the Sulphur Institute was initiated on 1 May 1973 to implement this development, more particularly, to introduce to the United States and adapt to her conditions the techniques under development in Canada.

Under Phase 1A of this study, basic engineering properties associated with highway pavement construction of sand-asphalt-sulphur (S-A-S) composites were evaluated through a laboratory program of mixture design, specimen preparation and testing. A limited theoretical analysis of the fatigue life of a sand-asphalt-sulphur pavement compared to a conventional asphaltic concrete system was also performed. Other activities included in this phase were:

(1) The consolidation of responsible and readily available sources of technical information and data concerning S-A-S pavements.

(2) The establishment of a literature and data bank on the general subject of the use of sulphur in pavements.

(3) Preparation of preliminary specifications and recommended design, construction and quality control procedures.

A report on Phase 1A [5] was completed in January 1974. Based on the data and information presented in this report, the following conclusions and recommendations were made:

1. Sand-asphalt-sulphur pavements made with inexpensive, poorly-graded sands have been shown to have properties at least equal to or better than conventional asphaltic concrete.
2. For best workability and strength, processing should be accomplished at $250°F \leq T \leq 300°F$. Results have shown that mixtures can be prepared at temperatures as high as 395°F but

at the sacrifice of uniformity in the dispersion of the sulphur phase and with the evolution of excessive H_2S.

3. No adverse trends in properties were indicated after 28 days of post-cure.

4. Properties of 80.5:6:13.5 weight percent S-A-S mixtures prepared in Phase 1A were in good agreement with the results reported by Shell. To offset the declining availability and increasing cost of asphalt predicted as a result of the current energy crisis, mixture designs with lower asphalt contents should also be investigated.

5. The design properties of a mix can be tailored to a predetermined stability, percent air voids or unit weight through adjustment of sulphur content.

6. Thermal properties of S-A-S appear to be reasonably compatible with conventional A/C.

7. Preparation of S-A-S materials should be accomplished with a minimum of compaction or densification effort. This could result in a significant economic advantage of S-A-S over A/C during construction.

8. Preliminary elastic-layer analysis using assumed material properties indicated fatigue life of S-A-S at low-to-moderate rates of loading to be better than asphaltic concrete and relatively equal at high rates.

9. Mean hydrogen sulfide concentrations measured during laboratory mixing and casting were below maximum allowable concentrations (MAC) suggested by ACGIH [6].

10. Economics of using S-A-S as a pavement material depends to a large extent on availability of low cost aggregate, and the cost and accessibility of sulphur to the user.

Technical effort on the current program, Phase 1B, was performed during the period 1 December 1973 to 30 June 1974 and extended the initial objectives to include the evaluation of S-A-S mixture designs under repetitive loading conditions.

2.0 Technical Program

2.1 Task I

2.1.1 General

To gain insight into the probable performance characteristics of S-A-S mixtures under repetitive loads, the effect of material variables such as sulphur-asphalt ratio, stiffness, air void content, moisture content and aggregate on fatigue behavior have been analyzed. Engineering properties evaluated include stiffness, resilient modulus and permanent deformation versus number of cycles to failure under constant stress and constant strain amplitude repeated loads. Macrostructural damage (i.e., breakdown of the bond between aggregate and sulphur phases) was also studied by measuring the change in volume (dilatation) of a number of S-A-S mixtures while under load. These properties were compared with those of a high grade asphaltic concrete system. The material properties measured in this task were incorporated into a theoretical analysis of equivalent pavement thickness requirements from which the relative construction costs of sulphur-asphalt and asphaltic concrete pavements were compared.

2.1.2 Materials

The sand-asphalt-sulphur (S-A-S) paving mixtures consist of the same materials and use the same preparation techniques discussed in Phase 1-A [5]. Elemental sulphur (i.e., sulphur in the free state) used in all mixes was a commercial grade, 99.8±% purity. However, commercial grade sulphurs of lower purity can also be used. S-A-S mixtures were prepared using two types of aggregate: a poorly graded beach sand (Sand I) and a more densely graded concrete sand (Sand II). The physical properties of these sands shown in Table I reflect the relatively high void contents in these mineral aggregates (VMA) as compared to a dense graded crushed limestone. The gradations for these aggregates are shown in Figure 1.

TABLE I - Physical Properties of Aggregates

Designation S-A-S	Aggregate Type	Specific Gravity	VMA %	Unit Wt. (lb/ft^3)
Sand I	Beach Sand	2.65	37.6	103
Sand II	Concrete Sand	2.65	33.1	111
Limestone	Crushed Limestone	2.65	17.8	136

The asphalt type is an AC-10 conforming to 1972 Texas Highway Department Standard Specifications, Item 300 [7]. The physical properties of this asphalt are given in Table II.

TABLE II - Physical Properties of Asphalt

Specific Gravity (77°F)	1.004
Penetration (77°F)	106
Viscosity, Stokes (140°F)	1392
Viscosity, Stokes (275°F)	3.2

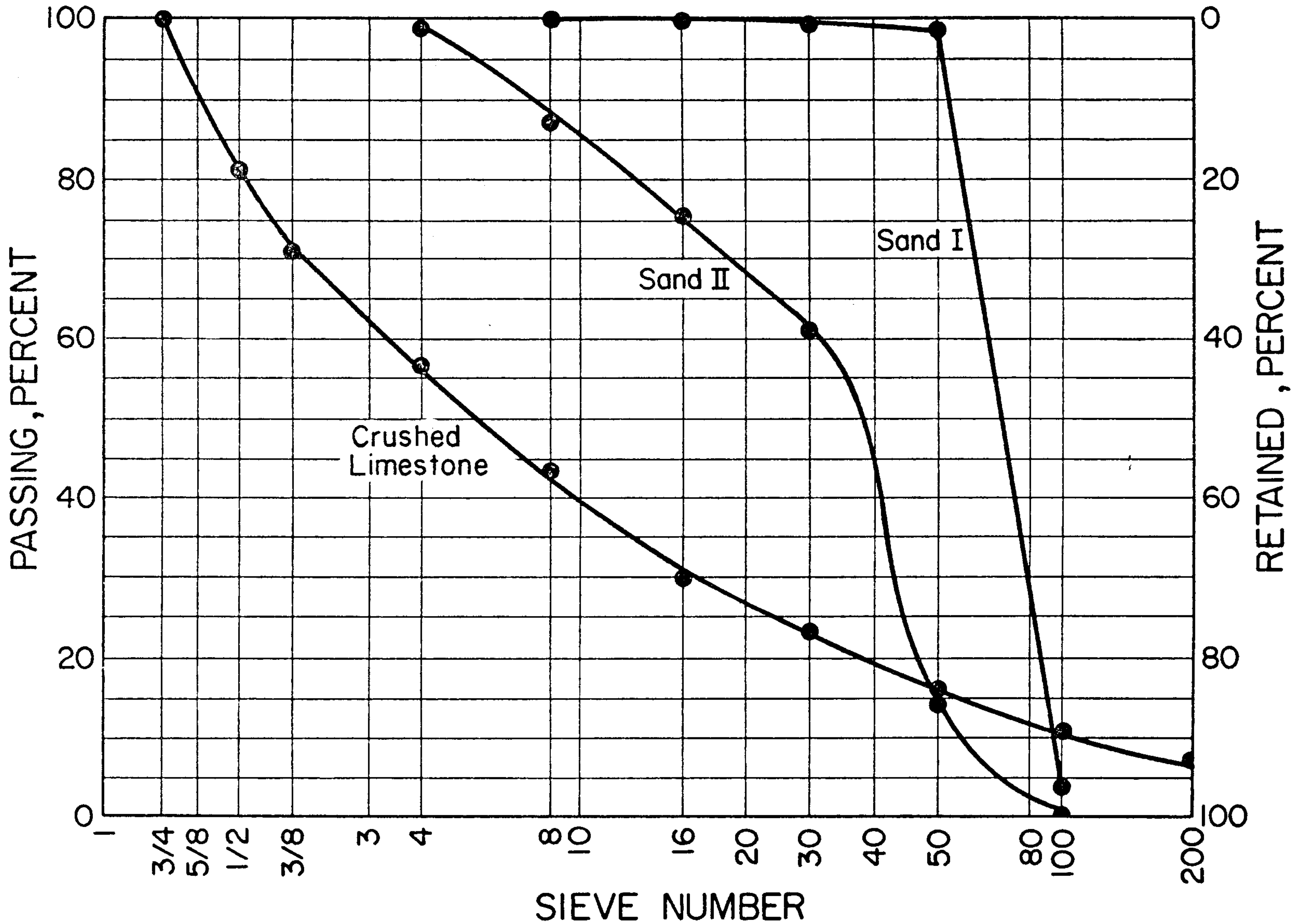


Fig. 1 Aggregate grading chart

Mixtures were prepared incorporating a wide variety of weight proportions of sand, asphalt and sulphur. In accordance with suggestions made by the sponsors, mixture designs were prepared using high concentrations of sulphur (greater than 10% by weight) to investigate the use of sulphur as a partial replacement for asphalt whose price and availability are being adversely affected by the current energy crisis. A matrix of the various sulphur-asphalt mixtures evaluated in this study are shown in Table III. All asphaltic concrete samples used for comparison were prepared using the crushed limestone shown in Figure 1.

TABLE III - Sand-Asphalt-Sulphur Mixture Ratios

Selected for Investigation

Sulphur Content*	Asphalt Content*			
	0	2	4	6
0		X	X	X
10	X	X	X	X
13.5	X	X	X	X
16		X	X	X
20	X	X	X	X

*Percent by weight of mix.

In conjunction with the processing of these mixtures the evolved gas analysis investigations initiated in Phase 1A were continued. Additional data on H_2S emissions as a function of mixture variables are being obtained so as to add to the statistical base available from Phase 1A.

2.1.3 Experimental Program

Laboratory evaluations of a selected number of S-A-S mixture designs have been completed. A brief discussion of the specific tests which were performed and their respective test conditions are given below.

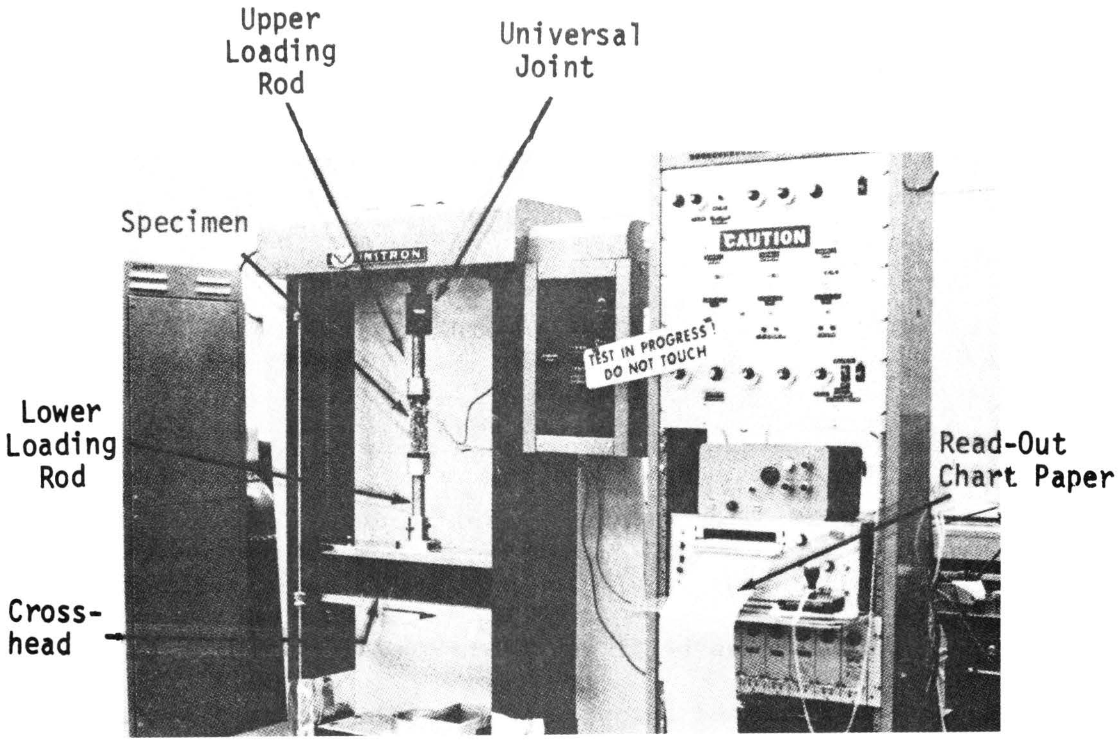
Direct Tension Test

A series of direct tension tests were run on eleven S-A-S mixtures. Test conditions included three test temperatures (20, 73 and 135°F), and three loading rates (0.02, 0.2 and 2.0 in./min.). Stiffness, defined by the initial (short time) slope of the stress-strain curve along with failure stress and strain were measured as a function of both sulphur and asphalt content over these test conditions. Samples prepared with both Sand I and Sand II were tested and the results compared with the tensile properties of the asphaltic concrete mixture.

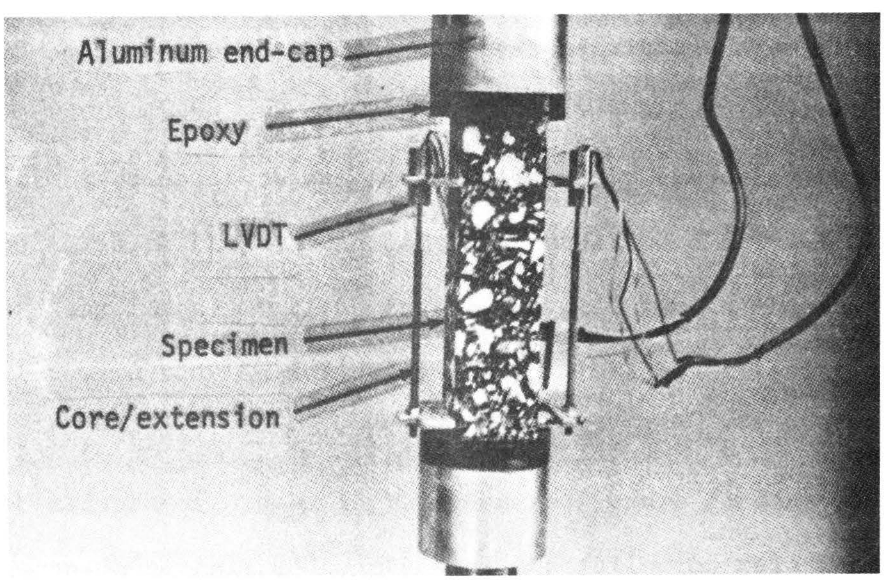
Specimens were 1 1/2" X 1 1/2" X 6" long, end-bonded to metal end plates [8]. All tests were run in triplicate on an Instron Universal Tensile Tester. Strain was measured over a four-inch gage length by 2-LVDT's mounted on opposite sides of the specimen. An illustration of a typical direct tension test set-up is shown in Figure 2.

Flexure Fatigue

Flexure specimens 3" X 3" X 12" long were tested in both controlled stress and controlled strain modes and the numbers of load applications to failure measured. The former loading condition is encountered in comparatively thick (greater than 6 in.), stiff pavements and has been shown, by laboratory tests, to provide a conservative estimate of fatigue life [9]. Layered system elastic analysis has shown that the controlled strain mode of loading is approached in pavements containing thin (2 in. or less) flexible pavement sections.



(a) Complete view of the instrumentation



(b) A close-up view of the specimen under test

FIG. 2 - Uniaxial tension test set-up.

A Gilmore closed-loop, feed back control, electrohydraulic tester was used for these tests (Figure 3). Loads were applied in third-point flexure (Figure 4a) with 1 in. clamps located 4 in. on center. Beams were tested in half-wave sine loading (Figure 4b) under controlled isothermal (70 ±1°F) conditions at a frequency of 100 cycles per min. Due to a slight deformation of the test frame, or possibly due to inertial effects, the beam underwent a slight deflection below its zero-load position as shown by the dotted line in Figure 4b. The amplitude of this effect represented a relatively small fraction of the peak deflection and was therefore neglected from further consideration. Loads were applied in automatic feedback control and were designed to shut off the machine when the specimen broke. Complete details of the control and operation of the Gilmore test equipment are given in Reference 10.

The above test conditions were selected because they either exactly duplicate [8, 10, 11] or very nearly duplicated [12, 13] those performed by other investigators. This facilitated the comparison of fatigue behavior of S-A-S and asphaltic concrete systems without requiring additional tests.

The effect of moisture was also evaluated by comparing the fatigue life of specimens which had been moisture conditioned for six weeks to that for dry specimens. Fatigue tests were also run on a number of samples which were redried following the moisture conditioning.

Moment, M, stress, σ, stiffness, E, and strain, ε, based on the deflection at midspan of a beam in third-point flexure loading, as shown in Figure 4a, can be calculated by means of the following relationships:

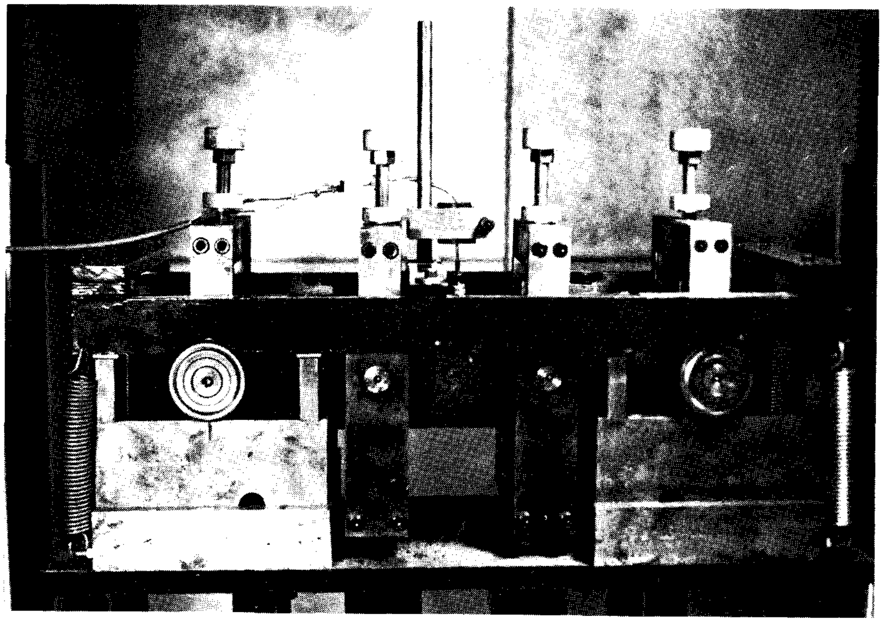
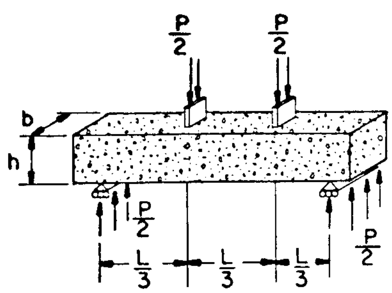
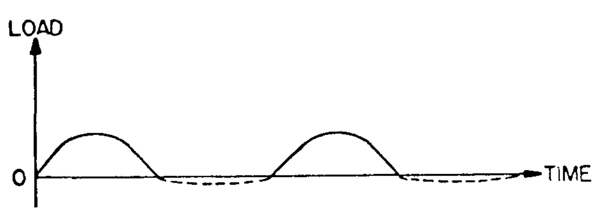


Fig. 3. Third-point flexure fatigue tester



a. Third-Point Loaded Beam



b. Half-Wave Sine Loading

Fig. 4. Flexure fatigue support and loading conditions

$$M_{max} = PL/6 \quad (1a)$$

$$\sigma_{max} = PL/bh^2 \quad (1b)$$

$$E = \frac{23PL}{1296wI}\left[1 + \frac{216(1 + \nu)h^2}{115L^2}\right] \quad (1c)$$

$$\varepsilon_{max} = \frac{\sigma_{max}}{E} = \frac{4.69wh}{L^2 + 1.88(1 + \nu)h^2} \quad (1d)$$

where

P = Load
L = Length of beam
w = Deflection at midspan
b = Width of beam
h = Height of beam
I = Moment of inertia = $\frac{bh^3}{12}$
ν = Poisson's ratio

The term outside the bracket in Equation 1c is the customary strength of materials solution for a third-point loaded beam, as shown in Figure 4a, in which shear deformation is neglected. The second term (inside the bracket) reflects the influence of shear deformation [10]. When this correction was used to reduce the test data the stiffness values were found to be as much as 15 percent greater than those computed using only the bending deformation.

Poisson's ratio, ν, for both the asphaltic concrete and S-A-S mixtures was taken to be 0.35 for these calculations. Substituting this value along with the beam dimensions into the above expressions gives the following working relationships:

$$M_{max} = 2P \quad (2a)$$

$$\sigma_{max} = 0.444P \quad (2b)$$

$$E = 5.26\,\frac{P}{w} \quad (2c)$$

$$\varepsilon_{max} = \frac{9w}{106.54} \quad (2d)$$

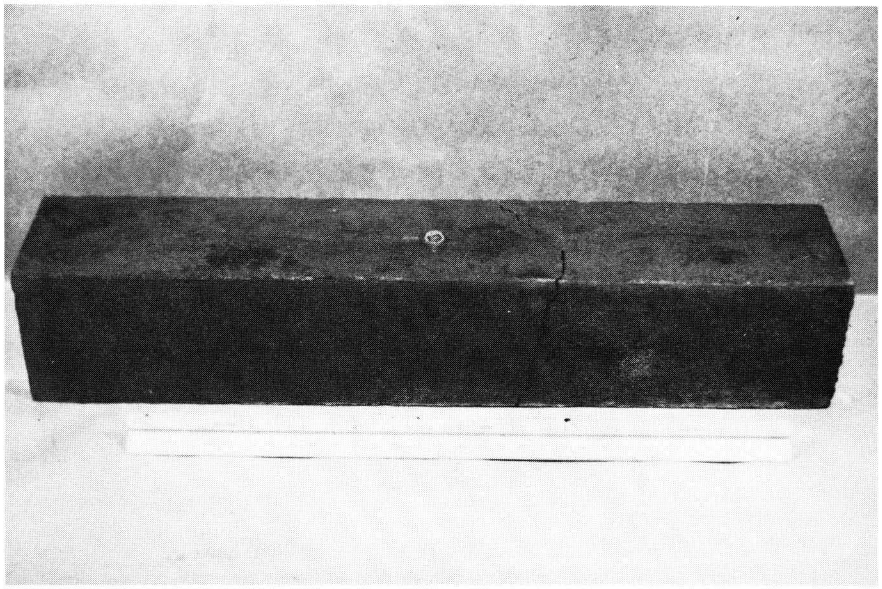
Failure was taken as the occurrence of a crack on the surface of the specimen which always originated on the side which was in tension. As shown in Figure 5, failures encountered in the stress-amplitude test were catastrophic in nature whereas those in the strain-amplitude tests had to be detected from sudden reductions in the load.

At the time of this writing all of the stress-amplitude tests have been completed. The strain-amplitude tests are still in progress and only those data currently available will be reported. The remainder will be presented in the next quarterly progress report.

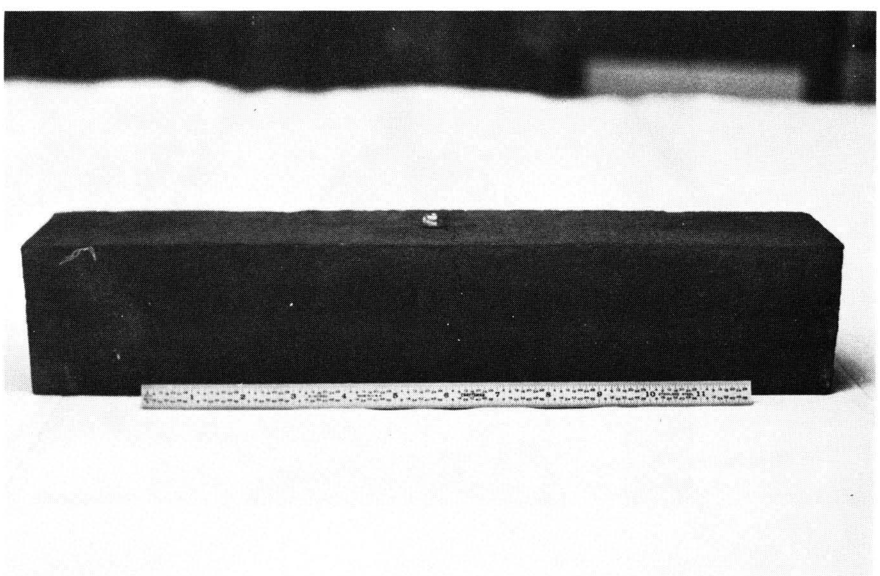
Resilient Modulus

Under short-duration, dynamic loads on a viscoelastic material the apparent Young's modulus, or stiffness, E, is frequently defined as the resilient modulus, M_R. This parameter is used in conjunction with layered-elastic or finite element design methods for determining pavement thickness and fatigue life. The test procedures and equipment used in this series of tests were similar to those developed by Schmidt [14].

A light pulsating load of 0.1 second-duration was applied every 3 seconds through a load cell across the vertical axis of a 4 in. diameter X 3 1/2 in. thick specimen. This load produced an elastic deformation across the specimen's horizontal diameter. This deflection was monitored by a pair of compensating, highly sensitive Schaevitz transducers (0.005 in. full-scale deflection). Air pulses were supplied to a Bellafram pneumatic cylinder from a MAC, electrically-activated solenoid valve. Pulse width was controlled by a Sizer timer and load magnitude by a Kendall Model 10 pressure regulator. The test set-up is shown in Figure 6.

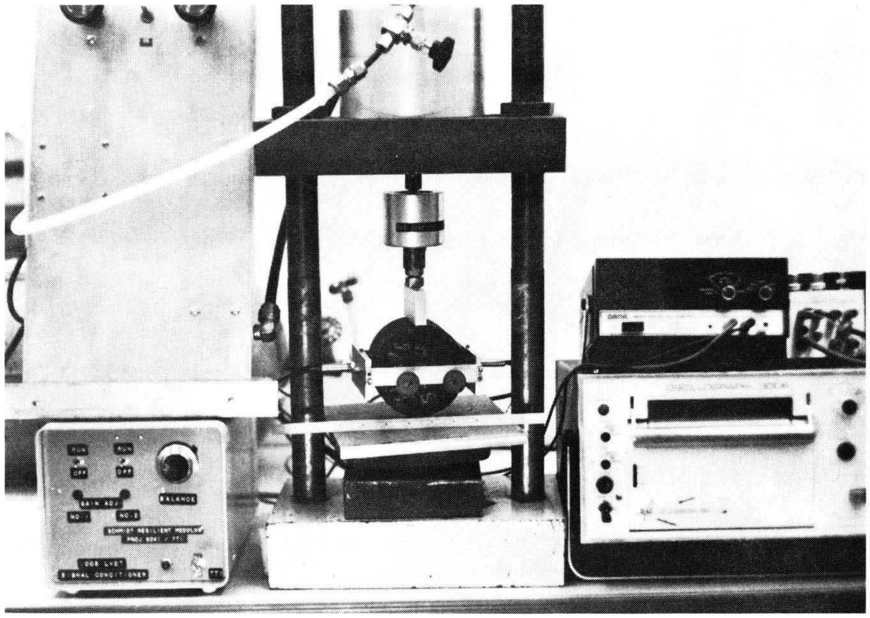


a. Stress Amplitude Failure



b. Strain Amplitude Failure

Fig. 5. Comparison of Stress Amplitude and Strain Amplitude Fatigue Fracture



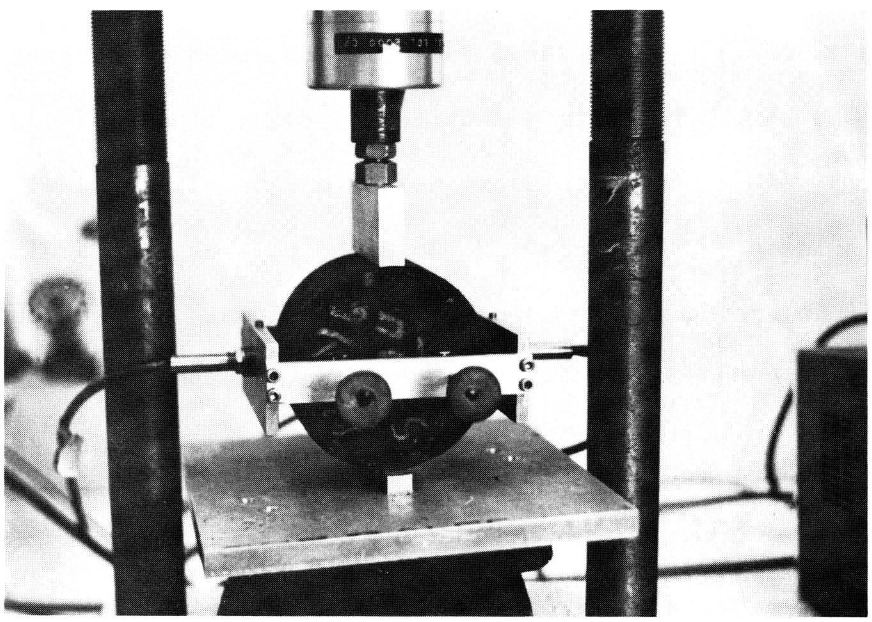


Fig. 6. Diametral resilient modulus (M_R) device.

The specimen was mounted in a yoke using a holder assemble, (as shown in Figure 7) by a pair of clamping screws. A locking nut was provided in the yoke to position and adjust the contract pressure of Schaevitz transducers after which the sample is removed from the holder and placed in the tester.

A typical loading pattern is shown in Figure 8 which indicates the dynamic load, P, and the total deformation, Δ. The resilient modulus for a sample of thickness, t, was computed from the following relation [14]:

$$M_R = \frac{P(\nu + 0.2734)}{t\Delta} \tag{3}$$

Poisson's ratio, ν, can be assumed over a wide range of values without introducing excessive error into the computed M_R. Schmidt suggested using a value of 0.35 for asphaltic concrete because it gave reasonable agreement with stiffness measured in direct tension at 73°F. On the same basis the value of Poisson's ratio for all S-A-S mixtures tested was set at 0.30.

Resilient moduli were measured at temperatures of 41, 68, and 95°F on 15 mixture designs. In addition, M_R values of dry specimens were compared with those for samples which had been vacuum saturated [15]. After testing these specimens were redried in a 90°F environmental chamber at 25° percent humidity for at least 3 weeks. The M_R values for S-A-S mixtures were compared with those for asphaltic concrete measured under similar test conditions. These data were used in the equivalent pavement thickness analysis to be discussed later.

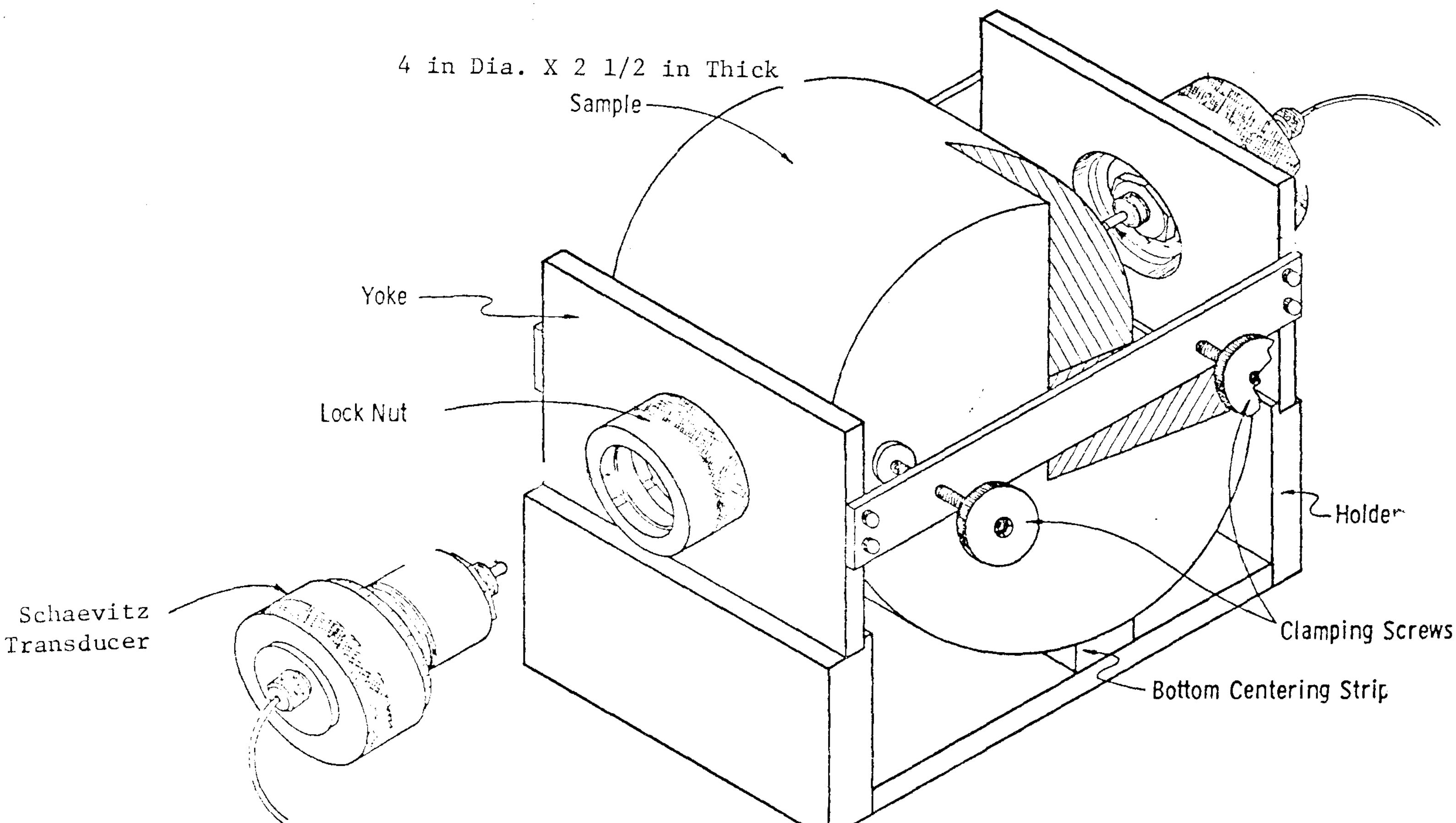


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Fig. 7. Diametral resilient modulus device yoke and holder assembly.

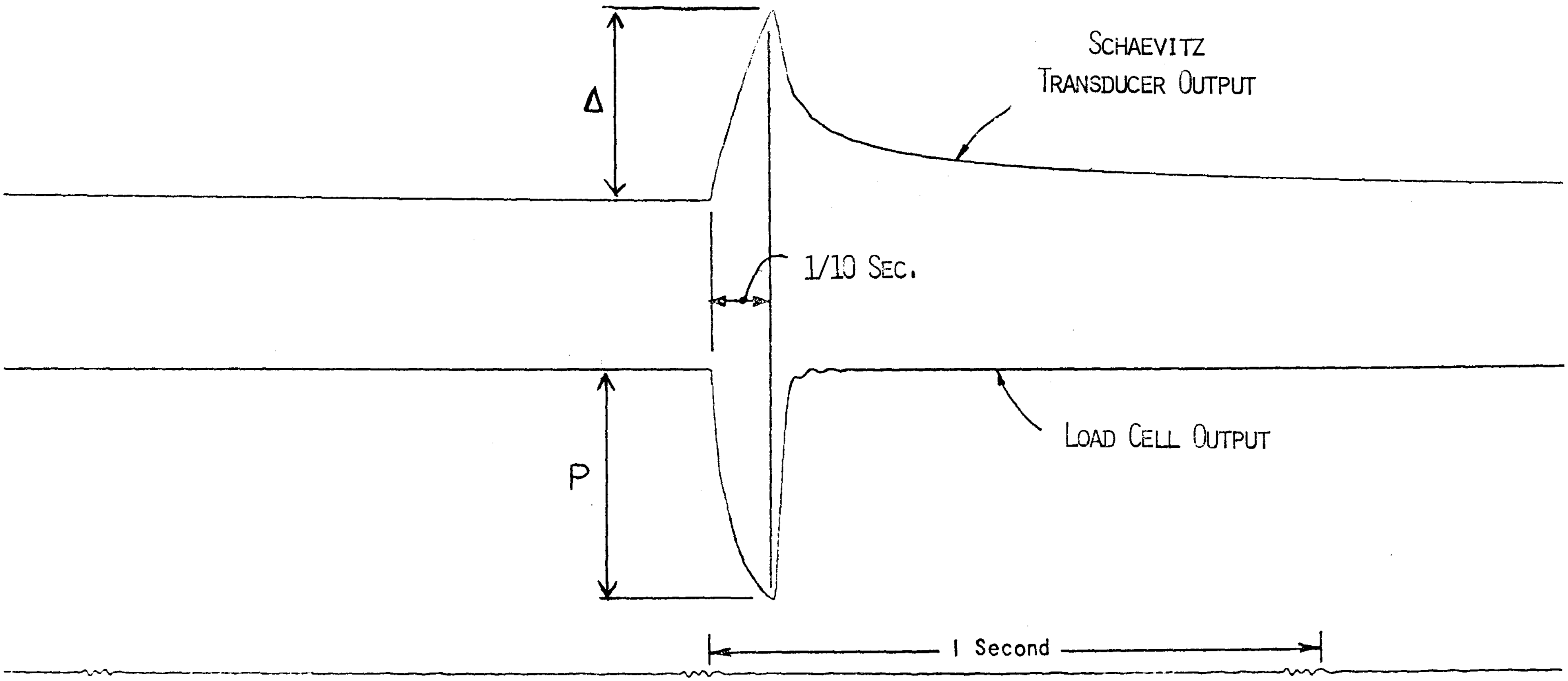

Fig. 8. Typical trace diametral measurement of resilient modulus.

Triaxial Testing

These tests were incorporated into the program to compare the load-deformation characteristics of S-A-S mixtures with asphaltic concrete under both static and repeated triaxial loads. The basic testing equipment used in this task was developed by Gandhi and Gallaway [16] and is basically a hydraulic-operated testing machine whose speed of loading and frequency of load applications is controlled by timer-actuated solenoid valves. A range of loading speeds and frequencies can be provided by using timers with different gear ratios.

An Industrial Timer Corporation timer was used to control the pulse width and frequency and the magnitude of the pulse was controlled by a Fairchild-Hiller pressure regulator. Complete details of the apparatus have been given elsewhere [17] and hence not discussed here. Two views of the test station are shown in Figure 9.

The specimens were 4" diameter X 8" long and were prepared in molds using the same procedures established in Phase 1A. Considerable thought was given to the degree of compaction given these samples to assure that no density gradients were produced. It was also important to assure that the density of the triaxial test specimen was the same as that for the other tests' specimens for the same mixture design. Marshall specimens were prepared by sawing a number of triaxial specimens representing different degrees of compaction at 2 1/2 in. intervals along their length. Marshall stability and density tests run on these specimens indicated that three blows with a 10 lb. weight to one face of the triaxial specimen was sufficient to achieve a material with a uniform density along its length. All triaxial specimens were, therefore, compacted in this manner.

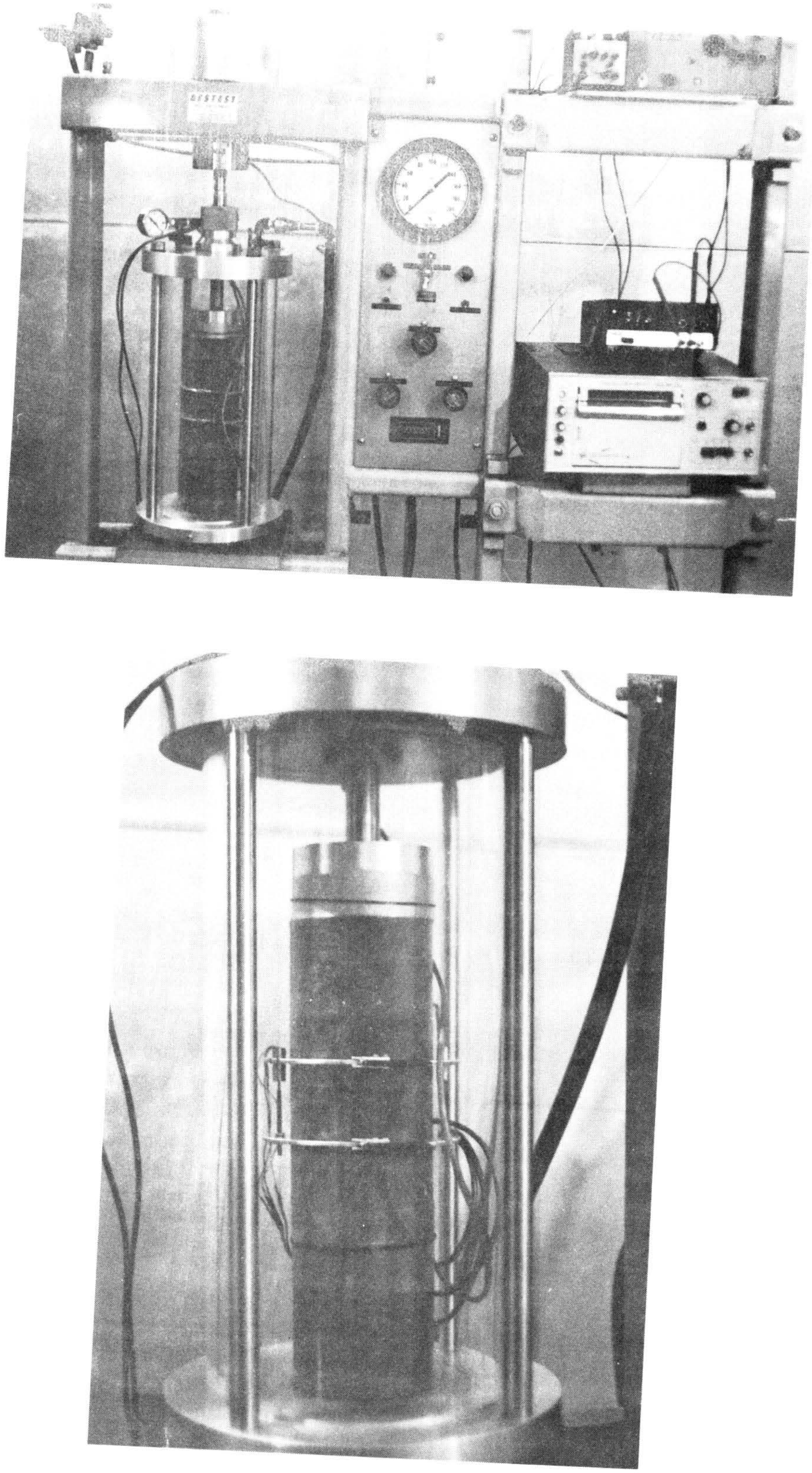

Fig. 9. Triaxial test setup.

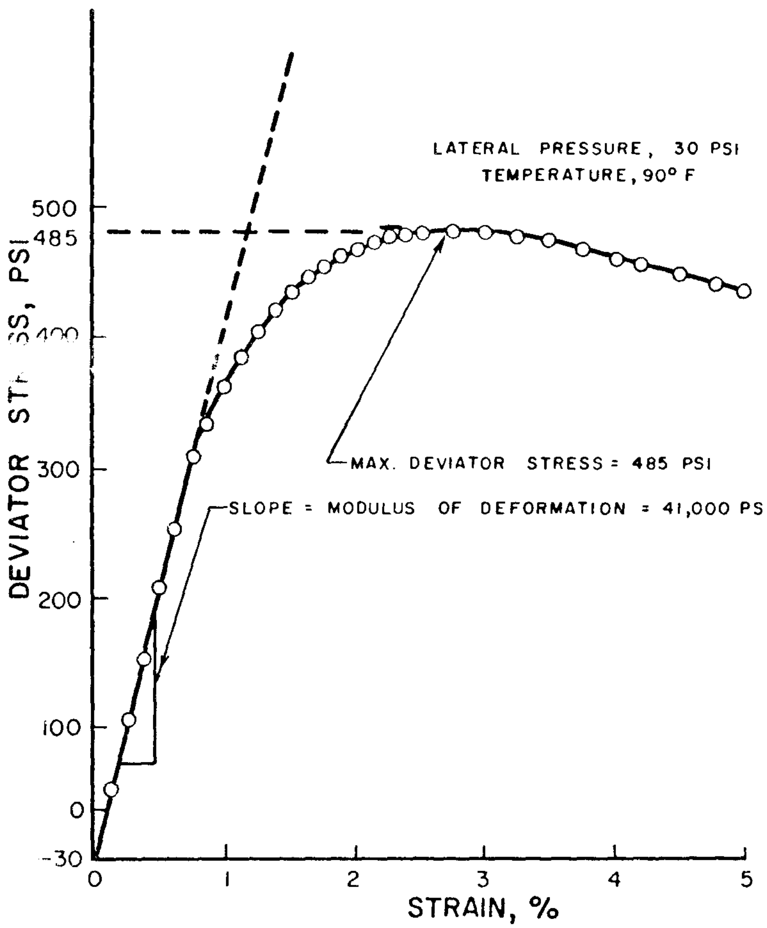

Fig. 10. Typical stress-strain curve (static triaxial test).

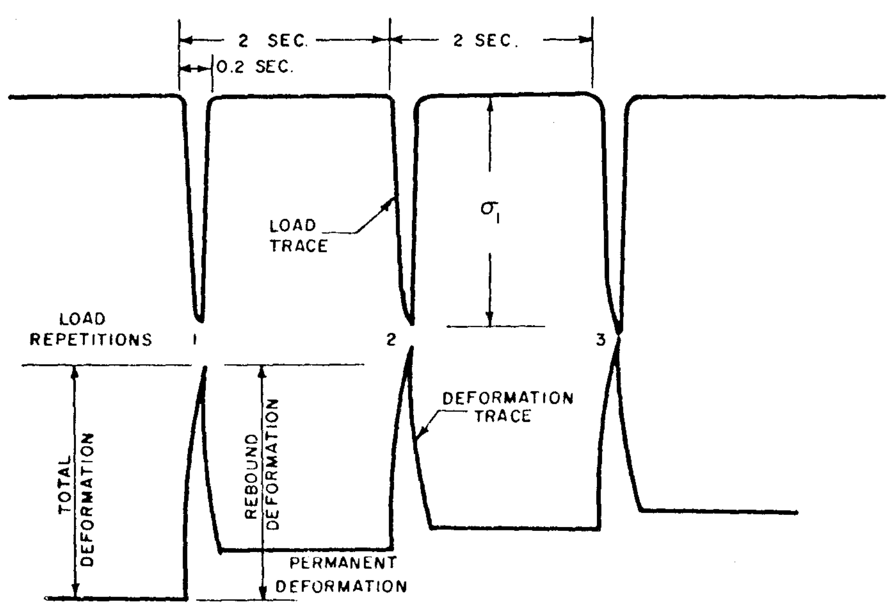

Fig. 11. Typcial load-deformation record (repeated load triaxial test).

The static load triaxial compression tests were conducted on three mixture designs at a temperature of 68°F. The specimens were tested at a constant deformation rate of 0.05 in/min at four superposed hydrostatic pressure levels (0, 10, 20 and 30 psi). The maximum deviator stress, $\sigma_1-\sigma_3$ and the modulus of deformation (static modulus) were calculated for each specimen tested. A typical stress-strain curve is shown in Figure 10 showing these parameters.

The repeated load triaxial tests are being conducted on three mixture designs at test temperatures (40, 68 and 90°F). A typical instantaneous load-deformation trace is shown in Figure 11. Three deviator stress levels --50, 100 and 150 psi--were chosen for these tests as this range tends to cover the loading conditions on highways, and to some extent on airfields. All of the repeated loads were run at σ_3 = 20 psi and the three stress deviators were achieved by changing, σ_1. During the course of the test the change in permanent strain ε_p relative to the number of load repetitions, N, was monitored by means of a matched pair of LVDTs mounted on each side of the specimen. The analysis of the data is presented in the discussion of results. These conditions also duplicate those used by Gandhi and Gallaway [16] for asphaltic concrete mixes using gravel, lightweight and limestone aggregates and thus permit a comparison of their results with S-A-S mixtures.

At the time of this writing all of the static tests have been completed. The repeated load tests are still in progress and will be presented in the next progress report.

Dilatation Tests

From an examination of the failure surfaces of broken samples it can be concluded that the failure mechanisms in S-A-S systems tend to be related to the breakdown of the bond between the asphalt-coated sand particles and the sulphur matrix. A gas dilatometer (Fig. 12), which is a constant volume chamber, has been routinely employed to measure stress-induced macrostructural damage in filled composites. The relative changes of volume, $\frac{\Delta V}{V_o}$, produced during deformation is called "dilatation" and can be related to the ability of a particulate-filled composite to resist fracture. This technique has also been used by soil mechanicians to evaluate the breakdown in cohesive strength in soils.

The dilatometer was mounted directly to an Instron Universal Tensile Testing Machine, as shown in Figure 13a. Specimens, 2" X 7" X 1/2" thick (see Figure 13b), were placed in the chamber, sealed and subjected to a tensile deformation at a rate of 0.02 in/min in the direction of the 2" dimension. Volume changes within the chamber and associated stress levels were simultaneously monitored on a dual pen recorder. A typical dilatation-stress curve is shown in Figure 14 which can be approximated by two straight lines.

$$\frac{\Delta V}{V_o} = 0 \qquad \sigma < \sigma_D$$

$$\frac{\Delta V}{V_o} = K(\sigma - \sigma_D) \qquad \sigma \geq \sigma$$

where K is the slope of the approximated curve.

At the early stages of the test, the measured dilatation is zero indicating that no damage has occurred. Eventually the stress level reaches

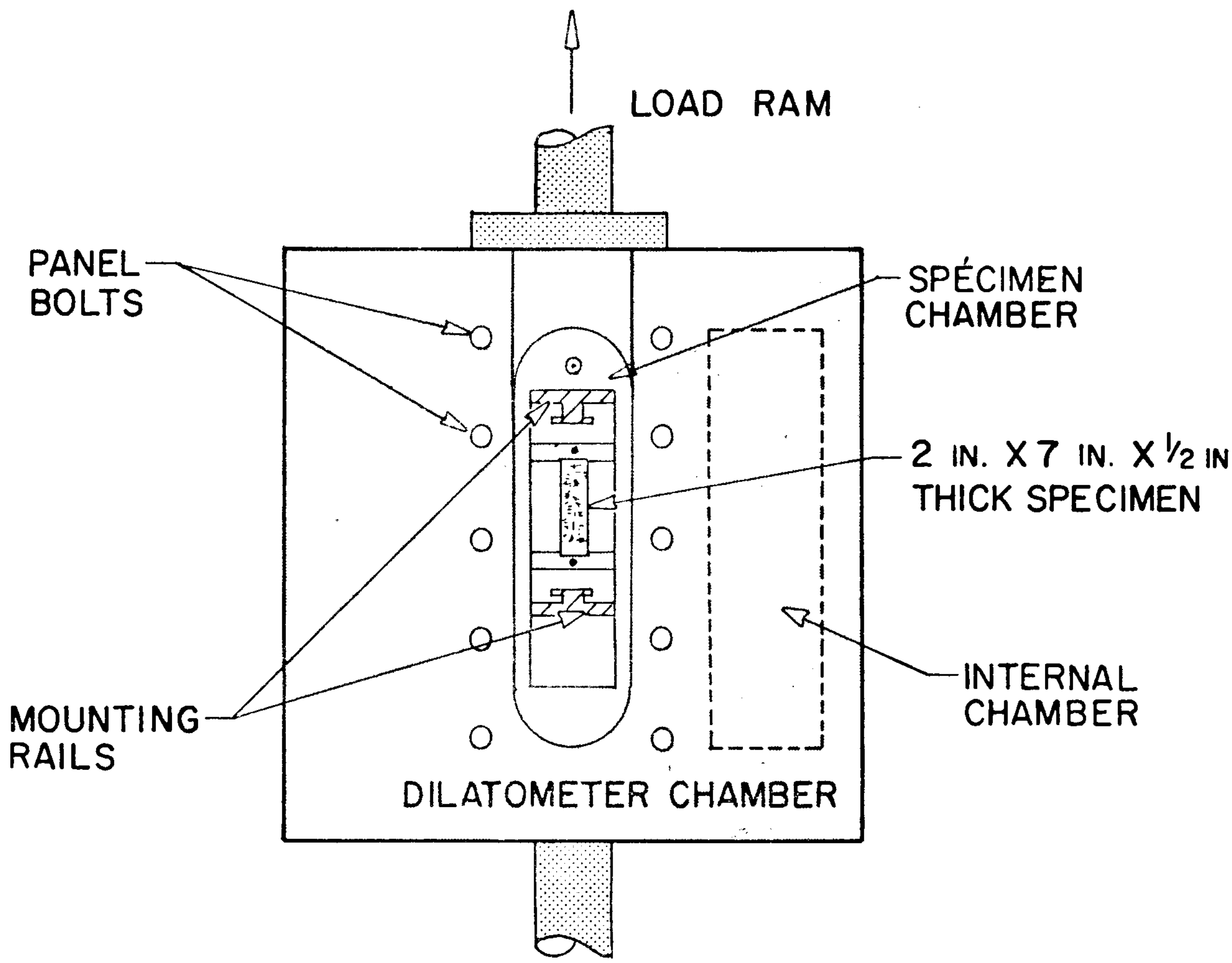

Fig. 12. Gas dilatometer.

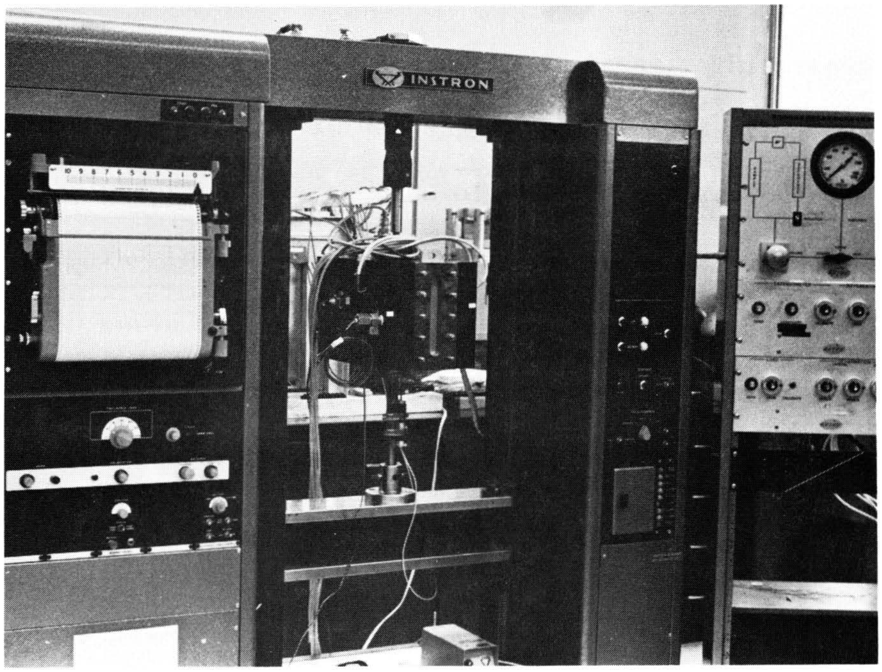

Fig. 13a. Test set-up for dilatation test.

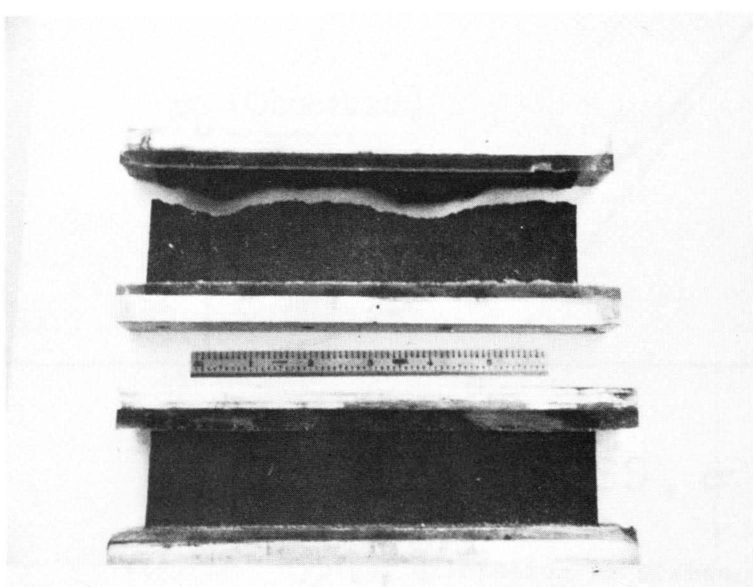

Fig. 13b. Dilatation samples before and after test.

a magnitude, σ_D beyond which the rate of volume change in the specimen begins to increase with the applied stress. This stress is called the damage stress, σ_D. It was suggested by Farris [18] that σ_D be established as the point of intersection of the approximate curve with the stress axes. The relative magnitude of the slope, K, of the approximated dilatation curve becomes a qualitative means of comparing the inherent rates of damage being accumulated by the specimen during deformation. This method was used to compare the relative cumulative damage potential of S-A-S and asphaltic concrete mixtures.

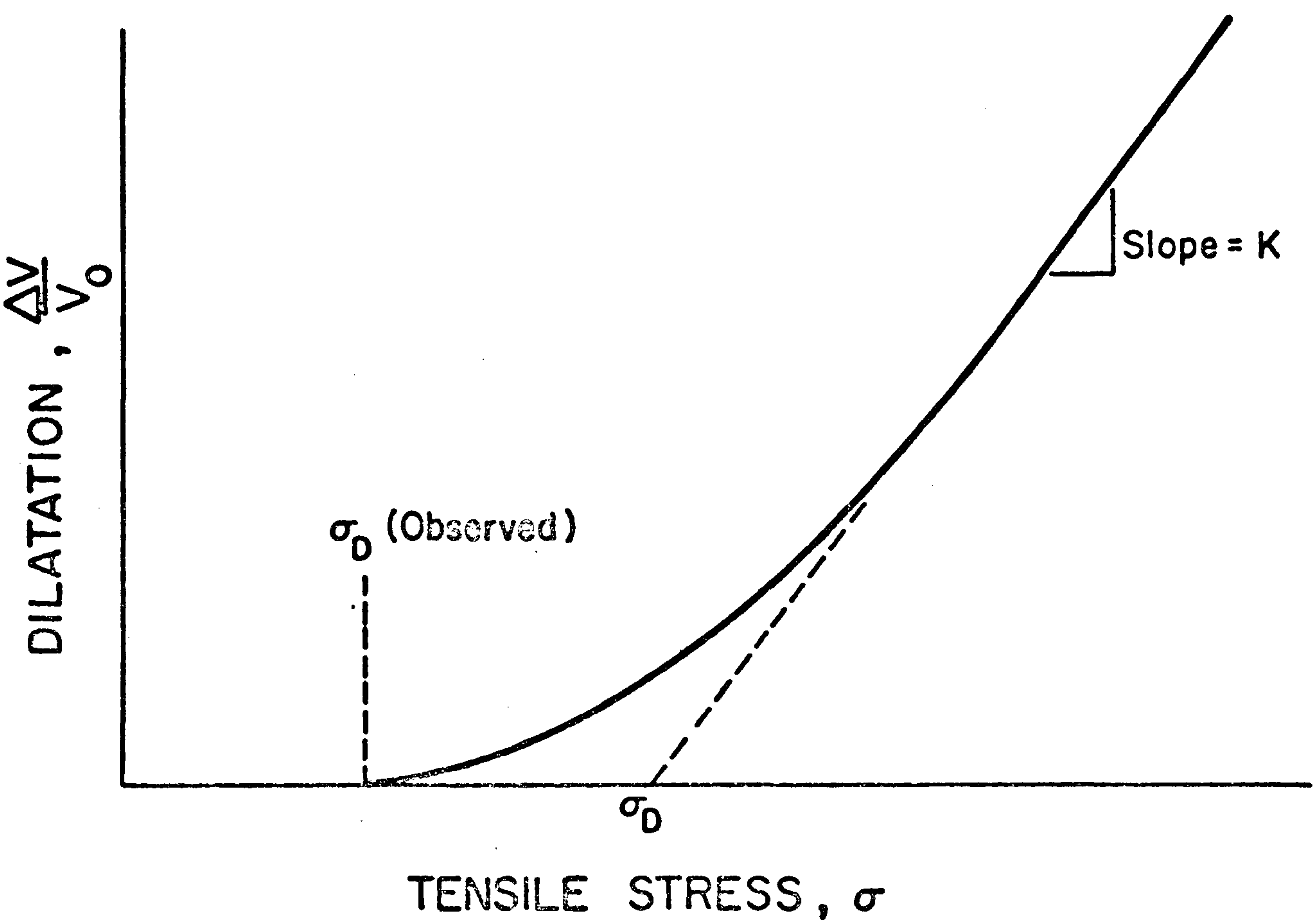

Fig. 14. Typical dilatation vs stress curve.

2.1.3.1 Discussion of REsults of Experimental Program

The results of the direct tension tests on S-A-S mixtures using Sand I and Sand II are given in Tables IV and V, respectively. For comparison, similar properties are shown in Table VI for the conventional asphaltic concrete prepared with the dense graded, crushed limestone aggregate. Rather than typical, this mixture would normally be considered a superior pavement material.

The data given in Tables IV and V indicate an increase in stiffness and failure stress with increasing sulphur content and decreasing asphalt content. On the other hand, failure strain was improved as sulphur content was lowered and asphalt content raised. The changes in stiffness reflect a rate dependence in S-A-S mixture which is more pronounced at the lower loading rates. This is shown more specifically in Figure 15 which illustrates the rate dependence and the stiffness of 13.5 weight percent sulphur mixes at various asphalt contents. Figure 16 shows a similar set of data for 6 weight percent asphalt mixes at various sulphur contents.

Consistent with the Phase 1-A studies, mixture stiffness increases with loading rate and sulphur content and decreases with aspahlt content. At low asphalt contents (i.e., less than 2 percent) and high sulphur contents the stiffness appears to approach a constant value. For higher asphalt and lower sulphur weight fractions the rate dependence becomes more pronounced. This viscoelastic behavior was attributed primarily to the presence of the asphalt in the mix.

TABLE IV - Uniaxial Tensile Properties of S-A-S Mixtures

Using Sand I.

Temper-ature °F	Deformation Rate, in./min.	Asphalt, percent	Sulphur, percent	Stiffness, psi	Failure Stress psi	Failure Stress in./in.
	0.02	6	13.5	$3.55X10^6$	320	0.025
20	0.20	6	13.5	$6.56X10^6$	334	0.014
	2.0	6	13.5	$5.64X10^6$	397	0.024
	0.02	6	13.5	190,000	38	0.153
	0.20	6	13.5	206,000	91	0.174
	2.0	6	13.5	460,000	179	0.240
	2.0	4	13.5	520,000	258	0.101
73	2.0	2	13.5	790,000	272	0.062
	2.0	4	16	1,025,000	207	0.080
	2.0	2	16	1,480,000	290	0.048
	2.0	4	20	1,455,000	233	0.062
	2.0	2	20	2,005,000	325	0.041
135	0.2	6	13.5	15,000	5.21	0.211
	2.0	6	13.5	43,000	17.50	0.190

TABLE V - Uniaxial Tensile Properties of S-A-S Mixture Using Sand II.

Temperature °F	Deformation Rate, in./min.	Asphalt, percent	Sulphur, percent	Stiffness, psi	Failure Stress, psi	Failure Strain in./in.
20	0.02	6	13.5	1.1 10^6	275	0.026
	0.20			2.73X10^6	283	0.018
	2.0			3.53X10^6	432	0.010
73	0.02	2	13.5	493,000	118	0.063
		4	13.5	125,000	30	0.116
		6	13.5	107,000	14	0.112
		6	16	200,000		0.16
		6	20	240,000	35	0.13
	0.20	4	13.5	260,000	83	0.100
		6	13.5	156,000	46	0.166
		6	16	310,000	61	0.117
		6	20	380,000	68	0.110
	2.00	2	13.5	624,000	258	0.055
		4	13.5	353,000	176	0.155
		6	13.5	327,000	123	0.205
		6	16	867,000	155	0.127
		6	20	1.08X10^6	182	0.103
135	0.20	6	13.5	6,000	1.24	0.059
	2.00	6	13.5	36,000	15.2	0.352

TABLE VI - Uniaxial Tensile Properties of Asphaltic Concrete Mixture.

Temperature °F	Deformation Rate, in./min.	Asphalt, percent	Sulphur, percent	Stiffness, psi	Failure Stress, psi	Failure Strain, in./in.
20	0.02	6.2	0	5.2 X 10^6	491	0.11
	0.20			5.3 X 10^6	412	0.015
	2.00			6.0 X 10^6	439	0.016
73	0.02	6.2	0	137,000	81	0.427
	0.20			255,000	148	0.53
	2.00			415,000	386	0.33
135	0.20	6.2	0	4,000	8.4	0.814
	2.00			14,000	14.0	0.958

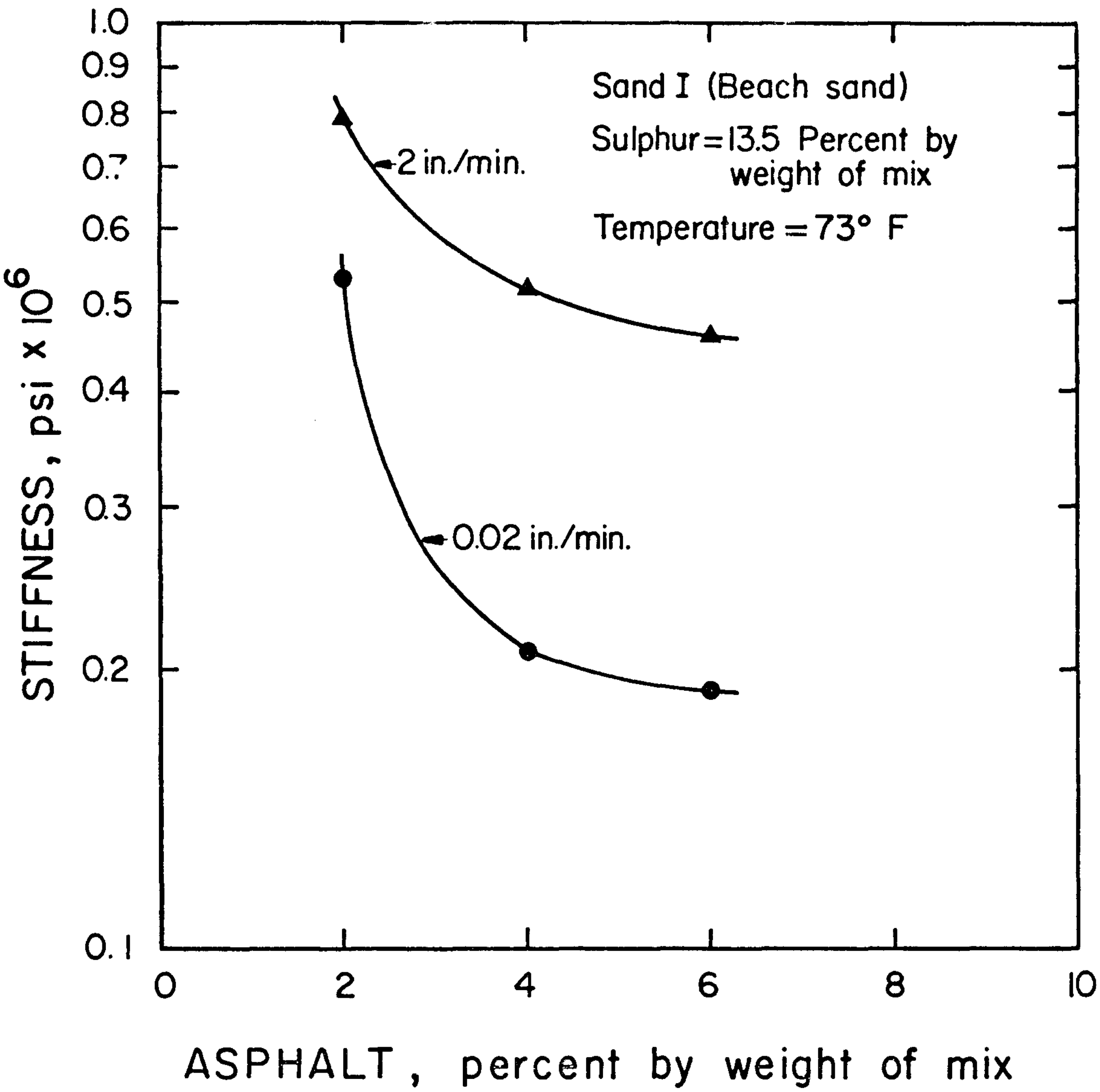

FIG. 15 - Effect of asphalt contents on the stiffness of sand-asphalt-sulphur mixes.

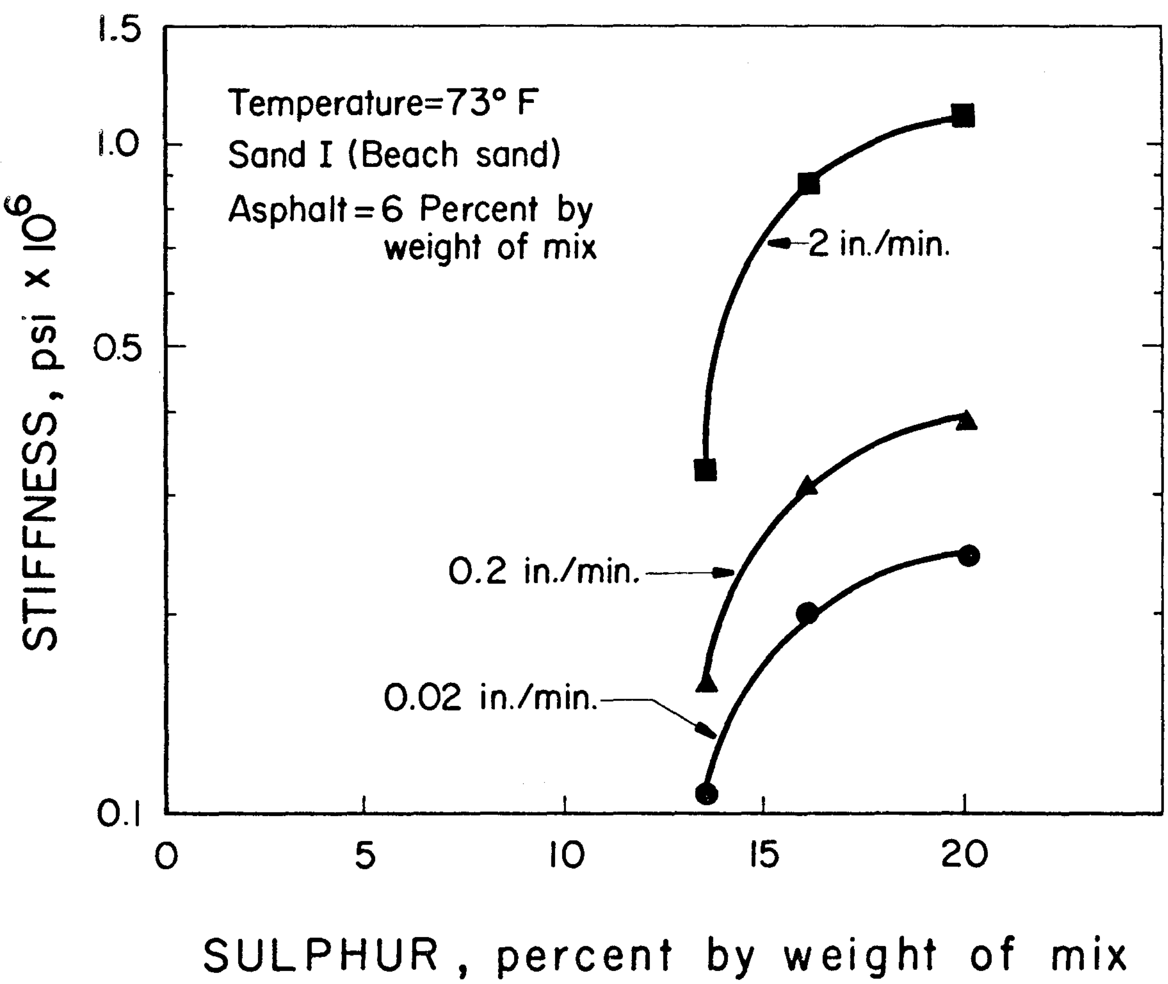

FIG. 16 - Effect of sulphur contents on the stiffness of sand-asphalt-sulphur mixes.

Figures 17 and 18 illustrate the influence of sulphur and asphalt contents, respectively, on failure properties. Failure stress is shown to increase with sulphur and decrease with asphalt content. In the case of failure strain, the increase is directly related to the amount of asphalt present and inversely related to the sulphur content.

A compariosn of the data in Sand I and Sand II in Tables IV and V shows the former to have the more desirable properties. This is contrary to that achieved in conventional flexible pavements using aggregates with a high degree of surface angularity. The improved properties of the poorly graded beach sand over the dense graded concrete sand was attributed to the sharp corners on the surface of the particles of Sand II, which tend to create stress concentrations in the crystalline sulphur subsequently reducing the deformation and load carrying capability of the final mixture. These results were also revealed in the stabilities and splitting tensile strengths as previously reported [5].

The effect of test temperature on a 80.5:6:13.5 S-A-S mixture using the two types of sands is shown in Figure 19 along with a compariosn with the asphaltic concrete used for comparison throughout this study. The stiffness of the mixture using Sand I was about 2.5 times that for asphaltic concrete at the high temperature and slightly lower at 20°F. Based on time (rate)-temperature correspondence considerations the data would indicate a greater degree of viscoelasticity in the asphaltic concrete over the temperature ranges tested and tends to support the premise that the viscoelastic behavior in S-A-S mixtures is primarily derived from the presence of the asphalt in the mix. As discussed above, the stiffness of the S-A-S mixtures prepared with Sand II were consistently lower

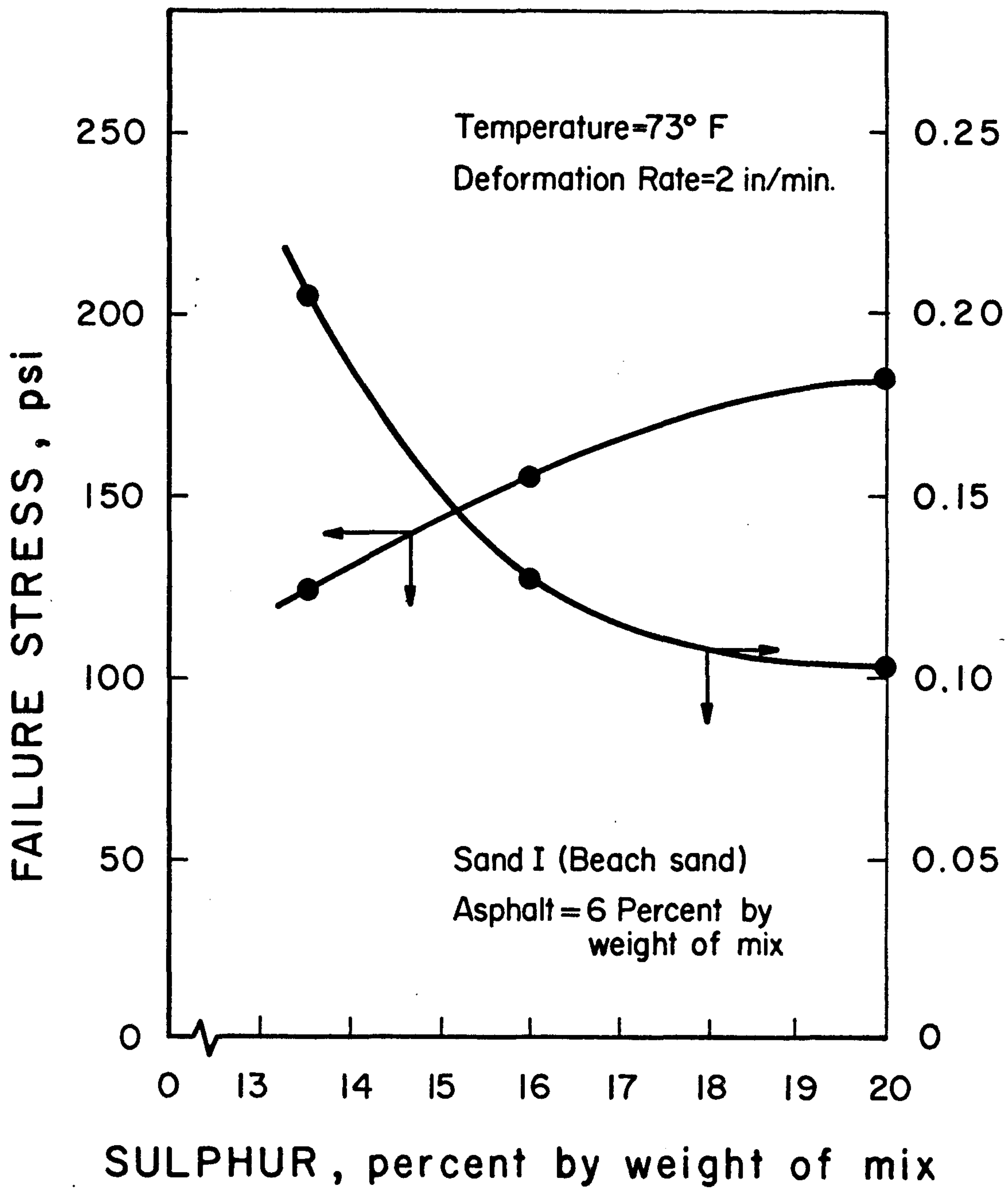

FIG. 17 - Effect of sulphur content on the stress and strain at failure of sand-asphalt-sulphur mixes.

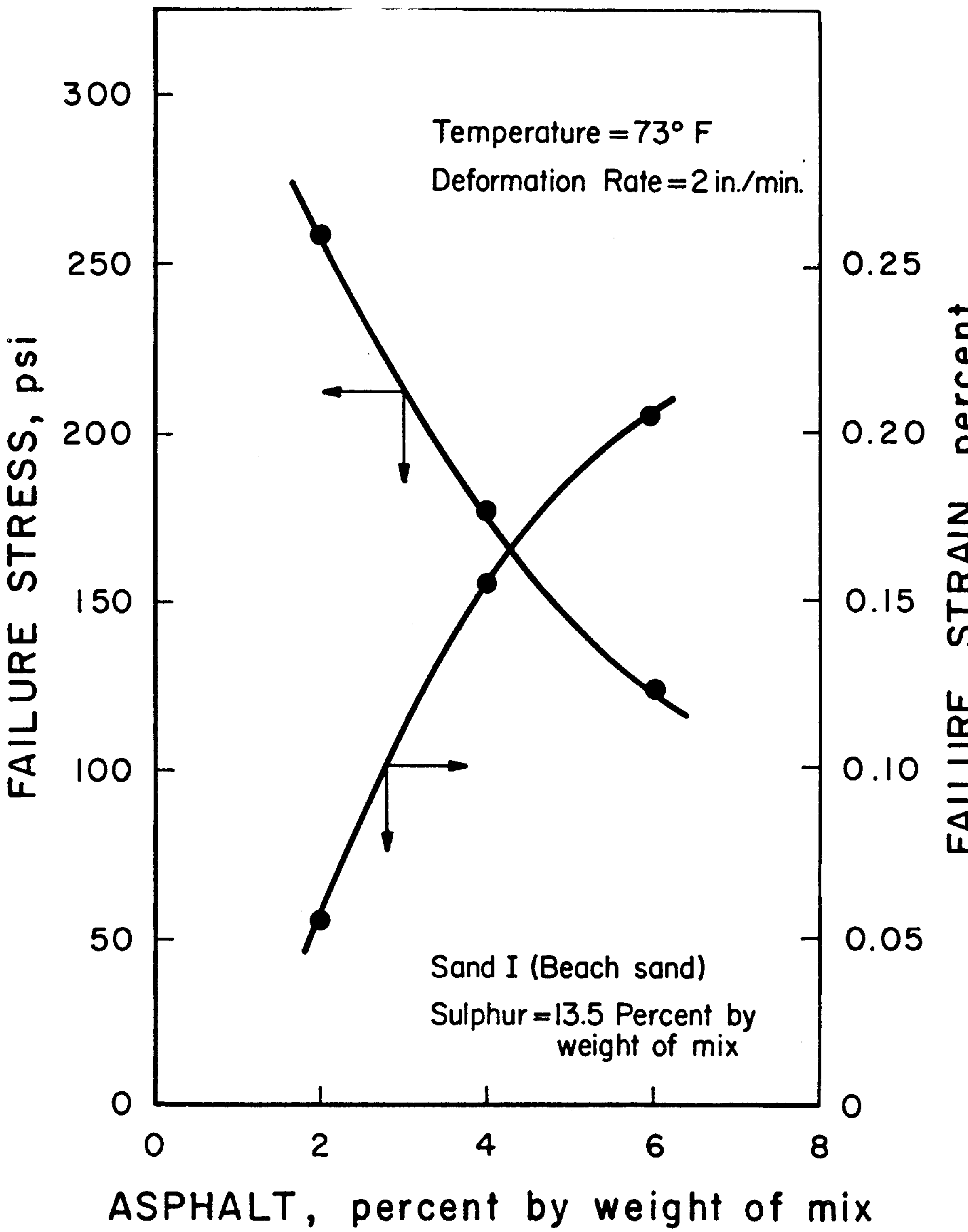

FIG. 18 - Effect of asphalt content on the stress and strain at failure of sand-asphalt-sulphur mixes.

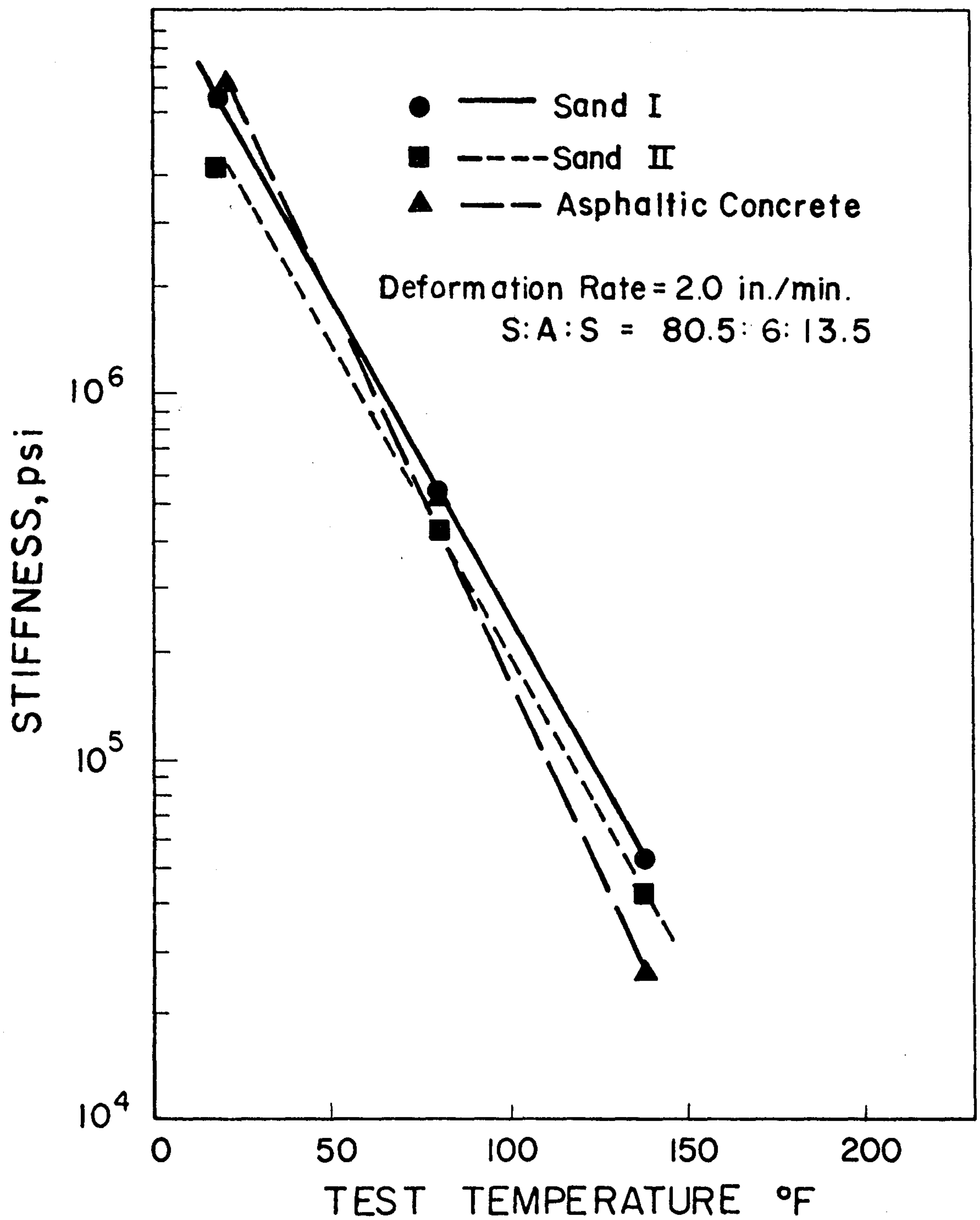

Fig. 19. Stiffness vs temperature for sulphur-asphalt and asphaltic concrete mistures.

than those prepared with Sand I.

The range of results obtained in these tests reveals how S-A-S mixtures can be tailored to produce a wide variety of properties. The data also indicate that decision criteria for optimizing a mixture design should be based on whether deformation or load carrying capability is the limiting structural factor. The stiffness values in Tables IV through VI were also used in the equivalent pavement thickness analysis and economic evaluation discussed later in this paper.

The fatigue behavior of S-A-S mixtures is being evaluated in both stress-amplitude and strain-amplitude loading modes. The stress-amplitude tests have been completed and the latter are still in progress and will be presented in the next progress report.

The results of the stress amplitude flexure fatigue tests run to date are shown in Figure 20. Published results of Kallas and Puzinauskas [12] and Irwin [10] for asphaltic concrete systems are also shown for purposes of comparison as they both utilized essentially the same type and frequency of loading.

Although the fatigue testing of S-A-S mixtures is still in progress, the data presented permits, at least, a cursory look into the relative fatigue behavior of sulphur-asphalt and asphaltic concrete mixtures. The 78:2:20 mixture represents the lowest asphalt and highest sulphur content and the 80.5:6:13.5 mixture represents the highest asphalt and lowest sulphur content in the mixtures to be tested. Also included are data on the 80.5:6:13.5 sample prepared using a Sand II and a similar sample which had been moisture conditioned for six weeks. Thus, the results, as presented, represent the extremes in both mixture design and conditioning.

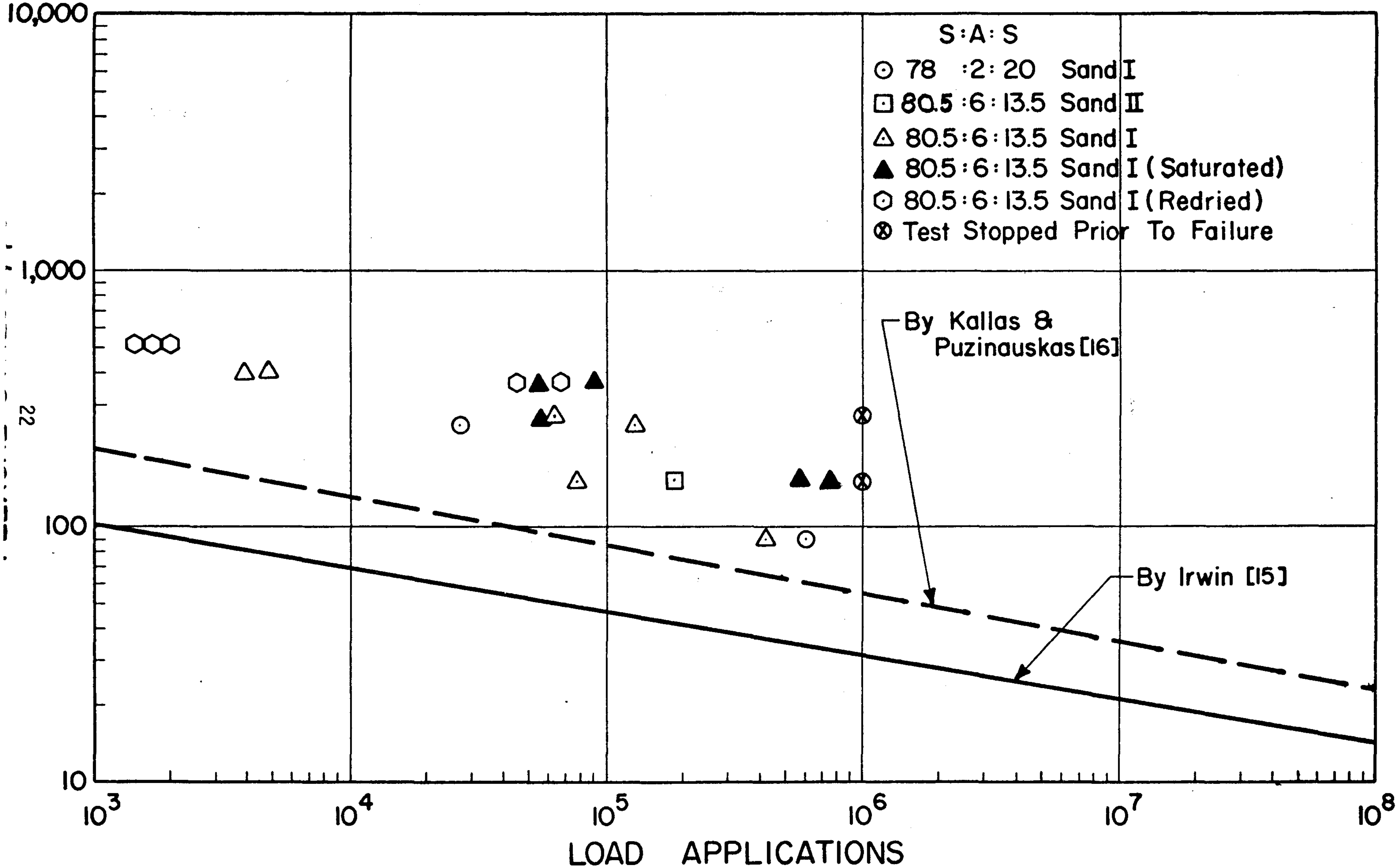

Fig. 20. Comparison of fatigue life of sulphur-asphalt and asphaltic concrete - three-point flexure at constant stress-amplitude.

The data in Figure 20 reflect the normal data scatter usually associated with fatigue testing. However, the results tend to indicate a superior fatigue behavior for all the S-A-S mixtures tested over those for the two asphaltic concrete system used for comparison. Two of the 20 percent sulphur samples which were subjected to a stress amplitude of 150 and 200 psi were stopped after 10^6 cycles at which time the samples had not yet failed.

The tests on the moisture conditioned samples were inconclusive. The saturated samples tested at 125 psi withstood approximately 7 X 10^5 additional cycles over that required to fail the dry specimens. No drastic change in fatigue behavior was achieved by redrying the samples. Upon examination, the failure surfaces of the moisture conditioned samples did not appear wet. This would indicate that the 6 weeks storage under water did not produce the fully saturated samples desired. On the other hand, this observation provides an indication of the impervious nature of the S-A-S mixtures expecially those with the higher sulphur contents.

The results of the resilient modulus tests are shown in Tables VII through IX. These data are consistent with direct and indirect tensile test results which indicate an increase in stiffness with sulphur content and reduction in temperature. Except for an apparent inconsistency at the 68°F test temperature, the mixtures using Sand I produce higher stiffnesses than those for Sand II. The range of moduli for the S-A-S mixtures extends from 240,000 to 1,929,000 psi and reemphasizes the ability to significantly tailor the mechanical properties of these mixtures by altering the sulphur and asphalt contents.

TABLE VII - Resilient Modulus vs Mixture Design and Test Temperature.

% Asphalt (by weight)	% Sulphur (by weight)	Resilient Modulus psi X 10^{-3}		
		40°F	68°F	90°F
0	10	1086	1102	1082
	13.5	1929	1649	1171
	20	----	4431	2061
2	10	----	610	571
	13.5	1321	854	594
	20	1704	1851	966
4	10	----	575	462
	13.5	1051	1194	449
	20	1403	1382	653
6	10	696	481	311
	13.5 (Sand I)	885	441	294
	13.5 (Sand II)	805	513	240
	20	864	542	413

TABLE VIII - Comparison of Resilient and Direct Tension Modului at Various Asphalt and Sulphur Contents.

Test Temperature: 70°F

% Asphalt	% Sulphur	Resilient Modulus (psi)	Direct Tension Modulus (psi) @ 20 in/min.
0	10.0	551,000	
	13.5	1,649,000	
	20.0	4,431,000	
2	10.0	610,000	
	13.5	854,000	790,000
	16.0	---	1,500,000
	20.0	1,851,000	2,000,000
4	10.0	575,000	---
	13.5	1,194,000	1,052,000
	16.0	---	1,025,000
	20.0	1,382,000	1,500,000
6	10.0	481,000	---
	13.5	441,000	460,000
	20.0	542,000	---
	13.5	513,000 (Sand II)	330,000
Asphaltic Concrete		385,000	415,000

TABLE IX - Resilient Modulus of Environmentally Conditioned Samples.

Sand-Asphalt-Sulphur Mixture Design	Temperature °F	Resilient Modulus psi X 10^{-3}		
		Dry	Saturated	Redried
80.5:6:13.5	40	885	716	811
	68	441	270	224
	90	240	136	223
78: 2:20	40	1704	976	1098
	68	1851	1333	1265
	90	1704	1047	1201

Table VIII shows a comparison of the stiffness measurements at 68°F obtained using the Schmidt device with those generated in the direct tension tests at a deformation rate of 20 in/min. Resilient and direct tension moduli for the asphaltic concrete mixtures were 385,000 and 415,000 psi, respectively and were slightly lower than any of those obtained for S-A-S mixtures using Sand I.

The results of tests on moisture conditioned samples are given in Table IX. All of the saturated samples showed a definite reduction in modulus for each test temperature. Some of this loss in stiffness was recovered upon redrying in some samples while others continued to exhibit additional degradation. No reason for this duality of behavior can be offered at this time.

A greater effect of moisture is indicated in these samples over that observed in the fatigue tests. One reason for this difference is that rather than submerging the samples in water the specimens used in these tests were vacuum saturated. Upon dissection these samples were found to be wet throughout their cross-section. Although both techniques are used to moisture condition samples the vacuum saturation technique will produce a degree of moisture penetration which is greater than actually experienced by a pavement in service.

A summary of the results of the static triaxial tests on a number of S-A-S mixtures is given in Table X along with some published data [16] on asphaltic concrete samples using three conventional aggregates. Both maximum deviator stress and modulus of deformation tend to increase with lateral pressure and sulphur content. These results are primarily

TABLE X - Static Triaxial Data

Test Temperature: 68°F.

Mix Type	Maximum Deviator Stress, psi			Modulus of Deformation, psi (in hundreds)		
	Lateral Pressure, psi			Lateral Pressure, psi		
	10	20	30	10	20	30
S:A:S (Sand I)						
80.5:6:13.5	287	405	Premature Failure	360	880	1100
80: 4:16	240	422	455	830	1720	2000
78: 2:20	486	480	650	2230	2530	2800
S:A:S (Sand II)						
80.5:6:13.5	153	213	230	350	430	520
Asphaltic Concrete [16]						
Gravel	109	147	184	116	184	260
Lightweight	300	352	415	278	305	349
Limestone	338	409	480	285	370	415

qualitative in nature in that they represent only one loading rate and thus are not totally representative of the wide variety of loading environments experienced in service.

Unlike the deviator stress results, the moduli generated were fairly reproducible. This was primarily due to the manner in which the specimens failed. After a certain deformation level some samples failed at a defective region in the sample which in most cases was out of the gage length. This premature failing lowered the maximum load achieved in the test. Since the modulus is computed for the low deformation portion of the deviator stress-strain curve, premature failures did not effect this parameter to the same extent.

A comparison of the moduli of S-A-S and asphaltic concrete show the former can be from two to seven times that of the latter. These results would indicate a superior behavior of S-A-S mixture over the three asphalt concrete systems. Sand I mixtures continue to reflect better resistence to static triaxial stress loadings than those prepared from Sand II. A final appraisal of the relative performance of these materials will avail the completion of the repetitive load tests.

2.1.4 Evolved Gas Analysis

Concurrent with the activity in Task I, an odors and emissions evaluation is being conducted. This evaluation is a continuation of the evolved gas analysis (EGA) data collected during Phase 1A. Using the Metronics "Rotorod" Gas Sampler, hydrogen sulfide gas concentrations are being monitored during the mixing cycles associated with the preparation of the S-A-S samples. Samplings were taken at the "average working distance" above the mix of 12-18 inches.

The results of the tests completed to date continue to confirm the conclusion of the earlier data. That is, the preparation of S-A-S samples in a well-ventilated laboratory will not normally produce harmful amounts of H_2S. The results taken to date show H_2S concentrations consistently lower than those measured during the initial tests of Phase 1A. Those initial tests showed an average H_2S concentration of 16.4 ppm (range 9-40 ppm). The current data generated in this phase show an average H_2S concentration of 3.5 ppm (range 0.38-13 ppm). This average value is much lower than the American Conference of Governmental Industrial Hygienists maximum allowable concentration (MAC) value of 20 ppm for toxicity and their suggested MAC of 10 ppm for eye irritation [20].

2.1.5 Theoretical Analysis

2.1.5.1 Equivalent Thickness Evaluations

A theoretical analysis using elastic layered systems was undertaken to make a comparative study of the thickness requirements for an 80.5:6: 13.5 sand-asphalt-sulphur and an asphaltic concrete pavement under identical loading and subgrade conditions.

The BISTRO elastic layer analysis computer program [21] and analysis [22] was used to compute the stresses and strains at various strategic locations in the pavement sections. These locations were directly under the wheel and at radial distances of 3 in. and 6 in. A typical pavement section with the loading conditions and the locations where the stresses and strains were computed (represented by dots) is shown in Figure 21. The critical conditions were located directly under the wheel and thus dictated the final thickness requirement.

In carrying out this analysis, the following assumptions were made:

1. The Poisson's ratio of the conventional asphaltic concrete is 0.35,
2. The Poisson's ratio of the sand-asphalt-sulphur mix is 0.30,
3. Shell design criteria [22] for asphaltic concrete and the sand-asphalt-sulphur paving material are identical.

Assumption 1 was made on the basis of the dynamic modulus values reported by Schmidt [14]. Assumption 2 was based on the fact that the sand-asphalt-sulphur mixes are slightly stiffer than the conventional asphaltic concrete. Generally, the more rigid the material the lower its Poisson's ratio. It was also observed in the direct tension test that the stiffness of the sand-asphalt-sulphur mixes increased with the reduction of asphalt contents as well as with the addition of sulphur. On the basis of this behavior, Poisson's ratios of sand-asphalt-sulphur mixes were assumed to be slightly lower than for asphaltic concrete. It should, however, be noted that the value of Poisson's ratio, although required as input data to the analysis, has a minimal effect of the stress and strain values computed by the elastic layered system [21].

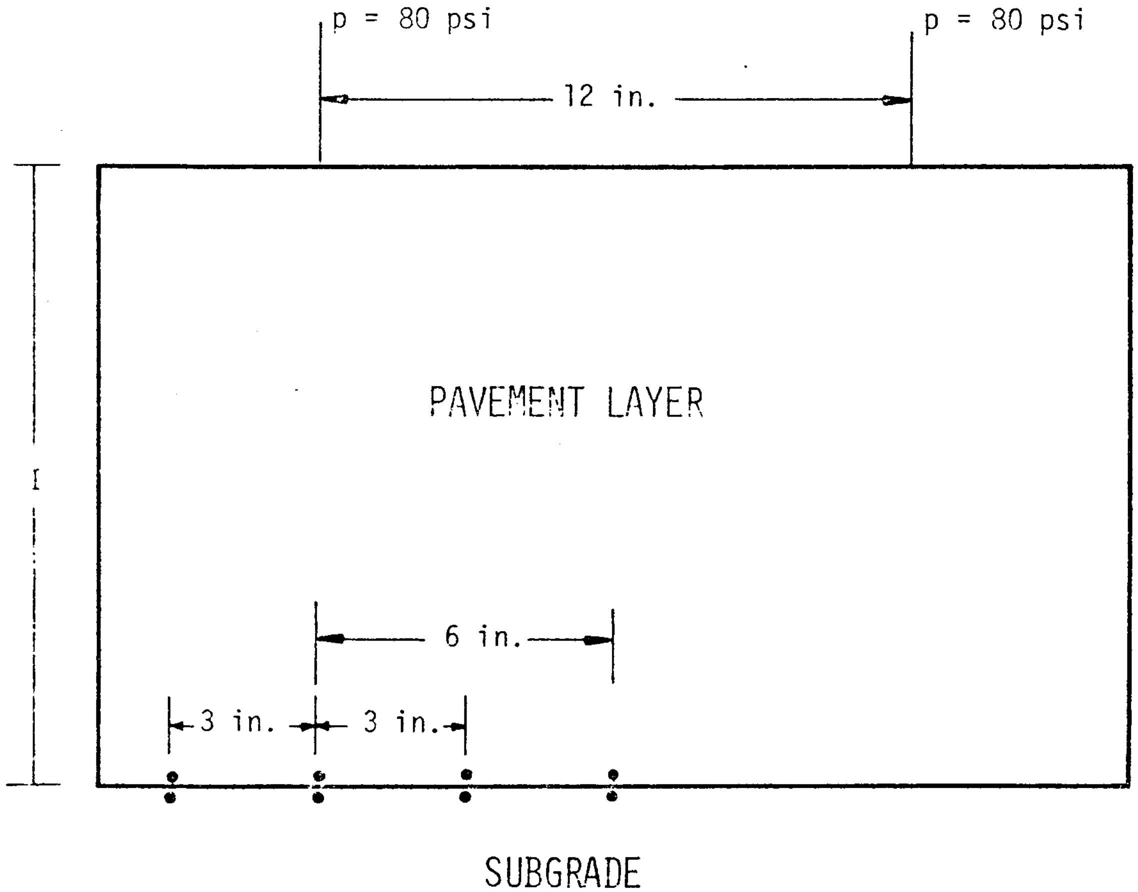

Fig. 21. Typical pavement section used in elastic layered analysis.

Assumption 3 was based on published data [1] for this mixture design. Since the initial results of the fatigue tests discussed earlier indicated a comparatively better fatigue life expectancy for S-A-S mixtures, this assumption could be considered to be conservative. The fatigue design criteria suggested by Shell [22] for designing asphaltic concrete pavements is shown in Figure 22 along with that for a 80.5:6:13.5 S-A-S mixture reported by Shell [1]. These curves relate the allowable subgrade compressive strain and the design tensile strain in the asphaltic concrete and S-A-S layers to their corresponding number of load applications to failure.

Accordingly, the allowable subgrade compression strain was set at 650 X 10^{-6} in./in. and the asphaltic concrete and S-A-S design tensile strains were set at 145 X 10^{-6} in./in. The stiffness for the asphaltic concrete as obtained by direct uniaxial tension tests at 73°F and a deformation rate of 2 in./min. was taken as 415,000 psi. This value also agrees with resilient moduli values reported by Schmidt [14]. Based on the M_R and direct tension stiffness values shown in Table VIII, a value 460,000 psi was used in this analysis for the S-A-S material. A modulus of 5,000 psi was assumed for the subgrade and was based on a California Bearing Ratio (CBR) of 3.25. A rough but reasonable correlation has been found to exist which estimate the stiffness to be equal to 1,500 times the CBR [22]. The elastic properties assumed in this analysis are shown in Table XI.

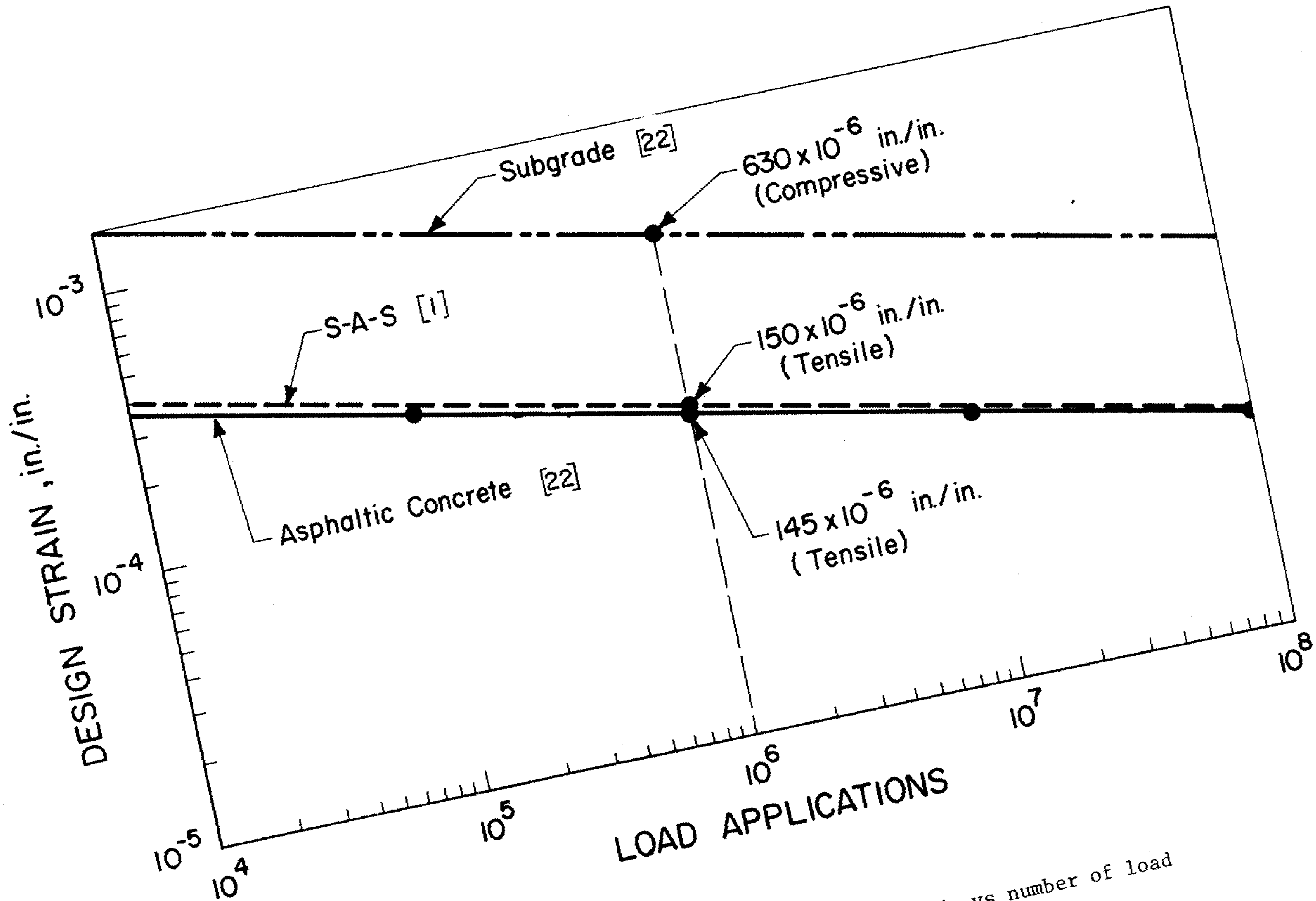

Fig. 22. Design strain of pavement and subgrade vs number of load applications.

TABLE XI - Elastic Properties of Materials Used in Elastic Layer Analysis.

Type of Material	Mix Ratio (% by weight) Sand:Asph:Sulph	Stiffness (psi)	Poisson's Ratio	Design* Strain (in/in) X 10^{-6}
Asphaltic Concrete	Ref [7]	415,000	0.35	+145
Sand:Asph:Sulph	80.5: 6 :13.5	460,000	0.30	+145
Subgrade	------	5,000	0.45	-650

* Plus (+) and minus (-) signs indicate tensile and compressive strains, respectively.

The specific S-A-S mixture chosen for this analysis was the only one for which sufficient design data were available at the time this report was being prepared. When this information is obtained in the other S-A-S mixtures, the thickness requirements for mixtures with higher sulphur contents will be evaluated.

Thickness requirements for each pavement section were established as that necessary to withstand the vehicle loading conditions itemized in Table XII.

TABLE XII - Vehicle Loading Conditions.

Tire pressure	80 psi
Radius of loaded area	4.2 in.
Center to center distance between two adjacent wheels	12 in.
Axle load	18,000 lb

Table XIII shows the pavement thickness requirements computed for the various mixes.

TABLE XIII - Equivalent Thickness Requirement to Withstand 10^6 Applications of an 18 KIP Axle Load.

Pavement Material Type	Required Pavement Thickness (in.)
Asphaltic Concrete	11
Sand-Asph.-Sulph. 80.5: 6 :13.5	10

It may be noted that the pavement thickness requirement for the high grade asphaltic concrete was 11 in., whereas by using the sand-asphalt-sulphur mix, the thickness requirement was reduced to 10 in. Thickness values computed using layered elastic theory are primarily influenced by the stiffness of the pavement which in the case of S-A-S mixtures can be tailored by changing the asphalt and sulphur contents (see Tables IV and V). Thus, utilization of mixture designs with higher stiffness may have a significant impact on further reducing pavement thickness and construction costs. The economic evaluation of these differences, along with other materials and construction costs will be discussed in the next section.

2.1.5.2 Economic Evaluation

The potential for using a sand-sulphur mixture as a paving material will depend not only on its engineering properties and required placement techniques but also on the availability, accessibility and cost of the ingredients. Therefore, the relative construction costs of pavements of sand-asphalt-sulphur mixtures as compared with conventional asphaltic concrete under similar conditions is an all important consideration. To emphasize the influence of materials transportation costs on these comparisons a hypothetical job site was sought for which beach sand and a 200 ton/hr. hot mix plant were nearby, but where crushed limestone had to be hauled a distance of 60 miles. This is in keeping with the original premise as reported in Reference 5 that S-A-S as a pavement material is primarily intended for use in those geographical areas in chich both sulphur and low cost aggregates were readily available to the user.

With the cooperation of the Texas Highway Department, construction contractors and material suppliers at different strategic locations across southeast Texas, the following variations of prices on different materials were established:

1. AC-10 asphalt: $30.00 to $102.00 per ton [23, 24].
2. Crushed limestone: $1.35 to $3.60 per ton [25, 26].
3. Sulphur: $20.00 per ton in liquid form [27]. $40.00 to $50.00 per ton in powdered form [28].
4. Beach sand: $0.36 per ton [29].

These prices were those prevailing in February, 1974, in the geographical area containing Corpus Christs, San Antonio, Bryan, Houston, Beaumont, and Port Arthur, Texas.

In the course of the survey, it was noted that midway between San Antonio and Corpus Christi (near the small towns of Jourdanton, Tilden, Fashing and Kenedy) liquid sulphur was locally available from the nearby oil and chemical industries. It was also found that the crushed limestone was available at San Antonio which was cheaper ($1.35 per ton, f.o.b. at the plant) than elsewhere. Beach sand was available nearby at the rate of $0.36 per ton delivered. Asphalt was available locally at Corpus Christi, San Antonio, Jourdanton and Kenedy at an average price of about $70.00 per ton (delivered to the job site).

On the basis of the above findings, a job site was selected midway between San Antonio and Corpus Christi which are directly connected by the U.S. Highway 281 and Interstate Highway 37. (The distance of each city from the center of the job site is about 60 miles.) This selection assured a significant cost for transporting crushed limestone from San Antonio to the job site while minimizing the cost of transporting sand. The average cost of loading and hauling the limestone a distance of 60 miles was found to be about $3.00 per ton [25, 29]. This selection had added significance to this program in that it was located near the area being considered for full scale field trials and evaluations under Phases IIA and IIB. These costs along with other assumptions [30] in this evaluation are summarized in Table XIV.

TABLE XIV - Assumptions Used in Economic Evaluation

PAVEMENT

Single Lane - One mile long, 12 feet wide - shoulder to shoulder
Location - Between San Antonio and Corpus Christi

MATERIALS COSTS PER TON*

AC-10 Asphalt	$70.00	
Crushed limestone	1.35	(plus $3.00/ton for hauling)
Sulphur (Liquid)	20.00	
Beach sand	.36	

CONSTRUCTION RATE

200 Tons/Hr.

*Delivered

In Texas, paving contractors are not required to report separately the cost of (1) ownership and operation of equipment or (2) the wages of the equipment operators and laborers. Consequently, the Texas Highway Department does not maintain such a separate cost list for these items. Therefore, for equipment and labor costs the figures quoted in the National Asphalt Pavement Association Report [31] prepared by Texas Engineering Experiment Station at Texas A&M University were used. These were the prices prevailing during 1972, and these figures were updated to February, 1974, prices using the average yearly cost index and multiplying factors for cost conversion, published periodically by the Engineering News-Record Magazine [32, 33]. The indexes and the multiplying factors are summarized in Table XV for the relevant periods.

TABLE XV - Cost Indexes and Multiplying Factors for Updating Old Costs (Engineering News-Record 20-Cities Cost Indexes, 1913 = 100) [34].

Year	Construction Cost Index	Multiplying Factor	Skilled Labor Index	Multiplying Factor
1972 (Average)	1752.23	1.11	1646	1.08
1974 (February)	1939.74		1782	

In this cost comparison, a single lane pavement section (12 ft wide from the inner edges of the shoulder to shoulder) and 1 mile long was selected. The estimated construction costs for each type of material along with the corresponding equipment and labor cost are presented in Tables XVI and XVII. A detailed step by step calculation of these estimated costs is presented in Appendix A.

The higher stiffness of the sand=asphalt-sulphur mixture was primarily responsible for the smaller thickness requirement over that of the conventional asphaltic concrete pavement as a result of which the total volume of sand-asphalt-sulphur materials required was reduced. The lower unit weight of sand-asphalt-sulphur caused a further reduction in materials requirements in terms of tonnage compared to that for the conventional asphaltic concrete. This, in turn, reduced the total working hours, vis-a-vis, the equipment and labor cost. The absence of the requirement for compaction and the associated labor cost also caused a reduction in the estimated construction cost of the sand-asphalt-sulphur pavement. The cheaper price and availability of beach sand compared to crushed limestone

TABLE XVI

SUMMARY OF THE ESTIMATED COSTS OF MATERIALS, LABOR AND EQUIPMENT FOR SELECTED PAVEMENT MIXTURES

Material Type	Estimated Costs, Dollars						
	Crushed Limestone	Sand	AC-10 Asphalt	Liquid Sulphur	Equipment	Labor	Totals
Asphaltic-Concrete	18,040	--	18,270	--	7,420	1,740	45,470
S A S 80.5:6:13.5	--	980	14,140	8,170	5,070	1,020	29,380

TABLE XVII SUMMARY OF THE ESTIMATED COSTS OF THE TWO PAVEMENT MIXTURES.

Pavement Material Type	Stiffness, E, psi	Estimated Cost, Dollars		Percentage of Total Cost of the Conventional Asphaltic Concrete
		Total Cost**	Cost per Sq. Yd.*	
Conventional Asphaltic Concrete	415,000	$54,020	$7.67	100
Sand:Asph.:Sulp. 80.5: 6 :13.5	500,000	$34,901	$4.96	65

*Note: Total surface area of the selected pavement section = $1760 \times \frac{12}{3} = 7040 \text{ yd.}^2$

**Note: These costs correspond to the totals in Table 12 with overhead and profit included.

also had a significant effect and appears to offset the cost of sulphur needed for these materials. This can be reflected in Table XVI which shows the cost of crushed limestone to be double the combined cost of sand and sulphur in the S-A-S system.

From the above discussion it may be concluded that the estimated total construction cost of sand=asphalt-sulphur pavements can be expected to decrease as the stiffness of the mixture is increased, either by the addition of more sulphur or by reducing the asphalt content. It may also be concluded that the economics of pavement construction using sand-asphalt-sulphur mixtures depends to a large extent upon the relative difference in cost between sand and conventional aggregates, and upon the current price and availability of sulphur.

3.0 Conclusion

A series of laboratory tests, an equivalent pavement thickness analysis and an economic evaluation of the costs associated with sand-asphalt-sulphur pavement construction are presented. The testing program was designed to qualitatively evaluate the structural adequacy of S-A-S mixture designs prepared with inexpensive, poorly graded aggregates relative to that achieved in high quality asphaltic concrete mixes. Engineering properties reflect high stiffness and excellent resistance to fatigue. Tensile strain capability appears to be significantly lower than that achieved in asphalt concrete mixtures as reflected in both direct tension and dilatation tests. Results of this latter test indicate that dilatation behavior is an attractive means of assessing the manner and rate at which damage and failure is incurred in particulate-filled paving materials.

Elastic layered design analysis, using data from the laboratory tests, indicated that, compared with asphaltic concrete, thinner pavements were permitted with S-A-S mixtures having sulphur contents exceeding 13.5 percent by weight. Thicknesses approximately 80 percent of that required for asphaltic concrete under similar loading conditions were computed with mixtures prepared with 13.5 percent sulphur.

Recent price hikes on asphalt which have trebled over the past year have shifted the relative cost of highway construction more in favor of sulphur-asphalt pavements. The final consideration is still dependent to a large extent on availability of sulphur and cheap aggregates. All conditions considered, the potential for using sulphur-asphalt mixture in highway pavement construction remains high.

4.0 Future Effort

A modification to Phase 1 (heretofore to be designated Phase 1-C) was authorized on 1 July 1974 to continue for a period of one year. This added effort is comprised of the following four tasks:

TASK A

This task is designed to provide clear concise information on H_2S emissions which might be encountered during construction, and to satisfy questions of workman, or their representatives, as well as inquiries from the various clean air control boards, with respect to safety and pollution. To this end, a field evaluation of the H_2S emissions at a hot-mix plant and during hauling and placing will be conducted.

TASK B

This task is oriented to the development of an analytical capability for the design of the various sulphur-asphalt pavement thicknesses to be used in Phase II, consistent with the conditions of the construction site. These designs will be developed in cooperation with the Bureau of Mines, The Sulphur Institute, and the sponsoring State and Federal Highway Departments. Statistical treatments will be performed to provide a suitable factorial for the evaluation of sulphur-asphalt sections relative to the performance of conventional asphaltic concrete systems. Data now being generated in Phase I-B will provide material properties and failure criteria for these analyses.

TASK C

This task provides for the generation of suitable instruction aids for the training of field personnel in the preparation and construction of sulphur-asphalt pavement. Included will be visual aids, handouts, and laboratory-scale demonstrations of the various phases of laying a sulphur-asphalt pavement. Aside from their immediate use in conjunction with Phase II, these instructional aids can also be used in short courses and work shops, as well as on other sulphur-asphalt construction projects.

TASK D

A preliminary investigation will be directed toward the materials characterization of dense graded hot mix, wherein a portion of the asphalt is replaced with an equal volume of sulphur. The objective of this effort would be the further utilization of sulphur and, possible more important, the conservation of our diminishing supplies of asphalt.

The researchers propose to investigate both crushed and naturally rounded aggregates. Moisture properties such as ratio of asphalt to sulphur, stability, voids, water susceptibility, and fatigue resistance, will be studied. Limited special testing will be carried out as dictated from responses of the standard tests performed.

Two activities originally purposed under Phase I-B will be continued into the next reporting period. These efforts include the strain-amplitude fatigue tests and the repeated load triaxial tests. A number of mechanical problems and the lengthy times associated with these tests made it virtually impossible to complete this work in the time provided. These tests will be accomplished at no added cost to the program.

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A P P E N D I X   A

ECONOMIC EVALUATION CALCULATIONS

APPENDIX A

Estimate for a Conventional Asphaltic Concrete Pavement

Width of the pavement = 12 ft.

Thickness of the pavement = 11 in.

Length of the pavement = 1 mile.

Equipment

Let it be assumed that the contractor has a paver with a rated capacity of 200 tph, one mixing plant with a rated capacity of 200 tph, two pneumatic and one breakdown rollers, necessary numbers of trucks and all needed small tools and miscellaneous equipment.

Materials

Crushed limestone (f.o.b. at the plant)	=	\$1.35 per ton
Loading and hauling to the job site	=	3.00 per ton
SUB TOTAL		\$4.35 per ton
AC-10 asphalt (f.o.b. at the job site)	=	\$70.00 per ton
Volume of mix required = $(\frac{11}{12})(12)(5280)$	=	58,080 cft
Unit weight	=	145 pcf
Total weight of the mix = (145)(58,080)lb	=	4,211 tons
Weight of crushed limestone (93.8%) = (0.938)(4,211)	=	3,950 tons
Include 5 percent waste in screening = (1.05)(3,950)	=	4,147 tons
Weight of asphalt cement (6.2%) = (0.062)(4,211)	=	261 tons
Cost of aggregate = (4.35)(4,147)	=	\$ 18,040.00
Cost of asphalt = (70)(261)	=	18,270.00
TOTAL MATERIALS COST	=	\$ 36,310.00

Labor

The number of working hours on this job will depend upon the capacity of the paver, which is 200 tph.

$$\text{Working hours} = \frac{4{,}147 + 261}{200} = 22.04 \text{ h}$$

Crews	Wage per hour 1972	Wage per hour February 1974
1 paver foreman	$ 8.00	$ 8.64
1 paver operator	6.50	7.02
Truck drivers	17.50	18.90
1 broom operator	5.00	5.40
3 roller operators	16.50	17.82
1 mixing plant operator	8.00	8.64
1 mixing plant laborer	5.00	5.40
1 front loader operator	6.50	7.02
SUB TOTAL	$73.00	$78.84

"The labor wage includes overtime, social security and workman's compensation" [30].

Equipment

Mixing plant	Cost per hour 1972	Cost per hour February 1974
Owning cost	$129.47	$143.72
Other equipment	29.07	32.27
Energy	49.98	55.48
Move-in	5.00	5.55

Paver	Cost per hour 1972	February 1974
1 paver	$ 22.21	$ 24.65
3 rollers	33.64	37.34
1 asphalt distributor	8.95	9.93
1 lube truck	7.83	8.69
Pick-ups	7.48	8.30
1 broom	6.88	7.64
Windrow equipment	2.72	3.02
SUB TOTAL	$303.23	$336.59

Total material cost for the job =	$ 36,310.00
Total labor cost for the job = (22.04)(78.84) =	1,740.00
Total equipment cost for the job = (22.04)(336.59) =	7,420.00
SUB TOTAL	$ 45,470.00
Overhead: Assume 8 percent of materials, labor and equipment cost [33] =	3,640.00
SUB TOTAL	$ 49,110.00
Profit: Assume 10 percent of all other costs [34]	4,910.00
Total estimated cost of the job =	$ 54,020.00

Estimate for an 80.5:6:13.5 Weight Percent Sand-Asphalt-Sulphur Pavement

The conventional asphaltic concrete mixing plant needs to be modified to accommodate the sulphur mixing cycle in preparing the sand-asphalt-sulphur mixtures. The conventional paver machine also requires some modification since the sand-asphalt-sulphur mixtures are to be laid in the manner of a concrete rather than an asphalt paving [1]. According to Shell Canada estimate, the top cost for such modification of the hot-mix plant and that for the paver would be about $3,000.00 and $5,000.00 (1972 prices), respectively [34]. In estimating the total construction cost for sand-asphalt-sulphur pavements, these modification costs are to be added with the owning and operating cost of equipment. These costs were computed by following the procedure used by Texas Engineering Experiment Station [30] and amounted to about $2.38 per h, when updated to February 1974 prices.

The owning and operating cost of rollers and the associated labor cost were not included in estimating the construction cost of sand-asphalt-sulphur pavement, for these materials do not need conventional type of rolling for consolidation. The vibratory screed attached to the paver as a result of modification of the paving machine would provide the necessary compaction to these materials. The estimated cost of labor and equipment for sand-asphalt-sulphur was computed as follows:

<u>Labor</u>	<u>Cost per h</u>
Conventional type cost =	$78.84
Subtract 3-roller operators cost =	-17.82
Total labor cost =	$61.02
<u>Equipment</u>	
Conventional type cost =	$336.59
Subtract 3-rollers cost =	-37.34
	$299.25

	$299.25
Add modification cost =	2.38
Total equipment cost =	$301.63

Sand:Asphalt:Sulphur — Thickness = 10 in.

80.5: 6 :13.5 — Unit weight = 127.3 pcf

Materials		Price per ton
Sand I (f.o.b. at the plant)		\$ 0.36
	SUB TOTAL	\$ 0.36
AC-10 asphalt (f.o.b. at the job site)		\$70.00
Liquid sulphur		\$17.00
Loading and hauling		1.00
	SUB TOTAL	\$18.00

Volume of mix required = $(\frac{10}{12})(12)(5280)$ =	52,800 cft
Total weight of the mix = $\frac{(127.3)(52,800)}{2000}$ =	3,361 tons
Weight of sand (80.5 percent) =	2,705 tons
Weight of asphalt (6 percent) =	202 tons
Weight of sulphur (13.5 percent) =	454 tons

Cost of sand = (2705)(0.36) =	\$ 980.00
Cost of asphalt = (202)(70.00) =	14,140.00
Cost of sulphur = (454)(18.00) =	8,170.00
Total materials cost =	\$ 23,290.00

Total working hours = $\frac{3361}{200}$ = 16.8 h

Total materials cost =		$ 23,290.00
Total equipment cost = (16.8)(301.63) =		5,070.00
Total labor cost = (16.8)(61.02) =		1,020.00
	SUB TOTAL	$ 29,380.00
Overhead (8 percent) =		2,350.00
	SUB TOTAL	$ 31,728.00
Profit (10 percent) =		3,173.00
	TOTAL ESTIMATED COST OF THE JOB =	$ 34,901.00