USE OF STONE SCREENINGS AS ROADBASE AGGREGATE

Stone screenings are used extensively in roadbase and subbase mixes and are used in combination with coarse aggregate. This type of use reduces the cost of the combined product because the screenings do not have to be separated and reblended. The Bureau of Mines' statistics (1) show that during 1977 more than 340 million Mg (375 million tons) of roadstone and roadbase aggregates were used in the United States. The reasons for that are basically two: (a) these combinations are lower-cost construction materials, and (b) the materials are exceptionally good and suitable for base construction without stabilizing additives.

Screenings have been used in roadbase construction ever since the first broken rock was produced by man. Due to modern technology available for mechanized construction, stone screenings for road construction are being used to an even greater extent. The past, present, and future role of unbound aggregates (a portion of which are stone screenings) in road construction are summed up in the proceedings (10) from a national conference in 1974. The subject of load-deformation characteristics, other fundamental properties, design procedures, production control systems, and quality assurance are extensively discussed in the proceedings.

NCSA staff, with the assistance of NCSA committee members, has prepared a number of manuals on the use of crushed stone products (including stone screenings) for specific purposes, such as construction of parking areas, streets, low-volume roads, highways, shoulders, and airports. Engineers and designers should consider the use of low-cost crushed stone materials for construction. These materials are available today, and the forecast for crushed stone by the year 2000 is on the order of 27 billion Mg (30 billion tons). Stone screenings account for 12 percent of that estimated total; therefore, more than 3 billion Mg (5 billion tons) of stone screenings will be used between now and then.

OTHER USES OF STONE SCREENINGS

Not all the uses of stone screenings for highway construction have been discussed here. The overall subject is very broad. Other applications of stone screenings include bedding materials, fillers, granulars for drain fields, fills, mixtures for de-icing, patches, slurry seals, surface treatment, and overlays.

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Sulphur-Asphalt Pavement Technology: A Review of Progress

Thomas W. Kennedy and Ralph Haas

This paper briefly summarizes the current status of sulphur-asphalt pavement technology with emphasis on sulphur-extended asphalts. The various processes that are currently available are discussed and compared, and the various field trials are described. Performance observations and engineering properties are also considered. Finally, the future use, applications, and problems of sulphur-asphalt are reviewed. Based on experience, the use of sulphur-asphalt mixtures can be expected to increase during the next few years. This is especially true of sulphur-extended asphalt mixtures, which have greater applicability and conserve asphalt and produce a corresponding reduction in cost.

The accumulation of surplus sulphur, the need for improved paving mixtures, and the dwindling supply of asphalt and its rapidly increasing cost have provided the incentive to develop new uses for sulphur for the paving industry. One of the largest such applications is the use of sulphur in sulphur-asphalt mixtures.

Two basic approaches have been used. Either sulphur can be added to the mixture or it can replace a portion of the asphalt [sulphur-extended asphalt (SEA)]. Both processes have definite applications, and each has

Table 1. Method for using sulphur in asphalt mixtures.

Basic Method	Example Sources	Features	Example Field Applications	Some Limitations, Actual and Possible
Liquid sulphur addition to hot sand-asphalt mixes	Shell Canada Ltd.	Use of marginal materials (i.e., unstable sands); no compaction requirements	Richmond, British Columbia, 1970 Tilsonburg, Ontario, 1972 Maclean, Saskatchewan, 1974 Sulphur, LA, 1977	Special equipment (i.e., insulated trucks); high quantities of sulphur; questionable economics, except for special situations
	Societe Nationale des Petroles d'Aquitaine	Potential economy; extension of asphalt supply; use of conventional paving equipment	Perimeter road of plant at Lacq in Western France, 1973 Lufkin, TX, 1975	Storage (i.e., costs, formation of H_2S, need for inert cover gas); need for additives to maintain storage stability; extra operators at plant; elemental sulphur vapor at paving site
Preblending of liquid sulphur and asphalt to produce SEA binder	Gulf Canada Ltd.	Potential economy; extension of asphalt supply; use of conventional paving equipment; production of binder, on site, on demand; no additives required	Alberta, 1974, 1977 Ontario, 1975, 1977, 1978, 1979 Michigan, 1977, 1979 Holland, 1978 Louisiana, 1978 Florida, 1979 Minnesota, 1979	Extra operators at plant; elemental sulphur vapor at paving site
	SUDIC	Potential economy; extension of asphalt supply; use of conventional paving equipment; production of binder, on site, on demand	Alberta, 1975, 1977 British Columbia, 1979	Extra operators at plant; elemental sulphur vapor at paving site
Pugmill blending of liquid sulphur and asphalt to produce SEA binder	U.S. Bureau of Mines	Potential economy; extension of asphalt supply; use of conventional paving equipment; no additives required	Nevada, 1977	Elemental sulphur vapor at paving site; uniformity of dispersion; aggregate coating

been used successfully in various field construction projects.

The purpose of this paper is to review these processes and the field trials that have been conducted to date and to illustrate some of the properties of paving mixtures that have sulphur addition.

AVAILABLE PROCESSES

A number of projects have incorporated elemental sulphur in asphalt mixtures. The general objectives were to use sulphur and to obtain improved mechanical properties of the mixtures. Current efforts also have these objectives; they are concerned with achieving improved economy and extending the available supplies of asphalt.

The first application of sulphur in the paving industry was on the Ohio Department of Highways experimental road in Hocking County in Ohio in 1935 (1). At about the same time, a paving-brick filler formulation named Sulmor was developed by Litehiser and Schofield (2). It consisted of asphalt and Thiokol-plasticized sulphur.

Another nearly concurrent effort was initiated by Bacon and Bencowitz in 1936 (3) and patented in 1939 (R. F. Bacon and I. Bencowitz, U.S. Patent 2 182 837, 1939). It included vigorous stirring of as much as 50 percent of elemental sulphur in asphalt at 149°C (300°F) and is known as the Texas Gulf process. Paving mixtures that contained this binder were tested extensively and a small experimental road was constructed.

The major methods currently available for using sulphur in asphalt mixtures, not including such paving materials as Sulphlex, which is currently being investigated by the Southwest Research Institute, have been developed in the mid-1960s to early 1970s. They can be classified as follows:

1. Addition of sulphur to hot sand-asphalt mixtures—Shell Thermopave process,
2. Preblending of sulphur and asphalt to produce SEA—Societe Nationale des Petroles d'Aquitaine (SNPA) process, Gulf Canada process, Sulphur Development Institute of Canada (SUDIC) (Pronk) process for Thermal Asphalt, and
3. Pugmill blending of sulphur and asphalt to produce SEA—U.S. Bureau of Mines process.

The basic approach in the first method is to add hot liquid elemental sulphur, essentially as a filler, to a hot sand-asphalt mix during a second mixing cycle, which occurs after the asphalt has been mixed with the aggregate. In the second method, the basic approach is to disperse hot liquid elemental sulphur in asphalt to create an SEA binder, which is then mixed with aggregate in the same way that asphalt alone is used in conventional mixtures. The third method also attempts to create an SEA binder by the separate addition of the components and pugmill blending of sulphur and asphalt, rather than by preblending. Table 1 summarizes information related to these processes.

Shell Process

The Shell Thermopave process, developed in the 1960s, involved the first substantial use of sulphur in asphalt (Shell International Research Maatschaapij, Ger. Offen. 2 149 676). The basic intent was to use large amounts of surplus sulphur by incorporating it in sand-asphalt mixtures of low stability (i.e., mixtures that contain poorly graded, unstable sands to produce mixtures of high stability).

The process, which has been described in several sources (4-10), essentially consists of the following two consecutive mixing cycles:

1. Mixing sand with asphalt and
2. Mixing sand-asphalt with molten, elemental sulphur.

Temperature of the mixing processes is between 132°C and 149°C (270°F and 300°F) and the final mixture composition has an aggregate-asphalt-sulphur weight ratio of approximately 82-6-12 (10).

The Thermopave mixture production operation requires plant modifications, as well as insulated trucks for hauling to avoid freezing, which occurs at about 116°C (240°F). The mixture can be placed by using either forms or a modified paving machine. No compaction is required.

Mechanical stability of the mixture is very high because the solidified sulphur, which fills the interstitial voids, becomes part of the aggregate structure.

Claims for a process somewhat similar to that of Shell's Thermopave were filed in 1961 by Standard Oil, Chicago (Standard Oil Company, Chicago, U.S. Patent 3 239 361, 1966). The similarity lies in the fact that sulphur is incorporated in the asphalt-aggregate mixture as a post-mix addition technique. However, the Standard Oil process adds the sulphur in finely divided or powdered form and includes the use of carbon (7.5 percent by weight).

More recently, the major emphasis in the Thermopave process has been in the area of maintenance, by using what is known as Thermopatch.

Aquitaine Process

The French SNPA, or Aquitaine, process is essentially a modification of the earlier Texas Gulf process. Instead of using plain elemental sulphur, preplasticized sulphur is used, and additives such as polysulfide (Thiokol LP3) are added before it is blended with the asphalt. Otherwise, the blending or homogenizing, composition, and applications are identical to the Texas Gulf process.

The purpose of the additives used by Aquitaine is basically for stabilization of the sulphur bitumen (S-B) emulsion. Numerous patents in the field of sulphur plasticization have been obtained by Aquitaine during the past 10 years (Societe Nationale des Petroles d'Aquitaine, U.S. Patent 1 303 318); however, generally Aquitaine binders contain only sulphur asphalt.

In 1973, Aquitaine described the application of the S-B emulsion in road paving (11). During the same year, a test strip was constructed outside the refinery, near Lacq, France. The process and the field application were described to the American Chemical Society in Los Angeles in 1974 (12). Additional examples of the use of this process have been described by Gallaway and Saylak (13).

The Aquitaine process offers potential benefits of economy, extension of existing asphalt supply, and use of conventional paving equipment; however, it requires additives in order to ensure stability if storage is required. Moreover, high levels of H_2S are formed in storage and a serious explosion danger can exist. The use of an inert gas (such as nitrogen) may be necessary to reduce these dangers. Apparently the use of additives does not significantly affect the amount of sulphur remaining in a crystalline state; rather, the additives seem to be required purely to maintain stability during storage.

Gulf Canada Process

The Gulf Canada process (14-24) also involves the dispersion of molten, elemental sulphur in asphalt. However, it does not incorporate any additives and uses the asphalt medium itself as a plasticizing agent.

The SEA binder is produced on demand at the paving site by using a sulphur-asphalt module (SAM). Essentially, this unit receives asphalt from a supply line to the asphalt storage tank and molten elemental sulphur from another storage tank, both at temperatures between about 132°C and 149°C (270°F and 300°F) and mixes them into a continuous stream of binder. This SEA binder is then fed into the pugmill. A bypass valve allows for switching to pure asphalt binder with no shutdown of the mixing plant. The SAM unit can be used with either a batch type or continuous type of mix plant and its use has been described in detail by Kennepohl (14).

Other Processes

The Thermal Asphalt process, now handled through SUDIC, produces a preblended SEA binder similar in nature to that produced in the Aquitaine and Gulf Canada processes (25, 26).

Production of an SEA binder is also claimed to be possible through separate addition of sulphur and asphalt to the pugmill, as reported by McBee and Sullivan (27). This process, developed through the U.S. Bureau of Mines, is apparently simpler than the preblending process and avoids patent problems. However, it still requires separate asphalt and sulphur storage plus pumping and metering, can require a longer mixing cycle, does not always result in the uniformity of dispersion achieved with preblending, can result in preferential coating for certain types and gradations of aggregate, and can result in mixtures that have certain properties and durability characteristics that are different from those achieved with preblending. It should be emphasized, however, that these are possible limitations and remain to be quantitatively demonstrated and documented.

FIELD TRIALS

Major field trials of sulphur use in asphalt mixtures during the past decade were started by Shell Canada Ltd. on their Thermopave test roads at Richmond, British Columbia (1970), at Tilsonburg, Ontario (1972), and at McLean, Saskatchewan (1974). These were followed by test roads that used the SNPA process in France (1973), the Gulf Canada process in Alberta (1974), the SUDIC process in Alberta (1975), and the U.S. Bureau of Mines process in Nevada (1977) (Table 1). The period between the mid-1970s and 1979 saw a considerable number of field trials constructed in North America and Europe. Table 2 contains a partial summary.

These field trials demonstrated that SEA binders could be easily produced on site in commercial quantities and that the mixes could be hauled, placed, and compacted with conventional equipment. Extensive, ongoing engineering evaluation of the mixes and test roads is being carried out by both of the previously noted developers of the processes and by the user agencies. A number of the quoted references contain certain interim evaluation information. The major objectives of the field trials have been to

1. Demonstrate full-scale construction feasibility;
2. Provide a basis for longer-term, in-service evaluation of sulphur-asphalt pavements and the effects of the variables that can affect behavior and performance; and
3. Provide a basis for developing a design technology for sulphur-asphalt pavements.

OBSERVATION OF PERFORMANCE

Experience to date has shown that paving mixes that have SEA binder can be routinely produced for regular, full-scale construction and that hauling, placing, and compaction can be accomplished with conventional equipment.

Observations of behavior and performance will, of course, continue for several years and it is premature to make extensive conclusions. Nevertheless, the following interim conclusions can be made.

1. Paving mixes made with SEA binder can vary markedly in stiffness response, depending on the grade of asphalt used and the sulphur-asphalt ratio, as subsequently illustrated. This allows considerable design flexibility in tailoring to particular conditions of traffic, temperature, subgrade support, and materials availability.

2. Thickness reductions due to increased stiffness are theoretically possible in certain situations, but this has not yet been verified by field observations. There are other situations where increased stiffness can in fact be counterproductive (i.e., where a thin slab effect and strain-controlled fatigue exist).

3. Overlay construction seems to have been particularly successful. The 1974 overlay at Windfall, Alberta, shows no significant distress to date.

4. Full-depth construction on granular bases has generally performed quite well, although certain conditions, particularly where soft subgrades are involved, can result in premature distress (28).

ENGINEERING PROPERTIES

The engineering properties of the various sulphur-asphalt binders have been evaluated by various investigators (17, 19). These properties have provided a basis for the design of actual field projects, including the structural design, and have been used to compare these materials to conventional mixtures. Engineering properties have included Marshall and Hveem mixture design properties, resilient moduli, fatigue behavior, low-temperature stiffness, temperature susceptibility, and tensile and compressive strengths.

Table 2. Partial summary of sulphur-asphalt field trials.

Process	Location	Date of Construction	Comments
Shell Canada	British Columbia	1970	Hot-mix, sand-sulphur-asphalt base for urban street construction
Shell Canada	Ontario	1972	Hot-mix, sand-asphalt-sulphur mix in rural highway application
SNPA	France	1973	SEA mix for perimeter road construction at SNPA plant
Gulf Canada	Port Colborne, Ontario	1974	Demonstrate operation of original SAM equipment and feasibility of full-scale production
Gulf Canada	Blue Ridge, Alberta	1974	Five sections of varying thickness; demonstration of full-scale production with conventional equipment and determination of layer equivalency values
Gulf Canada	Windfall, Alberta	1974	Two sections of overlay at two thicknesses, total length 1.6 km; demonstration of sulphur-asphalt overlay and determination of performance parameters such as rutting, crack reflection, and initiation
SNPA	Lufkin, TX	1975	Hot-mix base construction of varying thicknesses
Gulf Canada	Renfrew, Ontario	1975	Seven sections, 2900 m^2 each at 63.5 mm, total length 3.2 km; evaluation of effects of penetration, sulphur-asphalt ratio, binder, and antistripping agents
SUDIC	Calgary, Alberta	1975	Urban street applications of SEA binder hot-mix construction
Gulf Canada	Mellville, Saskatchewan	1976	Demonstration of production of SEA binder for drain mixing; testing for commercial SAM unit
SUDIC	Rocky Mountain House, Alberta	1977	Full-scale construction of several kilometers of SEA pavement plus several test sections of varying thickness
Shell Canada	Sulphur, LA	1977	Demonstration project of sulphur-sand-asphalt hot-mix base construction
U.S. Bureau of Mines	Nevada	1977	Demonstration of full-scale production of SEA mixes by using pugmill blending of sulphur and asphalt for test road
Gulf Canada	Midland, MI	1977	Four sections, 1.6 km total length, to overlay on portland concrete cement
Gulf Canada	Sturgeon Falls, Ontario	1977	Four sections, total length 3.2 km to evaluate SEA binder with soft asphalt for improvement of low-temperature performance
Gulf Canada	Rocky Mountain House, Alberta	1977	Full-scale production run plus 2 km of test sections of varying thickness to determine layer equivalencies
Gulf Canada	Woodstock, Ontario	1978	5000 m^2 at 127 mm; total length 0.8 km; evaluation of heavy traffic effect on SEA pavement with soft asphalt
Gulf Canada	Siddeburen, Holland	1978	2090 m^2 at 330 mm; total length 275 m; demonstration of sulphur-asphalt in the Netherlands
Gulf Canada	Rotterdam, Holland	1978	2500 m^2 at 300 mm; total length 550 m; full-depth SEA on sand base and as overlay under construction practices in Holland; major expressway estimated average daily traffic of 125 000
Gulf Canada	Louisiana	1978	10 800 m^2 at 175 mm; total length 1.6 km; evaluation of SEA in construction with low-quality aggregate (sands) as possible replacement of cement stabilized base construction
Gulf Canada	Gainesville, FL	1979	10 000 m^2 at 75, 125, and 175 mm; total length 1.2 km; demonstration of sulphur-asphalt construction; evaluation of sulphur-asphalt under high-volume traffic; layer equivalency
Gulf Canada	Route-63, MN	1979	Demonstration of SEA performance in overlay as part of longer test project with Petromat and carbon black; 0.8 km; use of drum mixer
Gulf Canada	MI-99, MI	1979	Overlay, 6.4 km long; varying thickness; two sulphur-asphalt ratios; use of drum mixer
Gulf Canada	Route-400, Ontario	1979	Varying thicknesses, from ¼ to 190 mm; on granular base, 1.6-km length; layer equivalencies
SUDIC	British Columbia	1979	SEA in hot-mix construction on highway project

Notes: 1 m^2 = 1.19 yd^2; 1 mm = 0.039 in; 1 km = 0.62 mile; 1 m = 1.09 yd.
Other sulphur-asphalt projects have occurred in Saudi Arabia, West Germany, Illinois, and Maine.

Marshall and Hveem Properties

Sulphur-asphalt mixtures can be designed by conventional methods. In addition, conventional design data and index properties are well understood. Table 3 (22) provides a comparison of average Marshall data for test specimens prepared by ASTM D 1559. The data show the sulphur-asphalt (SA) binder that contained 50 percent sulphur exhibited considerably higher stabilities than conventional mixtures. However, 20 percent asphalt-sulphur produced only a marginal increase. These higher stabilities resulted in no loss in flow properties. Figure 1 (13) illustrates a typical relationship between binder content and stability for conventional and sulphur-asphalt mixtures. Sand mixes (Thermopave) also generally have Marshall stabilities in excess of 9-11 kN (2000-2500 lbf) (10).

Sulphur-extended mixtures also can be expected to exhibit generally higher Hveem stability values. Table 4 and Figure 2 (13) illustrate typical relationships between Hveem stabilities for conventional and sulphur-asphalt mixtures.

Table 3. Stability values for sulphur-asphalt mixtures—Marshall test data.

Binder		Voids (%)	Flow (mm)	Voids in Mineral Aggregate (%)	Stability (N)
Type	Percentage by Weight				
40-50 Penetration Asphalt					
Asphalt	6.0	3.5	3.6	17.7	12 400
20/80 SA	6.5	3.1	3.0	17.5	12 800
50/50 SA	7.0	3.7	3.5	17.0	20 800
85-100 Penetration Asphalt					
Asphalt	6.0	2.6	3.1	16.3	9 800
20/80 SA	6.5	3.1	2.7	17.3	10 400
50/50 SA	7.0	4.0	3.3	16.9	22 400

Note: 1 mm = 0.039 in; 1 N = 0.224 lbf.

Figure 1. Relationships between Marshall stability and binder content showing effect of sulphur-asphalt ratio.

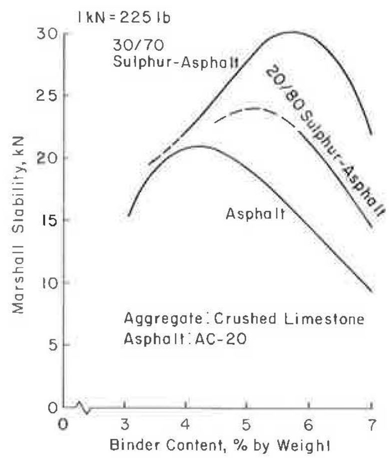
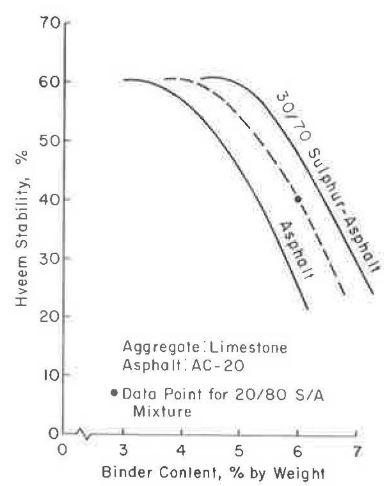


Figure 2. Relationships between Hveem stability and binder content showing effects of sulphur-asphalt ratio.



Resilient Modulus

Generally, the replacement of asphalt with sulphur can be expected to produce higher resilient moduli, but the increase is relatively small up to about 20 percent sulphur. However, for sulphur contents that exceed 50 percent, the resilient moduli increased significantly (17, 19, 22). Figure 3 provides typical resilient moduli for two different penetration grades of asphalt and three levels of sulphur. Other typical values for Texas mixtures are shown in Table 5 (13). Values can range as high as 6×10^6 kPa (890 000 lbf/in^2) and may actually be much higher at colder temperatures.

Fatigue Characteristics

The repeated-load indirect tensile test was also used to evaluate the fatigue behavior of sulphur-extended mixtures (17, 19). Typical fatigue life relationships for two penetration grades of asphalt and three levels of sulphur are shown in Figure 4. These results illustrate the effects of temperature and sulphur-asphalt ratio.

Under the stress-controlled loading, increasing the sulphur content to 50 percent provided a substantial increase in the fatigue life; however, there was essentially no improvement for 20 percent sulphur. Lytton (29), however, reported as a result of an analysis that used the VESYS computer program that the fatigue life was actually shortened. This is attributed to the fact that controlled strain conditions were being simulated.

Low-Temperature Stiffness

The addition of sulphur does not have any significant effect on the low-temperature stiffness of the sulphur-

Table 4. Stability values for sulphur-asphalt mixtures—Hveem stability.

Aggregate	Sulphur-Asphalt Mixture	Binder Content (% by weight)	Hveem Stability (%) Laboratory	Hveem Stability (%) Field Data
Limestone	0-100	4	57	
	0-100	5	46	
	0-100	6	26	
	20-80	6	40	
	30-70	5	44	
	30-70	6	37	
	30-70	7	30	
Lufkin sand	30-70	5	30	
	30-70	5.3		34
	30-70	5.5	33	
	30-70	6	31	34
	30-70	6.2		32
	30-70	7	29	29
	30-70	7.5		30
	30-70	8	31	
Lufkin type D	30-70	4.8		40
	30-70	5	44	
	30-70	5.3		39
	30-70	5.5	43	
	30-70	5.65		44
	30-70	6	37	37
	30-70	6.2		36
	30-70	6.5		38
	30-70	7	37	
	30-70	8	37	

Figure 3. Relationships between resilient modulus and sulphur content.

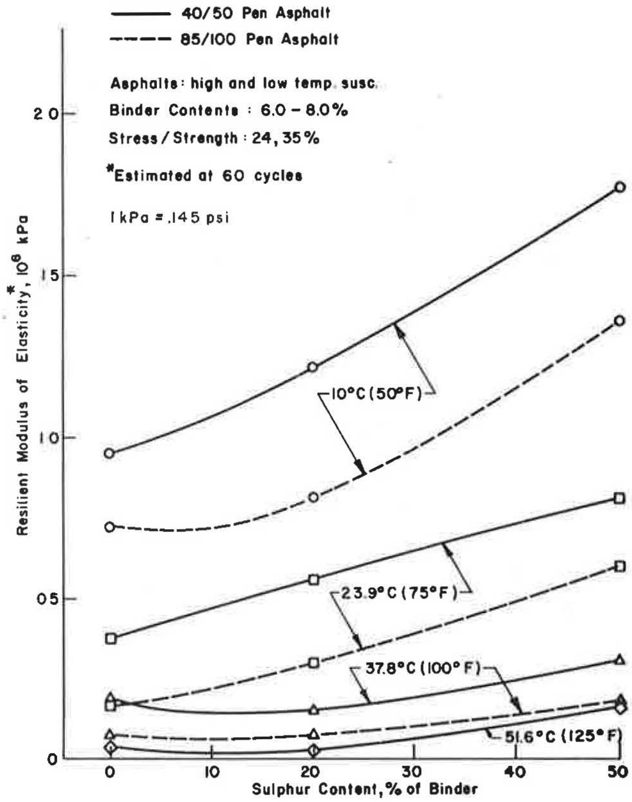
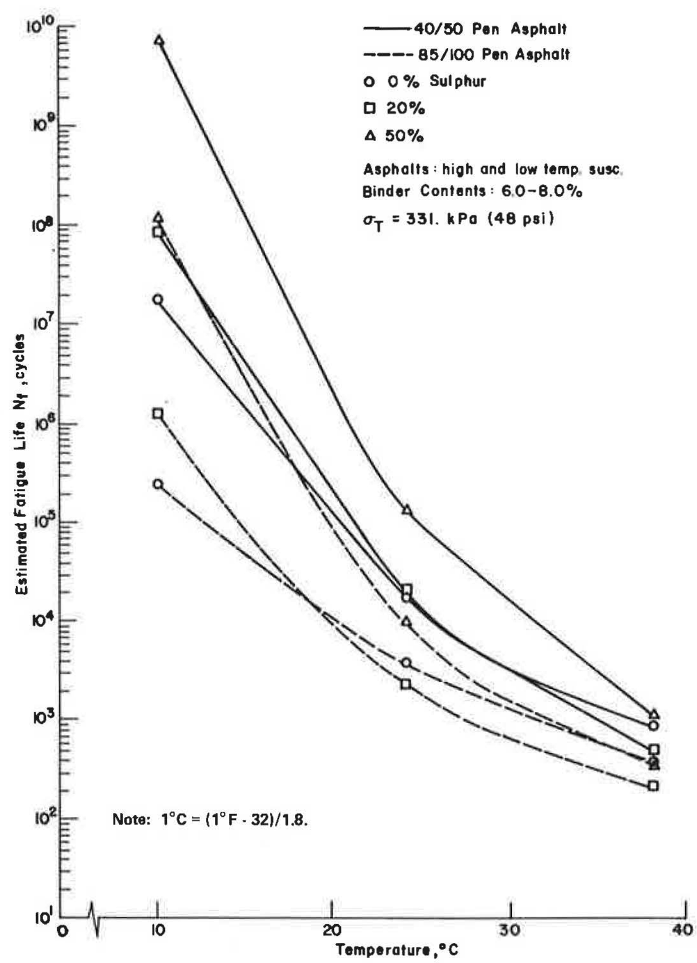


Figure 4. Relationships between fatigue life and temperature for sulphur-asphalt mixtures subjected to a low stress.



asphalt mixtures (22). The results of an extensive amount of testing over a range of properties indicated that the stiffness modulus of sulphur-asphalt mixtures is affected primarily by the consistency of the asphalt used in the binder and temperature (18). Thus, low-temperature cracking should not be adversely affected by the addition of sulphur to the binder. This has been verified by field observations (22).

Temperature Susceptibility Characteristics

The resilient moduli and low-temperature-stiffness modulus characteristics of SA mixtures can be combined in a single graph, as in Figure 5, to illustrate their temperature susceptibility characteristics over the entire

Table 5. Dynamic (resilient) modulus values for sulphur-asphalt mixtures.

Aggregate	Sulphur-Asphalt Mixture (by weight)	Binder Content (% by weight)	Resilient Modulus (kPa 000s)
Crushed limestone	0-100	5	2790
	0-100	6	2653
	0-100	7	1447
	20-80	6	3169
	30-70	4.5	3541
	30-70	6	6201
	30-70	7	5719
Lufkin type D	30-70	5.5	4134
Lufkin sand	30-70	8	723

Note: 1 kPa = 0.145 lbf/in².

Figure 5. Temperature susceptibility of sulphur-asphalt mixtures.

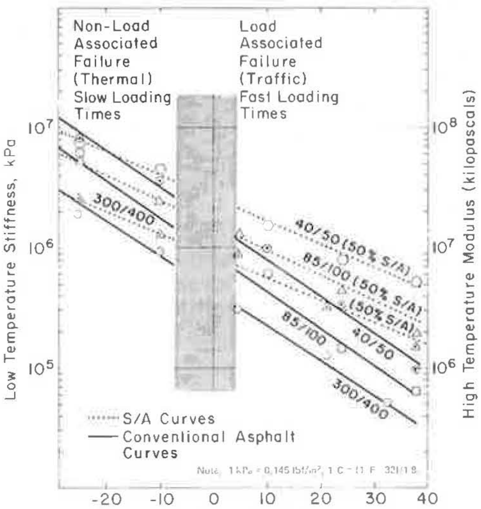
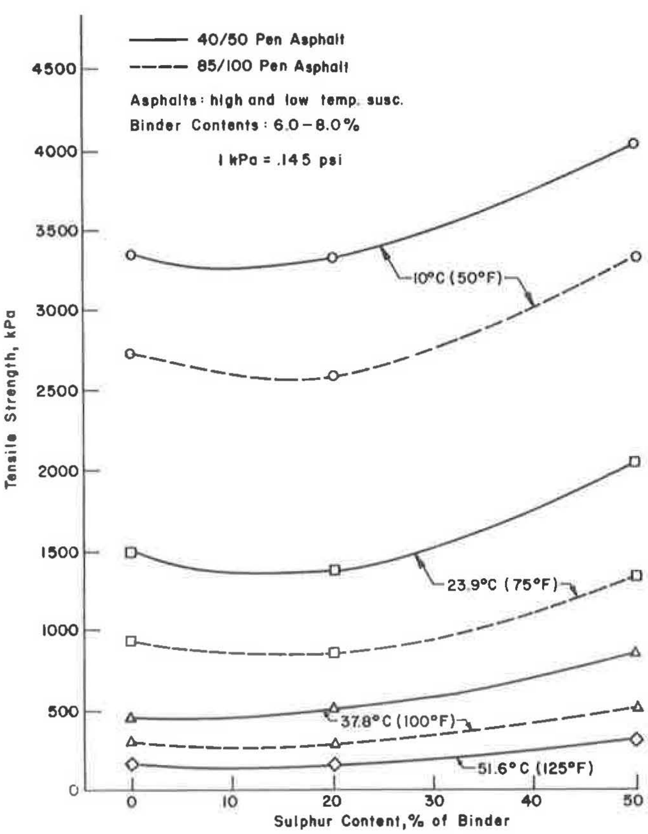


Figure 6. Relationships between tensile strength and sulphur content.



service temperature range (18).

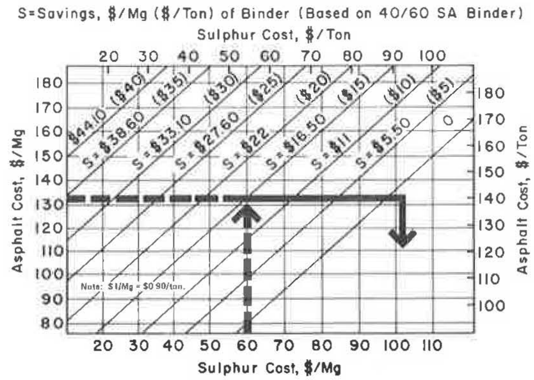
At high temperature, the addition of sulphur to a soft asphalt (e.g., 300-400 penetration) can increase its stiffness in terms of resilient modulus to that of the mixture made with 40-50 penetration asphalt alone. However, as previously noted at low temperatures, the addition of sulphur has no significant effect on stiffness. Thus, it is quite apparent that the effect of the addition of sulphur is very significant at high temperatures (and fast loading times) and insignificant at low temperatures (slow loading times) (22).

Table 6. Compressive strength properties of sulphur-asphalt mixtures.

Aggregate System	Sulphur-Asphalt Mixture	Binder Content (% by weight)	Compressive Strength (kPa)	Tensile Strength (kPa)
Limestone	0-100	5	3307	710
	0-100	6	3169	482
	30-70	5	5340	586
	30-70	6	5519	723
50-50 sand blend	30-70	5[a]	1860	379
	30-70	5.5[a]	4341	503
	30-70	6[a]	2997	427
Lufkin type D	30-70	5.5[a]	1447	379
Lufkin sand	30-70	8[a]	2274	255

Note: 1 kPa = 0.145 lbf/in^2.
[a]Mixtures used Texaco AC-20; all others used Exxon AC-10.

Figure 7. Binder cost savings with sulphur-extended asphalt binder.



Tensile and Compressive Strengths

Both the tensile and compressive strengths are increased by the addition of sulphur. In the case of tensile strength, the effect of the sulphur is essentially nonexistent until the amount of sulphur exceeds 20 percent (Figure 6). This is essentially the same type of behavior observed for fatigue life and resilient modulus. Additional values of tensile strength are shown in Table 6 for a variety of aggregates, sulphur-asphalt mixtures, and binder contents. Strengths tended to be related to the quality of the aggregate as well as the other two mixture variables. Compressive strengths are also continued in Table 6. As shown, substantial increases in strength generally occurred.

FUTURE POTENTIAL AND QUESTIONS

The use of sulphur in asphalt mixtures should become increasingly attractive from a substitution point of view, per se. For example, as shown in Figure 7, if asphalt is $132/Mg ($120/ton) and sulphur is $60.60/Mg ($55/ton), there would be a saving of $16.50/Mg ($15/ton) of binder used for 40-60 SA ratio. However, it appears that asphalt prices will be well above $132/Mg ($120/ton) in many areas of North America in 1980, whereas sulphur prices should not increase as rapidly.

The potential of design flexibility should also continue to make SEA binders more attractive in the future because mixtures can be produced to simultaneously satisfy both low-temperature shrinkage and higher-temperature traffic-loading requirements (17).

If savings in thickness can be realized, these will add to the substitution savings in the binder itself. Both the existing test roads and future planned construction, such as a large-scale overlay project scheduled on I-75 in Florida for late 1979, should allow at least some tentative conclusions to be drawn on this question in the relatively near future.

Extension of asphalt supply through the use of SEA binders should also become increasingly attractive. Spot shortages of asphalt, which have already appeared in 1979 in several areas of North America, can be expected to continue to occur, in association with general petroleum shortages.

The potential of SEA binder mixtures in recycling poses a major question, not so much in the short term but certainly as the first SEA pavements reach the end of their service lives. There seems no reason, however, why these mixtures cannot be recycled effectively, provided direct heating is not used. Also, the potential for using SEA binders in recycling of conventional mixtures should be good.

SUMMARY

Laboratory and field experience has demonstrated that sulphur-asphalt mixtures are more capable of providing improved engineering properties and probably improved field performance than many conventional asphalt mixtures. At this time, emphasis is on the use of SEAs because of their greater applicability and the reduction of asphalt consumption and the corresponding reduction in cost. However, most of the currently available processes can be used and are applicable to specific conditions. Based on current and past experience with sulphur-asphalt mixtures, the use of these materials can be expected to increase during the coming years.

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