PB 290184

Report No. FHWA-TS-79-204

EVALUATION OF SELECTED SOFTENING AGENTS USED IN FLEXIBLE PAVEMENT RECYCLING

April 1978

Prepared for

FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Washington, D.C. 20590

NOTICE

Final Report
April 1978

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Prepared in Cooperation with the U.S. Department of Transportation, Federal Highway Administration.

- ACKNOWLEDGMENTS -

Appreciation is extended by the author and study investigators to T. W. Kennedy, University of Texas at Austin, H. Plancher, Department of Energy, Laramie, Wyoming, J. W. Bunger, University of Utah and Wade B. Betenson, Utah D.O.T., for their services and comments throughout the study.

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INTRODUCTION AND RESEARCH APPROACH

The recycling of asphaltic concrete is becoming more feasible as a method of rehabilitating distressed pavements. The drastic increase in the cost of materials and labor, as well as the energy shortage, has forced the pavement industry to face the issue. Significant reductions in cost have been reported, and many speculate that greater increases in service life will be realized than if a conventional overlay were used. The potential of recycling warrants a great deal of study to perfect adequate methods of reusing certain in-place materials.

Flexible pavement recycling is facing many problems however. The difficulty in meeting air-quality standards and the lack of established design procedures are two of the major problems which need to be addressed.

There are a wide range of softening (rejuvenating) agents used to restore properties of the asphalt in recycled mixes. These agents can be used in varying quantities which will have differing effects on the properties of the recycled mix and on the future performance of the pavement. Additional information is required on the need for softening agents and the quantity in which they should be used for different in-place pavements planned for recycling.

The aim of this study was to evaluate various softening agents used in the recycling process. The objectives of the study were as follows:

1. Determine what the effect is on the mix and asphalt properties of adding various rejuvenating agents in varying amounts during the recycling of asphalt concrete.

2. Determine the effect on the resilient modular and creep properties of mixtures after additions of various amounts of rejuvenating agents.

3. Obtain information relating the change in material properties in the first few months after recycling due to aging and/or any delayed effect of the rejuvenating processes.

SAMPLE PREPARATION AND RECYCLED BINDER CONSISTENCY

Softening Agents

Twenty-three different softening agents were tested to determine their physical properties and chemical components. The results of these tests are listed in Table 1.

With the exception of the Tenneco Flux Oil, the agents are very low in asphaltenes content. It is speculated that this contributes to the low viscosity values measured, since previous studies have related low asphaltenes contents to low viscosities in asphalts.(1, 2) The higher level of asphaltenes (15.5%) in the Flux Oil possibly contributes to its relatively higher measured viscosity values at temperatures between 100° and 275°F. (38° and 135°C.).

Additional relationships between the physical and chemical properties of these softening agents are discussed in Appendix A.

From the available softening agents, four were selected for further analysis in this study as follows:

Flux Oil (Tenneco)

Reclamite Base (70% residue)

Dutrex 739

Dust Oil (Cenex)

These four agents were selected since they have been used previously, and represent a wide range in physical and chemical properties.

TABLE 1

PROPERTIES OF SOFTENING AGENTS

ASPHALT PROPERTIES	Tenneco Flux	Reclamite Base *	Dutrex 739	Cenex Dust Oil	McMillan 2000 VR	McMillan WD 700	Paxole 407	Paxole 509	Paxole 558	Paxole 958	Paxole 1009	Paxole 1107
Viscosity @ 100°F, CS	41,000	885	3170	99	520	148	30	117			3040	
Viscosity @ 140°F, CS	4,320	139	230	26	115	45	12	33	38	178	178	170
Viscosity @ 210°F, CS	250.6	17.6	23.3	5.6	20.2	10.2	3.6	6.9	7.0	20.2	21.0	20.2
Viscosity @ 275°F, CS	61.0	5.2	9.0	2.5	7.0	4.5	1.8	3.0	3.1	7.0	8.0	7.0
Specific Gravity	.998	.985	1.023	1.070	.946	.941	.985	.986	.992	.989	1.038	1.002
Pounds/Gallon	8.31	8.22	8.25	8.91	7.88	7.83	8.22	8.21			8.65	
Smoke Point, °F	327	250	279	258	383	295	246	235	248	278	284	295
Flash Point coc °F	494	410	415	350	545	433	356	358	365	414	419	448
Fire Point, °F	550	436	464	410	599	491	394	399	417	488	486	508
Volatility	0.08		0.1			.28		1.1			0.36	
Mixed Analine PT, °F	150	115	83	106	163	154	97	87	94	117	76	118
Refractive Index, 20°C	1.573	1.548	1.589	1.642	1.529	1.526	1.563	1.575			1.600	
Asphaltenes, %	15.5	0.5	0	4.1	0	0	0.3	0.5	TR	TR	0	TR
Polar Compounds, %	18.7	17.7	23.1	14.4	4.3	3.1	4.7	14.3	15.6	08.6	25.9	14.6
1st Acidaffins, %	21.3	16.4	29.2	40.7	15.5	15.1	15.1	20.8	15.7	15.6	26.2	22.5
2nd Acidaffins, %	24.6	38.6	42.0	26.0	44.7	42.2	64.2	53.7	55.8	56.3	41.6	44.4
Saturates, %	20.0	26.8	5.7	14.8	35.5	39.6	15.6	10.6	13.0	19.7	6.6	18.5

ASPHALT PROPERTIES	Whitco 2819	Whitco 3928	Whitco 3930	Whitco Cycle-Pave	Califlux G.P.	M.D.A	Ashland RD-384P	Ashland RD-632Q1	Ashland RD-633Q1	Rejuv-Acote-Base	Arizona 510
Viscosity @ 100°F, CS	774	1800	92400		1470	14	258	81	444	600	150
Viscosity @ 140°F, CS	114	178	3240	109	197	7	39	25	81	99	40
Viscosity @ 210°F, CS	20.1	19.8	110	16.8	13.8	2.6	10.2	6.2	14.1	13.8	7.3
Viscosity @ 275°F, CS	5.0	8.0	21.0	7.3	6.6	1.0	3.4	2.8	5.3	5.5	3.2
Specific Gravity	.981	1.010	1.015	0.978	1.002	1.045	1.148	.979	.949	.999	.991
Pounds/Gallon	8.17	8.42	8.46		8.35	8.71	9.57	8.16	7.92	8.33	8.26
Smoke Point, °F	275	257	333	280	284	190	248	275	308	217	217
Flash Point, coc, °F	419	410	491	402	410	325	395	424	462	378	365
Fire Point, °F	460	460	541	450	464	365	464	459	512	406	421
Volatility					0.88		1.38	.28		1.66	1.16
Mixed Analine PT, °F	123	94	99	121	100	60	80	119	126	103	102
Refractive Index, 20°C	1.550	1.572	1.586		1.566	1.636	1.674	1.552	1.560	1.522	1.559
Asphaltenes, %	TR	0.4	0.8	TR	0	2.7	1.6	0.8	0.6	2.9	1.1
Polar Compounds, %	15.7	31.8	31.2	17.1	20.4	3.0	11.7	7.7	11.0	15.7	13.7
1st Acidaffins, %	17.7	21.5	20.7	16.0	17.5	36.8	51.7	20.0	20.6	20.0	19.4
2nd Acidaffins, %	38.6	44.8	37.5	39.5	47.5	57.3	34.2	47.1	44.7	43.9	47.6
Saturates, %	28.0	11.7	9.7	27.5	14.5	0.2	0.8	24.5	23.0	17.6	18.2

* Emulsified Solution (Residue 70%)

(Prepared By Max L. Wiley, Utah DOT)

Pavements for Recycling

Two pavements which are being considered for recycling were selected for investigation using the four softening agents. Table 2 gives a general description of these pavements, and Table 3 lists the gradations, mix properties and asphalt properties of the inplace materials.

Pavement No. 1 showed a greater variability in the inplace asphalt content than did pavement No. 2. This resulted in a wider variation in the recycled binder content and asphalt consistency when a specific amount of softening agent was added to a given sample. In turn the measured properties of the mixes showed a greater variability for pavement No. 1 as will be seen in the following discussions.

Table 4 lists the measured physical and chemical properties of the aggregate sources in the two mixes.

Both pavements are cracked extensively, and show high deflections relative to their respective traffic loadings. A 3 1/2 inch (8.9 cm) overlay, increasing the thickness to 7 inches (17.8 cm) would be needed on pavement No. 1 to extend its life by 20 years. By recycling and increasing the total thickness to only 5 inches (12.7 cm), it is estimated that the 20 year life can be achieved for less materials cost, and without the likelihood of reflective cracking. An estimated 7 inch (17.8 cm) overlay would be needed to increase the life of pavement No. 2 by 20 years. This would increase the thickness to 14 1/2 inches (36.8 cm). A total thickness of only 8 1/2 inches (21.6 cm) is projected by recycling the inplace material.

TABLE 2
PROJECT DESCRIPTION

	PROJECT NUMBER	DESCRIPTION	LENGTH	WIDTH	THICKNESS
PAVEMENT NO. 1	RF-027-2(3)	Hatch to Bryce Cyn.	8.3 miles (13.4 Km)	36 Ft. (11.0 m)	3.5 in. (8.9 cm)
PAVEMENT NO. 2	IR-15-3(18)121	Wildcat Int. to Sulphurdale Int.	8.8 miles (14.2 Km)	38 Ft. (11.6 m)	7.5 in. (19.1 cm)

TABLE 3

PROPERTIES OF CORE SAMPLES

		GRADATION - % PASSING									MIX PROPERTIES					ASPHALT PROPERTIES			
		1"	3/4"	1/2"	3/8"	#4	#8	#16	#50	#200	%ASPH.	%VOIDS	DENSITY	STAB.	FLOW	VIS @ 140°F	VIS @ 275°F	PEN	DUCT.
Pavement No. 1 Hatch to Bryce Cyn	Mean	100	96.9	86.7	80.1	64.2	53.7	46.1	27.2	8.1	6.5	7.7	2.25	1,950	19	3,617	335	57	6
	S.D.	0	1.6	2.7	2.6	2.5	2.7	2.3	1.6	1.3	0.4	---	0.02	221	2.0	---	---	---	---
Pavement No.2 Beaver to Pine Creek	Mean	100	98.2	90.2	82.2	57.8	43.3	33.0	18.3	10.9	6.1	5.6	2.33	2,920	15	5,420	462	36	3
	S.D.	0	0.8	2.2	2.3	2.2	2.0	1.6	1.0	0.6	0.2	---	0.02	290	1.2	5,600	---	10	---

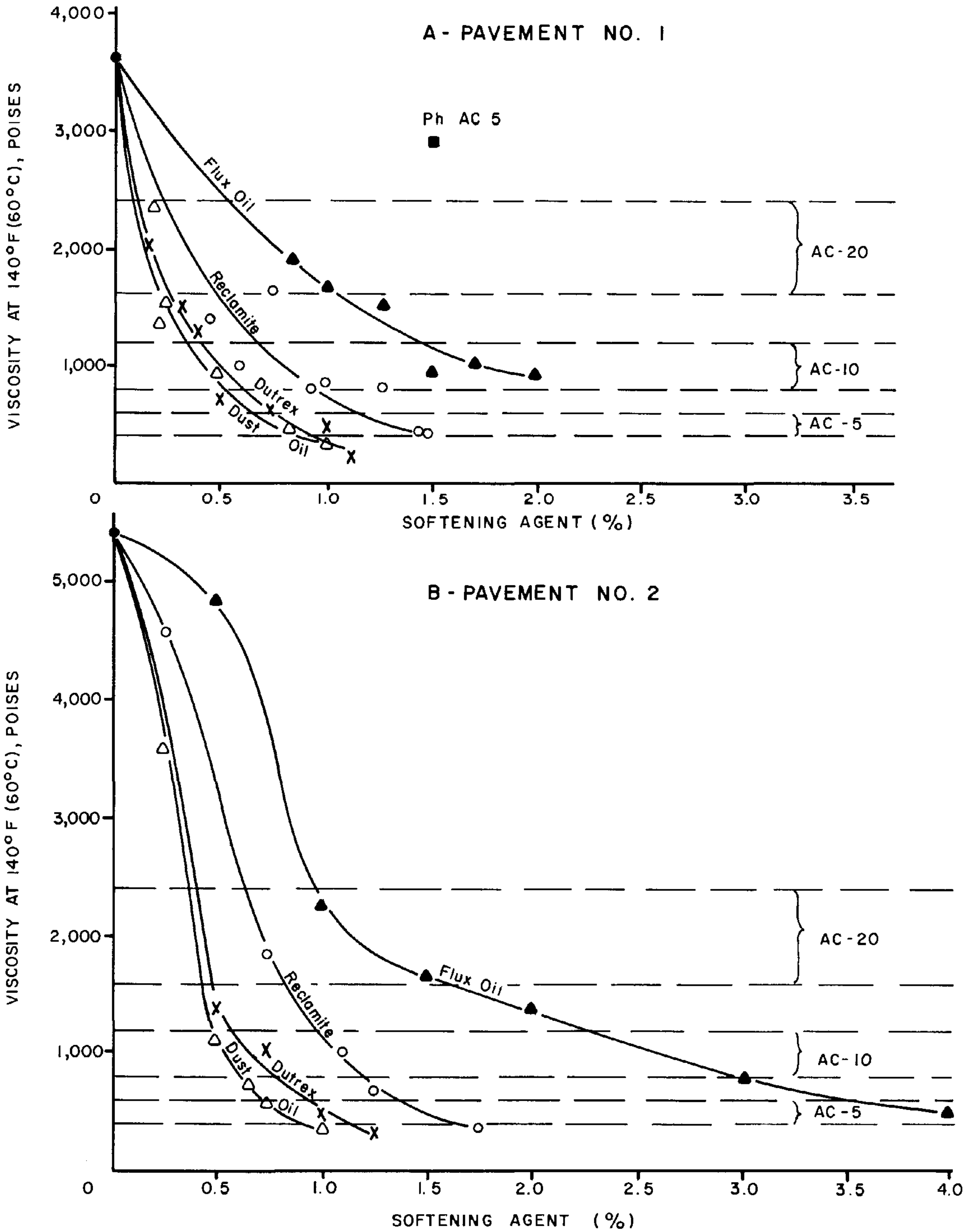
TABLE 4
PROPERTIES OF AGGREGATE
SOURCES

	Property	Pavement No. 1	Pavement No. 2
Physical Properties	Liquid Limit	NA	21
	Plastic Index	Nonplastic	Nonplastic
	Absorption	3.03%	3.3%
	Abrasion	27.7%	30%
	Fractured Face	91.0%	90%
	Soundness	9.86%	17.4%
	Specific Gravity	2.56	--
Chemical Properties	SiO_2	54.7%	64.3%
	Fe_2O_3	9.3%	5.3%
	Al_2O_3	15.7%	15.1%
	CaO	8.2%	3.5%
	MgO	2.7%	1.5%
	Na_2O(Sol.)	0.1%	0.1%
	Na_2O(Insol.)	2.1%	2.9%
	K_2O(Sol.)	0.1%	0.1%
	K_2O(Insol.)	2.0%	3.3%
	CO_2	3.0%	0.4%
	SO_4	0%	0%
	Cl	0%	trace
	Moisture	1.2%	0.8%
	Organic	0.6%	2.0%
	pH(Water Sol.)	8.5	8.8

Binder Consistency

Various amounts of each of the four softening agents were added to extracted asphalt from each of the two pavements. The absolute viscosity at 140°F (60°C) of these mixtures was measured, resulting in the curves shown in Figures 1A and B. From these curves, the percentages of each softening agent was determined to obtain the three target binder consistencies AC20, AC10 and AC5 as listed in Table 5. The values are percentages by weight of the total mix. Nine samples for each cell were prepared at

FIGURE I
ABSOLUTE VISCOSITY AT 140°F (60°C)
VS
PERCENT SOFTENING AGENT



these levels for testing. Standard Marshall samples were used throughout the study formed according to AASHTO T245-74.

TABLE 5

CELLS FOR SAMPLE PREPARATION

		Flux Oil	Reclamite Base	Dutrex 739	Dust Oil
Pavement No. 1	No Additive	0%			
	AC 20	0.85%	0.35%	0.15%	0.21%
	AC 10	1.5%	0.60%	0.45%	0.50%
	AC 5	2.0%*	1.4%	1.0%	0.85%
Pavement No. 2	No Additive	0%			
	AC 20	1.0%	0.75%	0.50%	0.30%
	AC 10	2.5%	1.1%	0.75%	0.50%
	AC 5	3.5%	1.6%	1.0%	0.75%

*AC 5 was not obtained

As can be seen, the Dust oil and Dutrex were the most efficient softening agents requiring additions of only about 1% to reduce the binder to the AC5 level for both pavements. The Reclamite required about 1-1/2% to reach the AC5 level, and in excess of 3% Flux Oil was needed to obtain this level for pavement No. 2. An AC5 consistency was not reached for pavement No. 1 using the Flux Oil due to the fact that so much agent was needed that the percentage of air voids was reduced to an intolerable level. The lesser effectiveness of the Flux Oil to soften the binder may be related to its higher relative viscosity, and higher percentage of asphaltenes content.

The kinematic viscosity at 275°F (135°C) of each mixture was measured and the resulting values vs percent softening agent are plotted in Figures 2A and B. The viscosity of the binder at this temperature is controlled to insure a proper mixing consistency. Again the Dust oil was the most effective in reducing the viscosity at this temperature followed by Dutrex, Reclamite and Flux Oil respectively.

The measured penetration values at 77°F (25°C) are plotted vs percent softening agent in Figures 3A and B. The relative amount of softening for each agent is similar to that shown by the viscosity values.

The penetration grading system is used by many agencies as a standard of asphalt consistency, and the common grade levels are illustrated in Figure 3.

The relationships between added softening agent and ductility for the various mixes are shown in Figures 4A and B. The relative effectiveness of the agents to increase the ductility corresponds to the viscosity and penetration curves. A value of 100+ was obtained with each agent with the exception of the Flux Oil. The ductility using Flux Oil was increased only to a range of 10 to 20 cm. at the 2% level.

Ordinary Phillips AC5 asphalt was added to the mix from pavement No. 1 for comparison and plotted in Figures 1 through 4. The 1-1/2% asphalt was relatively ineffective at softening the asphalt.

FIGURE 2
VISCOSITY AT 275°F (135° C)
VS
PERCENT SOFTENING AGENT

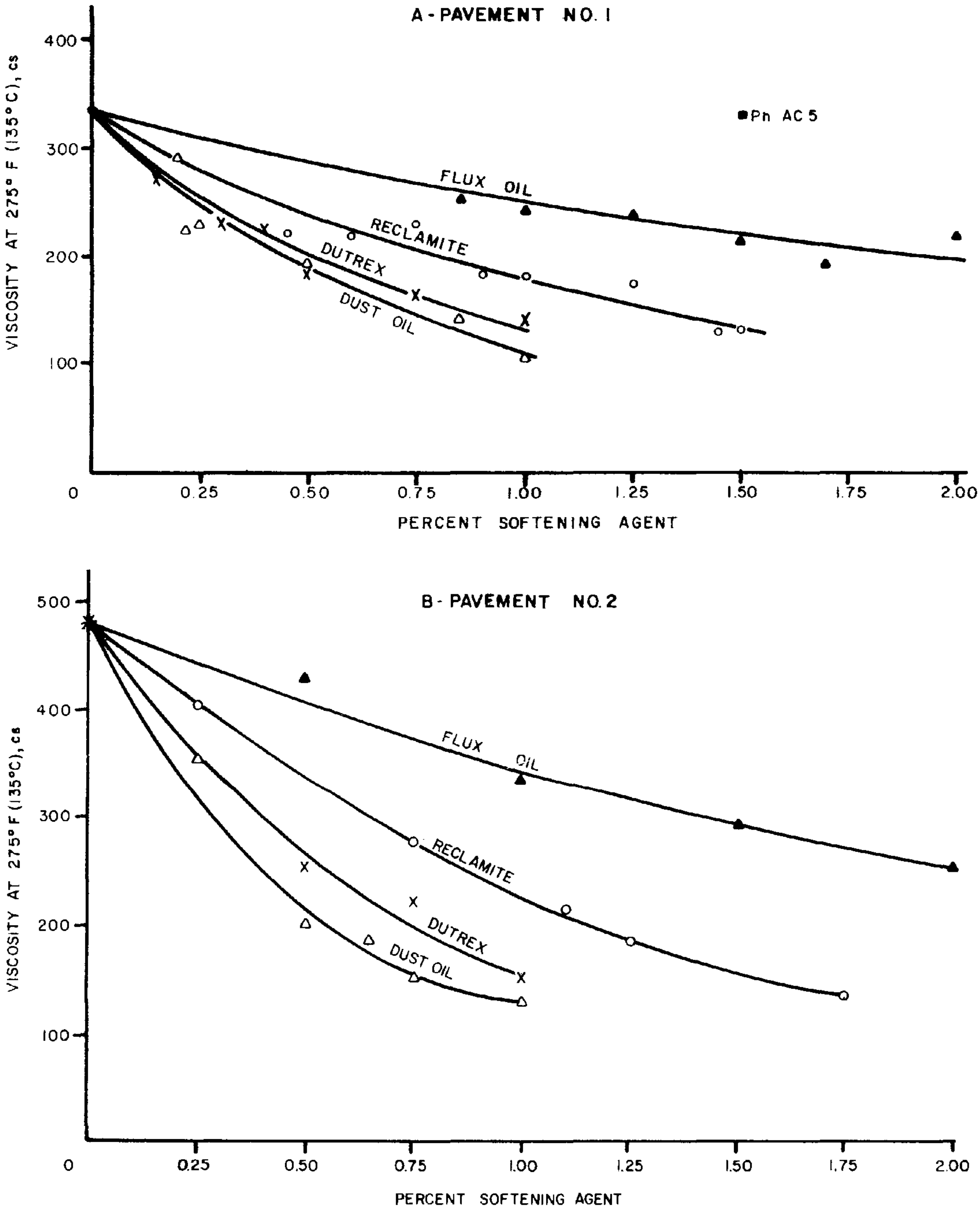


FIGURE 3
PENETRATION AT 77°F (25°C)
VS
PERCENT SOFTENING AGENT

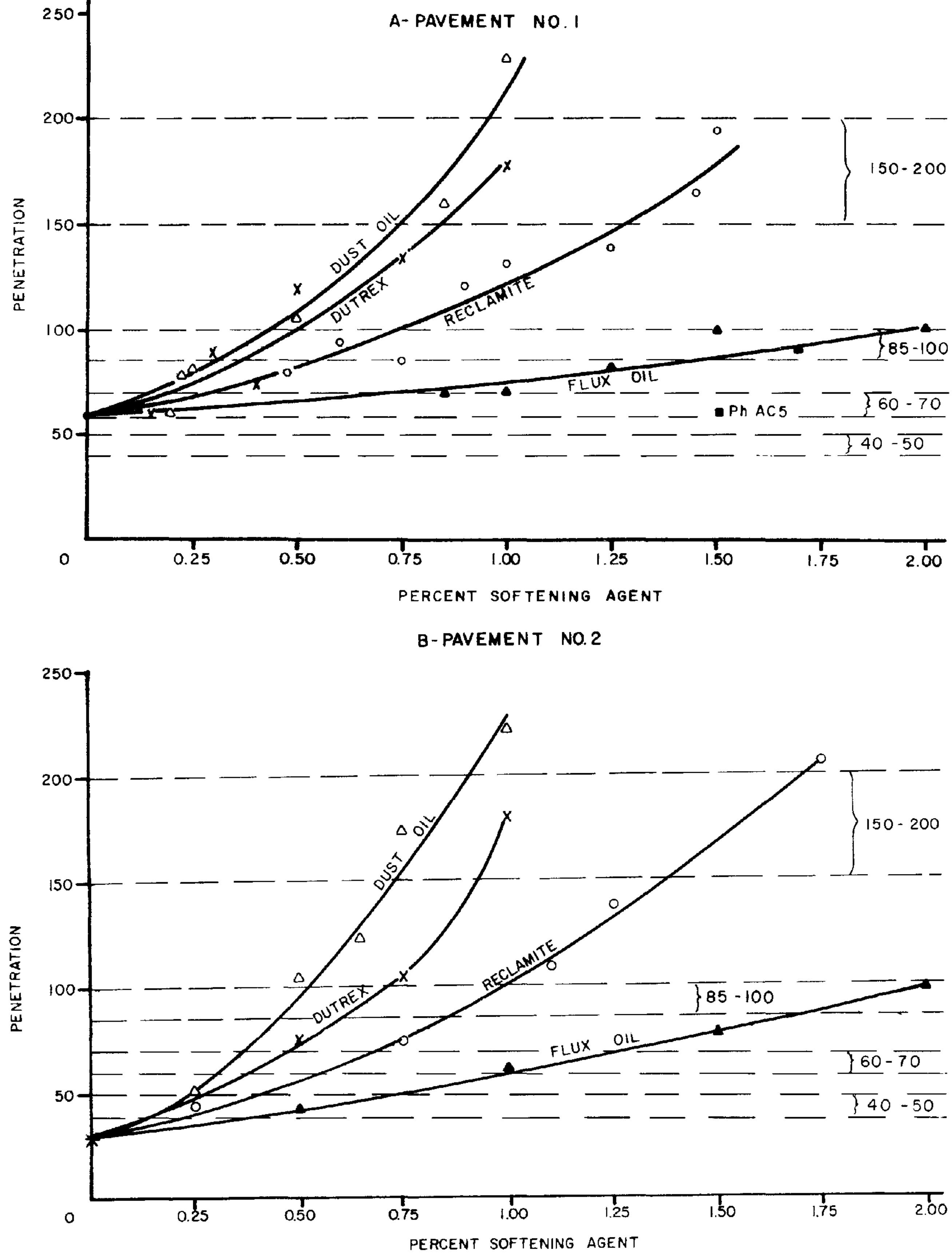
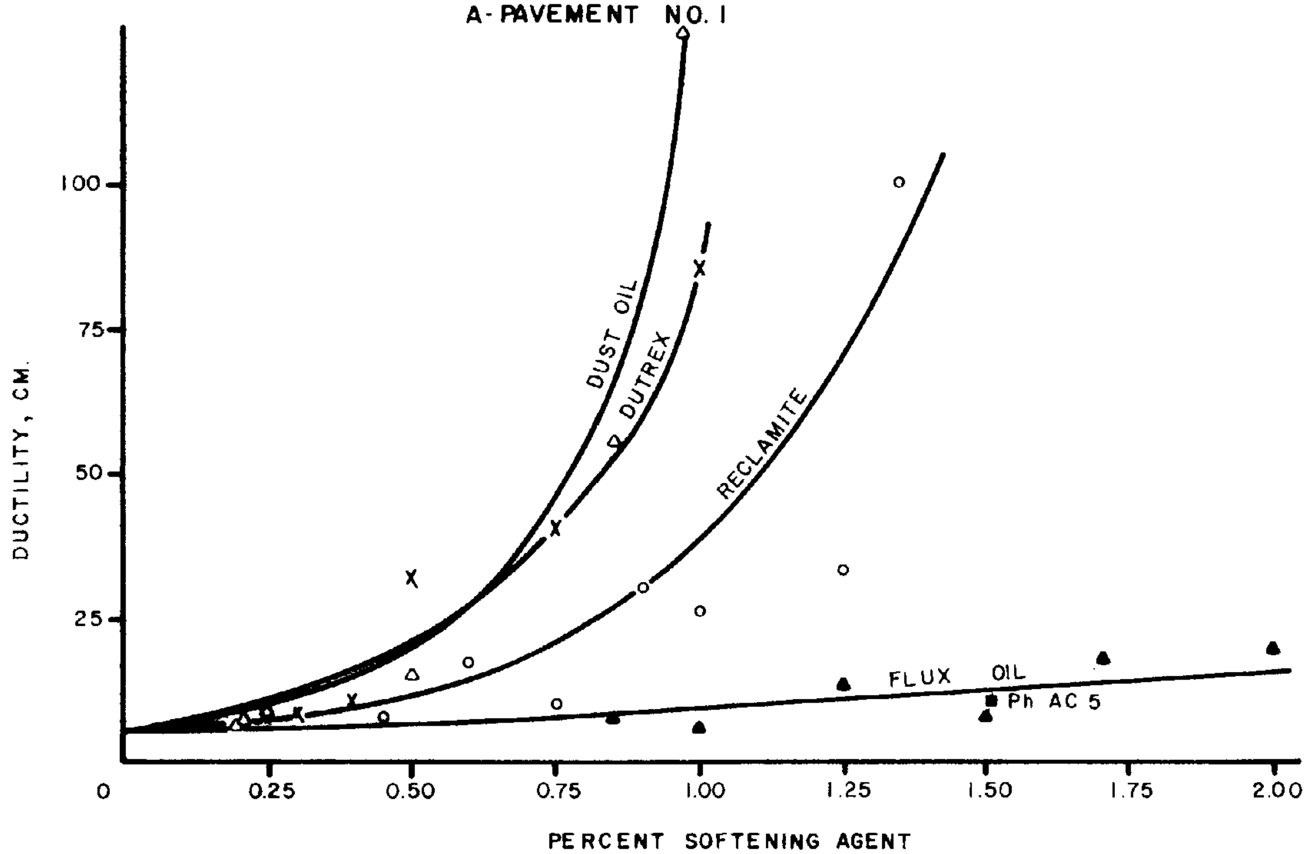
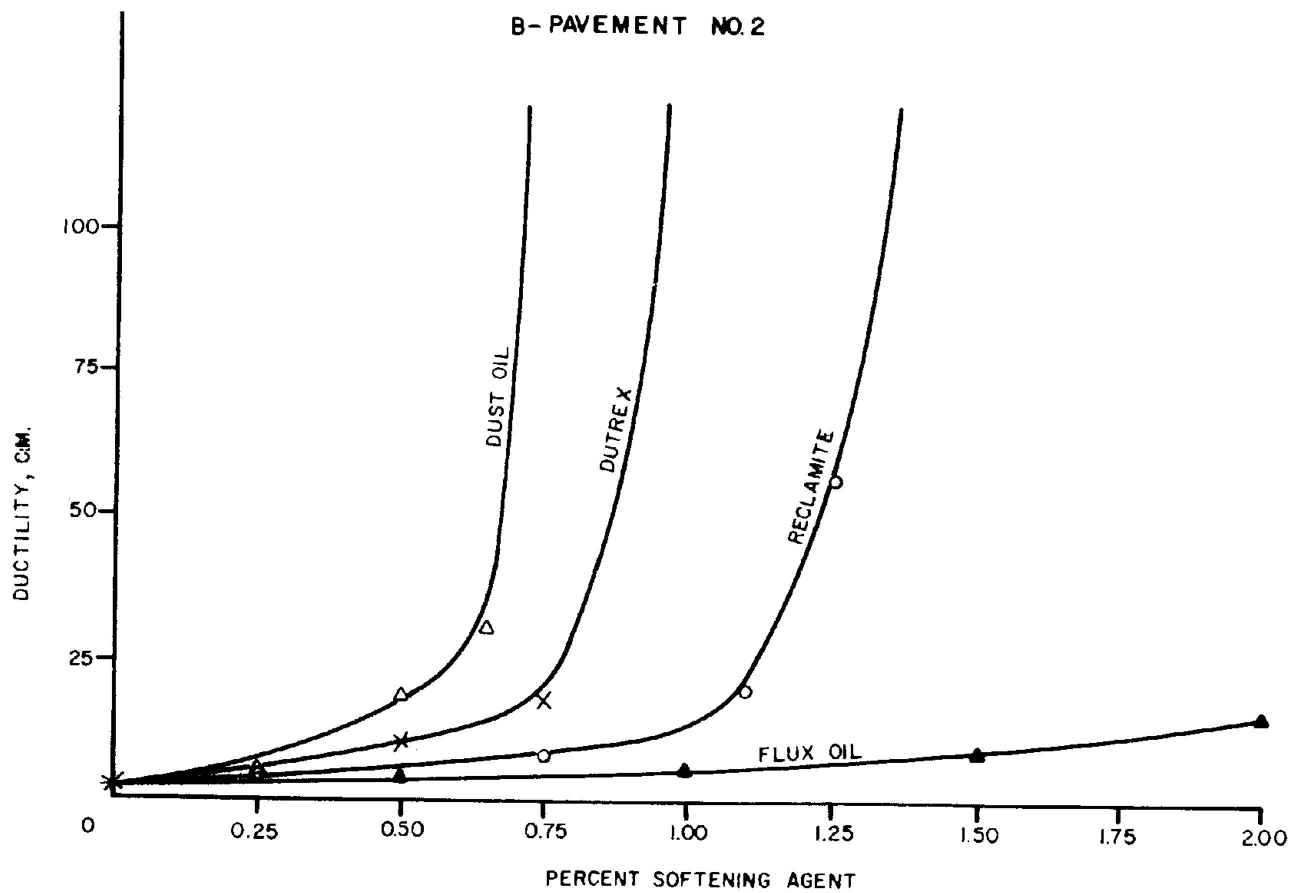


FIGURE 4
DUCTILITY AT 39.2°F (4°C)
VS
PERCENT SOFTENING AGENT

A-PAVEMENT NO. 1



B-PAVEMENT NO. 2



MIX PROPERTIES

Using the Marshall samples prepared for each cell, the properties of each mix were measured.

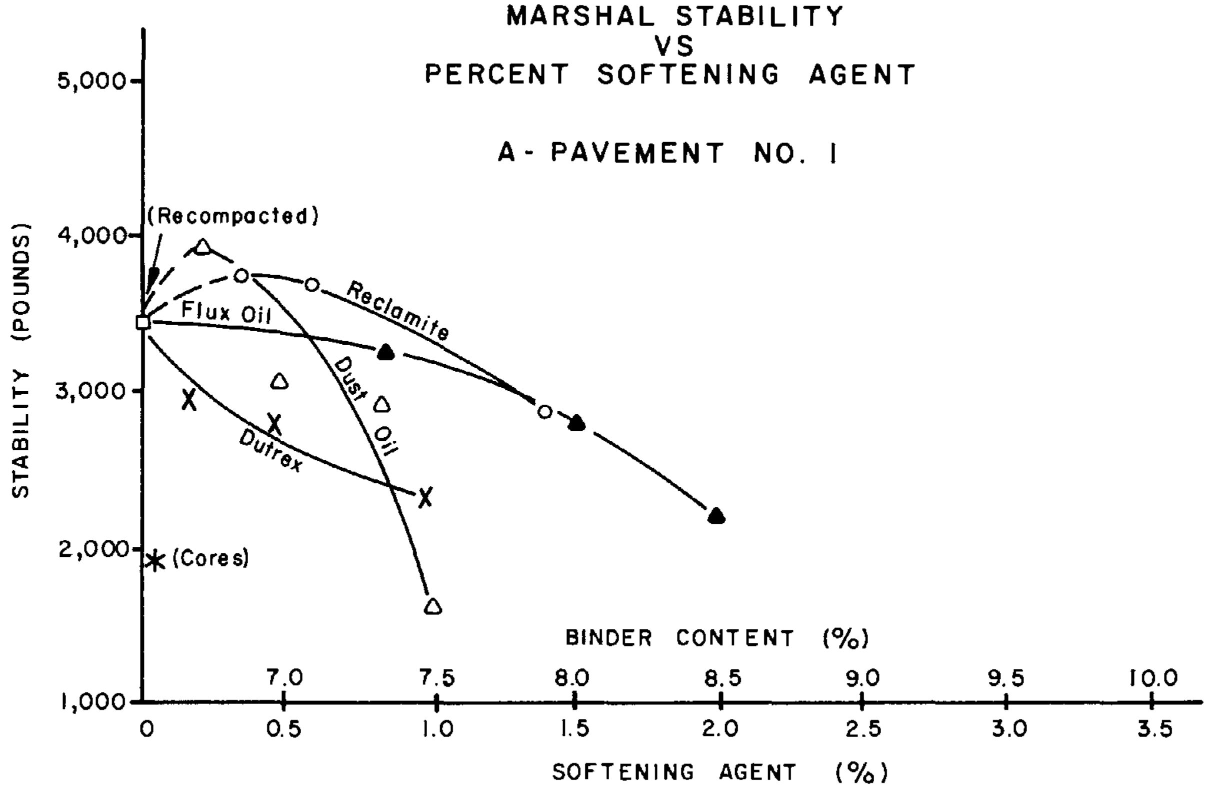
Marshall Stability

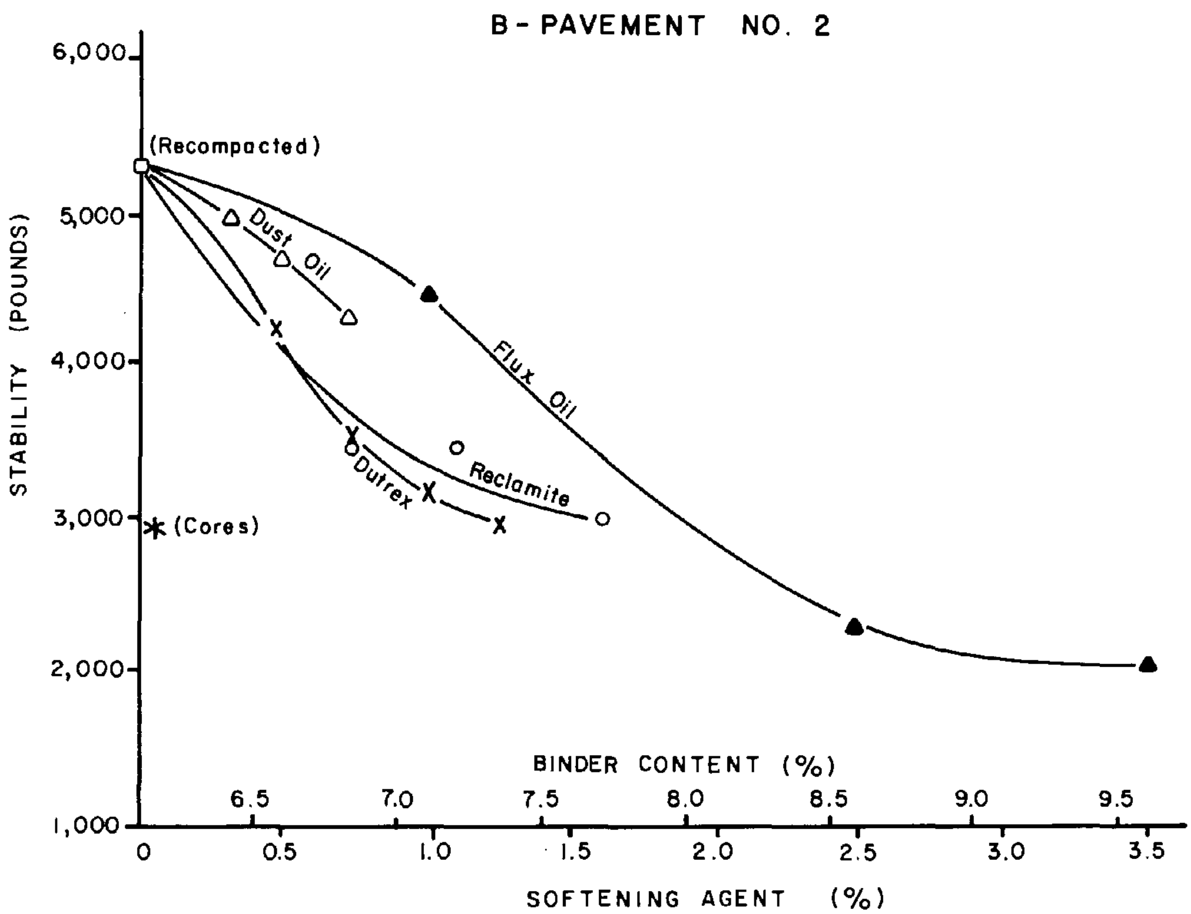
The Marshall stability values vs percent softening agent are illustrated for the two pavements in Figures 5A and B. The reheating and recompacting of the core samples increased the stability values considerably for both pavements. In many cases, an increase in strength simply due to recompaction could prove to be the major improvement to a recycled mix, particularly where stripping has been a problem. Where extremely brittle asphalts are present, however, an increase in Marshall stability may not be beneficial and a softening agent should be added.

A general decrease in stability was observed as greater quantities of softening agent were added to the mixes. For the Dust Oil and Reclamite on pavement No. 1, an increase in the first 1/4 to 1/2% range was observed. This could be due to the asphalt content being below optimum at recompaction, and the addition of softening agent increasing the stability much like that in a standard Marshall design. Also, the wider variability in properties existed in pavement No. 1 could be affecting the curves.

These stability values achieved after recycling are within reasonable limits as compared to the design values on new pavements.

FIGURE 5
MARSHAL STABILITY
VS
PERCENT SOFTENING AGENT





Air Voids

The drop in stability with the addition of softening agent was due to a combination of the increase in total binder content and the softening of the binder in the mixes. The curves only roughly correspond to the binder consistency curves in Figures 1 through 4. The total binder content seems to have a greater affect on the stability as seen in the air voids vs binder content curves in Figures 6A and B, which correspond to the stability curves quite well.

As can be seen the air voids were kept at reasonable levels for all cells. A large amount of Flux Oil was needed to obtain the target viscosity levels of AC10 and AC5. These levels were obtained for pavement No. 2, but the AC5 level was not acceptable using the Flux Oil on pavement No. 1 due to the intolerably low percentage of air voids measured for the mix.

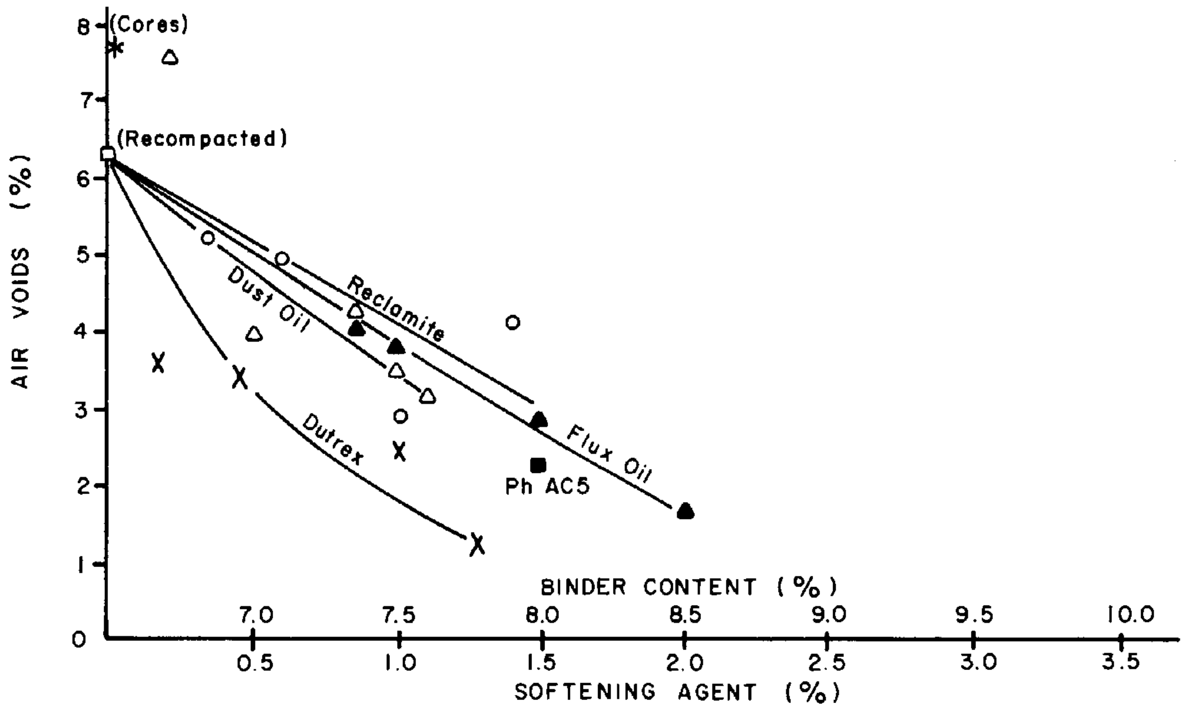
The recompaction process with no additive lowered the percentage of air voids measured on the core samples taken from both pavements. This is surprising since some of the base was removed with each core. A portion of this reduction in air voids could be related to higher recompaction temperatures and/or a greater compactive effort in the laboratory. The reduction of air voids at this level is a beneficial process since greater asphalt hardening has been related to higher air voids in flexible pavements.(1, 3, 4, 5)

Creep and Resilient Modulus Test Procedures

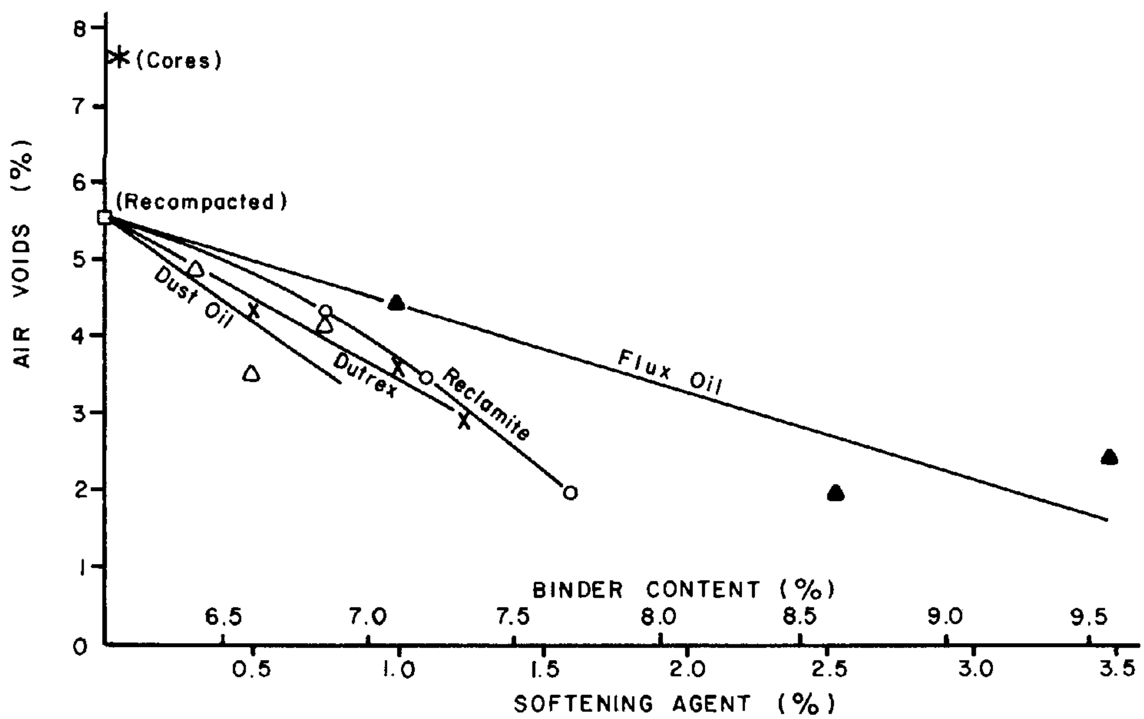
Creep compliance J(t) and resilient modulus M_R values were calculated for each cell using the indirect tensile method.(6, 7, 8, 9) An MTS system

FIGURE 6
PERCENT AIR VOIDS
VS
PERCENT SOFTENING AGENT

A - PAVEMENT NO. 1



B - PAVEMENT NO. 2



was used to generate the required loading, and linear variable differential transducers (LVDT) were used to monitor the vertical and horizontal deformations on a strip chart recorder. All tests were performed at room temperature. A more detailed discussion of the test apparatus and calculation methods is in Appendix B.

The creep tests were performed by applying a constant 20 psi (138,000 pascals) compressive stress to each sample for 1,000 seconds, and monitoring the vertical deformation vs time. The compressive strain was calculated (Appendix B), and the creep compliance function was obtained as follows:

$$J(t) = \frac{\epsilon_y(t)}{\sigma_y}$$

where $\epsilon_{y(t)}$ is the compressive strain function and σ_y is the applied compressive stress of 20 psi (138,000 pascals).

The resilient modulus was obtained by subjecting the samples to a series of 200 cyclic haversine loads, each consisting of a 0.1 second loading period and a 0.9 second unload period. A peak stress level of 60 psi (414,000 pascals) was used and each resulting instantaneous horizontal deformation H_{RI} was monitored. The resilient modulus was calculated at the 200th cycle as follows:

$$M_R = \frac{P}{H_{RI}h}(.2692 + .9974\,\nu) = \frac{76.4}{H_{RI}h}$$

where P is the applied load of 314 lbs. (142 kg), h is the sample height of 2.5 inches (6.35 cm), and ν is the poissons ration (0.34).

Creep Compliance

The creep compliance values measured at 1 second and 1,000 seconds of loading are plotted vs percent softening agent in Figures 7 and 8 respectively. The asphalt consistency seems to have a significant effect on the creep compliance with the agents appearing in a similar order in which they soften the asphalt as seen in Figures 1 through 4. The softer the binder the more readily the material deformed under loading as expected.

The total binder content also had an effect on the creep compliance measured. Very high values were observed where more than about 1-1/2% softening agent was added, increasing the binder content above 8.0% on pavement No. 1, and 7.6% on pavement No. 2. For these two pavements this appears to be the upper limit of softening agent that can be tolerated. Previous studies indicate that creep compliance values in this range are related to high rutting.(10)

Resilient Modulus

The resilient modulus is plotted vs the percent softening agent for the two pavements in Figures 9A and B. Again the binder consistency affected the reduction in resilient modulus with the curves corresponding closely with those in Figures 1 through 4. Addition of the Flux Oil changed the viscosity of the binder and thus the resilient modulus much less than the Dust Oil and Dutrex, which caused more significant changes with less additive in both the viscosity and resilient modulus values.

The total percentage of binder seemed to have very little affect on the resilient modulus for pavement No. 1. The binder content did,

FIGURE 7
CREEP COMPLIANCE AT 1 SECOND
VS
PERCENT SOFTENING AGENT

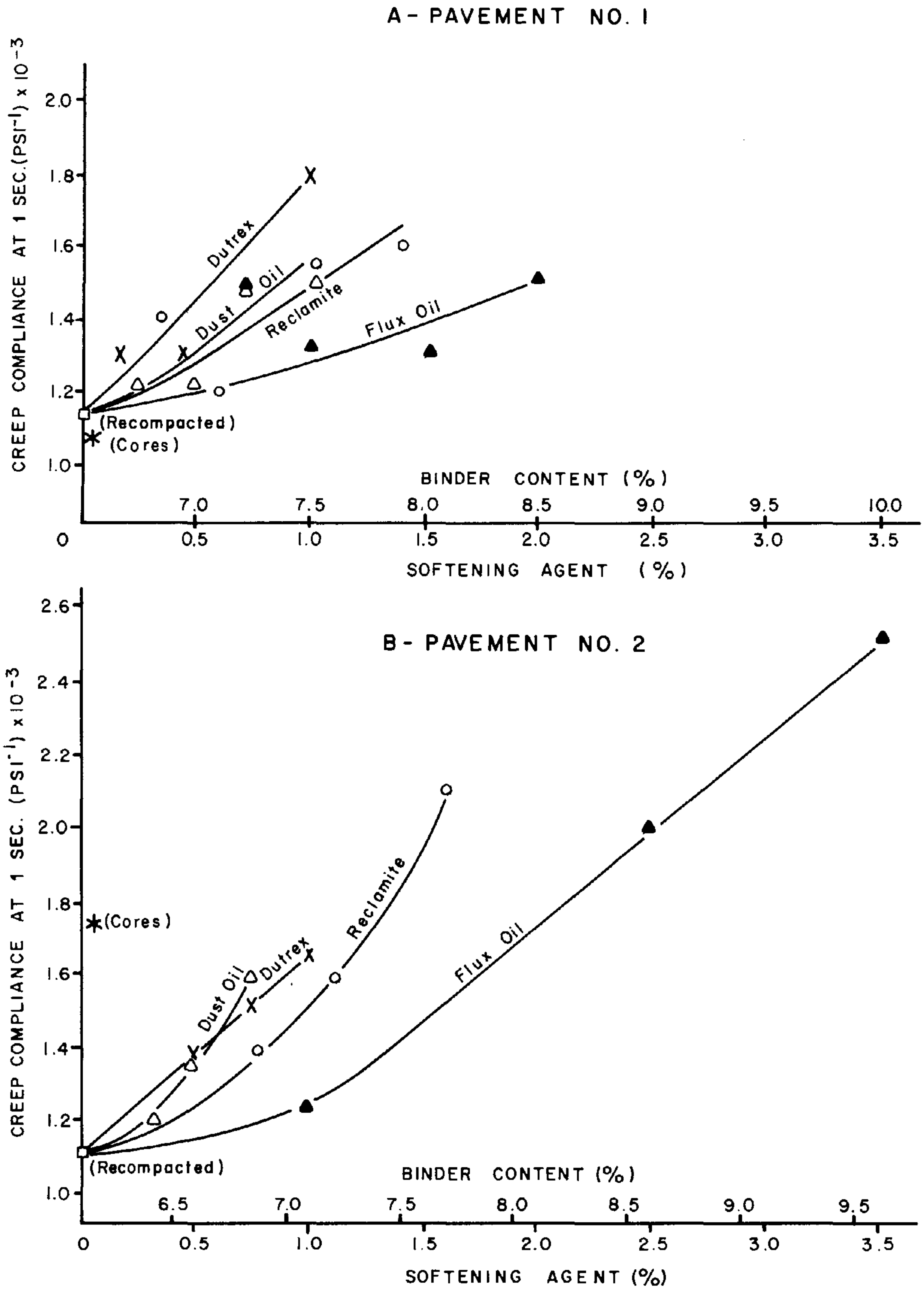


FIGURE 8
CREEP COMPLIANCE AT 1,000 SECONDS
VS
PERCENT SOFTENING AGENT

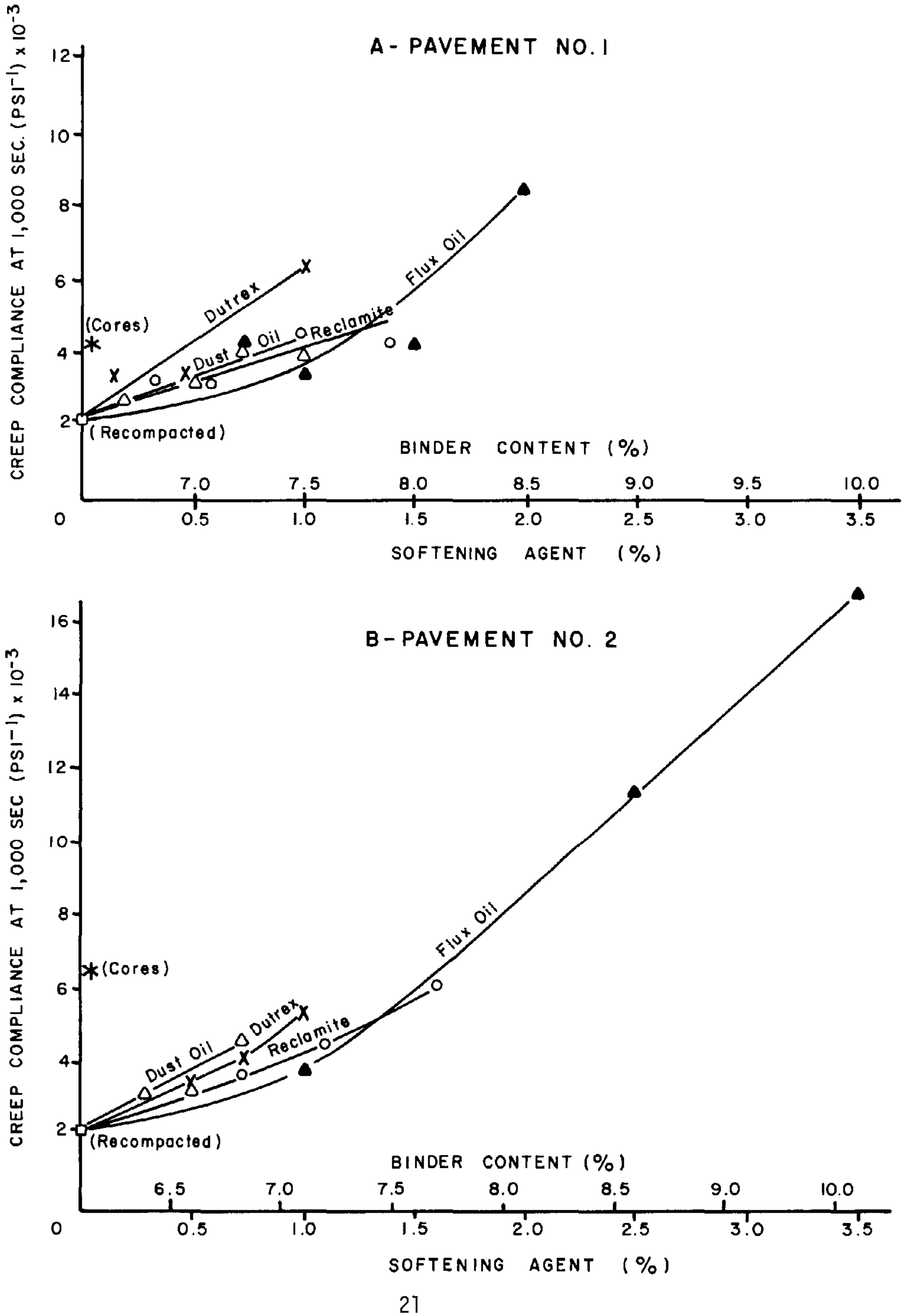
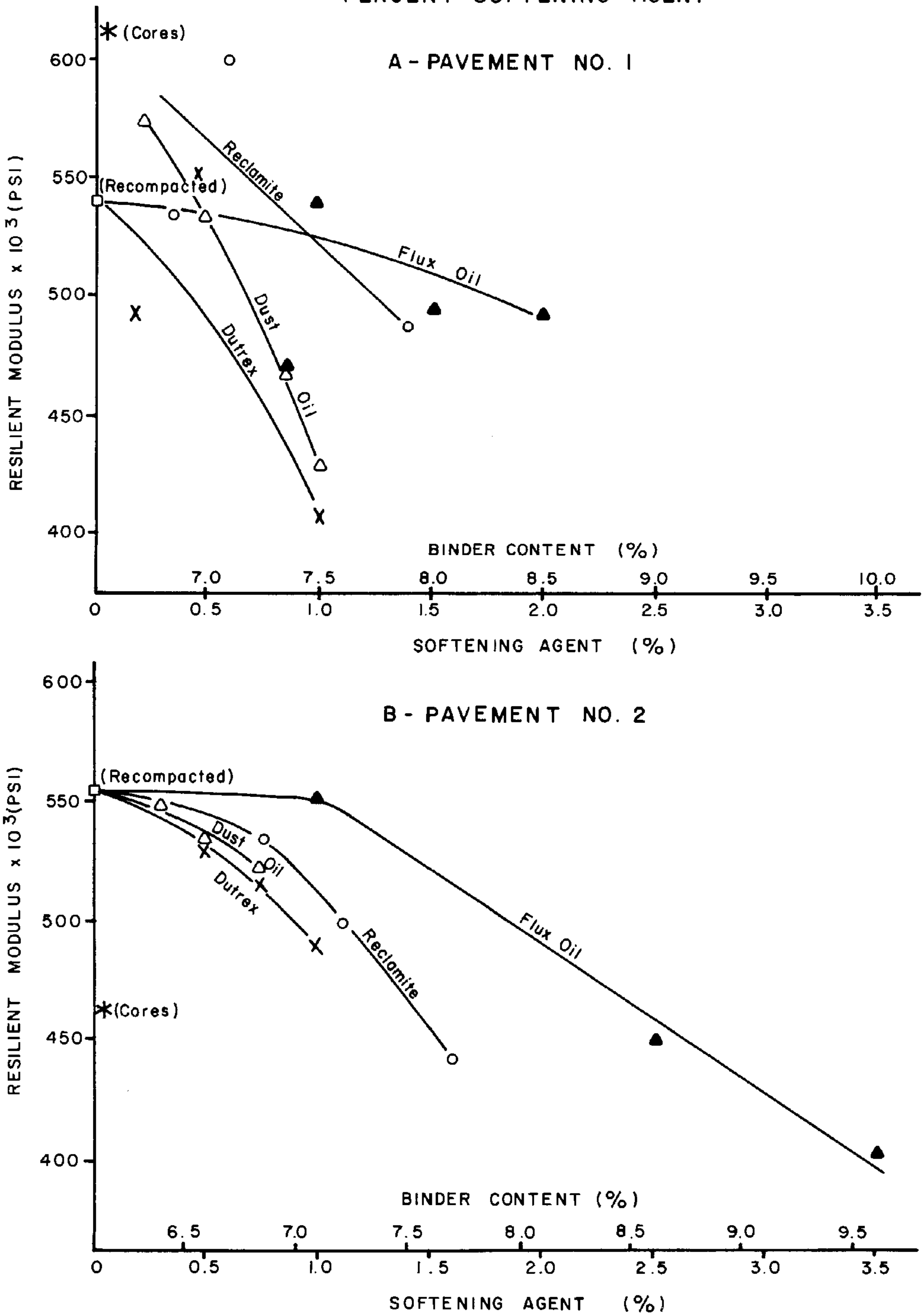


FIGURE 9
RESILIENT MODULUS
VS
PERCENT SOFTENING AGENT



however, influence the resilient moduli for pavement No. 2, since a general relationship exists independent of the softening agent used. The values dropped to much lower levels at binder contents above 7-1/2%.

This measured range of resilient modulus values for the recycled mixes is comparable to values measured on new pavements.(11)

CHANGE IN ASPHALT AND MIX PROPERTIES DUE TO AGING

A select group of samples were prepared to determine the effect on asphalt and mix properties due to aging. From pavement No. 1, nine samples were formed corresponding to each of the following mixes:

No Additive (Recompacted)
AC5 (1-1/2%)
Flux Oil (1%)
Reclamite Base (1%)
Dutrex (1%)
Dust Oil (1%)

To maintain the percent air voids at a uniform level for each of the four mixes containing the softening agents, a value of 1% of each was added. This resulted in a range in air voids of 2.5 to 3.8% for these mixes. The no additive and 1-1/2% AC5 mixes were formed for comparison with the softening agent mixes, resulting in air voids contents of 6.3% and 2.3% respectively.

Three of the samples from each group were tested prior to aging to obtain the initial properties of each mix. The remaining six samples were subjected to aging.

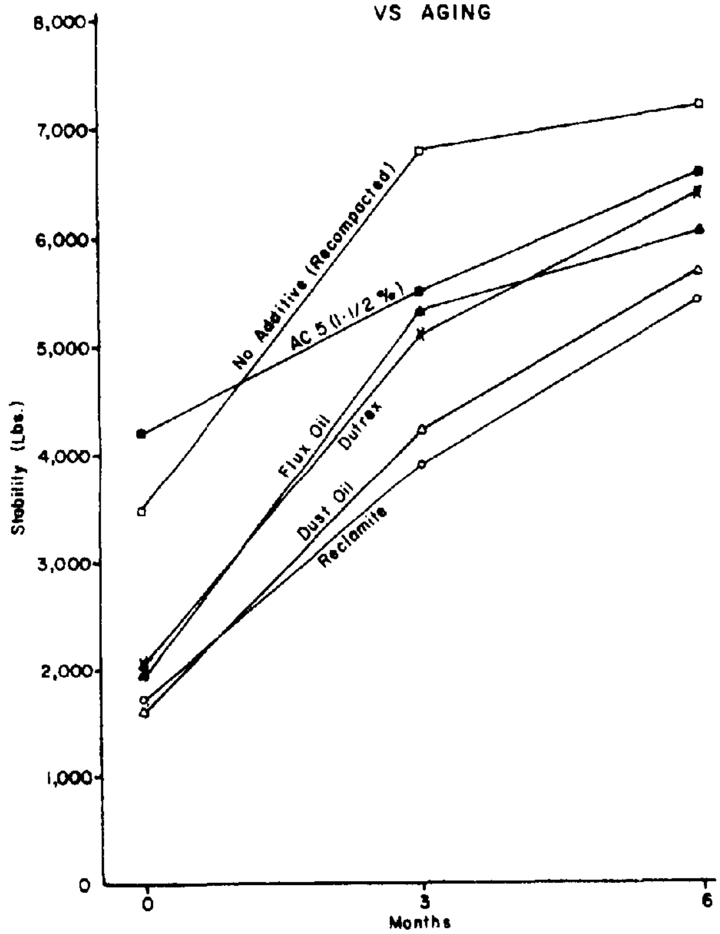
Oven Aging

During the first three month period the samples were aged for six weeks exposed to the outside conditions, and subjected to an oven at 140°F (60°C) for the remaining six weeks. At this time the mix properties were measured on three more of the samples. The changes in the mix properties after the first three months were found to not be of a desired magnitude. Therefore, more harsh conditions were applied to the samples during the second aging period. For the full three months the samples were left in the 140°F (60°C) oven. This second period was found to produce a greater change in mix properties than the initial aging period in most cases.

Marshall Stability After Aging

An increase in stability was observed for all mixes as seen in Figure 10. A smaller increase occurred in the second three month period even though the induced aging was more severe during that time. This smaller change in stability at higher levels has been previously observed.

FIGURE 10
MARSHALL STABILITY
VS AGING



The Marshall stability values of the mixes containing softening agent remained lower after aging than the mix containing 1 1/2% AC5. No drastic difference in the increase in stability due to aging could be determined from one softening agent to another.

Creep Compliance After Aging

In Figures 11 and 12, the creep compliance at 1 second and 1,000 seconds respectively is plotted vs aging time. The mixes decreased in creep compliance with aging over the six month period, demonstrating a hardening effect. The no additive and AC5 mixes showed an increase in creep compliance at 1 second during the first three months, but then decreased significantly during the second three months.

The mix containing Reclamite decreased the most, dropping from the highest value initially to the lowest of the mixes containing softening agent after six months.

Resilient Modulus After Aging

The change in resilient modulus due to aging is shown in Figure 13. The increase in modulus indicates a stiffening of the mix due to the heat aging. The Flux Oil showed the smallest increase in resilient modulus being the highest of the four softening agents initially, but resulting in the lowest modulus after six months of aging. Similar to the creep compliance the Reclamite was the lowest in resilient modulus prior to aging, but increased to a value higher than the other three softening agents after aging. The 1-1/2% AC5 mix remained highest in resilient modulus after aging.

FIGURE 11
CREEP COMPLIANCE AT 1 SECOND
VS AGING

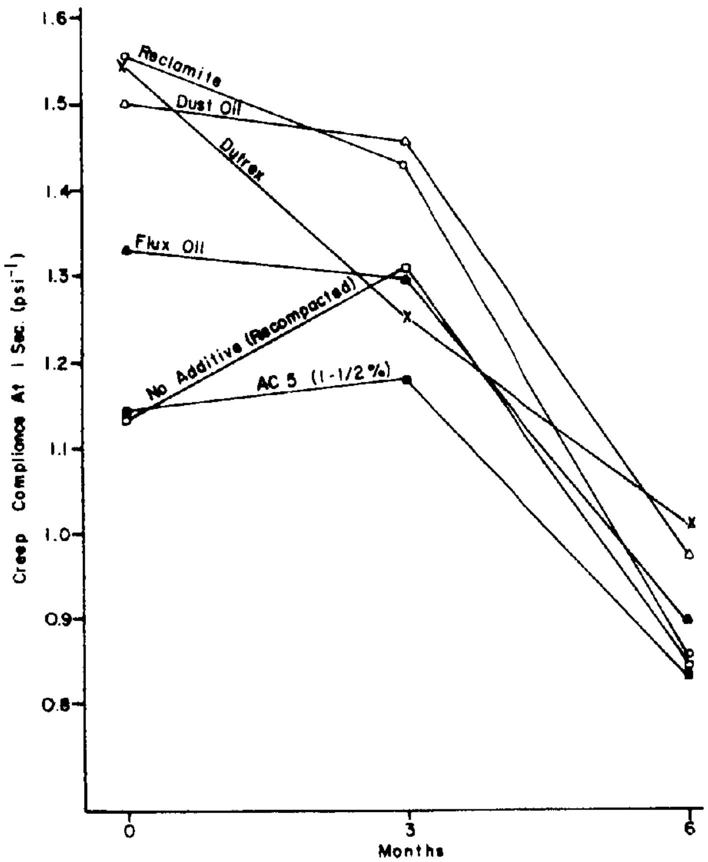
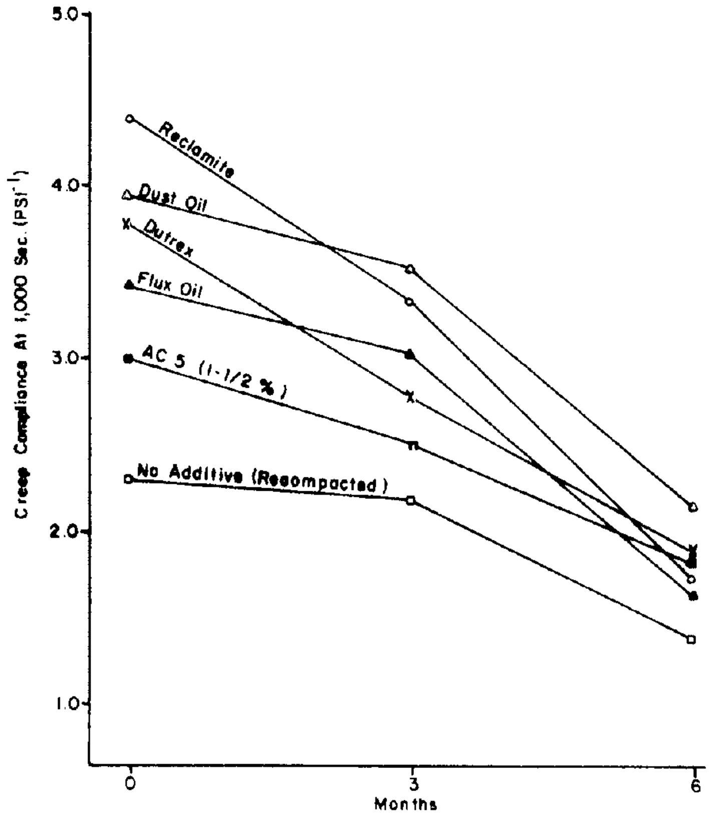
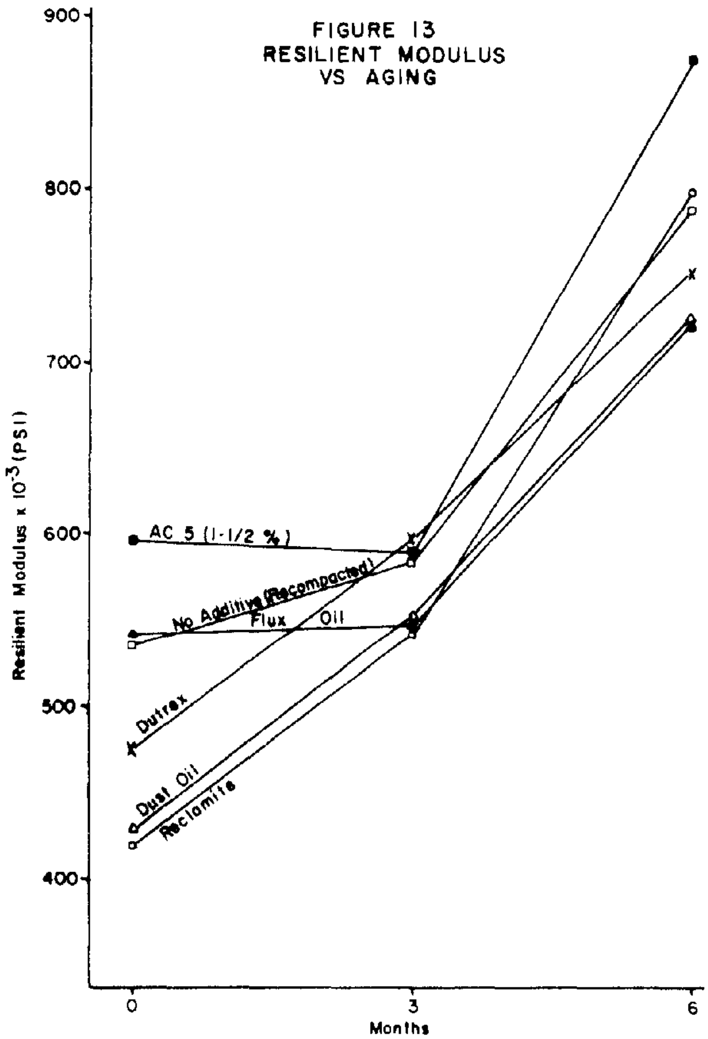


FIGURE 12
CREEP COMPLIANCE AT 1,000 SEC.
VS AGING





Binder Aging

The binder was extracted from the samples after the oven hardening, and the physical properties of the asphalts were measured.

The change in properties due to the induced aging is illustrated in Figures 14 through 17.

FIGURE 14
VISCOSITY AT 140°F (60°C)
VS OVEN AGING

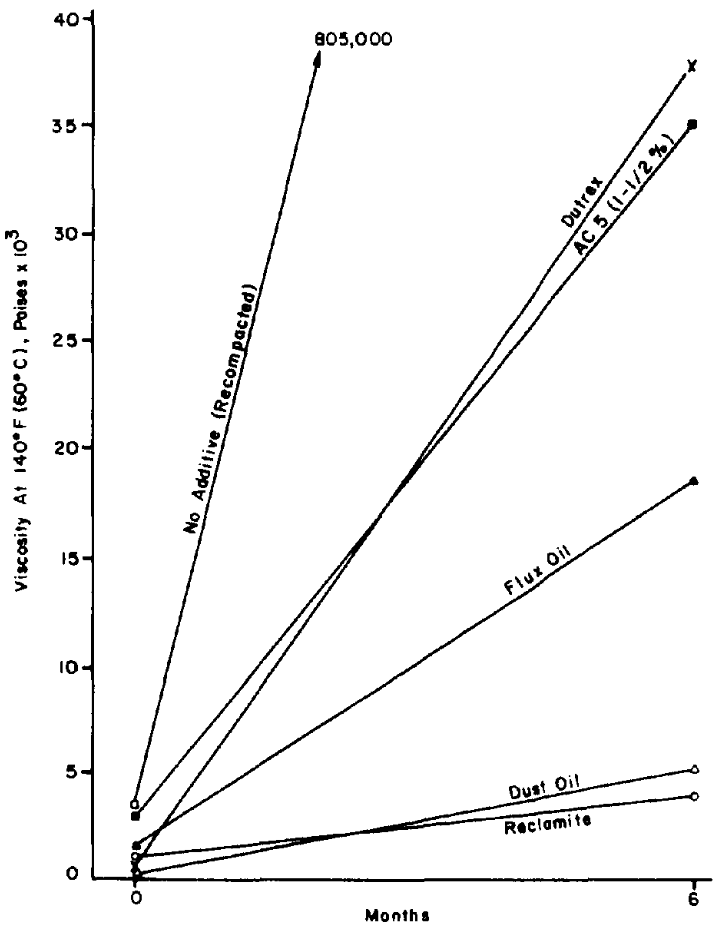


FIGURE 15
VISCOSITY AT 275°F (135°C)
VS OVEN AGING

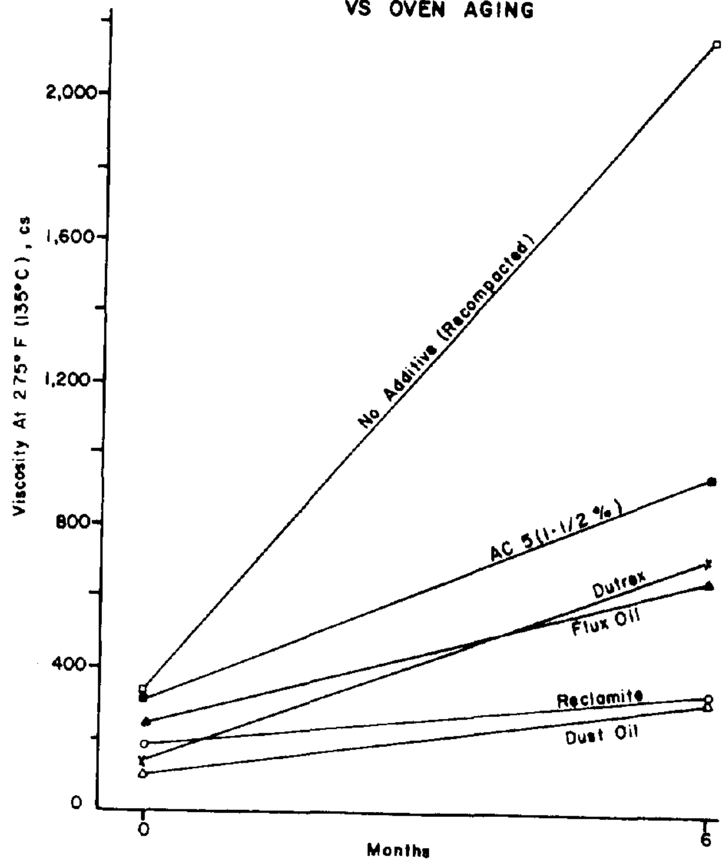


FIGURE 16
PENETRATION
VS OVEN AGING

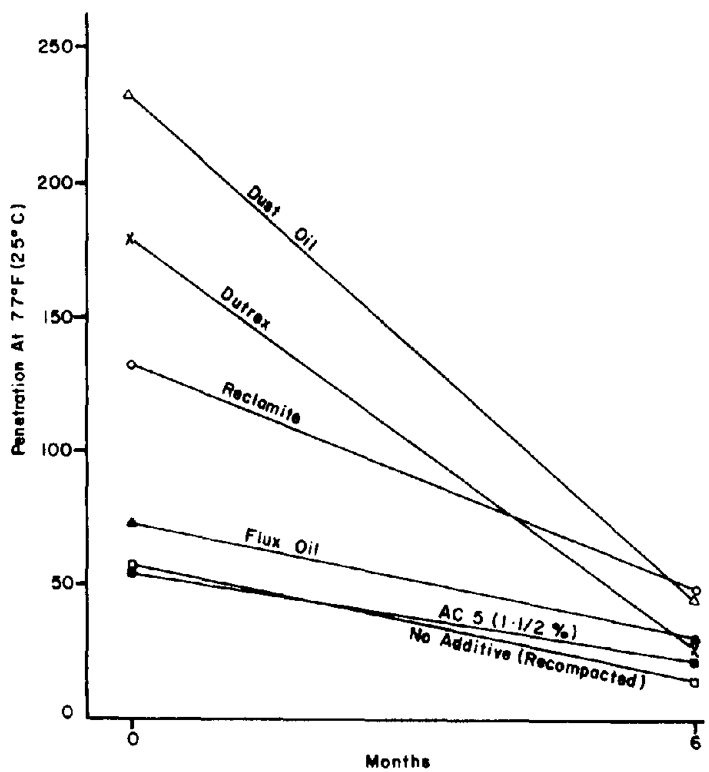
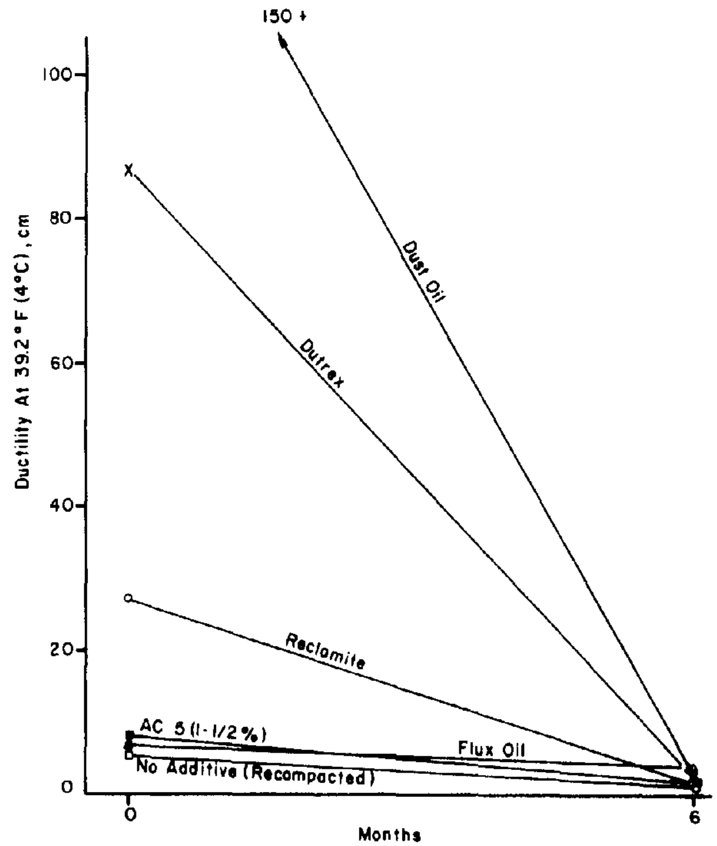


FIGURE 17
DUCTILITY
VS OVEN AGING



The recompacted mix reflected a very extreme brittleness after aging. This no doubt can be related to the higher air voids in the mix as well as the more brittle consistency of the asphalt at the time of recompaction.

The Dutrex mixture increased more in viscosity than the other softening agent mixtures. The Flux Oil increased somewhat less and the Dust Oil and Reclamite showed a much lower increase in viscosity.

A similar change in penetration was observed with the recompacted mix dropping to 14. The Dutrex and Flux Oil mixtures were reduced to 26 and 29 respectively, while the Dust Oil and Reclamite dropped to 44 and 48.

The ductility was reduced to values below 2 cm in all cases. This lack of ductility is indicative of a very brittle binder, and has been related to the occurrence of transverse cracking.(1, 13, 14, 15)

The lesser hardening of the Reclamite mix is believed to be due to the fact that it is an emulsion and contains 30% water. It is theorized that the cations in the agent tie up some of the acids in the form of salts, thus reducing the hardening of the binder.(12) This phenomenon is also seen when extracted asphalts are softer after wet seasons.

It is interesting that the Reclamite mix changed in creep compliance and resilient modulus more in the oven than any of the four softening agents, but changed less in viscosity and penetration due to the heat aging. The reason why the lesser hardening of the binder does not in turn retard the change in creep compliance and resilient modulus for this mix is not clear.

Possibly the Reclamite didn't mix as well as the other softening agents leaving the asphalt in the mix exposed to greater aging and stiffness of the mix. But due to the extraction process the binder was thoroughly mixed resulting in the relatively softer binder after aging.

The viscosity and penetration values before and after heat aging corresponds closely with the stability and creep compliance values as seen in Figures 18 through 21. This demonstrates the relationship between the properties of the binder and the mix properties for a given aggregate type and gradation.

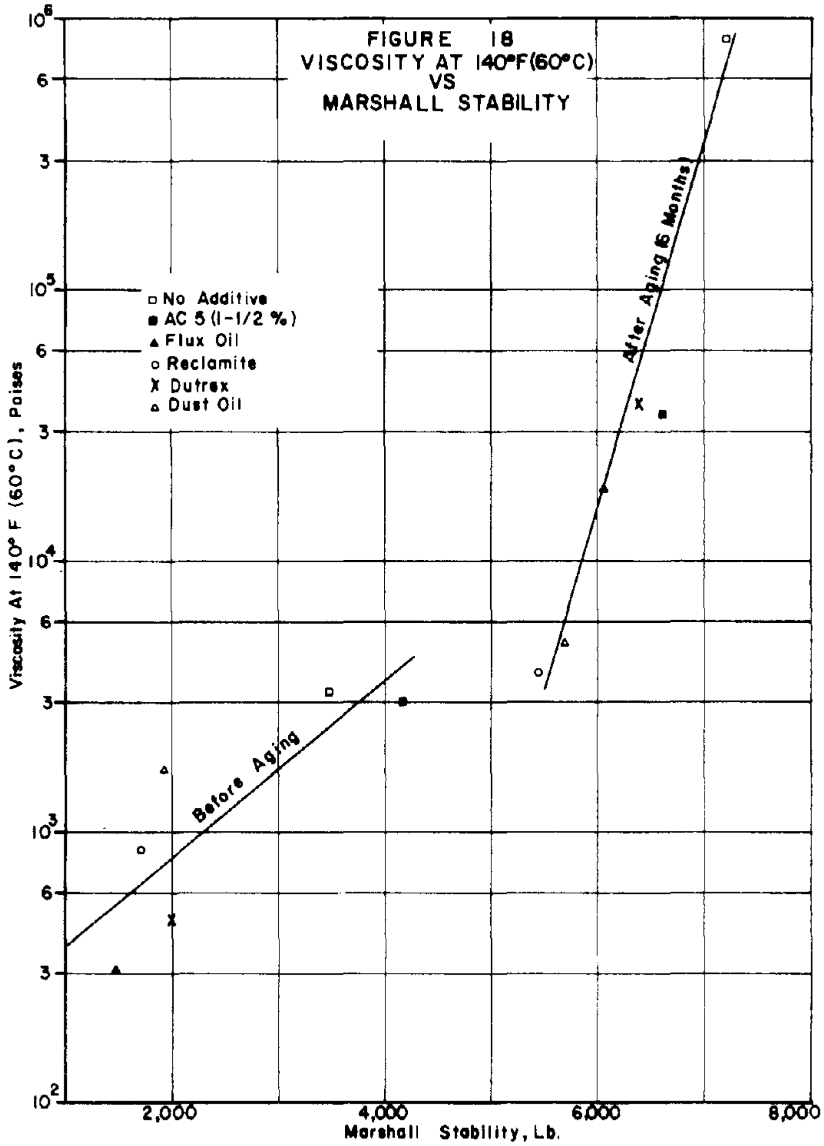
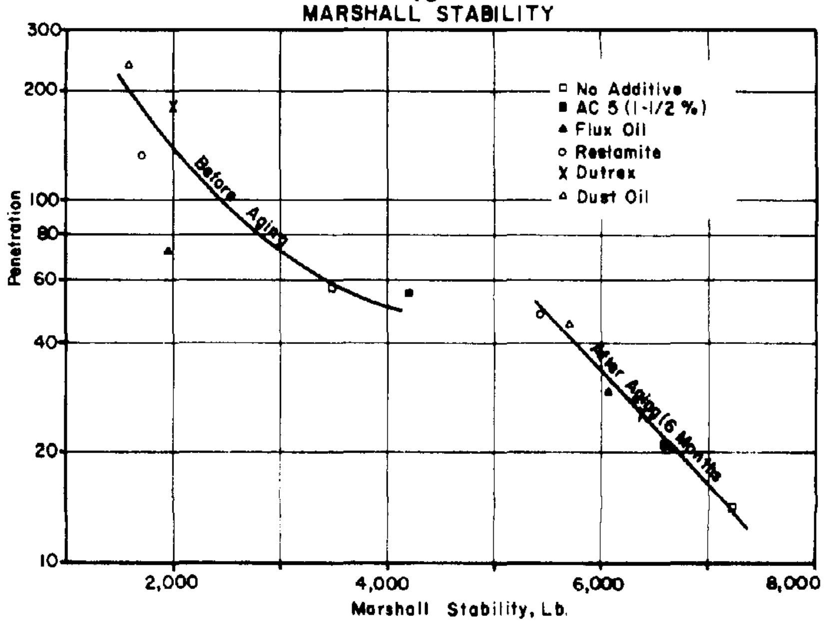


FIGURE 19
PENETRATION
VS
MARSHALL STABILITY



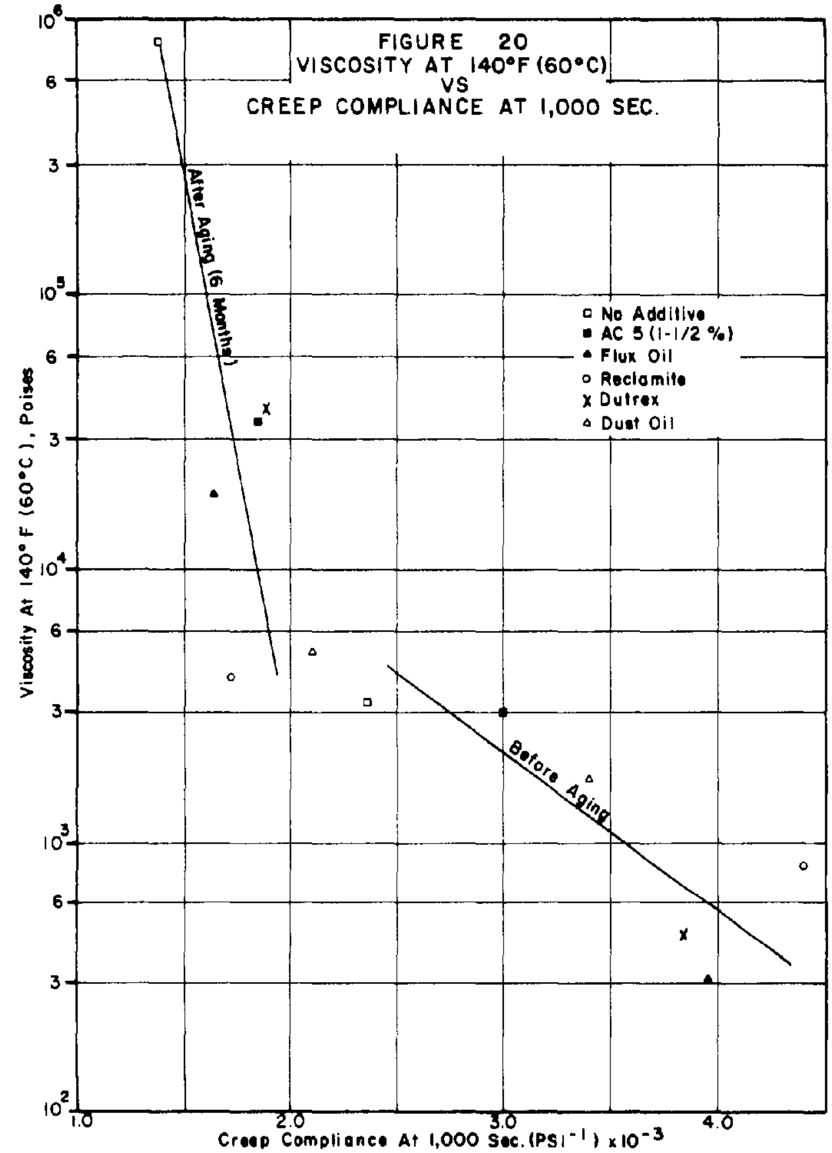
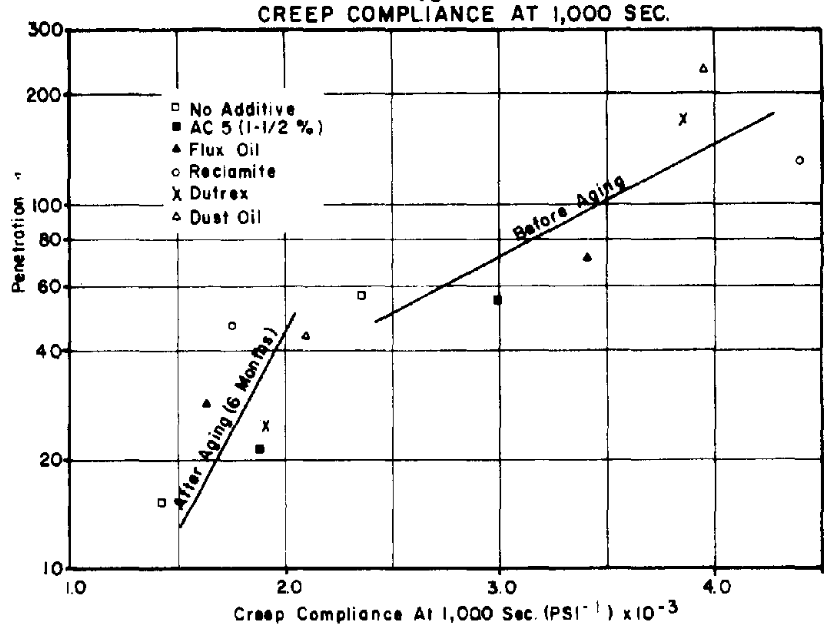


FIGURE 21
PENETRATION
VS
CREEP COMPLIANCE AT 1,000 SEC.



MIX DESIGN CRITERIA

Many factors must be considered when designing a recycled mix. An initial consideration is of course the air-quality constraints that will be imposed at the project site. The present state of the art does not account for the pollution problem using 100% recycling in most areas of the country. A 50% recycled - 50% new material combination has been successful in Iowa and Minnesota with a minimum of air pollution.

For many inplace mixes which are considered candidates for 100% recycling, the simple remixing of the asphaltic concrete or the adding of new asphalt while remixing is not adequate to obtain a mix comparable to a virgin mix. In most cases, both the mix properties and the asphalt properties cannot be obtained within ranges presently considered to be acceptable when asphalt alone is added. To obtain both binder consistencies and mix properties within these conventional ranges, ordinarily a softening agent must be used. Where additional aggregate is added to the mix and thus a larger percentage of virgin asphalt, the binder may be softened enough to dispense with the use of a softening agent. If the inplace binder is soft enough without the addition of a softening agent, simple reheating, adding a small amount of asphalt, and recompaction may be sufficient in the recycling process.

When designing a recycled pavement it would be desirable to use one of the more "rational" design procedures recently developed, which apply cyclic loading in the laboratory testing to predict rutting, fatigue cracking and transverse cracking.(16, 17) These methods have been shown to be advantageous due to their more direct approach simulating traffic loading and environmental conditions. Also by obtaining output in the form of distress and serviceability, designs can be more easily compared.(10) Designs obtained by these methods could be quite different from those obtained using conventional methods, since optimum values may vary. For example, the binder content optima for fatigue designs are 5 to 10% higher then using the Marshall Method.(18)

The drawbacks of these new design methods are: the increased number and length of laboratory tests, the expensive equipment needed to perform these tests, and the lack of expertise at this time by the state agencies to use the procedures.

Some agencies are employing parameters such as the resilient modulus, which uses cyclic loading, but does not necessitate the time and expense of these mechanistic methods. Much more work is needed in this area to determine what parameters adequately define a good performing recycled mix.

Regardless of the parameters used to measure the binder and mix properties, the target levels for these parameters should be related to factors such as the traffic loading, base layer support, and environmental conditions for each pavement. This in turn should indicate the best type and amount, if any, of softening agent to specify for a given pavement.

CONCLUSIONS

1. A majority of the softening agents investigated in this study contained very little, if any, asphaltenes. This most likely contributed to the very low viscosity values observed for these substances.

2. For the pavements investigated in this study the addition of asphalt alone was not acceptable using 100% recycling. Traditional binder consistency levels for new pavements could not be reached before the air voids in the mixes became too low. Softening agent was needed to achieve both binder and mix properties at adequate levels.

3. The Dust Oil and Dutrex were very effective at softening the binder in both pavements evaluated, requiring the addition of less than 1% additive to obtain an AC5 level. The Reclamite was somewhat less effective requiring 1 1/4% to 1 1/2% of the agent to achieve an AC5 grade. The Flux Oil was relatively ineffective requiring greater percentages than the air voids would allow to reach the AC5 level on pavement No. 1. On pavement No. 2, percentages of Flux Oil in excess of 3 1/2% was required.

Penetration, ductility and viscosity at 275°F (135°C) values showed similar relationships with the four softening agents used.

4. The Marshall stability values increased significantly due to simply remixing, reheating and recompacting core samples from either pavement. The addition of the softening agents resulted generally in reductions in the stability. This drop in stability was generally related to the change in binder consistency, but mainly depended upon the total binder

content. The stability values after recycling are within reasonable limits as compared to the design values on new pavements.

5. The creep compliance measured for the mixes was generally decreased after recompaction, indicating a reduction in deformation under loading. The values increased proportionately as softening agent was added. The major factors controlling this increase in creep complaince were the softening of the binder, and the increase in binder content. At binder contents above, about 8.0% for pavement No. 1 and 7.6% for pavement No. 2, the creep compliance for these mixes was high enough to result in high rutting under most conditions. Creep compliance values measured at lower binder contents were within acceptable levels.

6. A general reduction in resilient modulus was observed by adding softening agent. Again the binder consistency affected the resilient modulus values. For pavement No. 1 the total binder content had little affect on the modulus, but it did seem to play a role for pavement No. 2. The measured range in resilient modulus after recycling is within ranges measured on new pavements.

7. A stiffening of the mixes due to the laboratory aging was observed, and was generally related to the measured hardening of the binders. The Reclamite mix, however, stiffened more than the other mixes containing softening agent, but the binder in the Reclamite mix hardened less than the other agents. The fact that the Reclamite is an emulsion has been speculated to be the reason for the lesser hardening. The Dutrex mixture hardened more due to aging than the other agents in terms of binder consistency. It was comparable, however, to the other softening agents in mix properties after aging.

8. For many inplace mixes, 100% recycling is feasible in terms of binder and mix properties. This is due to the wide variety of softening agents available to meet many of the wide variety of inplace materials.

The pollution problem accompanying flexible pavement recycling is of major concern.

IMPLEMENTATION

The data gathered in this study has been useful in the selection of both the type and amount of softening agent to be used on the pavements evaluated in this study. The general relationships developed for binder and mix properties with the various agents, should prove useful in future recycling mix designs.

The findings of this study have been used to enhance Utah's recycling design process. The use of the creep compliance and resilient modulus parameters will be included to evaluate recycled mixes. These tests will not only be used in the design, but also as indicators of mix properties after recycling by testing core samples.

FUTURE STUDIES

1. Research should be carried on at an increasing rate to find methods of recycling flexible pavements within present air quality standards.
2. Studies should be done to determine how recycled mixes compare to virgin mixes in terms of rutting, fatigue, temperature cracking and stripping.
3. More detailed analyses of the chemical makeup of softening agents is needed to determine how they affect binder quality and aging characteristics.

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APPENDIX A

RELATIONSHIPS BETWEEN PROPERTIES OF THE SOFTENING AGENTS

Refractive Index

The refractive indices of the softening agents were measured on a Bausch and Lomb (catalog no. 334558) refractometer. The refractive index was found to be related linearly to the first acidaffins content and inversely to the saturates content (Figures A1 and A2) measured for the agents. This indicates that in general the lower a softening agent is in first acidaffins and the higher the saturates content, the more readily light travels through the substance.

Specific Gravity

The specific gravity of the softening agents is shown in Figure A3 to be related to the saturates content. The higher percentages of saturates corresponds to a lower specific gravity. This indicates that the saturates are a lighter substance in terms of mass as well as light refraction.

Temperature Susceptibility

The temperature susceptibility (TS) was calculated for each softening agent using the following:

$$TS = \frac{\log \log \eta_1 - \log \log \eta_2}{\log T_2 - \log T_1}$$

where η_1 and η_2 are viscosity values (in centistokes) at temperatures T_1 and T_2 (in absolute temperature) respectively. The temperature susceptibility was found to correlate inversely with the saturates contents of the softening agents (Figure A4). This is not surprising since the saturates were shown to be lighter than the other components as related to specific gravity and refractive index. What is interesting is that the temperature susceptibility, when compared to paving asphalt, has been

FIGURE A1
REFRACTIVE INDEX
VS
FIRST ACIDAFFINS CONTENT

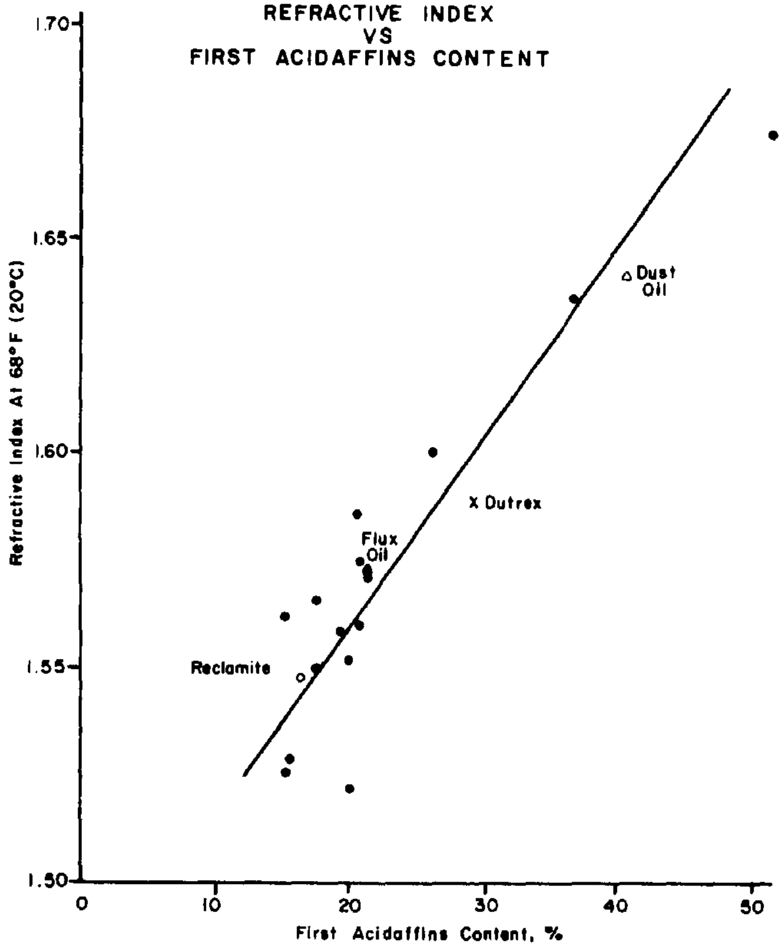


FIGURE A 2
REFRACTIVE INDEX
VS
SATURATES CONTENT

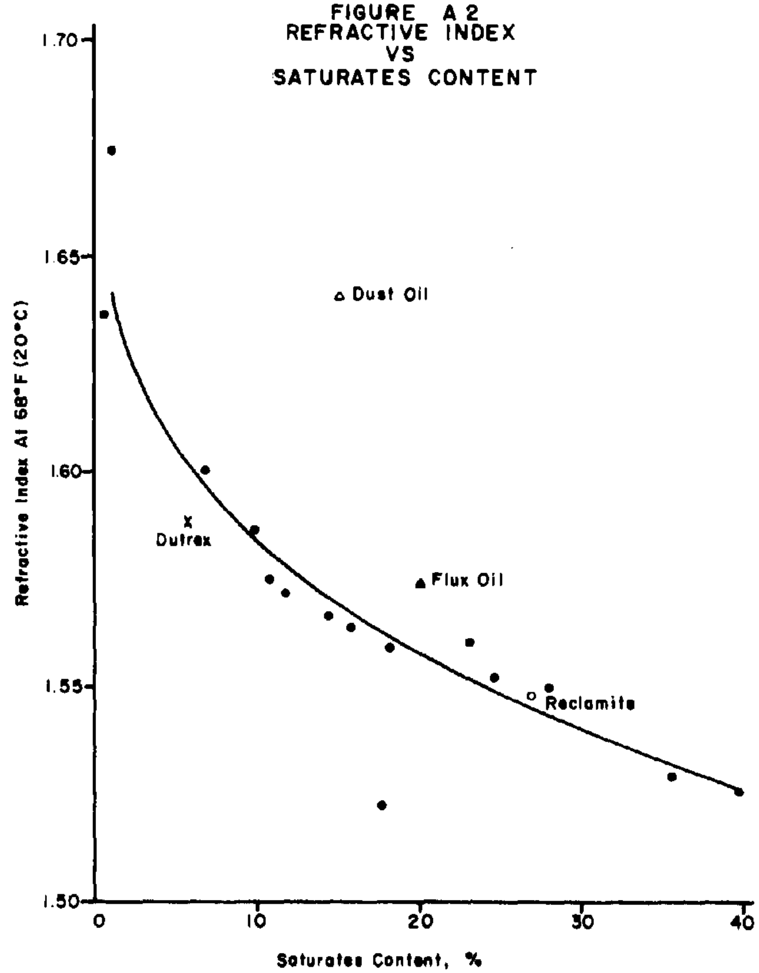


FIGURE A3
SPECIFIC GRAVITY
VS
SATURATES CONTENT

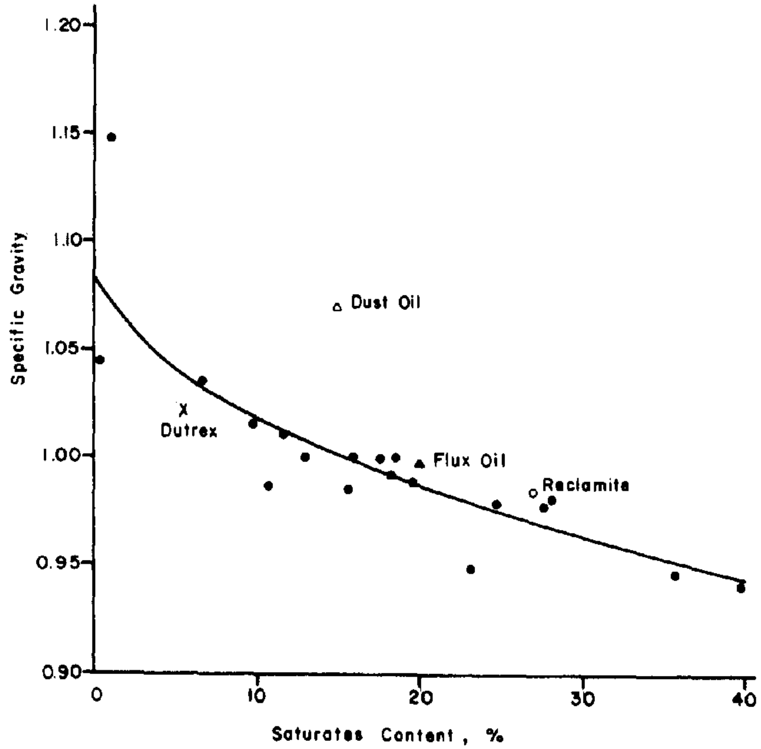
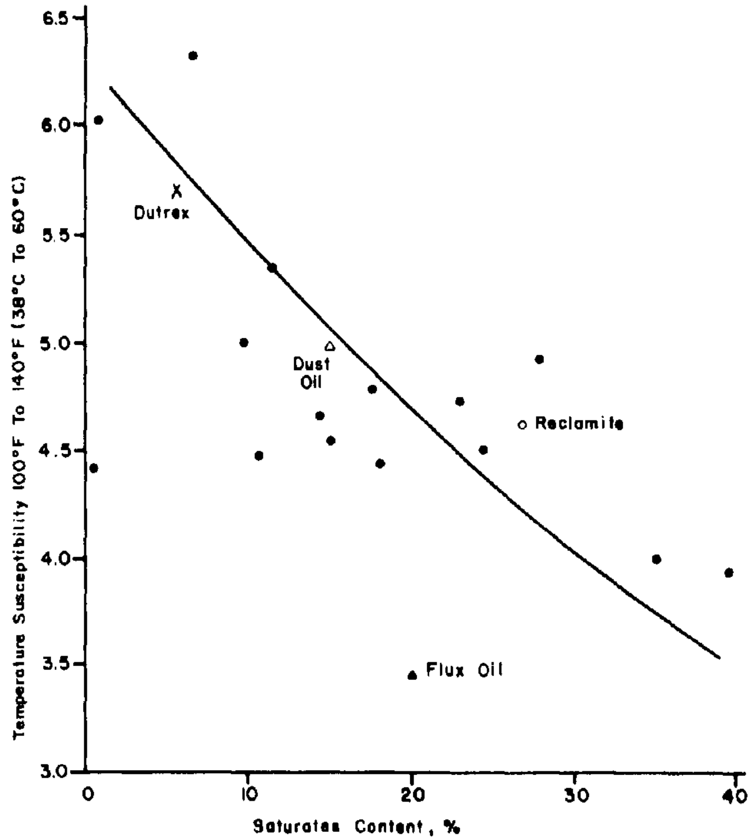


FIGURE A4
TEMPERATURE SUSCEPTIBILITY
VS
SATURATES CONTENT



shown to correlate directly with saturates content as seen in Figure A5.(1) Apparently the saturates taken from normal asphalts are reacting quite different from those contained in the softening agents. More sophisticated chemical analysis would be necessary to definitely identify any differences in the makeup of these saturates, and is beyond the scope of this study.

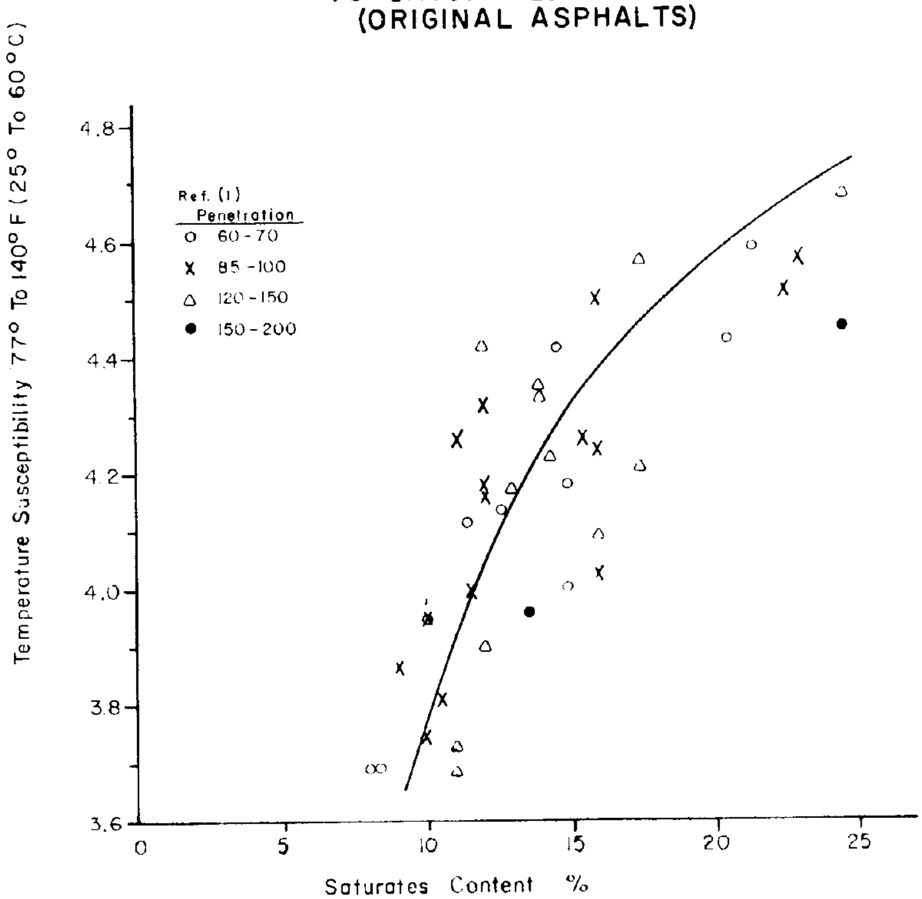
It is speculated that the saturates in the Utah asphalts are mainly made up of paraffins, which consist of long chain molecules. This long chain structure is responsible for a more waxy consistency, and thus the direct relationship with the temperature susceptibility. The saturates in the softening agents, however, are mainly made up of nonparaffinic substances, which consist of cyclic chain molecules. This shorter chain structure results in the lower temperature susceptibility for higher saturates contents in the softening agents.(19)

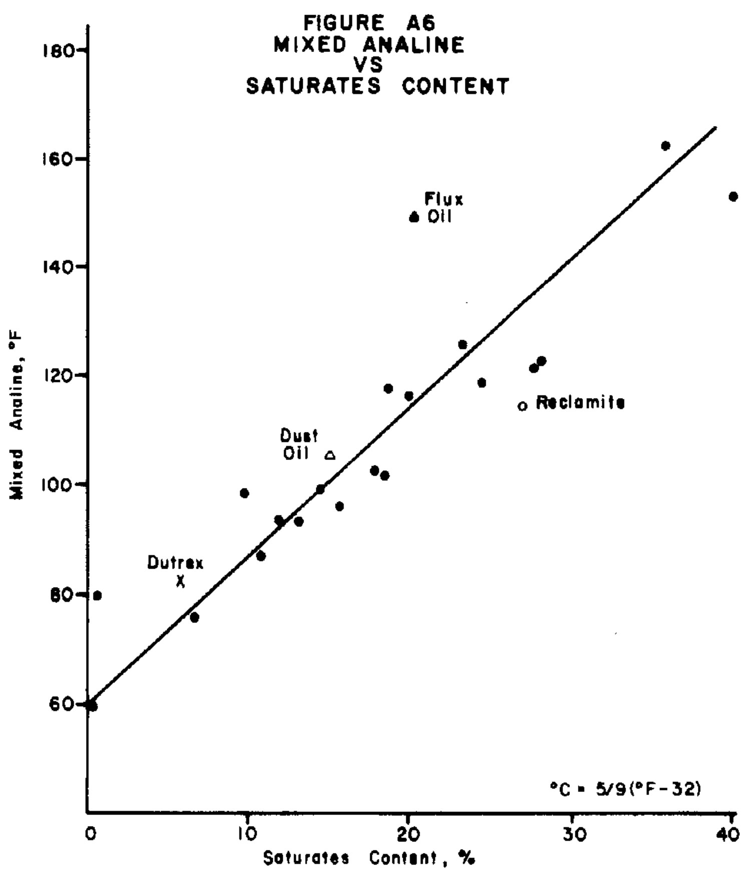
The temperature susceptibility of the binder has been related to transverse cracking in flexible pavements.(1, 20) By reducing the temperature susceptibility of the binder in recycled pavements, it may be possible to reduce the chance for transverse cracking.

Mixed Analine

The mixed analine test measures the temperature at which analine will react with a substance. For the softening agents investigated here, the mixed analine correlated with the saturates content (Figure A6). The saturates have been shown to be a relatively nonreactive component in asphalts (1), which could account for the higher required temperature for a reaction to take place with the mixed analine.

FIGURE A5
TEMPERATURE SUSCEPTIBILITY
VS SATURATES CONTENT
(ORIGINAL ASPHALTS)





APPENDIX B

TEST EQUIPMENT AND THE INDIRECT TENSILE METHOD

The apparatus used to perform the tests includes a system for applying a specified load, either static or cyclic, and instrumentation to monitor the vertical and horizontal deformations of the specimen throughout the test.

An MTS system was used to apply the loads. The system is capable of applying a static loading for the preconditioning and creep tests, or a haversine wave loading configuration for the resilient modulus testing. The load was monitored on a strip chart recorder, which provided a continuous record.

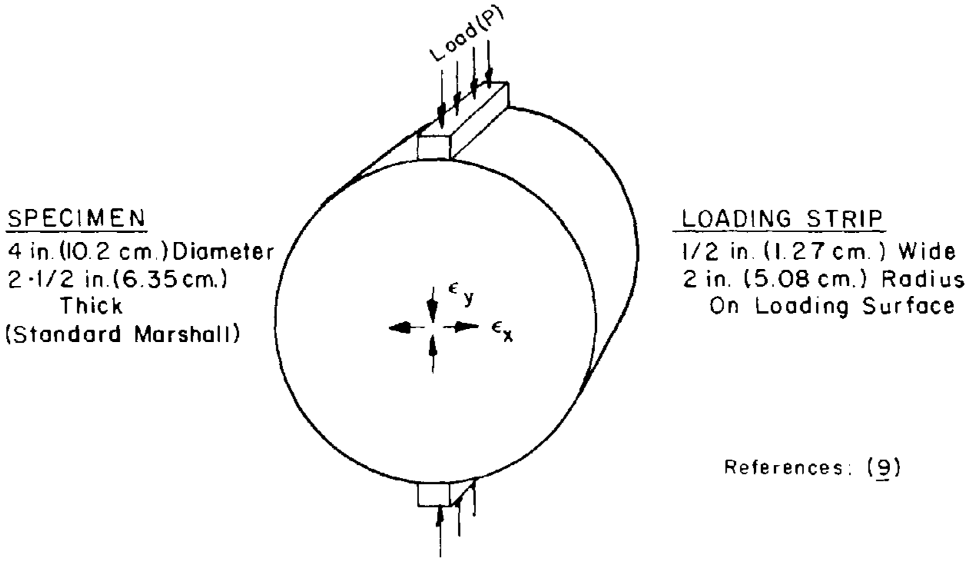
Linear variable differential transducers (LVDT) were used to measure the vertical and horizontal deformations of all specimens. These measurements were also plotted continuously on a dual-channel strip chart recorder.

The indirect tensile test method (6, 7, 8, 9) was used to obtain the creep compliance and resilient modulus values for each cell. Standard Marshall samples were found adequate and were used (ASTM D-1559). The indirect tensile test employs a biaxial stress state at the center element of the cylindrical specimen. This is done by loading the specimen in compression along the vertical diametral plane (Figure B1). The loading is applied through a 1/2 inch (1.27 cm.) wide loading strip formed with a contact face equal in radius to the sample insuring a constant loading area during testing.

Monitoring of the vertical and horizontal deformations is done throughout the test by using the LVDT's as shown in Figure B2. Using these deformations and the applied loads, values of the vertical and horizontal strains and stresses at the center element were computed using the equations described in Figure B1. The equations apply to the

FIGURE B1

SPECIMEN FAILING IN TENSION UNDER COMPRESSIVE LOAD



References: (9)

FOR A 4 in. (10.2 cm.) DIAMETER AT SPECIMEN CENTER

$$\epsilon_y(t) = 0.151 \; Y(t)$$

$$\epsilon_x(t) = 0.517 \; X(t)$$

$$\sigma_y = -3\sigma_x = 0.191 \; P$$

WHERE σ_x & σ_y = Horizontal And Vertical Stresses Repectively

$\epsilon_y(t)$ = Compressive Strain At Time t

$\epsilon_x(t)$ = Tensile Strain At Time t

$Y(t)$ = Vertical Deformation At Time t (Inches)

$X(t)$ = Horizontal Deformation At Time t (Inches)

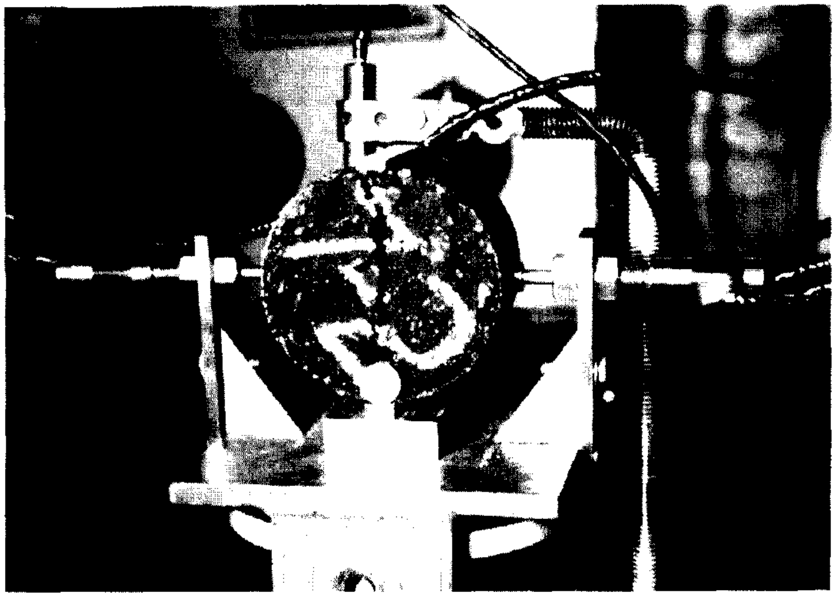


FIGURE B2: INDIRECT TENSION SPECIMEN WITH LVDT'S

4 in. dia x 2 1/2 in. (10.2 cm dia x 6.35 cm) specimen employed in the study. The general equations and the constants for indirect tensile properties are shown in Tables B1 and B2.

TABLE B1 EQUATIONS FOR CALCULATING TENSILE PROPERTIES

Static Properties

(1) Tensile strength S_T , psi $= \frac{P_{Fail}}{h} \cdot A_0$

(2) Poisson's ratio ν $= \frac{DR \cdot A_1 + B_1}{DR \cdot A_2 + B_2}$

(3) Modulus of elasticity E , psi $= \frac{S_H}{h} (A_3 - \nu \cdot A_4)$

(4) Tensile strain ϵ_T $= X_T \left[\frac{A_5 - \nu \cdot A_6}{A_1 - \nu \cdot A_2}\right]$

(5) Compressive strain ϵ_C $= Y_T \left[\frac{B_3 - \nu \cdot B_4}{B_1 - \nu \cdot B_2}\right]$

Repeated-Load Properties

(6) Instantaneous resilient Poisson's ratio ν_{RI} $= \frac{\frac{V_{RI}}{H_{RI}} A_1 + B_1}{\frac{V_{RI}}{H_{RI}} A_2 + B_2}$

(7) Instantaneous resilient modulus of elasticity E_{RI} , psi $= \frac{P}{H_{RI} h} (A_3 - \nu_{RI} \cdot A_4)$

P_{Fail} = total load at failure (maximum load P_{max} or load at first inflection point), pounds

P = applied load or repeated load, pounds

h = height of specimen, inches

DR = deformation ratio $\frac{Y_T}{X_T}$ (the slope of line of best fit* between vertical deformation Y_T and the corresponding horizontal deformation X_T up to failure load)

X_T = total horizontal deformation, inches

Y_T = total vertical deformation, inches

S_H = horizontal tangent modulus $\frac{P}{X_T}$ (the slope of the line of best fit* between load P and horizontal deformation X_T for loads up to failure load)

H_{RI} , V_{RI} = instantaneous resilient horizontal and vertical deformations, respectively

A_0 , A_1 , A_2 , A_3 , A_4 , A_5 , A_6 , B_1 , B_2 , B_3 , B_4 = constants (see Table 2).

---

*It is recommended that the line of best fit be determined by the method of least squares.

TABLE B2 CONSTANTS FOR EQUATIONS FOR INDIRECT TENSILE PROPERTIES (5)

Diameter, inches	A_0	A_1	A_2	A_3	A_4	A_5	A_6	B_1	B_2	B_3	B_4
3.5	.177	.0766	-.2847	.2680	-.9966	.05056	-.1545	-.9765	-.0204	-.1545	.05056
3.6	.172	.0745	-.2769	.2683	-.9968	.04786	-.1461	-.9590	-.0193	-.1461	.04786
3.7	.168	.0726	-.2694	.2685	-.9970	.04537	-.1384	-.9422	-.0183	-.1384	.04537
3.8	.164	.0707	-.2624	.2688	-.9971	.04307	-.1312	-.9260	-.0173	-.1312	.04307
3.9	.160	.0690	-.2557	.2690	-.9973	.04094	-.1246	-.9104	-.0165	-.1247	.04094
4.0	.156	.0673	-.2494	.2692	-.9974	.03896	-.1185	-.8954	-.0156	-.1185	.03896
4.1	.152	.0657	-.2433	.2694	-.9975	.03712	-.1129	-.8810	-.0149	-.1129	.03712
4.2	.149	.0642	-.2375	.2696	-.9976	.03541	-.1076	-.8671	-.0142	-.1076	.03541
4.3	.145	.0627	-.2320	.2698	-.9977	.03381	-.1027	-.8537	-.0136	-.1027	.03381
4.4	.142	.0613	-.2268	.2699	-.9978	.03232	-.0981	-.8407	-.0130	-.0981	.03232
4.5	.139	.0600	-.2218	.2701	-.9979	.03092	-.0938	-.8282	-.0124	-.0938	.03092
4.6	.136	.0587	-.2170	.2702	-.9980	.02961	-.0898	-.8161	-.0118	-.0898	.02961
4.7	.133	.0575	-.2124	.2703	-.9981	.02838	-.0860	-.8043	-.0114	-.0860	.02839
4.8	.131	.0563	-.2080	.2704	-.9982	.02723	-.0825	-.7930	-.0109	-.0825	.02723
4.9	.128	.0552	-.2037	.2706	-.9983	.02615	-.0792	-.7820	-.0105	-.0792	.02615
5.0	.126	.0541	-.1997	.2707	-.9983	.02512	-.0760	-.7714	-.0100	-.0761	.02513
5.1	.123	.0531	-.1958	.2708	-.9984	.02416	-.0731	-.7610	-.0097	-.0731	.02416
5.2	.121	.0521	-.1920	.2709	-.9985	.02325	-.0703	-.7510	-.0093	-.0703	.02325
5.3	.119	.0511	-.1884	.2709	-.9985	.02239	-.0677	-.7413	-.0090	-.0677	.02240
5.4	.116	.0502	-.1849	.2710	-.9986	.02158	-.0652	-.7319	-.0086	-.0652	.02158
5.5	.114	.0493	-.1816	.2711	-.9986	.02081	-.0629	-.7227	-.0083	-.0629	.02081
5.6	.112	.0484	-.1783	.2712	-.9987	.02008	-.0607	-.7138	-.0080	-.0607	.02008
5.7	.110	.0476	-.1752	.2713	-.9987	.01939	-.0586	-.7051	-.0078	-.0586	.01939
5.8	.109	.0468	-.1722	.2713	-.9988	.01874	-.0566	-.6967	-.0075	-.0566	.01874
5.9	.107	.0460	-.1693	.2714	-.9988	.01811	-.0547	-.6884	-.0072	-.0547	.01811
6.0	.105	.0452	-.1665	.2714	-.9988	.01752	-.0529	-.6804	-.0070	-.0529	.01752
6.1	.103	.0445	-.1638	.2715	-.9989	.01695	-.0512	-.6727	-.0068	-.0512	.01696
6.2	.102	.0438	-.1611	.2716	-.9989	.01642	-.0495	-.6651	-.0066	-.0495	.01642
6.3	.100	.0431	-.1586	.2716	-.9989	.01590	-.0480	-.6577	-.0064	-.0480	.01591
6.4	.099	.0424	-.1561	.2717	-.9990	.01542	-.0465	-.6504	-.0062	-.0465	.01542
6.5	.097	.0418	-.1537	.2717	-.9990	.01495	-.0451	-.6434	-.0060	-.0451	.01495

Strip width a = 0.5 in.

APPENDIX C

RELATIONSHIPS BETWEEN PROPERTIES
OF THE RECYCLED MIXES

FIGURE C1
ABSOLUTE VISCOSITY AT 140°F (60°C)
VS CREEP COMPLIANCE AT 1 SECOND

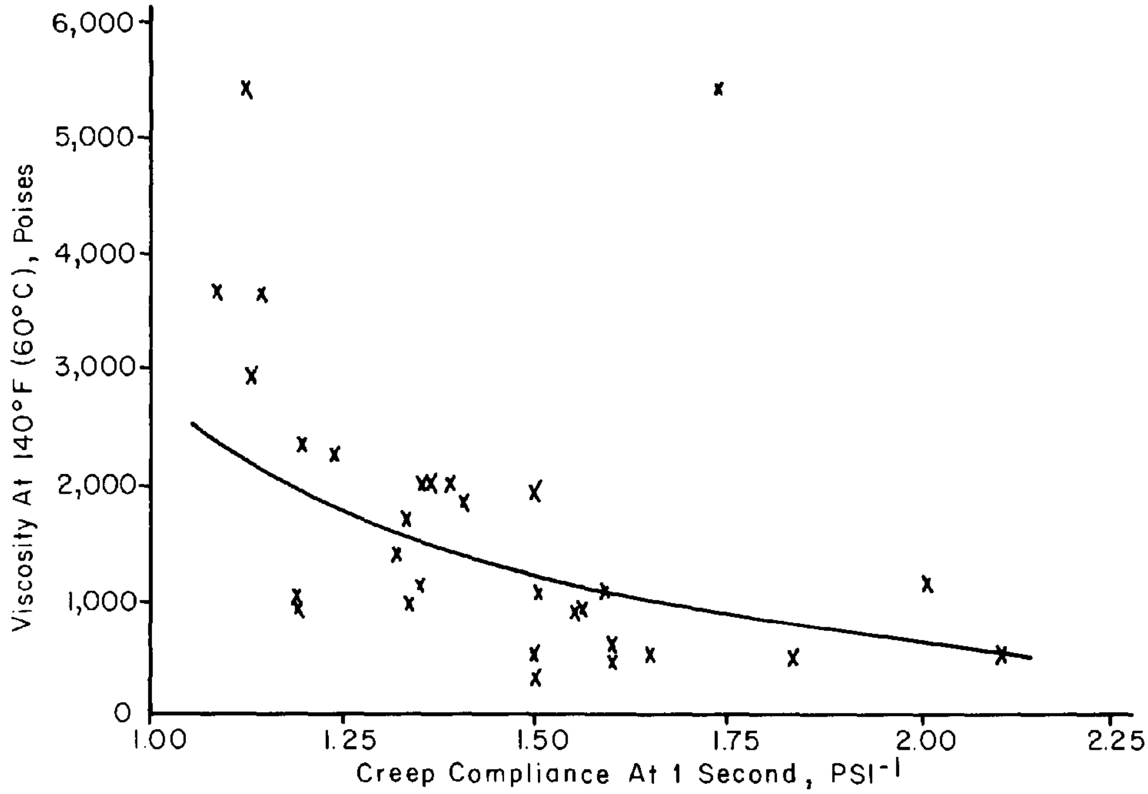


FIGURE C2
PENETRATION VS
CREEP COMPLIANCE AT 1 SECOND

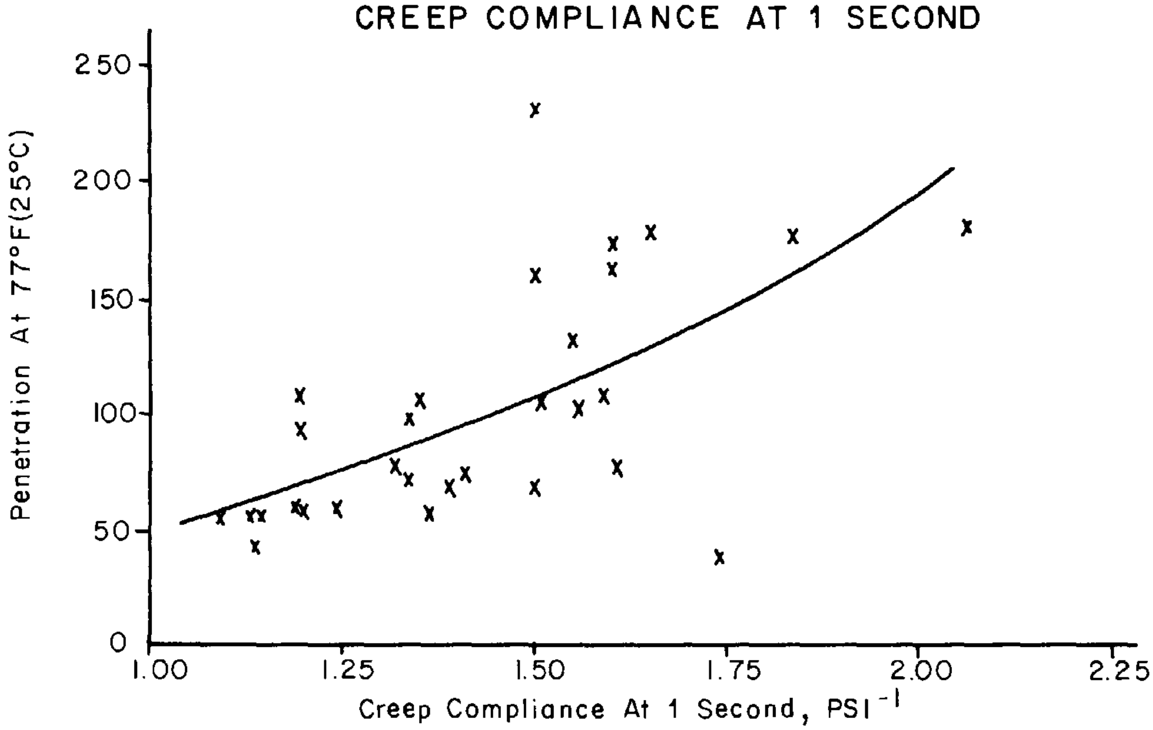


FIGURE C3
ASPHALTENES CONTENT
VS CREEP COMPLIANCE AT 1 SECOND

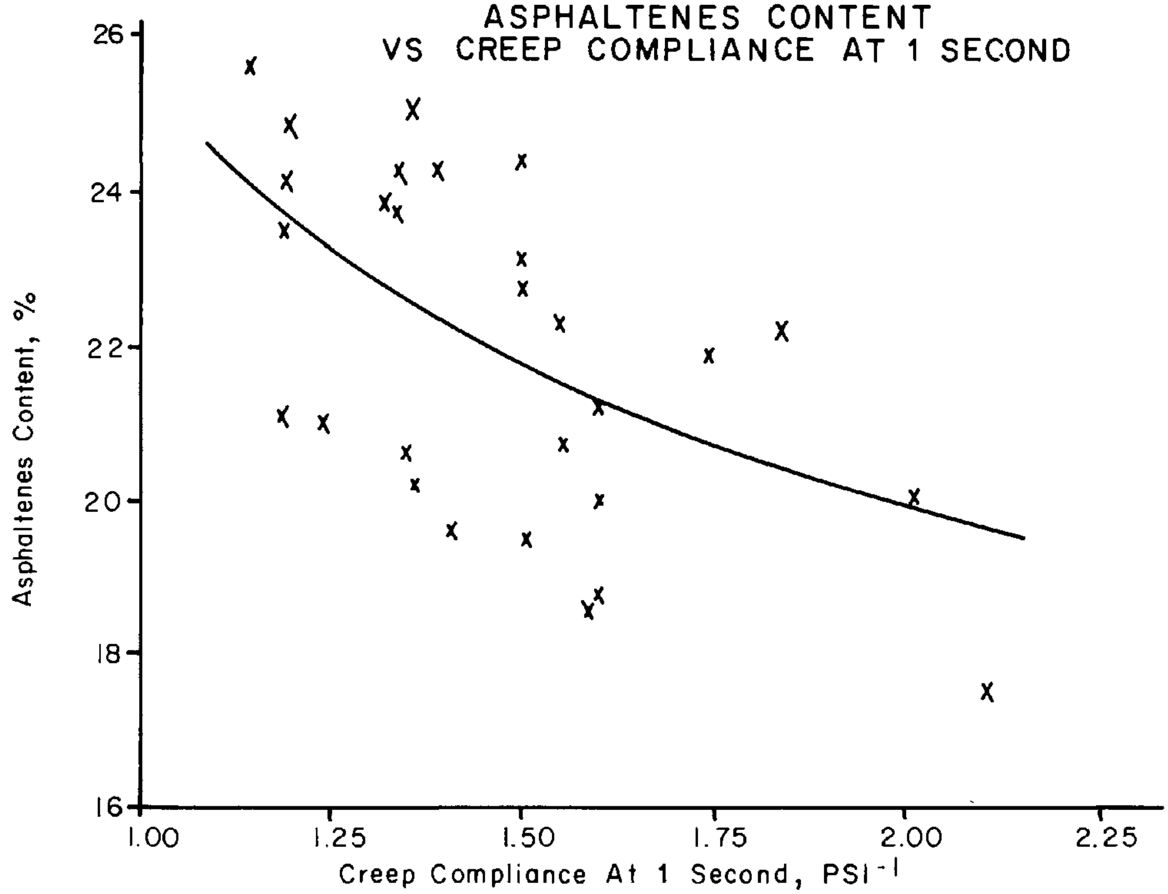


FIGURE C4
PENETRATION VS
RESILIENT MODULUS