A Sulphlex Mixture Design Method Based on the Indirect Tensile Test

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A method of designing Sulphlex mixtures was developed based on the indirect tension test. The design procedure allows prediction of paving mix performance from the ultimate tensile properties. These properties were found to be sensitive to binder content variation. The toughness of Sulphlex and asphalt concrete mixes was shown to reach a well-defined peak, which corresponds very closely to the optimum binder content. The variation of toughness with changes in aggregate angularity, temperature, and rate of loading was examined. A more detailed analysis of mixture performance was based on the failure envelope. The concept of a window on the failure stress-strain plot formed by boundary curves representing types of pavement distress was developed. Boundary curves were established for the permanent deformation and thermal cracking modes of failure. A method of estimating the fatigue life of a paving mixture was based on the relationship between resilient modulus and temperature using the conventional approach of analyzing fatigue data. The procedure for optimizing a mixture design was outlined, and an example is included.

Sulphlex, a form of plasticized sulfur, is a promising substitute for asphalt cement as a flexible pavement binder. Although the Sulphlex binder is chemically and physically quite different from asphalt cement, a Sulphlex paving mixture behaves much like asphalt concrete, and some methods of analyzing asphalt concrete behavior may be extended for use with Sulphlex. To properly study Sulphlex as a paving material, a method of mixture design must be developed.

Mixture design establishes the proportion of binder to aggregate that produces a paving mix that will serve the longest time without serious pavement distress. Mixture design is often a compromise between high stiffness, which insures strength and resistance to permanent deformation, and flexibility, which aids fatigue and fracture resistance.

The two most common methods for designing an asphalt concrete mix are the Marshall and Hvemm methods. Both of these methods are based on simple tests that have complex states of stress. The results of these tests have been correlated with many years of field experience with asphalt concrete pavements to establish material design parameters. The criteria developed for asphalt concrete mixture design cannot be extended for use with Sulphlex without substantive field experience. Marshall tests performed on Sulphlex samples yield much higher stability and flow than those for conventional asphalt concrete. This substantial difference in Marshall properties casts doubt on the rationale of simply extending these criteria to Sulphlex.

The Hveem test procedure is insensitive to variations in binder properties and mainly reflects the internal friction of the aggregate. Therefore, a new method of mixture design based on material properties was proposed for Sulphlex.

The indirect tension test was chosen to provide data for Sulphlex mixture design. The indirect tensile test is quick and easy to perform and yields two material properties: the tensile strength and the tensile strain at failure. A cylindrical sample, such as a Marshall sample, is loaded with a compressive load along the vertical diametral plane. A relatively uniform tensile stress is generated along the vertical diametral plane, and failure occurs in tension.

Although Sulphlex performance cannot be judged confidently based on criteria established for asphalt concrete, laboratory mixing and sample fabrication

procedures are identical to those for hot asphalt concrete mixtures. A factorial study of the effects of mixing temperature, compaction effort, compaction method, compaction temperature, and binder type (for asphalt concrete versus several versions of Sulphlex) proved that conventional mixing and compaction procedures are acceptable for Sulphlex.

Sulphlex

The Sulphlex formulation used in this research was developed by the Southwest Research Institute under contract to the FHWA. There are many formulations of Sulphlex. The formulation studied in this research was selected because its properties are most like AC-10 ([1]). The formulation consists of 70 percent sulfur and 30 percent plasticizers. The plasticizers consisted of three olefins: dicyclopentadiene, dipentene, and vinyl toluene.

Both the relative proportions of the components and the reaction time and temperature of mixing the olefins with the molten sulfur affect the physical and chemical properties of Sulphlex. For this test two different binders were produced by using identical formulas of sulfur and olefins but processing one at 150°C (302°F) and the other at 170°C (338°F), both were processed for 6.5 hr. The Sulphlex produced at 150°C will be referred to as S-1, and the Sulphlex produced at 170°C will be referred to as S-2.

Toughness

One method of analyzing the indirect tension test results is by applying the toughness concept. Toughness is the amount of force required to cause a unit volume of a sample to fail. The force is measured in psi in./in. and is the area under the tensile stress strain curve.

As the binder content for a given aggregate is varied, the toughness reaches a peak value as shown in Figure 1. The binder content producing this maximum toughness was found to be very close to the optimum binder content determined by further analysis. Toughness has proven to be a very good first estimate of the optimum (or design) binder content. Although the peak toughness occurs at the same binder content regardless of the temperature or loading rate used in testing, the peak is more well defined at conditions of about 77°F and 2.0 in./min stroke rate.

Figure 1. Toughness curves for Sulphlex S-2 mixes (tests were performed at a stroke rate of 2.0 in./min and 77°F).
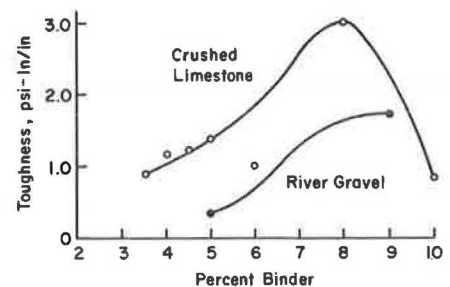
Figure 1 also shows that differences in aggregate angularity and composition affect toughness. It was found that an increased stroke rate generally increased the value of toughness. Toughness reaches a peak value as the temperature is increased, as shown in Figure 2. Sulphlex and asphalt mixes reach a peak toughness at temperatures between 50° and 80°F. However, the toughness at low and high temperatures (lower than 32°F or higher than 100°F) is a much better indicator of pavement performance, as these are the temperatures at which an actual pavement is much more susceptible to pavement distress.

The Failure Envelope

The indirect tension test results may also be analyzed by using the failure envelope. Smith (2) presented the failure envelope, shown in Figure 3, to describe the behavior of an ideal elastomer. If stress strain curves are obtained at different combinations of temperature and strain rate, the failure points are connected to form a failure envelope. As the temperature is decreased or the strain rate is increased, the failure point moves counterclockwise around the envelope.

Point A on the failure envelope in Figure 3 represents elastic behavior. Moving towards point B, the viscous components become more dominant and the total strain to failure increases. From B to C the rate of bond rupture, or the damage factor, increases faster than the strain rate, and the strain to failure decreases. Smith states that this behavior must occur if a material is linearly viscoelastic and that the failure envelope is independent of the type of test employed. Thus the failure envelope is a basic way to characterize the ultimate tensile properties of a paving material.

Both Sulphlex and asphalt concrete have been shown to be approximately linear viscoelastic materials. Indirect tensile results from this study were used to create failure envelopes for Sulphlex S-1, Sulphlex S-2, and AC-10 mixtures. Figure 4 shows an example of a failure envelope for a Sulphlex S-1 crushed limestone mix containing 8 percent binder. It was found that for all mixtures tested, an increase in the binder content shifted the failure envelope upward and to the right. An example of this behavior is shown in Figure 5. Similarly, a change in the aggregate will cause the failure envelope to shift, as in Figure 6.

The position of the failure envelope on the stress-strain plot (Figure 7) is an indication of the type of material tested. A failure envelope positioned to the left of the stress-strain plot represents a material which may fail at low strains. This type of material would be susceptible to fatigue or thermal cracking. A failure envelope to the far right of the stress-strain plot would indicate a low stiffness material which exhibits a large failure strain. Such a mixture would be susceptible to excessive permanent deformation or rutting.

A set of boundary curves can be superimposed on this stress-strain plot to indicate areas in which the material might be too brittle or too ductile. The curves form a window, shown in Figure 7, into which the failure envelope of a satisfactory paving mix will fall. Such boundary curves were developed

Figure 2. Effect of temperature on toughness of crushed limestone mixes (Sulphlex mixes contain 8 percent binder, AC-10 mix contains 5 percent binder, and a stroke rate of 2.0 in./min was used).
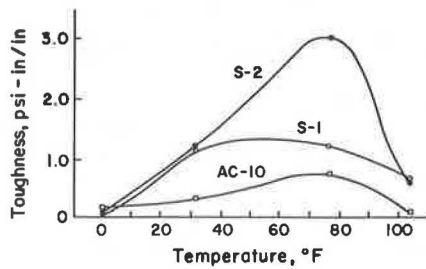

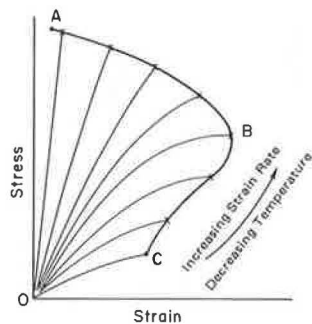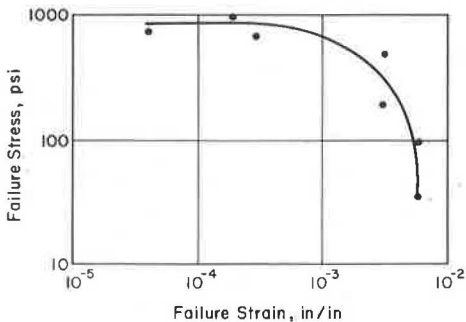Figure 3. Smith's characterization of elastomer ultimate tensile properties (2).

Figure 5. Shift of failure envelope with a change in binder content for a Sulphlex S-1 crushed limestone mix.

Figure 4. Failure envelope for a Sulphlex S-1 crushed limestone mix containing 8 percent binder by weight of aggregate.
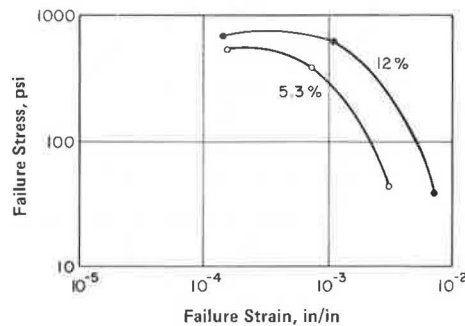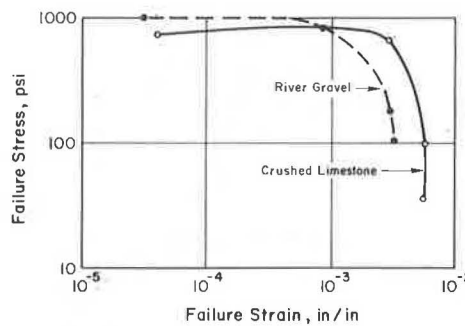

Figure 6. Shift in the failure envelope with a change in the aggregate for Sulphlex S-1 (8 percent binder content).

for Sulphlex binders based on the thermal cracking and permanent deformation modes of distress.

The boundary curve for thermal cracking was based on the calculated thermally induced tensile stress for a pavement. It was noted that at cold temperatures the failure strain is independent of the binder content. The failure strain is used as the basis for predicting thermal cracking. The boundary curve shown in Figure 8 represents the thermally induced stress expected at varying temperatures plotted against the failure strain occurring at the corresponding temperature. For example, for a low temperature, T, and a corresponding failure strain level, ϵ_T, a failure envelope plotting above the boundary curve at ϵ_T would represent a mixture (mix A) with sufficient tensile strength to resist thermal cracking. The thermally induced stress would exceed the tensile strength of a mixture (mix B) with a failure envelope below the boundary curve, and thermal cracking would occur. The expected thermally induced stress was calculated using a viscoelastic solution contained in a computer program developed by Chang (3). Plots of thermally induced stress versus temperature were developed for different cooling rates; an example is shown in Figure 9. By plotting the expected thermally induced stress against the failure strain at the corresponding temperature, boundary curves for thermal cracking were developed. Figure 10 shows an example.

The permanent deformation boundary curves were based on rut depths predicted by the Shell method (4,5). As the binder content is increased, the lower portion of the failure envelope moves progressively to the right, as shown in Figure 11. For a specific climate, pavement thickness, and number of equivalent axle loads (EALs), each binder content has a corresponding rut depth. The failure envelope corresponding to the binder content that yields an unacceptable (or critical) rut depth becomes the boundary curve for that mix. A failure envelope plotted to the right of the boundary curve indicates an excessive binder content and excessive permanent deformation. A failure envelope plotted to the left of the boundary curve indicates no rutting problems.

A rut depth was calculated for each of several combinations of pavement thickness, climate, number of EALs (or load applications), and binder content for both the S-1 and S-2 binder using the Shell method. The Shell method is based on a plot of mixture stiffness (S_{mix}) as a function of binder stiffness (S_{binder}). Such a diagram was developed for both S-1 and S-2; an example is given in Figure 12. The calculated rut depth for each combination of conditions was plotted versus binder content, as in Figure 13. A limiting rut depth of 0.25 inches was set. The failure envelope of the binder content that yields the limiting rut depth becomes the boundary curve for each set of conditions. An example of permanent deformation boundary curves is given in Figure 14.

A quick method for estimating the fatigue life of Sulphlex mixtures using the resilient modulus was

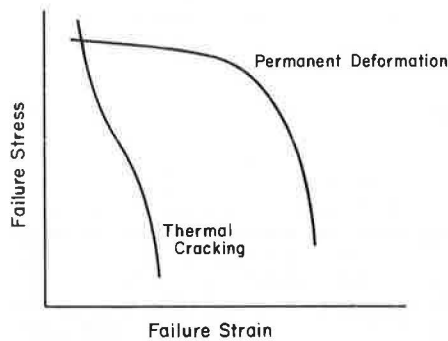Figure 7. Possible locations of boundary curves.

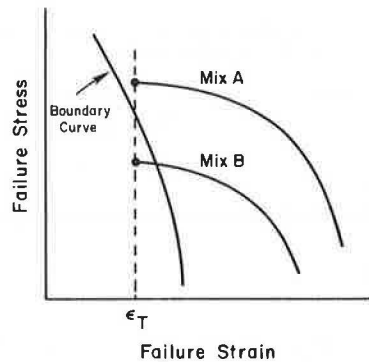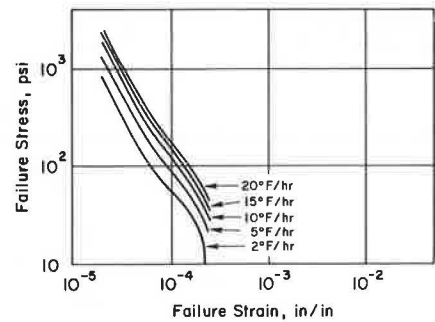Figure 8. Prediction of thermal cracking using the boundary curve.

Figure 9. Thermally induced tensile stresses calculated using Chang's computer code for a S-1 crushed limestone mix assuming a constant rate of cooling.
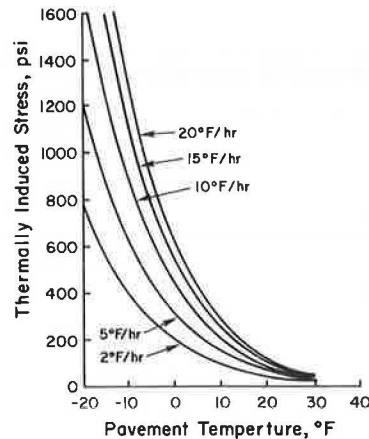

Figure 10. Thermal cracking design chart for S-1 and varying cooling rates.
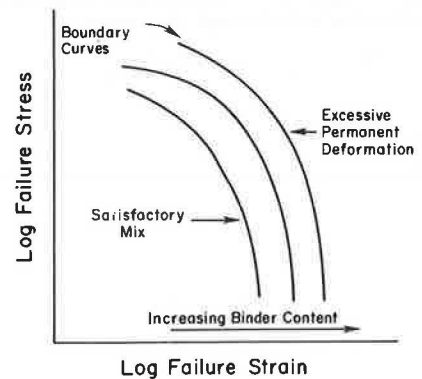

Figure 11. Position of the permanent deformation boundary curve.

Figure 12. S_{mix} as a function of S_{binder} curves for S-1 mixes with varying binder content.

Figure 14. Permanent deformation design chart for S-1, in a warm climate.
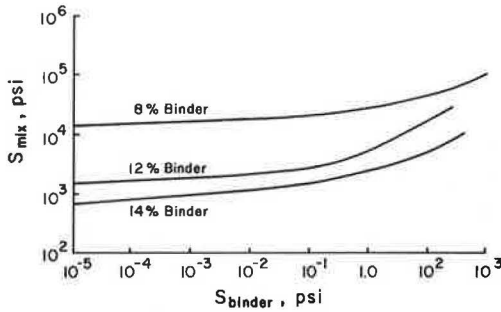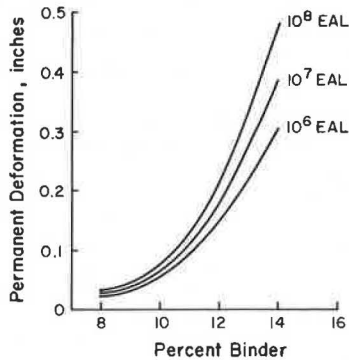

Figure 13. Calculated permanent deformation for a thick S-1 pavement in a warm climate. [Numbers on charts refer to number of equivalent (or standard) axle load applications (EALS)].
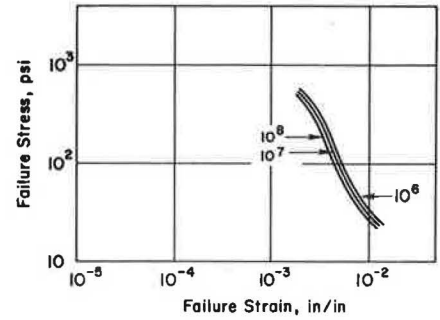

Figure 15. Fatigue design chart for S-1 with a subgrade modulus of 3,000 psi and pavement thickness of 3 in.

developed. Constant stress beam fatigue tests were performed on mixtures of S-1 and S-2. From the test results an empirical relation of the form

$$N_f = K_1 \left(1/\epsilon\right)^{K_2}$$

was derived where N_f is the number of load applications to failure, ϵ is the bending strain, and K_1 and K_2 are equation constants. The fatigue life was calculated for many combinations of resilient modulus and temperature. K_1 and K_2 were varied with temperature according to the guidelines given in the VESYS Users Manual (6). Knowing the elastic modulus (resilient modulus), the tensile strain in a pavement layer, ϵ, was calculated using a two-layer elastic solution given by Santucci (7). A lab to field shift factor of 13 was applied. Fatigue design charts were developed by plotting contours of constant fatigue life on a resilient modulus versus temperature diagram, as in Figure 15. Fatigue life can be estimated from this chart by plotting the resilient modulus of a mix at the effective yearly pavement temperature.

The K_1 and K_2 temperature corrections used are based on asphalt concrete fatigue data. However, such corrections are now being developed for Sulphlex by Texas A&M University under contract with FHWA. In addition, the laboratory to field shift factor of 13 is based on research done by Finn and others with AASHO Road Test asphalt concrete materials (8). More realistic shift factors are now being determined for Sulphlex by Texas A&M University under contract with FHWA.

Mixture Design

The following procedure is suggested for determining the optimum Sulphlex binder content.

1. Test a group of samples in indirect tension,
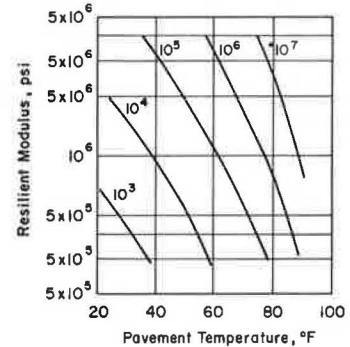
increasing the binder content by 1 percent increments. Plot toughness as a function of binder content. A small range of binder contents at the maximum toughness is selected for further analysis using the failure envelope.

2. For the small range of binder contents found in step 1 develop failure envelopes by testing at several temperatures including the lowest and highest temperature expected in service. Base the design charts on a stroke rate of 0.02 in./min.

3. Select a boundary curve for thermal cracking for the type of binder and the winter cooling rate. A permanent deformation boundary curve is selected taking into consideration climate, type of binder, pavement thickness, and number of load applications. A large number of design charts are given by Richey (9).

4. Plot the failure envelopes on a graph with the boundary curves. The failure envelope best fitting the window formed by the boundary curves represents the design binder content.

5. Check this binder content for fatigue resistance by performing resilient modulus tests at the yearly effective pavement temperature (T_{eff}). If the fatigue life is not adequate, the design binder content may be adjusted.

6. Use a moisture-conditioning procedure, such as the immersion-compression test (AASHTO T-165, T-167) or the Lottman procedure (10), to check for water susceptibility.

An example is included for clarification. For a dense-graded crushed limestone and Sulphlex S-1 mixture, the toughness versus binder content plot indicated that the maximum toughness occurred at about 8 percent binder. Failure envelopes for binder contents of 7, 8, and 9 percent were plotted with the boundary curves. Figure 16 shows that the 9 percent binder content would give excessive permanent deformation while the 7 percent binder content mixture would have potential thermal cracking problems. The 8 percent binder content completely satisfies permanent deformation and thermal cracking requirements.

Figure 16. Window formed by boundary curves for S-1 in a moderate climate at a winter cooling rate of 10° F/hr.
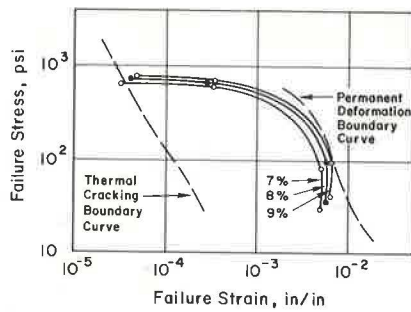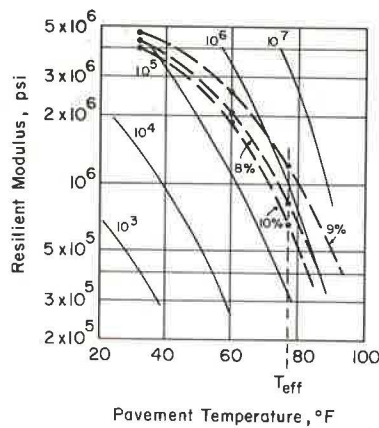

Figure 17. Fatigue design chart for S-1 with a subgrade modulus of 6,000 psi and pavement thickness of 3 in. (Long dashed lines represent resilient moduli for mixes with varying binder content).

The fatigue chart and the results of the resilient modulus test in Figure 17 show that the 9 percent content mixture would have the maximum fatigue life. A design binder content of about 8.5 percent would be recommended.

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