

Effect of Composition on Asphalt Recycling Agent Performance

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Experiments have been conducted to determine the effect of metals, asphaltenes, and paraffins (oils and waxes) content on the properties of recycled aged asphalts. Recycling agents were produced by using a large Corbett type apparatus to fractionate asphalt fractions that had been previously separated from asphalt by supercritical fractionation. The material was separated into asphaltenes, aromatics, oils, and waxes, which were mixed in different ratios and blended with oxidized asphalts. The blends were then aged to study the composition effects during aging. In general, metals had little effect. Asphaltenes increase the hardening rate but not the oxidation rate. The effect of saturates depended on the asphaltene content. Waxes showed little, if any, effect on the measured properties. In general, highly aromatic recycling agents yielded material superior in the measured properties to the original asphalts.

Recycling of asphalt pavements is a very attractive concept, both environmentally and economically. Currently, about 27 million tons of asphalt binder and half a billion tons of rock are consumed each year in the building and maintenance of the nation's roads. Reuse of a significant portion of this material would eliminate an enormous amount of waste and greatly reduce the cost of our transportation system. Furthermore, if the recycling process could be used to optimize and improve the performance of the pavement, the costs of road maintenance could be reduced, and the general quality of roads could be improved.

During asphalt oxidative aging, the saturates (also known as paraffins) remain the same while the solubilizing aromatics decrease in quantity. The aromatics react with oxygen to produce asphaltenes, which causes the asphaltene content to increase. Because the saturates and asphaltenes are not soluble in one another, the increase in asphaltenes, accompanied by the decrease in solubilizing aromatics, leads to incompatibility. The incompatibility causes sharply increased viscosities and decreased ductility.

The softening agents presently used are often just a soft asphalt, which does little or nothing to improve, and can even exacerbate, the instability within the binder material. Thus, recycling agents that will reestablish the compatibility and performance of the old material on a long-term basis are much needed.

The main objective of this research is to determine what types of materials are suitable for use as asphalt recycling agents. Any material under consideration must of course be low in viscosity, so that the aged material can be blended back to new asphalt viscosity, using the smallest amount of recycling agent possible. Furthermore, the material must be highly aromatic, to replace the aromatic materials that have been consumed by oxidation reactions. It must be low in asphaltenes to maintain low viscosity and because the aged asphalt is already too rich in asphaltenes. Finally, recycle blends should have good aging characteristics.

METHODS

To produce recycling agents of specific compositions and measure their effects on the aging properties of reblended asphalts, experiments were designed in which the various components were produced, mixed in controlled amounts, and artificially aged. Typically, the materials used for recycling agents were fractionated using a procedure based loosely on the one developed by Corbett (1). The aim of this "Giant Corbett" procedure was to produce similar fractions, but in larger amounts than the Corbett procedure. Tank asphalts were artificially aged and recycling agents were mixed with them, yielding reblended asphalts that could be tested by artificial aging in a pressurized oxygen vessel (POV). The basic properties of interest in these experiments were the zero shear viscosity and the carbonyl area, an indicator of oxidation obtained through infrared spectrometry. These properties were measured on aged and unaged blends. In one experiment it was also necessary to measure the nickel and vanadium content of the samples using atomic absorption. It has been shown that the amount of increase of \ln (viscosity) relative to the corresponding increase in carbonyl area is a unique linear function for each asphalt (2,3) and is an excellent measure of aging. It is called the hardening susceptibility.

The modified Corbett procedure was a fractionation based on polarity. It was used to separate asphalt into four fractions—*asphaltenes*, *polar aromatics*, *naphthene aromatics*, and *paraffins*—in analytical amounts. The enlarged version was developed to produce these or similar fractions in larger amounts. Using the Giant Corbett procedure, a sample of up to 250 g may be processed, also yielding four fractions: *asphaltenes*, which roughly correspond to Corbett's asphaltenes; *aromatics*, which are basically a mixture of *polar* and *naphthene aromatics*; *oils*; and *waxes*. The asphaltenes are separated by precipitation, and the aromatics and paraffins are split by adsorption-elution chromatography on an enlarged alumina bed (about 1 kg). The last two fractions come from a further separation of the paraffin fraction based on the procedure described by Hoiberg and Garris (4).

The sample to be fractionated, either asphalt or supercritical fraction, is dissolved in 10 mL of hexane per gram of material and vacuum filtered. If asphaltenes are present, they are collected on the filter. The material still dissolved is then recovered using the Abson procedure, ASTM D1856-79, and redissolved in *n*-heptane. This solution is poured over a bed of activated alumina. A mixture of paraffin and solvent flows into a reboiling flask, where the solvent is boiled away, recondensed, and allowed to flow back into the top of the column and into the alumina bed. Over 3 hr this removes all of the paraffinic material, which, when recovered, resembles petrolatum in appearance and texture.

Once the paraffins have been removed from the bed, the column is drained of heptane. A new solvent composed of 85 percent

trichloroethylene and 15 percent ethanol dissolves the aromatic material adsorbed on the bed. Over another 3 hr this fraction, which contains both the naphthene and polar aromatics, is recovered and reported as aromatics.

The paraffins are dissolved in a solvent composed of two parts dichloromethane and one part acetone. This solution is then chilled to 0°C and vacuum filtered. The solid collected is a white or yellowish wax and is reported as waxes. The material that remains dissolved, when recovered, is a light yellow or brown oil and is reported as oils.

Although the asphaltenes may be slightly different from Corbett's asphaltenes due to the use of hexane rather than heptane for the precipitation, the difference is one of necessity. To ensure that all of the heptane-insolubles, which will plug the alumina column very quickly, are removed, it is necessary either to precipitate the asphaltenes from a highly dilute solution (100 mL solvent per gram of asphalt) or to use a weaker solvent. Corbett analysis of the fractions indicates that the aromatics contain no paraffins and that the paraffins contain no aromatics. However, IR analysis shows some aromatic pressure in the oils.

Supercritical fractions were obtained in a four-stage pilot unit capable of producing kilogram quantities of material (5). For this study two runs were made on the asphalt. The first removed asphaltenes and produced a large lower-molecular weight material fraction. This fraction was rerun to produce four more fractions. The lightest of these fractions is designated as Fraction 1 and the next as Fraction 2, and these were used in this study in several experiments.

To produce large amounts of aged material suitable for recycling, tank asphalts from various sources were artificially hardened in the laboratory by bubbling oxygen through molten asphalt at 450°F. Asphalts were also artificially aged in the POV. This was done at 190°F and 300 psia oxygen for some previously determined time period.

Once suitable materials were obtained or created using the preceding procedures, they were blended in controlled ways to test the effect of each fraction on the overall properties. A typical test blend consisted of a recycling agent, either selected from some available material or made up of the various Giant Corbett fractions, which was mixed with an aged asphalt. A series of blends was designed in each experiment to test the various compositional effects and artificially aged in a POV. This procedure is described by Lau et al. (3).

A Carri-Med CSL-500 controlled stress rheometer was used to measure the zero-shear complex viscosity of the samples at 60°C.

A Mattson Galaxy Series 5000 FTIR was used to measure the infrared spectra of samples using the attenuated total reflection (ATR) method, in which the IR beam passes through a prism and reflects off the inside of the sample surface (6). A slight penetration of the beam into the sample allows measurement of the spectra.

The trace metal content, specifically that of nickel and vanadium, was determined using an atomic absorption method based on the method described by Davison et al. (7), but which allowed use of smaller sample size and more efficient sample preparation.

EXPERIMENTAL DESIGN AND RESULTS

To accomplish the goals of the research several experiments were performed. They involved selecting or producing materials, mak-

ing blends from these materials, and performing POV aging tests on the blends. The experiments were designed to examine the following properties: effect of oils on aging of aromatic fractions; effect of metals and asphaltenes on aging; and effect of oils, waxes, and asphaltenes on reblended asphalt aging.

Some temperature gradient problems made kinetic analysis impossible in several experiments, but this does not affect the hardening susceptibility, which is independent of aging temperature.

Oils and Aromatics (Experiment 1)

On the basis of considerations already discussed, it was decided that the Giant Corbett aromatic fraction would be a good material to use as a recycling agent. However, it was found that aromatic fractions from asphalt had viscosities at 60°C as high as 4000 poise and that even aromatics from light supercritical fractions were a minimum of 100 to 200 poise. To bring the recycling agents into the required range, low-viscosity (typically less than 2-poise) oils could be added, but their effect on aging would have to be examined. To do this, a Fina supercritical fraction #1 was fractionated into four components using the Giant Corbett. From the oils and aromatics, three blends were made. They contained 20, 40, and 60 percent oil, respectively. These blends were POV aged at 180°F and 300 psia along with the pure oil and pure aromatic for periods of 4, 8, 12, and 16 days. Both change in \ln viscosity and carbonyl are linear in time, and a plot of $\ln \eta$ versus carbonyl (Figure 1) yields the hardening susceptibility as the slope.

The pure oil fraction experienced little or no aging during the test period. As the oil content of the blends decreased, the viscosity and carbonyl aging rates increased for all of the blends that contained oil. This trend did not apply to the pure aromatic fraction, which had lower aging rates after 4 days than the 20 percent oil blend, but this almost certainly was due to the temperature gradient in the POV together with the hypothesis that the aging rates should actually have been an average of the rates for the pure components. This possibility is supported by the hardening susceptibilities (a property independent of aging temperature) and their linear dependence on oil content as shown in Figure 2. The hardening susceptibility of each blend is actually an average of the hardening susceptibility of its components.

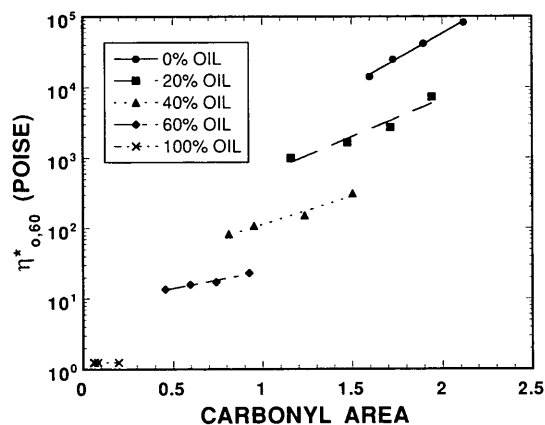


FIGURE 1 Experiment 1: hardening susceptibilities.

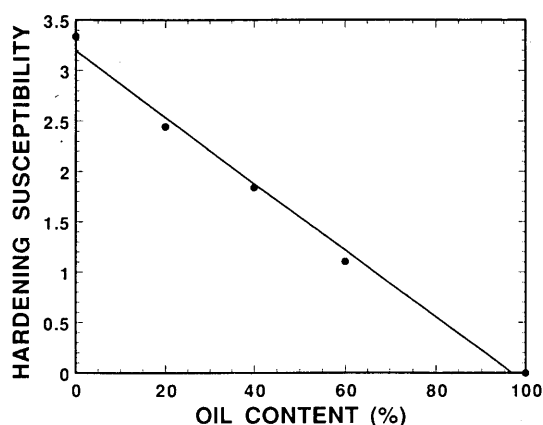


FIGURE 2 Hardening susceptibility versus oil content.

Metals and Asphaltenes (Experiment 2)

This experiment was designed to examine the effects of trace metals and asphaltenes on aging. Jemison (6) showed a strong correlation between hardening susceptibility and both metals (nickel and vanadium) and asphaltenes. There was some difficulty deciding how to isolate these two effects, since the asphaltenes typically contain almost all of the metals from the asphalt or fraction. The solution was to use asphaltenes from three different asphalts with different levels of metals. Blending these materials with an aromatic base would yield blends in which the asphaltene and metal contents would not be interdependent.

To perform the experiment, three tank asphalts were fractionated using the Giant Corbett: the McMillan low metal AC-20, the intermediate metals Exxon AC-20, and the Coastal AC-20 high levels. Nickel and vanadium content of the fractions was determined using atomic absorption. To make the asphaltene measurement more consistent, the heptane asphaltenes were measured for the asphaltene and aromatic fractions. (Since the bulk asphaltene

precipitation was not a careful analytical separation, there was a significant amount of asphaltene in the aromatic, and vice versa.) These data are presented in Table 1. The aromatic fractions were combined and used as a base, with 15 percent oil added to reduce viscosity. The three types of asphaltenes were blended with this material, producing nine blends with varying levels of metals and asphaltenes. The resulting blend compositions are given in Table 2. These blends were all aged in the POV at 180°F and 300 psia for periods of 4, 8, 11, and 14 days, and the viscosities and carbonyl areas were measured. The results show some scatter because of the temperature gradient problem, but the results are still interesting. Figure 3 shows no effect of metals on hardening susceptibility, whereas Figure 4 shows a definite correlation with asphaltenes. This leads to the surprising result shown in Figure 5 that starting asphaltenes have essentially no effect on the oxidation rate but definitely increase the hardening rate through the adverse effect on hardening susceptibility.

Supercritical Fractions as Recycling Agents

Three sets of experiments were performed using light supercritical fractions directly as recycling agents or they were used after alteration of the oil, wax, and asphaltene content. In the first set of experiments (Experiment 3), two light supercritical fractions were chosen: a Fina fraction #2 and a Coastal fraction #1. In addition, the same fractions were dewaxed using the procedure for the oil and wax separation from the Giant Corbett, and the dewaxed materials were used as two more recycling agents. These four agents were blended with five artificially aged asphalts to make 10 blends. Table 3 gives the composition based on Corbett analysis and the viscosity of each recycling agent, aged asphalt, and re-blended asphalt. The hardening susceptibilities are also given in Table 3 except for blends R1, R7, and R8, which either hardened too little or too much because of a temperature control problem. The saturate content was much higher in this experiment than in the other two, and the hardening susceptibilities, as will be shown later, are anomalous.

TABLE 1 Asphaltenes and Metals of Starting Fractions

Material	Starting % Asphaltenes	Nickel (PPM)	Vanadium (PPM)
Coastal Asphaltenes	78.1	142.1	966.7
Coastal Aromatics	2.2	32.1	160.9
Exxon Asphaltenes	80.6	20.5	32.1
Exxon Aromatics	2.8	9.0	13.3
McMillan Asphaltenes	48.1	82.5	288.7
McMillan Aromatics	3.6	22.1	60.7

TABLE 2 Compositions of Blends in Experiment 2

Blend	Base % Aromatic	Starting % Asphaltene	Nickel (PPM)	Vanadium (PPM)
L-10	88.67	11.33	45.3	54.6
L-20	83.21	16.79	22.2	46.8
I-10	89.79	10.21	24.2	88.5
I-20	80.05	19.95	27.6	83.3
I-30	73.15	26.85	26.7	75.1
H-10	89.96	10.04	29.2	137.7
H-20	82.19	17.81	32.7	128.1
H-30	74.37	25.63	36.3	118.5
Aromatic Base	97.38	2.62	16.9	47.3

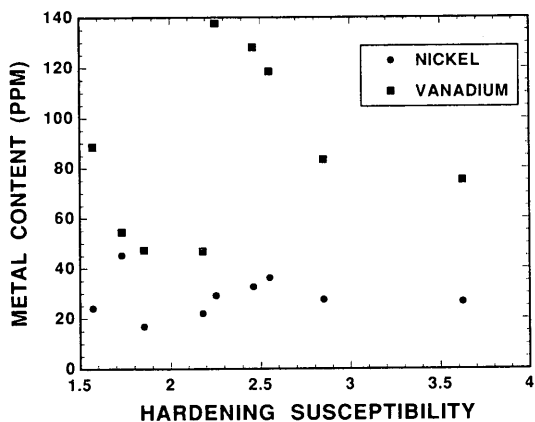


FIGURE 3 Effect of metals on hardening susceptibility.

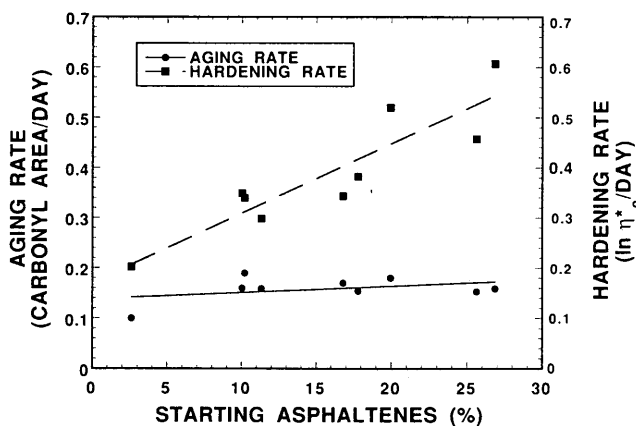


FIGURE 5 Effect of asphaltenes on hardening rate and carbonyl formation rate.

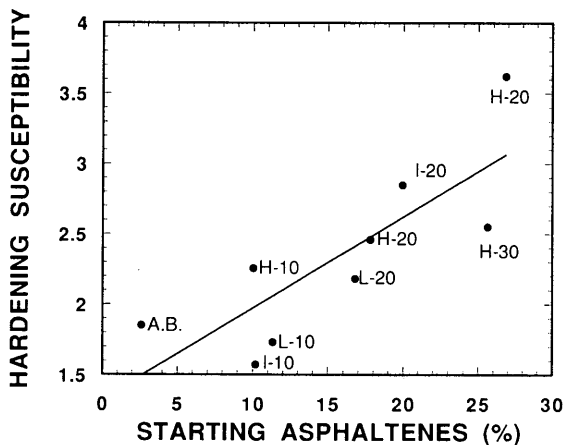


FIGURE 4 Effect of asphaltenes on hardening susceptibilities.

Although the ductility was not measured in this research, there were samples from this experiment that had visibly poor ductility. At viscosities of only several thousand poise, the material from the POV trays would crumble and had the texture of soft cheese. It is thought that the high paraffin content caused incompatibility and the resultant loss in ductility. Evidence of this effect also came from the viscosity data. The frequency sweeps run to determine the zero-shear viscosities tended to become flat very soon in the run, as expected with these low viscosities, but later jump to a higher viscosity and level out again. A typical frequency sweep and one exhibiting this behavior are shown in Figure 6. This effect was especially notable at higher saturate levels and became more pronounced as the blends aged.

In Experiment 4, a Coastal supercritical fraction #1 was fractionated and its oils and aromatics and waxes were used to make four recycling agents. They contained 15.28 percent oil, 8.26 per-

TABLE 3 Compositions and Viscosities of Materials in Experiment 3

Material	Blend Makeup	% Par.	% Orig. Asph.	Mix Ratio %	Hard. Susc.	Viscosity (P)
Coastal SC Fraction 1	NA	20.33	0.33	NA	NM	0.599
FINA SC Fraction 2	NA	33.67	0.67	NA	NM	0.631
DW Coastal SC Fraction	NA	18.04	0.35	NA	NM	1.358
DW FINA SC Fraction	NA	30.21	0.72	NA	NM	1.185
Aged Ampet AC-20 #1	NA	8.33	12.33	NA	NM	83,000
Aged Ampet AC-20 #2	NA	8.33	12.33	NA	NM	260,000
Aged Ampet AC-20 #3	NA	8.33	12.33	NA	NM	160,000
Aged Cosden AC-20	NA	13.00	16.00	NA	NM	105,000
Aged Texaco AC-20	NA	8.22	18.41	NA	NM	230,000
Blend R1	Ampet #2/ Coastal SC	13.57	8.95	56/44	NM	270
Blend R2	Ampet #2/ Fina SC	19.25	9.16	57/43	2.05	265
Blend R3	Ampet #3/ Fina SC	18.47	9.60	59/41	2.09	271
Blend R4	Ampet #3/ DW Coast.	12.07	8.95	61/39	2.25	333
Blend R5	Cosden/ DW Coast.	15.43	10.50	52/48	2.06	130
Blend R6	Cosden/ DW Fina	21.33	10.67	52/48	2.48	261
Blend R7	Texaco/ DW Fina	17.10	12.65	60/40	NM	568
Blend R8	Texaco/ Coastal SC	13.45	12.64	57/43	NM	470
Blend R9	Ampet #1/ Coastal SC	15.58	6.88	37/63	1.41	30.3
Blend R10	Ampet #1/ DW Coast.	14.67	5.09	35/65	1.90	70.2

NA Not Applicable
 NM Not Measured

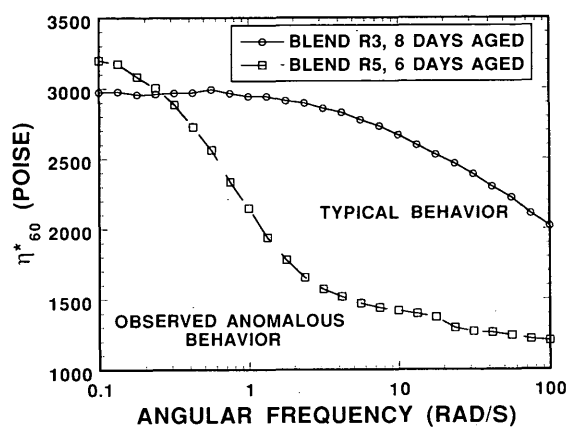


FIGURE 6 Asphalt viscosity frequency sweep.

cent oil, 7.71 percent oil plus 4.09 percent wax, and one with no oil or wax. They were named A, B, C, and D, respectively. They were blended with four aged asphalts to make 11 blends. Table 4 gives the viscosities of the asphalts, agents, and blends and the mixing ratios for each blend and composition.

Unfortunately, continued temperature problems ruined many of the kinetic data from this experiment. However, the hardening

susceptibilities of the blends could still be analyzed, and they revealed some important results. Figure 7 shows combined viscosity versus carbonyl curves from all three aging temperatures for the various blends for the aged Coastal asphalt. In addition, the thick line above the blend data shows the viscosity/carbonyl relationship previously measured for the original asphalt. The slopes of these lines, the hardening susceptibilities, are actually lower in every case for the rebled material than for the original asphalt, indicating that the aged asphalt was improved by the recycling agent, at least from the standpoint of this analysis. There was less improvement for the Ampet materials than for the Texaco and Coastal, presumably because the Ampet was originally a better material. The improvements in hardening susceptibilities for the Texaco and Coastal asphalts are significant.

The fifth experiment was very similar to the fourth in that recycling agents were designed to have a specific composition. This time, however, more variation was used in the amount of wax in the blends, and asphaltenes were included. Also, the temperature gradient in the POV had been eliminated. The materials for the recycling agents came from an Exxon Supercritical fraction #1, which was further fractionated by the Giant Corbett. Only one-half of the paraffin fraction was separated into oil and wax; the other was left alone. Six recycling agents containing varying amounts of oils, paraffins, aromatics, and asphaltenes were made from these materials. They were labeled E, F, G, H, I, and J, respectively. The agents were blended with an artificially aged

TABLE 4 Viscosities and Blending Ratios for Experiment 4

Material	Visc. (P)	Mix Ratio (%) (Asph./Agnt.)	Hard. Susc.	Temp. Susc.	% Orig. Asph.	% Sat.
Agent A	20.2	NA	NM	NM	0	15.28
Agent B	47.7	NA	NM	NM	0	8.26
Agent C	37.6	NA	NM	NM	0	11.8
Agent D	183	NA	NM	NM	0	0
(7.71 oil, 4.09 wax)						
Ampet AC-20	20,200	NA	NM	NM	12.33	8.33
Coastal AC-20	41,000	NA	NM	NM	19.41	8.91
Texaco AC-20	89,700	NA	NM	NM	18.41	8.22
Blend AA	1230	70/30	2.32	19746	8.63	10.41
Blend AB [†]	500	63/37	1.79	20597	12.22	8.30
Blend AC	1055	65/35	1.95	19242	8.02	9.54
Blend AA*	615	45/55	2.42	19000	5.55	12.15
Blend CA	750	64/36	2.33	18748	7.89	11.20
Blend CB	495	56/44	2.02	19046	10.87	8.62
Blend CC	535	58/42	2.21	18215	11.26	10.12
Blend CD	518	40/60	1.74	19231	7.76	3.56
Blend TA	436	58/42	1.79	17935	10.67	11.18
Blend TB	445	50/50	1.93	18876	9.21	8.24
Blend TC	450	52/48	1.90	18064	9.57	9.93
Blend TD	555	36/64	1.39	18970	6.63	2.95

(Notation for blends: A = Ampet, C = Coastal, T = Texaco;

A = Agent A, B = Agent B, C = Agent C, D = Agent D;

Example: Blend CB contains Coastal AC-20 and Agent B.)

NA Not Applicable

NM Not Measured

[†] Due to a shortage of material, a more highly aged Ampet asphalt was used for this blend, which had a viscosity of 260,000 Poise.

* Also due to a shortage of material, this blend contains the same recycling agent as blend AA.

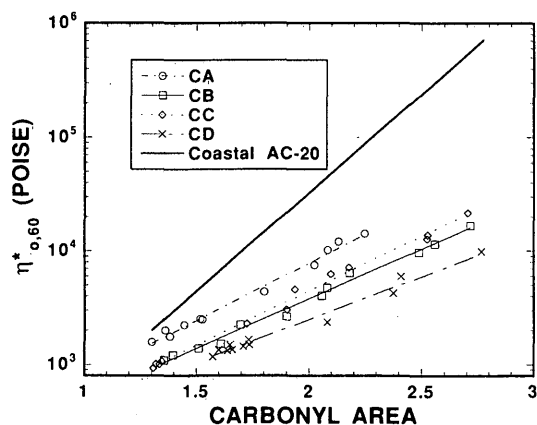


FIGURE 7 Coastal blend hardening susceptibilities.

Texaco asphalt. Table 5 gives the component viscosities, mixing ratios, and resulting viscosities and compositions for each reblend.

These recycled blends were aged in the POV at 300 psia and 160°F for 8, 12, 14, and 16 days; at 175°F for 10, 13, 16, and 19 days; and at 190°F for 4, 6, 8, and 10 days. All of the blends have roughly the same aging rate except for I and J, which contain

wax. This behavior was observed at all three temperatures; moreover, at two temperatures the carbonyl growth rate decreased as wax content increased. (The actual wax content was not measured; the reblending agent that contained only paraffins would have approximately twice as much wax as the one containing paraffins and oil.) Examination of the viscosity data reveals similar behavior. This would indicate that, although the aging rates seemed to be lower for the blends with waxes, the hardening susceptibilities should be close to the same. Arrhenius plots indicate no obvious effect of composition on activation energies.

Also of importance are the differences between the aging rates for the original and recycled asphalts. Aging data previously collected for the Texaco AC-20 (8) reveal similar rates of carbonyl growth. At 160°F, the asphalt's carbonyl area increased by approximately 0.3 over 10 days, whereas the blends in this experiment displayed increases of approximately 0.25 over 9 days at the same temperature. At the same time, the asphalt's viscosity increased by about half an order of magnitude, whereas the blends only hardened half that much (which is consistent with the hardening susceptibility). Furthermore, the 20-day, 160°F aged asphalt had a viscosity of about 100 000 poise from a tank value of 2500; a typical blend viscosity from a similar aging time was 6000 poise from an initial 600.

TABLE 5 Viscosity and Mixing Data for Experiment 5

Material	% Sat.	% Asph.	Visc(P)	Hard. Susc.	Temp. Susc. ($\times 10^{-4}$)	Mixing Ratio % (Asphalt) /Agent)
Agent E	20.4	0	36	NM	NM	NA
Agent F	14.9	0	37	NM	NM	NA
Agent G	10.2	2.8	111	NM	NM	NA
Agent H	9.9	5.4	132	NM	NM	NA
Agent I*	11.2 (6.1 oil, 5.1 paraffin)	0	37	NM	NM	NA
Agent J*	10.6 (all paraffin)	0	63	NM	NM	NA
Aged Texaco AC-20	8.22	18.41	160,000	NM	NM	NA
Blend E	13.1	11.0	358	2.25	1.87	60/40
Blend F	10.9	11.0	579	2.16	1.89	60/40
Blend G	8.9	13.4	945	2.02	1.92	68/32
Blend H	8.2	14.5	1169	1.97	1.97	70/30
Blend I	9.4	11.0	755	1.88	1.9	60/40
Blend J	9.1	11.8	865	2.03	1.93	64/36

NM Not Measured

NA Not Applicable

* Saturates in agent I are part oil and part unseparated paraffin. In agent J, saturates are all paraffin. The wax in these agents is contained in the paraffin.

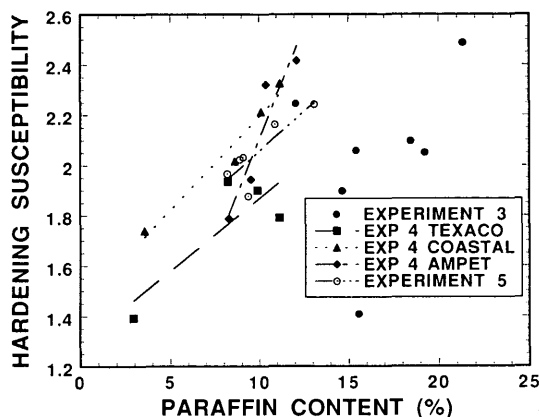


FIGURE 8 Effect of paraffins on hardening susceptibilities.

Effect of Saturates on Hardening Susceptibility and Temperature Susceptibility

In Experiments 3 through 5, hardening susceptibilities were measured for each blend. They are plotted versus saturate content in Figure 8. As expected, there is considerable variation because a variety of aged asphalts and blending agents were used, but in general the hardening susceptibility increases with saturate content. This most clearly is seen in Experiment 5, in which a single aged asphalt and a single recycling agent base stock were used. This result is contrary to the data in Experiment 1, in which oils and aromatics were aged, but confirms the adverse effect of asphaltenes in Experiment 2.

There is no apparent effect of wax in these experiments, which is not surprising since these hardening susceptibilities are based on 60°C viscosities, whereas the detrimental effects of wax are at low temperature.

Most of the Experiment 3 data appear anomalous. There are two possible explanations. The first is that Experiment 3 composites are based on Corbett analysis, whereas in Experiments 4 and 5 they were made by weight. Perhaps there is a systematic error. The other possibility is that the strange frequency sweeps seen in Figure 9 are giving erroneous viscosities as a result of phase separation.

In Experiments 4 and 5 viscosities were run from 0°C to 60°C. The logarithms of viscosities were plotted versus reciprocal absolute temperature to obtain the temperature susceptibility, the slope of these lines (Tables 4 and 5). These values are plotted as a function of saturate content in Figure 9. The property shows no sensitivity to wax but correlates with total saturate content. In all cases, temperature susceptibility decreases with paraffin content. The temperature susceptibilities of the original asphalts are markedly larger than the reblended aged material.

CONCLUSIONS

Recycling agents should be highly aromatic, and if so the recycled pavement can be superior to the original pavement. Both hardening susceptibility and temperature susceptibility were generally

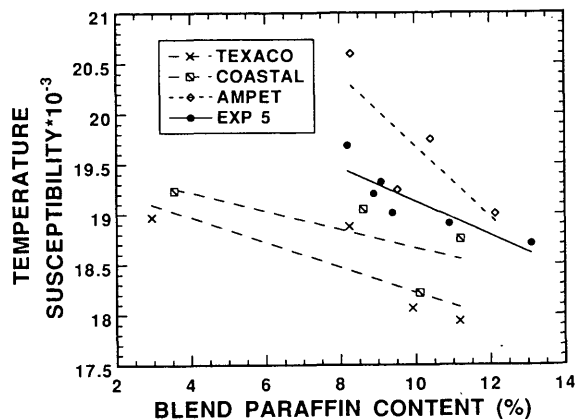


FIGURE 9 Effect of paraffins on temperature susceptibilities.

improved by adding highly aromatic agents. Saturates reduce the hardening susceptibility of the aromatic fraction in the absence of asphaltenes. In the recycling of aged material containing large amounts of asphaltenes, saturates increase hardening susceptibility but improve temperature susceptibility. Wax had little effect at the small amounts added, but both waxes and saturates almost certainly affect ductility adversely at levels as low as 15 percent, and wax has been reported to affect low-temperature properties.

The metal study indicated that metals appear to have little if any effect on either oxidation rate or hardening susceptibility. The apparent effect often reported probably results from the high correlation between metal content and asphaltenes. The oxidation rate is primarily determined by the reactivity of the aromatic fraction.

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