Engineering Evaluation of Sulphur-Asphalt Mixtures

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A comprehensive laboratory testing program was conducted as a part of an engineering evaluation of sulphur-asphalt paving mixtures. The purpose was to see (a) if sulphur-asphalt mixtures have better engineering properties than similar conventional asphalt mixtures and (b) what effects various sulphur-asphalt mixture variables and testing variables produce. Static and repeated load indirect tensile tests were used to evaluate these engineering properties: fatigue life, resilient modulus of elasticity, and tensile strength. The major factors evaluated were asphalt consistency in terms of penetration, type of asphalt in terms of temperature susceptibility, binder content, sulphur-asphalt ratio, stress level, and test temperature. The results indicated that sulphur-asphalt mixtures exhibit significantly better engineering properties, in terms of the above three, than comparable asphalt mixtures. All these engineering properties were significantly improved by the use of up to 50 percent sulphur. In addition, using sulphur-asphalt binders can improve the stiffness and fatigue characteristics of softer asphalts. Additional field and laboratory work to verify potential economic and structural benefits of using sulphur-asphalt mixtures is recommended.

The benefits of using sulphur in conventional paving mixtures have been successfully demonstrated in field trials during the past few years (1,2). A sulphur-asphalt binder must be produced by high shear rate mixing of liquid sulphur with liquid asphalt and no additives, using a patented process (2). This binder, in which a part of the asphalt normally used has actually been replaced by sulphur, is then used in a conventional manner with conventional equipment for mix production, transport to the job site, placing, and compaction. Because of the potential economy of replacing part of the asphalt with sulphur, which will be abundant for some years to come, the process has attracted attention from both user agencies and industry.

Field trials have demonstrated the full-scale construction capability of the process, but continued laboratory experiments and periodic in-service performance measurements remain to be done. Therefore, we conducted a comprehensive laboratory testing program to answer these two basic questions: Do sulphur-asphalt mixtures have better, equal, or inferior engineering properties than similar mixtures with asphalt alone? What are the effects of various sulphur-asphalt mixture and testing variables?

Sulphur-asphalt mixtures and comparable mixtures with asphalt alone were evaluated for their engineering properties: (a) tensile strength, (b) resilient modulus of elasticity, and (c) fatigue life.

The purpose of this paper is to report the results of the laboratory experiments and the potential implications of these results.

TEST METHOD

The basic test method was the static and repeated load indirect tensile test, in which a cylindrical specimen is loaded with a single or repeated compressive load that acts parallel to and along the vertical diametral plane. This loading configuration develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametral plane. This stress ultimately causes the specimen to fail by splitting along the vertical diameter. Loads were transmitted to the specimen through a 19-mm (0.75-in) wide, curved loading strip.

In the repeated load tests, the specimens were subjected to a 1.0 Hz load pulse applied for 0.1 s and followed by a 0.9-s rest period (Figure 1). During testing, the resulting horizontal deformations were recorded on a light-beam oscillograph. The equipment used for the repeated load tests is shown in Figure 2.

First we established tensile strength and then used this information to generate fatigue life versus stress relations, under dynamic loading. Stress was chosen as a percentage of the strength. Resilient modulus of elasticity was measured as a part of the dynamic testing for fatigue life.

Because of the unique nature of the sulphur-asphalt binder, the foregoing sequence was applied to a num-

Figure 1. Load pulse and associated deformation data for repeated load indirect tensile test.

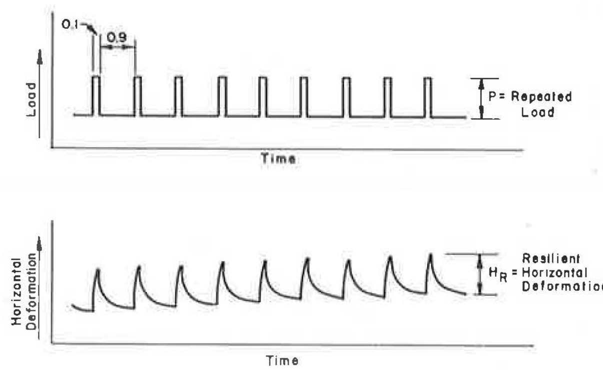
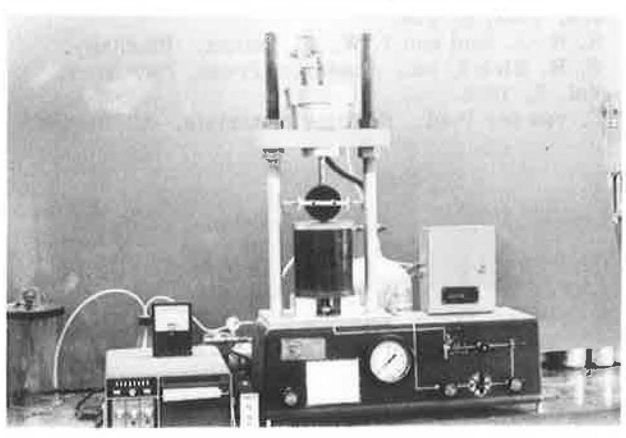


Figure 2. Laboratory equipment used in repeated load tests.



ber of possible combinations of variables in order to define as clearly as possible the binder's use limitations.

Tensile Strength

The tensile strength (S_T) is the horizontal tensile stress (σ_T) produced by the maximum load, or the load at failure, and can be calculated by using Hardy, Hudson, and Kennedy's equation (3):

$$S_T = (2P/\pi ah)(\sin 2\alpha - a/2R) \quad (1)$$

where

S_T = indirect tensile stress in megapascals,
P = total vertical load applied to the specimen in newtons,
a = width of the loading strip in millimeters,
h = height of the specimen at the beginning of the test in millimeters,
2α = angle at the center of the specimen subtended by the width of the loading strip in radians, and
R = radius of the specimen in millimeters.

The primary purpose of conducting tensile strength tests was to establish stress levels for subsequent fatigue testing.

Resilient Modulus of Elasticity

The resilient modulus of elasticity (E_R) is related to the recoverable, or resilient, deformation (H_R) (Figure 1) and can be calculated from the following equation (4) by assuming a value for Poisson's ratio.

$$E_R = (P/H_R h)(\nu + 0.27) \quad (2)$$

where

E_R = resilient modulus of elasticity in megapascals,
P = repeated load in newtons,
H_R = recoverable horizontal deformation in millimeters,
h = height of specimen in millimeters, and
ν = Poisson's ratio.

Values of Poisson's ratio can theoretically range from 0 to 0.50 and can vary with temperature, stiffness, and stress level. A review of past studies suggested that we could reasonably assume that Poisson's ratio varied from 0.18 to 0.50 for the testing temperature range of 10 to 52°C (50 to 125°F).

Fatigue Life

Fatigue life is the number of load applications required for the specimen to completely fail. Because fatigue life is obviously a function of the magnitude of the applied stress, the results are often expressed in terms of the logarithmic relation between stress and fatigue life, which for asphalt mixtures is generally linear. Although it is possible that this linearity does not exist for sulphur-asphalt mixtures, we considered it acceptable for the purposes of our investigation. This relation for the indirect tensile test can be expressed as

$$N_f = K_2(1/\sigma_T)^{n_2} = K_2'(1/\Delta\sigma)^{n_2} \simeq K_2'(1/4\sigma_T)^{n_2} \quad (3)$$

where

N_f = fatigue life in cycles to failure,
σ_T = repeated tensile stress,
$\Delta\sigma$ = stress difference or deviator stress,
n_2 = slope of the logarithmic relation,
K_2 = antilog of the intercept of the logarithmic relation between N_f and σ_T, and
K_2' = antilog of the intercept of the logarithmic relation between N_f and $\Delta\sigma$.

The form, based on stress difference, partially accounts for the biaxial state of stress present in the indirect tensile test. The value $4\sigma_T$ approximates the stress difference, or deviator stress, that acts on the center element.

EXPERIMENT DESIGN

The major factors incorporated into the design were

1. Asphalt consistency at two levels: 40/50 and 85/100 penetration grades. These two grades represent a medium and a hard asphalt cement, respectively, and should provide an estimate of the importance of consistency.
2. Temperature susceptibility at two levels: low and high viscosity. Asphalts from two different crude sources in Alberta and Saskatchewan were obtained. The characteristics of the asphalts are summarized elsewhere (6).
3. Binder content at four levels: 6.0, 6.5, 7.0, and 8.0 percent by weight. The range included the optimum binder content obtained by the Marshall method, which allowed nonlinear behavior to be evaluated.
4. Sulphur-asphalt ratio at three levels: 0/100, 20/80, and 50/50. This allowed nonlinear behavior to be evaluated. We could also determine whether the addition of sulphur improved the engineering properties of the final mixtures.
5. Test temperature at four levels: 10, 24, 38, and 52°C (50, 75, 100, and 125°F). The majority of the tests were conducted at 10, 24, and 38°C; a limited number were conducted at 52°C and provided an estimate of behavior at high temperatures.
6. Tensile stress at two levels: low and high. In order to characterize the fatigue behavior (stress-fatigue relations), it was necessary to test at least two stress levels and to assume a linear logarithmic relation. Because of the wide temperature range, it was impossible to use the same two stress levels for all four temperatures. Therefore, two stress levels were used but were defined as high and low stress-to-strength ratios. The high ratio was selected as 35 percent and the low ratio as 24 percent.

These factors are described in more detail and the combinations shown elsewhere (6).

MATERIALS AND SPECIMENS

The specimens, 102 mm (4 in) in diameter and 51 mm (2 in) thick, were produced by the Research and Development Department of Gulf Oil Canada Limited. We tested 180 specimens statically for strength and 198 under repeated loads for resilient modulus of elasticity and fatigue life.

These specimens were prepared according to ASTM D-1559 and mechanically compacted at 60 blows per face [(6) contains data on aggregate gradation and Marshall test results].

The optimum binder contents as determined by the Marshall methods were 6.0 percent by weight for the conventional asphalt mixtures, 6.5 percent for the 20/80 sulphur-asphalt mixtures, and 8.0 percent for the 50/50 sulphur-asphalt mixtures.

DISCUSSION OF RESULTS

Fatigue Life

Fatigue lives were difficult to analyze in their "raw" form, because the various combinations of variables produced specimens with different tensile strengths. We therefore applied a different absolute stress level of each test or combination of variables, which normalized the actual fatigue lives. Fatigue behavior was expressed as a linear relation between the logarithm of fatigue life and the logarithm of stress (Equation 3). These relations were generally parallel and had similar n_2 values.

By extrapolating or interpolating these relations, it was possible to obtain an estimated fatigue life for a high tensile stress of 490 kPa (71 lbf/in^2 and for a low tensile stress of 331 kPa (48 lbf/in^2), which were the average of the high and low stresses used at 24°C (75°F).

Values of n_2 and K_2' (6) can be used to predict fatigue cracking in actual pavement structures by applying certain computerized design and analysis systems (the U.S. Federal Highway Administration's VESYS IIM system). They can also be used to estimate the fatigue life of a given pavement structure, under given conditions, using elastic layer analysis to calculate stresses.

An analysis of variance conducted on the estimated fatigue lives at 331 and 490 kPa indicated that, in addition to the effect of stress, fatigue life was significantly affected by sulphur-asphalt ratio, penetration of the asphalt cement, and temperature.

Effect of Sulphur-Asphalt Ratio

The addition of sulphur increased the fatigue life of the mixtures, but the nature of the increase is uncertain. As shown in Figure 3, the fatigue lives for the mixtures containing 50 percent sulphur at a stress of 331 kPa were generally greater than for the conventional mixtures. In some cases the effect of adding 20 percent sulphur was inconsistent, in that the fatigue lives were actually somewhat lower than for 0 percent sulphur. However, all of these lower fatigue lives are well within the limits of experimental error, and it is quite possible that, under field conditions, mixtures with 0 and 20 percent sulphur would have similar fatigue lives. The estimated fatigue relations at 490 kPa were essentially the same (6).

Figure 4 shows the effect of temperature on fatigue life. As might be expected, temperature is a very dominant factor. However, the major point of interest of Figures 3 and 4 is that the use of 50 percent sulphur has an effect similar to that achieved by decreasing the penetration from 85/100 to 40/50.

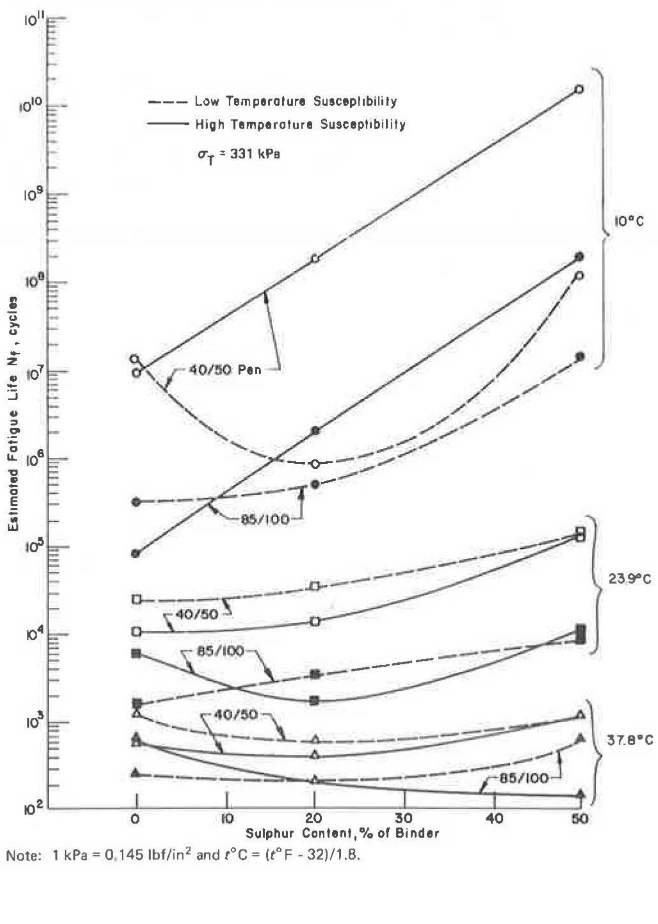
Effects of Temperature and Penetration

Penetration is also shown in Figure 4 to be a major factor, especially at the lower temperatures. The 40/50 penetration asphalt exhibits a significantly longer fatigue life. Thus, for controlled stress tests similar to those conducted in this study or for thick pavement sections, fatigue life would be expected to increase significantly with decreased temperature and decreased penetration.

Effect of Binder Content

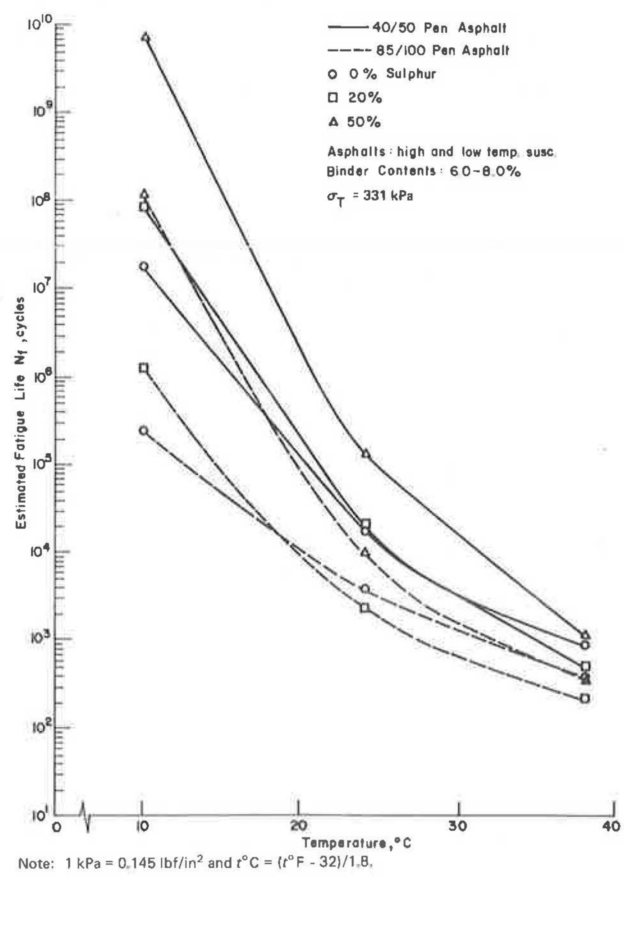
In this study, binder content was not significant. However, the range was not large and the effects of binder content were very erratic. Nevertheless, we can conclude that there was an optimum for maximum fatigue

Figure 3. Relation between estimated fatigue life and sulphur content for mixtures subjected to low tensile stress.



Note: 1 kPa = 0.145 lbf/in^2 and t°C = (t°F - 32)/1.8.

Figure 4. Relation between fatigue life and temperature for sulphur-asphalt mixtures subjected to low stress.



Note: 1 kPa = 0.145 lbf/in^2 and t°C = (t°F - 32)/1.8.

life and that this optimum was larger than the optimum for maximum strength. This finding would be consistent with the normal mix design approach of using sufficient binder for durability.

Summary of Fatigue Life Results

The addition of more than 20 percent sulphur produced a significant increase in fatigue life, whereas the increase produced by adding 50 percent sulphur was approximately equal to that by using a 40/50 rather than an 85/100 penetration asphalt.

There is an optimum binder content for maximum fatigue life, and it is somewhat greater than the optimum for maximum strength or resilient modulus of elasticity.

Resilient Modulus of Elasticity

The sulphur-asphalt mixtures exhibited higher stiffnesses, in terms of resilient moduli of elasticity, than the conventional asphalt mixtures. In general, moduli values ranged from 145 000 to 19 500 000 kPa (21 000 to 2 830 000 lbf/in^2); the actual values depended on sulphur-asphalt ratio, penetration of the asphalt cement, and temperature, each of which produced highly significant effects.

Binder content had a relatively small effect for the range considered, and stress level and temperature susceptibility had no effect. A number of interaction effects involving two or more factors were also found to be statistically significant but to have no practical engineering importance.

Effect of Sulphur-Asphalt Ratio

The addition of sulphur produced a substantial increase in stiffness in terms of resilient modulus of elasticity (Figure 5). Twenty percent sulphur did not significantly increase the modulus of the sulphur-asphalt mixtures containing the 85/100 penetration asphalt, but the addition of 50 percent sulphur produced a substantial increase. For the 40/50 penetration asphalt, at 10 and 24°C (50 and 75°F), the addition of 20 percent sulphur produced a substantial increase. This would suggest an interaction effect involving sulphur content, penetration of the asphalt, and temperature.

Effects of Temperature and Penetration

Temperature was again a dominant factor, as might be expected, and produced approximately 75 percent of the total observed variation. As shown in Figure 6, most of the increase occurred between 10 and 24°C.

Mixtures with the 40/50 penetration asphalt, again as might be expected, were much stiffer than those with the 85/100 penetration asphalt (Figures 5 and 6). The absolute magnitude of the difference was much larger at the lower testing temperatures, although the relative magnitude of the difference was much larger at the higher temperatures.

Effect of Binder Content

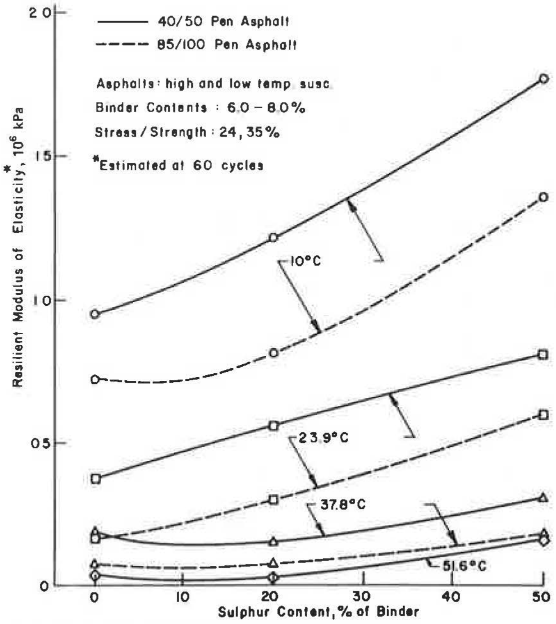
For maximum resilient modulus of elasticity, there seemed to be an optimum binder content of less than 6 percent in many cases, which is similar to the optimum for maximum strength. In addition, the modulus did not appear to be sensitive to small changes in binder content within the range of values investigated.

Summary of Modulus Results

The addition of sulphur produced a significant increase in stiffness in terms of resilient modulus of elasticity. Generally, this increase required the addition of 50 percent sulphur, although in a few cases 20 percent sulphur produced a substantial increase.

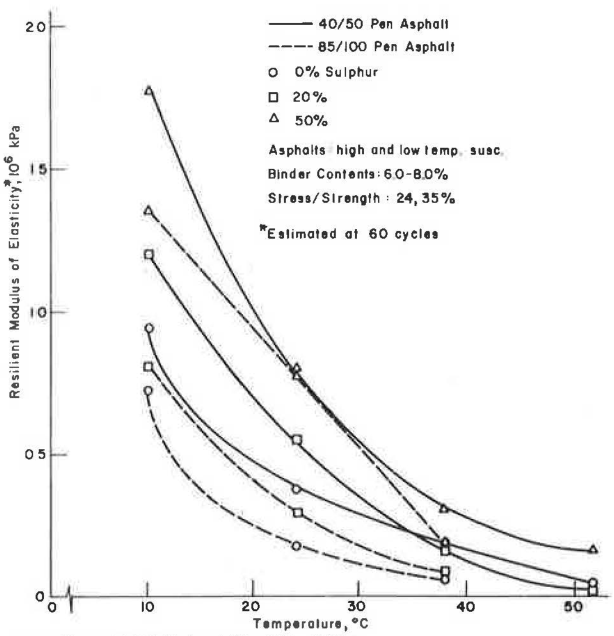
The optimum binder content for maximum resilient modulus of elasticity was not well defined but appeared to be 6 percent or less. However, higher binder contents, which are more consistent with mix durability considerations, only resulted in a marginal decrease in modulus.

Figure 5. Relation between resilient modulus of elasticity and content.



Note: 1 kPa = 0.145 lbf/in^2 and t°C = (t°F - 32)/1.8.

Figure 6. Relation between resilient modulus of elasticity and temperature.



Note: 1 kPa = 0.145 lbf/in^2 and t°C = (t°F - 32)/1.8.

Tensile Strength

The strengths of the sulphur-asphalt mixtures were higher than the strengths of the conventional mixtures. Strength values ranged from 103 to 4650 kPa (15 to 674 lbf/in^2) and were found by analysis of variance to be significantly affected by sulphur-asphalt ratio, penetration of the asphalt cement, and temperature. The binder content was also found to influence strength, but only slightly.

Strengths did not depend on the type of asphalt, as identified by temperature susceptibility. In addition, there were numerous interaction effects, many of which involved temperature. However, in a practical sense, there was no real engineering significance.

Effect of Sulphur-Asphalt Ratio

As shown in Figures 7 and 8, there was little, if any, increase in strength produced by adding 20 percent sulphur. However, the addition of 50 percent sulphur resulted in a significant increase in strength and had the same effect as decreasing the penetration from 85/100 to 40/50 penetration (Figure 7).

Thus, the addition of sulphur is beneficial in terms of strength. Furthermore, although the addition of 20 percent sulphur did not improve the strength of the mixtures, the asphalt content and thus the potential cost were lowered without a loss of strength. The addition of 50 percent brought cost savings and significantly increased strength.

Effects of Temperature and Penetration

Temperature, as expected, had the greatest effect on the strength values (Figure 7) and accounted for approximately 88 percent of the strength differences. This increase in strength should continue with decreasing temperature until the strength of the aggregate becomes the determining influence.

Only about 5 percent of the total variation was caused by the change in penetration. The 40/50 pentration asphalt cements produced signficantly stronger mixtures than the 85/100 penetration asphalts.

Effect of Binder Content

Strength was not sensitive to binder content within the range tested, except possibly at lower temperatures. The results suggest an optimum binder content that appears to have been less than 6 percent in many cases. Strength, however, is not the controlling factor. In addition, low total binder content can adversely affect factors such as durability.

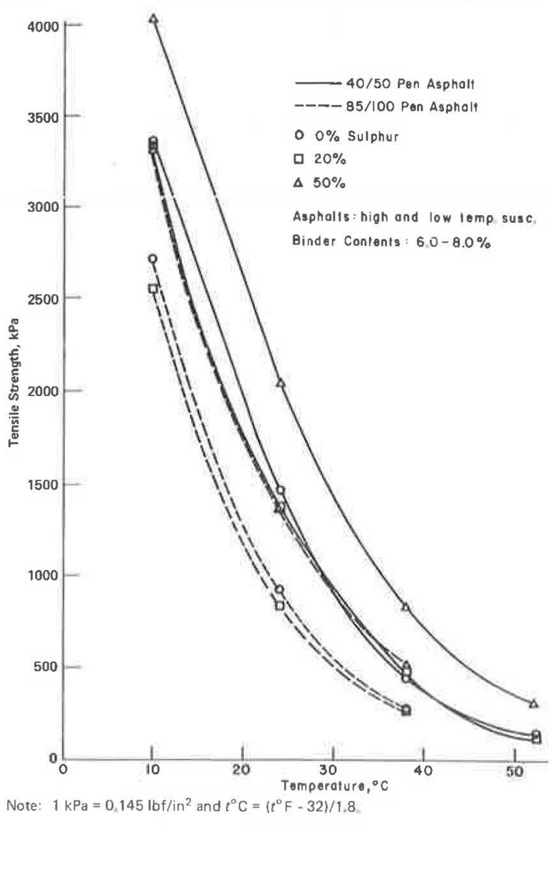
Relation Between Tensile Strength and Marshall Stability

There was no strong relation between Marshall stability and tensile strength, although there did appear to be some general trends for a given temperature and asphalt penetration. These differences, in terms of penetration, tended to diminish as the test temperature increased and approached the temperature used with the Marshall test [-60°C (-140°F)]. At best, it can only be said that mixtures with high Marshall stabilities tended to have higher tensile strengths.

Summary of Strength Test Results

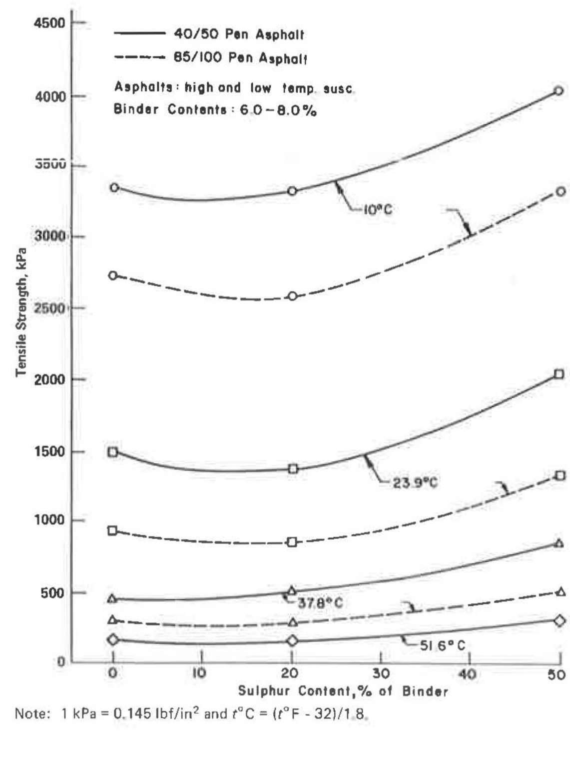
The addition of 20 percent sulphur did not increase the strength, but the addition of more than 20 percent increased strength significantly. The increase produced by adding 50 percent sulphur was approximately

Figure 7. Relation between tensile strength and temperature.



Note: 1 kPa = 0.145 lbf/in^2 and t°C = (t°F - 32)/1.8.

Figure 8. Relation between tensile strength and sulphur content.



Note: 1 kPa = 0.145 lbf/in^2 and t°C = (t°F - 32)/1.8.

equal to that achieved with a 40/50 rather than an 85/100 penetration asphalt cement.

An optimum binder content for maximum strength exists but, again, is not well defined, and a change in binder content for the range evaluated had little, if any, effect on strength.

There was no significant relation between indirect tensile strength and Marshall stability.

POTENTIAL BENEFITS OF SULPHUR-ASPHALT MIXTURES

The use of sulphur-asphalt binders in paving mixtures has potential benefits in terms of economy, resource conservation, and improved pavement performance.

The economic benefits can result from replacing a portion of more expensive material, asphalt, with a less expensive and more plentiful material, sulphur. In some areas of North America, sulphur is substantially less expensive than asphalt. In other areas, however, shipping costs may make sulphur nearly as expensive as asphalt. Nevertheless, the long-term benefits of sulphur use are based on stable costs because of relative abundance. In addition, increased use of low-grade, high sulphur content coal for electric power generation and the removal of substantial quantities of sulphur from the Alaskan crude oils could add significantly to projected North American sulphur supplies.

Asphalt can be conserved as a resource by partially replacing it with sulphur. In view of dwindling petroleum reserves, it is possible that at some future time the demand for asphalt may exceed both raw supply and the capacity of refineries to produce it.

Pavement performance can be improved in terms of increased fatigue life for thick sections, as indicated by the stress-controlled fatigue testing of this investigation. Of course, this must be verified by field observations. For thinner sections, some caution may be required, especially where very stiff sulphur-asphalt mixtures are used on a weak foundation, which could result in a thin, stiff slab effect.

Fortunately, the pavement designer has considerable flexibility in tailoring a sulphur-asphalt mixture to the particular design situation. Both sulphur-asphalt ratio and grade of asphalt can be varied to modify the temperature susceptibility of the mix, thereby adapting it to a very wide range of in-service temperature, load, and foundation conditions (5).

CONCLUSIONS

The results of this experimental program indicate that sulphur-asphalt mixtures exhibit significantly better engineering properties than conventional mixtures. Fatigue life in a stress-controlled testing, resilient modulus of elasticity, and tensile strength were significantly improved by the addition of up to 50 percent sulphur. The effects produced by various mixture and test variables have been summarized and illustrated.

Further work with sulphur-asphalt mixtures seems well justified in terms of both engineering properties and potential cost effectiveness. This work should identify the combinations of pavement layer materials, thicknesses, and subgrade conditions where sulphur-asphalt mixtures can be demonstrated to have clear economic and performance advantages.

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REFERENCES

1. G. J. A. Kennepohl, A. Logan, and D. C. Bean. "Conventional" Paving Mixes With Sulphur-Asphalt Binders. Proc., AAPT, 1975.
2. B. J. A. Kennepohl. The Gulf Canada Sulphur-Asphalt Process for Pavements. Proc., Symposium on New Uses of Sulphur and Pyrites, Madrid, 1976.
3. W. O. Hadley, W. R. Hudson, and T. W. Kennedy. A Method of Estimating Tensile Properties of Materials Tested in Indirect Tension. Center for Highway Research, Univ. of Texas at Austin, Research Rept. 98-7, July 1970.
4. G. Gonzalez, T. W. Kennedy, and J. N. Anagnos. Evaluation of the Resilient Elastic Characteristics of Asphalt Mixtures Using the Indirect Tensile Test. Center for Highway Research, Univ. of Texas at Austin, Research Rept. 183-6, Dec. 1975.
5. F. R. P. Meyer, E. T. Hignell, G. J. A. Kennepohl, and R. Haas. Temperature Susceptibility Evaluation of Sulphur-Asphalt Mixtures. Paper presented to AAPT, San Antonio, Feb. 1977.
6. T. W. Kennedy, P. Smith, and R. Haas. An Engineering Evaluation of Sulphur-Asphalt Mixtures. Austin Research Engineers, Contract Rept. GC-1, June 1976.

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