Iowa Engineering Experiment Station

final report

BEHAVIOR OF ASPHALTS DURING PRODUCTION OF ASPHALTIC CONCRETE MIXES

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INTRODUCTION

When mixing asphalt in thin film and at high temperatures, as in the production of asphalt concrete, it has been shown that asphalt will harden due essentially to two factors: (1) losses of volatiles and (2) oxidation. The degree of hardening as expressed by percent loss in penetration varied from as low as 7% to about 57%(1-3) depending on mixing temperatures, aggregate types, gradation, asphalt content, penetration and other characteristics of asphalts used.

Methods used to predict hardening during mixing include loss on heat and thin film oven tests, with the latter showing better correlation with the field findings(4-6). However, information on other physical and chemical changes that may occur as a result of mixing in the production of hot-mix asphaltic concrete is limited.

The purpose of this research project was to ascertain the changes of asphalt cement properties, both physical and chemical, during mixing operation and to determine whether one or more of the several tests of asphalt cements were critical enough to indicate these changes.

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(1) ASTM STP. 277, 3 (1959)
(2) Proc. AAPT. 9, 165 (1937)
(3) Proc. AAPT. 33, 285 (1964)
(4) Public Roads 22, 2 (1941)
(5) Proc. AAPT. 11, 86 (1940)
(6) Proc. AAPT. 12, 14 (1940)

The laboratory study was conducted in the following general areas:

1. To study the variation of ten 85-100 pen. asphalt cements which were used on actual paving projects.

2. To study the changes, both physical and chemical, during mixing operation.

3. To investigate the possibility of using heat treatment procedure to predict or identify these changes during mixing by one or more of the routine tests.

At the end of the first year, it was decided to extent and broaden the study for another six months to include the following:

4. To study the changes occurred in the first year road service on five of the ten original asphalts.

5. To study the feasibility of using kinematic capillary viscometer as laboratory routine viscosity test.

AUTHORIZATION

The Iowa Highway Research Board on June 11, 1964, approved Project HR-107 entitled, "Behavior of Asphalts during Production of Asphaltic Concrete Mixes." Upon approval of the Iowa Highway Commission and allocation of funds, a contract for the execution of the work on the project was awarded to the Engineering Experiment Station of Iowa State University with the date for completion of the work set for June 10, 1965. This study under the same title was designated Project 540-S of the Engineering Experiment Station.

Based upon the progress made in the investigation at the time of the original completion date, the Iowa Highway Research Board approved an extension of the project for an additional six months to December 1, 1965.

This report recovers the entire work completed up to December 1, 1965.

PROCEDURE

This project was started in June, 1964. During the year ten 2-gallon samples of 85-100 pen. asphalt cement and ten 100 lb. samples of asphaltic concrete were taken from tanks and mixers of asphalt plants at various Iowa Highway Commission paving projects and were delivered to the Bituminous Research Laboratory, Iowa State University. At the end of one year, field cores from five of the ten original projects were taken (Table I).

Studies were made in the following phases:

Phase I. Study the variation among the ten original asphalts as indicated by the following tests:

a. Penetration at 77°F.

b. Softening point, Ring and Ball.

c. Thin film oven test and penetration, viscosity, spot test and asphaltene content determination(7) on residue.

d. Viscosity at 77°F by Shell sliding plate microviscometer.
Viscosity at 140°F by Cannon-Manning vacuum capillary viscometer.
Viscosity at 275°F by Zeitfuchs Cross-Arm viscometer.

e. Surface tension by DuNouy Tensiometer.

f. Ductility
Standard at 77°F and 55°F.
Micro(3) at 77°F and 50°F.

g. Oliensis spot test

h. Asphaltene content determination

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(7) Proc. AAPT. 23, 64 (1954).

Phase II. Study the changes in asphalt during mixing and one year road service. The ten asphaltic concrete samples from mixers were tested as follows:

a. Extraction of the asphalt cement from the mix by modified Colorado Method.

b. Recovery of the asphalt cement by the Absen Method.

c. The recovered asphalts were compared in quality with the original asphalt cements, as expressed by tests in Phase I.

The asphaltic concrete field cores taken at the end of one year road service from five of the ten original projects were tested as follows:

a. Bulk density, maximum theoretical density and percent voids.

b. Extraction of the asphalt cement by modified Colorado method.

c. Recovery of asphalt by the Absen Method.

d. The recovered asphalt cements were compared in quality with the original asphalt cements, as expressed by tests in Phase I.

Phase III. Study the effects of heat treatment on asphalts. Specimens of asphalt cement samples No. 2 and No. 10, selected by Iowa Highway Commission engineers, were heated in 500ml tall form beakers for 24 hours in a controlled temperature oven at $250^{\circ}F$, $300^{\circ}F$, $350^{\circ}F$, $400^{\circ}F$ and $450^{\circ}F$.

After being heated, each specimen was tested by the same methods used for original asphalt cements in Phase I.

DISCUSSION

I. Variations Among the Ten Original Asphalt Cements:

Although all the asphalt cements studied were of 85-100 pen. grade, the test results indicated that they varied, especially on consistency and chemical composition:

a. Specific gravity ranged between 0.993 and 1.029.

b. Consistency as measured by:

1. Penetration: Ranged from 76 to 91 with a mean of 84.1 and a coefficient of variation of 5.8%.

2. Softening point: Ranged from 105°F and 120°F with a mean of 115°F and a coefficient of variation of 3.6%.

3. Viscosity at 77°F: Varied from 8 x 10^5 to 5.7 x 10^5 poises with a mean of 6.6 x 10^5 poises and coefficient of variation of 12.1%.

   Viscosity at 140°F: Varied from 1.6 x 10^3 to 2.6 x 10^3 poises with a mean of 2.0 x 10^3 poises and a coefficient of 16.5%.

   Viscosity at 275°F: Varied from 3.4 to 5.2 poises with a mean of 4.0 poises and a coefficient of variation of 20.1%.

c. Asphaltene content: Asphaltene content precipitated by Skelly F ranged from 10.6% to 18.4%.

d. Thin film oven test (TFOT): Varied between a loss of 0.23% by weight and a gain of 0.19% by weight.

e. Standard ductility: When tested at 77°F, all specimens had ductility in excess of 150 cm. when this test was conducted at 50°F, the results ranged from 22 cm to 38 cm. Micro ductility at 77°F ranged between 63 and 77 cm and at 50°F the variation was between 3 and 6 cm.

f. The Oliensis spot test showed all asphalts to be negative.

II. Effects on Asphalts During Mixing:

As expected, all ten asphalts hardened during mixing operation (Fig. 1-3). Hardening during mixing as measured by ratio of penetration of original asphalts to that of recovered asphalts (hardness taken as reciprocal of penetration) and by ratio of absolute viscosity at 77°F of recovered asphalts to that of original asphalts, together with hardening during thin film oven tests, were tabulated in Table IV.

Even though the degree of hardening as measured by various consistency scales is not always consistent, a general trend can be noted.

a. Hardening of asphalts during mixing approaches that of thin film oven tests, especially when measured by penetration ratio or percent loss in penetration (Fig. 5).

b. Asphalts with higher asphaltene content hardened less percentage-wise during mixing than those with lower asphaltene content.

c. Mix with low bitumen index(8) or thinner film in general hardened more than those with high bitumen index or thicker asphalt films (Fig. 6).

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(8) Proc. AAPT. 28, 149 (1959).

d. Though correlation is not very good (Fig 7) it is noted that asphalts with higher penetration (or low initial viscosity) hardened more during mixing than asphalts of low penetration. From the durability point of view, the use of softer asphalts as a definite advantage needs more research.

e. Contrary to general belief, ductility increased in eight of the ten asphalts even though they hardened during mixing. This appears to mean two significant points:

1. There may exist an optimum viscosity for maximum ductility.
2. Dependibility and significance of microductility at 77°F should be further evaluated.

III. Changes in Asphalts During the First Year Road Service:

Degrees of asphalt hardening in first year service as measured by penetration ratio and viscosity ratio were tabulated in Table V. The decrease in penetration, increase in softening point, viscosity and asphaltene content of recovered asphalts were shown in Figs. 1-4.

It has been shown that even under identical exposure conditions no two asphalts oxidized and hardened at the same rate(9). It was expected in this study that the results on rate of hardening in the field would diverse widely. One thing is definite: All asphalts in pavements harden with time.

With limited data, the following were noted:

a. Hardening is closely associated with voids in the paving mixtures as indicated in Table V. The general trend is that

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(9) Ind. Engr. Chem. 39, 1512 (1947).

asphalts hardened less in the pavement with low voids than those in the pavement with high air voids.

b. From the point of view of hardening measured by absolute viscosity at 77°F and increase in asphaltene content, it appears that changes during mixing are similar to that during first year service, under Iowa climatic and traffic conditions (Figs. 2 and 4).

c. Plotting percent hardening of asphalts as measured by penetration ratio during mixing against additional hardening in service (Fig. 8), it is noted, except for asphalt No. 2, that asphalts hardened more during mixing hardened less or slower in the pavement during the first year. Thus, it may prove that initial hardening during mixing may not necessarily be detrimental but may protect the main film from further oxidation hardening. More research is needed in this regard which could change current philosophy of asphalt paving mixture design.

IV. Changes in Asphalts Due to Heat Treatment:

Test results on the two special asphalts No. 2 and No. 10 were tabulated in Table III and plotted in Figs. 8-13.

a. Penetration: Both asphalts decreased in penetration with increase in heating temperature at almost an identical rate (Fig. 9). Both reached a penetration about equal to that noted for the recovered asphalts from the mixer when heated to 450°F. Penetration tests have been criticized for their inability to measure the rheological properties of asphalt in absolute terms. However, the degree of hardening as measured by penetration in this study has been found relatively consistent.

b. Viscosity at 77°F: The viscosity of asphalts increased with heating temperature at about the same rate (Fig. 10).

c. Thin film oven loss: Both asphalts showed loss up to 350°F, then they began to gain weight at higher temperatures (Fig. 11). This suggests that loss of flux oils ceased at slightly over 300°F and chemical changes began to occur.

d. Softening point: Both asphalts increased in softening point as the temperature of heating increased (Fig. 12). Both reached the softening point noted for the asphalts recovered after mixing at 400°F.

e. Surface tension: Due to the limitation of the tensiometer used and high viscosity effects at lower temperatures, surface tension results were not conclusive. Yet the following can be noted:

   1. Surface tension decreases with increase of temperature.
   2. Surface tension increased with heat treatment.

f. Ductility: Heating specimens to higher temperatures had no apparent effect on standard ductility at 77°F. All test results were 150+.

Standard ductility tests at 50°F showed a gradual loss (after an initial gain at around 250°F to 300°F) in ductility.

Micro ductility tests at 77°F were not consistent. When run at 50°F they showed a gradual loss in ductility with increase in heating temperature.

The standard ductility tests at 50°F yield the most significant effects of heating (Fig. 13).

g. Asphaltene content: Both asphalts showed increase in asphaltene content with increase in heating temperature at an increasing rate (Fig. 14).

CORRELATION

I. Viscosity: In this study, viscosity at 77°F was determined by sliding plate microviscometer, viscosity at 140°F was determined by Cannon-Manning vacuum viscometer, and viscosity at 275°F was determined by Zeitfuchs cross-arm viscometer. Results were converted into units of poises and the following were noted:

a. Viscosities determined by these three types of viscometers at three different temperatures correlated very well. All original asphalts gave essentially straight line relationships on a log viscosity against log temperature plot. However, as hardening occurred, all the curves concaved downward and became not only more viscous but also more temperature susceptible, especially at lower temperatures.

b. The viscosity at one temperature does indicate the relative viscosities at other temperatures, though the slope of the viscosity-temperature curve may differ from one asphalt to another.

c. The log viscosity against log rate of shear plot at 77°F, indicated that all ten asphalts, original or recovered, behaved as non-Newtonian liquid at that temperature.

d. Figure 15 is a viscosity-temperature band resulting from plotting all ten asphalts studied. It is seen that, although all asphalts were of 85-100 pen., their absolute viscosities do differ, even at 77°F, the temperature at which the penetration was measured. From a practical point of view, this fact is significant. If the asphalt is to be mixed at the optimum viscosity of say 2 poises, then it would be necessary to make a temperature adjustment of the asphalt of as much as 20°F if we want to insure producing a uniform mix. If all mixes are compacted at one temperature, such as, 210°F, the viscosity of the asphalt in the mix may vary as much as 30 poises.

e. According to our experience with capillary viscometers, we feel that if viscosities of asphalts at 140°F and 275°F are to be determined, the Cannon-Manning viscometers alone would appear to be sufficient. Cannon-Manning viscometers are favored over Zeitfuchs cross-arm viscometers because:

   1. They provide wider range information on viscosity without specific gravity factor.
   2. They can be more easily filled and cleaned.
   3. They are tougher and less expensive.
   4. They give two readings on each run. Results can be checked more readily. It has been shown in our experience that the variations of the two readings are usually within 2% of the mean.

II. Specific Gravity:

a. Specific gravity of the original asphalts ranged from 0.993 to 1.029. For individual asphalts, there is a general increase in specific gravity as material becomes harder under normal heating and oxidation conditions.

b. From a plot of specific gravity against asphaltene content

(Fig. 16) it is noted that specific gravity appears to be proportional to asphaltene content.

c. Under extended periods of heating (Study Phase III) both asphalts increased in specific gravity up to 350°F. When heated above this temperature, both decreased in specific gravity which suggests that evaporation of flux oils had ceased at that temperature and chemical changes were occurring.

III. Penetration: The relationships between absolute viscosity at various temperatures and penetration at 77°F of all original and recovered asphalts are shown in Fig. 17. It is noted that:

a. Linear trend exists between log viscosity and log penetration. Best correlation exists between viscosity at 77°F and penetration.

b. As temperature increases, the slopes of the lines flatten accordingly, which means that at higher temperatures there is less viscosity difference among asphalts of different penetration.

c. The viscosity characteristics of recovered asphalts had wider spread than those of the original asphalts.

IV. Ductility: Due to the limited quantity of recovered asphalt that would be available, all ductility tests on recovered asphalts were made on micro ductility mold developed by the Phillips Petroleum Company (3). Prior to the starting of this project, attempts were made to correlate standard ductility at 77°F, 5^{cm} per minute pull and micro ductility at 77°F, 5^{cm} per minute pull and 1^{cm} per minute pull. Three asphalt cements were arbitrarily chosen. They were heated in ovens to reduce ductility after each set of run. Results were shown in Fig. 18. Correlations were only fair, but linear trend can be seen from log standard ductility against log micro ductility plot. In general, standard ductility equals to about 4-5 times micro ductility when standard ductilities are under 150^{cm} and both run at a speed of 5^{cm} per minute.

It is felt that ductility run at 50^{o}F is more indicative than at 77^{o}F.

V. Asphaltene Content:

a. Asphalts from different sources may have different asphaltene content. The ten asphalts studied had asphaltene contents from 10.4% to 18.4%.

b. For all ten asphalts studied, an increase in viscosity was always accompanied by an increase in asphaltene content or vice versa. The plot of log viscosity at 77^{o}F against asphaltene content (Fig. 19) showed that they approach a straight line relationship with slight variation on their slopes. This relationship, if it holds true for all asphalt cements, could be very significant in predicting hardening or aging of asphalts.

c. With limited data resulted from this study, it appears that an asphaltene content of about 20% is a border line for negativeness and positiveness of Oliensis spot test.

CONCLUSIONS

Realizing that this was not a closely controlled research project and that many variables have entered into the study (important variables including asphalt sources, asphalt mix composition, mixing temperature, aggregate characteristics, etc.), it would be expected that correlations were not exact nor definite. However, many significant trends were detected. Within the limits of this study, the following conclusions were drawn:

1. Although all ten asphalts studied were 85-100 pen. their viscosities differed widely, even at 77°F the temperature at which the penetration is measured. From the practical point of view, if all mixes are to be mixed and compacted at optimum viscosities, the following have to be done for all asphalts used in each project to insure uniform product: (a) determine temperature-viscosity relationship and (b) close control of mixing and compacting temperatures accordingly.

2. For all ten asphalts studied, log viscosity against log temperature is fairly linear over the temperature range that is most important from the point of view of paving construction.

3. The thin film oven test appears to be the most critical in denoting material difference between the asphalts studied.

4. Asphalts hardened more during the mixing operation than in first year service. This hardening as measured by penetration ratio ranged from 130% to 180%.

5. Hardening of asphalts during mixing operation approached in degree to that of thin film oven test, especially when measured by

penetration ratio.

6. In the mixing process, the following were noted:
    a. Asphalts with lower penetration hardened less percentagewise than those with higher penetration.
    b. Asphalt hardening during mixing is a function of its bitumen index or film thickness.

7. In the first year road service, the following were noted:
    a. The degree of additional hardening is a function of air voids in the pavement.
    b. The percent of additional hardening as measured by penetration is related to its initial hardening during mixing.

8. Within the limited scope of this study, the following relationships among asphalt characteristics were found:
    a. Linear relationship between log viscosity and log penetration with better correlation at 77^{o}F than at other temperatures.
    b. Linear relationship between log viscosity of original asphalts and log temperature in degree Fahrenheit.
    c. Linear relationship between log standard ductility and log micro ductility, both at 77^{o}F and 5^{cm} per minute pull, within a ductility range of 150^{cm}.
    d. Linear relationship between specific gravity and percent asphaltene content.
    e. For each individual asphalt, there appeared to be a linear relationship between its log viscosity and its asphaltene content.

9. Continued research is needed in the area of asphalt durability on a local basis. Since definite relationships have been found among percent hardening, absolute viscosity, penetration, asphaltene content, specific gravity, and to some extent, spot test, they should be used as measures for durability evaluation.

FURTHER WORK

Without applying knowledge gained in previous research for future study this knowledge is meaningless; without applying the findings of engineering research for practical engineering usage the research is of little value. With the information obtained in Project HR-107, "Behavior of Asphalts in the Production of Asphaltic Concrete" additional research is needed to study the durability of asphalt on a local basis and to develop a laboratory accelerated durability test for classifying and evaluating asphalts and to predict the life of asphalt under Iowa weather and traffic conditions.

Table I. Samples of Asphalt Cement, Asphaltic Concrete Mixes and Field Cores

Sample No.	Paving Contract	County	IHC Mix. No.	IHC A.C.No.	One Year Field Core
1	S-462(9)	Adair	ABC4-705	AB4-155	
2	FN-712	Appanoose	ABC4-922	AB4-171	X
3	FN-292	Clinton	ABC4-1201	AB4-181	
4	FN-103	Delaware	ABC4-1109	AB4-180	X
5	FN-32	Des Moines	ABC4-709	AB4-156	X
6	FN-172(3)	Fayette	ABC4-618	AB4-150	X
7	FN-111(2)	Kossuth	ABC4-1135	AB4-157	
8	FN-321&221	Muscatine	ABC4-444	AB4-126	X
9	--	--	C4-214	AB4-120	
10	FN-150	Wayne	ABC4-2555	AB4-260	

Results

Test results on Phase I and Phase II were tabulated in Table II. Test results on Phase III study were shown in Table III.

Table II. Properties of original asphalts, asphalts recovered after mixing and asphalts recovered from field cores.

A.C. No.	1			2			3			4			5			6			7			
Descript.	Original	Mix	1	0	M	1	0	M	1	0	M	1	0	M	1	0	M	1	0	M	1	
Test No.	AB4-155	ABC4-705		AB4-171	ABC4-922	FN-712	AB4-181	ABC4-1201		AB4-180	ABC4-1109	FN-103	AB4-156	ABC4-709	FN-32	AB4-150	ABC4-618	FN-172	AB4-157	ABC4-1135		A
Sp.Gr. Original	1.026	1.035		1.029	1.035	1.061	1.011	1.007		1.016	1.022	1.042	0.997	1.005	1.023	1.013	1.023	1.026	1.001	1.008		1
Residue	1.049	1.029		-	1.036	1.051	1.014	1.016		1.022	1.018	1.048	0.989	0.992	1.018	1.016	1.014	1.035	0.997	1.001		1
TFOT loss %	0.06	0.25		1.91	0.06	0.26	0.18	0.19		0.04	0.33	0.50	+0.09	0.24	0.34	0.20	0.22	0.23	+0.05	0.23		0
Softening Point, F	115.5	121.0		112.0	122.0	129.0	116.0	123.0		114.0	122.0	123.0	119.5	126.5	129.0	114.0	122.0	126.5	116.0	127.5		119
Penetration O^{x}	76	60		91	53	35	80	55		82	58	46	84	47	42	84	50	43	82	51		88
R^{xx}	46	45		53	44	29	50	43		44	40	31	53	37	31	49	37	37	51	38		60
% Original	61	75		58	83	83	63	78		54	69	68	63	88	74	48	74	86	62	74		68
Ductility cm.																						
N-77°F	150+			150+			150+			150+			150+			150+			150+			150
N-50°F	28			34			38			34			26			22			25			24
M-77°F	77	101		73	95	63	76	59		74	99	90	69	63	18	73	97	84	64	66		63
M-50°F	3.3			5			4			5			4			6			5			4
Spot Test O	-	+		-	+	+	-	+		-	-	+	-	-	±	-	-	+	-	±		
R	-	+		-	+	+	-	+		-	+	+	-	±	±	-	±	+	-	±		
Viscosity, P.																						
77°F O	8.0×10^{5}	1.4×10^{6}		7.0×10^{5}	1.7×10^{6}	5.6×10^{6}	7.4×10^{5}	2.4×10^{6}		5.7×10^{5}	1.9×10^{6}	4.7×10^{6}	6.3×10^{5}	3.5×10^{6}	6.7×10^{6}	5.9×10^{5}	1.7×10^{6}	4.2×10^{6}	6.5×10^{5}	2.9×10^{6}		7.
R	24.0×10^{5}	3.3×10^{6}		23.5×10^{5}	3.0×10^{6}	8.1×10^{6}	22.8×10^{5}	4.1×10^{6}		35.5×10^{5}	4.4×10^{6}	7.3×10^{6}	24.5×10^{5}	5.1×10^{6}	9.8×10^{6}	23.1×10^{5}	4.0×10^{6}	$7\ 1 \times 10^{6}$	18.0×10^{5}	4.8×10^{6}		22.
140°F O	1.7×10^{3}	2.7×10^{3}		1.8×10^{3}	2.6×10^{3}	5.7×10^{3}	1.9×10^{3}	3.6×10^{3}		2.0×10^{3}	2.8×10^{3}	3.9×10^{3}	2.6×10^{3}	5.9×10^{3}	8.0×10^{3}	1.7×10^{3}	3.1×10^{3}	4.0×10^{3}	2.4×10^{3}	5.3×10^{3}		2.
R	5.0×10^{3}	5.3×10^{3}		4.6×10^{3}	4.5×10^{3}	10.5×10^{3}	5.1×10^{3}	6.3×10^{3}		4.3×10^{3}	5.6×10^{3}	7.3×10^{3}	4.7×10^{3}	8.9×10^{3}	16.2×10^{3}	5.0×10^{3}	5.9×10^{3}	7.1×10^{3}	6.0×10^{3}	12.5×10^{3}		5.
275°F O	3.4	4.3		3.4	4.1	6.1	3.6	4.4		3.6	4.3	5.0	5.0	6.8	7.8	3.7	4.3	5.0	5.2	9.4		3.
R	5.4	5.9		5.2	5.4	7.2	5.1	5.6		5.4	5.8	6.9	6.4	8.0	9.9	5.7	5.9	6.8	7.5	10.4		4.
Surface tension																						
325°F	26.4	26.8		26.5	28.9	29.8	28.1	26.4		29.8	29.0	28.8	26.5	29.1	29.2	26.7	28.2	29.2	28.5	29.0		28.
275°F	28.7	28.8		28.7	31.7	33.0	32.3	28.8		32.5	31.8	32.5	29.2	32.4	32.4	28.5	30.8	33.3	30.9	32.8		31.
225°F	31.0	31.5		31.7	37.0	45.7	36.4	31.1		35.2	39.0	40.5	31.8	42.1	47.5	30.4	37.5	42.3	33.4	46.0		34.
Asphaltene, %																						
O	17.5	20.7		17.5	21.3	24.0	18.0	21.6		14.1	16.5	20.3	12.8	15.8	17.3	15.8	16.9	18.5	12.5	15.5		18.
R	20.3	22.7		20.3	22.6	26.3	21.2	22.9		18.8	20.1	20.9	14.4	16.7	17.9	18.2	19.4	20.6	15.4	17.8		19.

x original asphalt
xx residue from thin film oven test

from field cores.

3		4			5			6			7			8			9			10		
M	1	0	M	1	0	M	1	0	M	1	0	M	1	0	M	1	0	M	1	0	M	1
ABC4-1201		AB4-180	ABC4-1109	FN-103	AB4-156	ABC4-709	FN-32	AB4-150	ABC4-618	FN-172	AB4-157	ABC4-1135		AB4-126	ABC4-444	FN-372	c-210	C4-214		AB4-260	ABC4-2555	
1.007		1.016	1.022	1.042	0.997	1.005	1.023	1.013	1.023	1.026	1.001	1.008		1.005	1.011	1.030	0.993	1.002		1.012	1.012	
1.016		1.022	1.018	1.048	0.989	0.992	1.018	1.016	1.014	1.035	0.997	1.001		1.012	1.025	1.030	0.998	1.000		1.013	1.007	
0.19		0.04	0.33	0.50	+0.09	0.24	0.34	0.20	0.22	0.23	+0.05	0.23		0.16	0.25	0.47	+0.05	0.12		0.23	0.19	
123.0		114.0	122.0	123.0	119.5	126.5	129.0	114.0	122.0	126.5	116.0	127.5		119.5	124.0	131.5	116.0	124.0		105.0	122.0	
55		82	58	46	84	47	42	84	50	43	82	51		88	54	45	84	64		90	56	
43		44	40	31	53	37	31	49	37	37	51	38		60	39	36	49	48		48	40	
78		54	69	68	63	88	74	48	74	86	62	74		68	72	80	58	75		53	71	
		150+			150+			150+			150+			150+			150+			150+		
		34			26			22			25			24			26			33		
59	-	74	99	90	69	63	18	73	97	84	64	66		63	69	24	64	73		74	120	
		5			4			6			5			4			6			3		
+		-	-	+	-	-	±	-	-	+	-	±		-	-	-	-	-		-	-	
+		-	+	+	-	±	±	-	±	+	-	±		-	±	-	-	±		-	-	
2.4×10^6		5.7×10^5	1.9×10^6	4.7×10^6	6.3×10^5	3.5×10^6	6.7×10^6	5.9×10^5	1.7×10^6	4.2×10^6	6.5×10^5	2.9×10^6		7.4×10^5	1.7×10^6	4.7×10^6	5.7×10^5	1.8×10^6		6.1×10^5	2.1×10^6	
4.1×10^6		35.5×10^5	4.4×10^6	7.3×10^6	24.5×10^5	5.1×10^6	9.8×10^6	23.1×10^5	4.0×10^6	$7\ 1 \times 10^6$	18.0×10^5	4.8×10^6		22.0×10^5	3.6×10^6	6.3×10^6	20.7×10^5	3.8×10^6		26.5×10^5	4.5×10^6	
3.6×10^3		2.0×10^3	2.8×10^3	3.9×10^3	2.6×10^3	5.9×10^3	8.0×10^3	1.7×10^3	3.1×10^3	4.0×10^3	2.4×10^3	5.3×10^3		2.0×10^3	3.5×10^3	6.2×10^3	2.2×10^3	2.8×10^3		1.6×10^3	2.4×10^3	
6.3×10^3		4.3×10^3	5.6×10^3	7.3×10^3	4.7×10^3	8.9×10^3	16.2×10^3	5.0×10^3	5.9×10^3	7.1×10^3	6.0×10^3	12.5×10^3		5.1×10^3	7.4×10^3	12.8×10^3	34.8×10^3	5.9×10^3		4.3×10^3	4.9×10^3	
4.4		3.6	4.3	5.0	5.0	6.8	7.8	3.7	4.3	5.0	5.2	9.4		3.6	4.1	5.6	4.8	5.2		3.7	4.8	
5.6		5.4	5.8	6.9	6.4	8.0	9.9	5.7	5.9	6.8	7.5	10.4		4.7	5.4	6.8	6.2	6.8		5.3	6.3	
26.4		29.8	29.0	28.8	26.5	29.1	29.2	26.7	28.2	29.2	28.5	29.0		28.3	28.0	29.2	27.7	28.0		29.2	29.2	
28.8		32.5	31.8	32.5	29.2	32.4	32.4	28.5	30.8	33.3	30.9	32.8		31.1	30.8	32.5	29.9	30.3		31.5	31.8	
31.1		35.2	39.0	40.5	31.8	42.1	47.5	30.4	37.5	42.3	33.4	46.0		34.0	37.5	42.3	32.2	35.0		36.2	37.5	
21.6		14.1	16.5	20.3	12.8	15.8	17.3	15.8	16.9	18.5	12.5	15.5		18.4	21.1	24.5	13.4	16.5		10.6	13.7	
22.9		18.8	20.1	20.9	14.4	16.7	17.9	18.2	19.4	20.6	15.4	17.8		19.4	23.8	24.7	16.5	18.2		13.6	15.8	

Table III. Heat Treatment of Asphalts

A.C. No.	2						10				
Temperature °F, 24 hr.	No	250	300	350	400	450	No	300	350	400	450
Sp. Gr. 0^{x}	1.029	1.030	1.020	1.032	1.026	1.024	1.012	1.011	1.011	1.003	1.009
R^{xx}	-	-	-	-	-	-	1.013	1.018	1.011	1.012	1.013
TFOT loss %	1.91	1.01	+0.03	+0.06	+0.05	+0.10	0.23	0.14	+0.03	0	+0.05
Softening point, °F	112.0	114.0	118.0	118.0	120.0	127.5	105.0	117.0	118.5	120.0	124.0
Penetration											
*O	91	87	80	72	69	55	90	79	75	70	54
**R	53	51	48	46	40	35	48	49	43	43	34
***P.I.	0	+0.3	+0.6	+0.3	+0.5	+0.7	-0.8	+0.3	+0.5	+0.5	+0.2
Ductility											
N-77°F	150+	150+	150+	150+	150+	150+	150+	150+	150+	150+	150+
N-50°F	34	35	27	20	13	9	33	43	38	21	11
M-77°F	73	65	63	82	73	75	72	69	82	74	84
M-50°F	5	5	4	3	2	2	3	3	3	2	2
Spot Test											
O	-	-	-	-	-	-	-	-	-	-	-
R	-	-	-	+	+	+	-	-	-	-	-
Viscosity - O	7.0×10^5	6.9×10^5	8.4×10^5	7.9×10^5	11.4×10^5	2.18×10^6	6.1×10^5	8.2×10^5	1.2×10^6	1.1×10^6	2.4×10^6
Viscosity - R Poise, 77°F	2.4×10^6	2.3×10^6	2.7×10^6	3.2×10^6	3.7×10^6	5.2×10^6	2.7×10^6	2.7×10^6	3.3×10^6	3.1×10^6	5.5×10^6
Surface Tension (dynes/cm)											
325°F	26.5	26.5	27.3	28.7	28.8	28.7	29.2	29.4	29.6	29.5	30.1
275°F	28.7	28.8	32.7	32.0	31.6	31.6	31.5	31.9	32.6	32.7	33.2
225°F	31.7	31.3	38.2	35.3	37.0	39.5	36.2	36.4	38.8	39.0	41.6
Asphaltene- O	17.5	17.6	19.4	19.3	19.4	21.3	10.6	10.7	11.1	11.5	13.3
% - R	20.3	20.4	20.2	21.1	21.5	22.3	13.6	13.8	14.7	14.8	17.0

*O - original asphalt

**R - residue from thin film oven test

***P.I. - penetration index (Pfeiffer, J.Ph., the properties of asphaltic bitumen. pp. 167-171.)

Table IV. Percent Hardening During Mixing

A.C.No.	1	2	3	4	5	6	7	8	9	10
% Hardening during mixing by Penetration[1]	127.0	172.0	146.0	141.0	179.0	168.0	160.0	163.0	131.0	161.0
by Viscosity[2] at 77°F	175.0	242.0	324.0	334.0	555.0	289.0	446.0	230.0	316.0	345.0
% Hardening during TFOT by Penetration	165.0	172.0	160.0	186.0	159.0	171.0	160.0	147.0	172.0	187.0
by Viscosity at 77°F	300.0	336.0	309.0	625.0	395.0	477.0	277.0	298.0	364.0	435.0
Original Pentration	76	91	80	82	84	84	82	88	84	90
Bitumen Index[3] x 10^3	1.66	1.47	1.52	1.90	1.29	1.71	1.66	1.35	--	1.82
Original Asphaltene content, %	17.5	17.5	18.0	14.1	12.8	15.8	12.5	18.4	13.4	10.6

1.) Po/Pr x 100 where Po = Pen. original asphalt; Pr = Pen. recovered asphalt.
2.) Nr/No x 100 where No = Viscosity of original asphalt; Nr = Viscosity of recovered asphalt, both at 77°F.
3.) Proc. AAPT Vol. 28, pp. 149-178, (1959).

Table V. Percent Hardening in Pavement

A.C.No.	2	4	5	6	8
% Hardening by Penetration[1]	260.0	178.0	200.0	195.0	195.0
Viscosity[2] at 77°F	800.0	825.0	1090.0	713.0	635.0
% Air Voids	4.4	3.7	4.3	2.6	3.9

1.) Po/Pr x 100 where Po = Pen. original asphalt; Pr = Pen. recovered asphalt.

2.) Nr/No x 100 where No = Viscosity of original asphalt; Nr = Viscosity of recovered asphalt, both at 77°F.

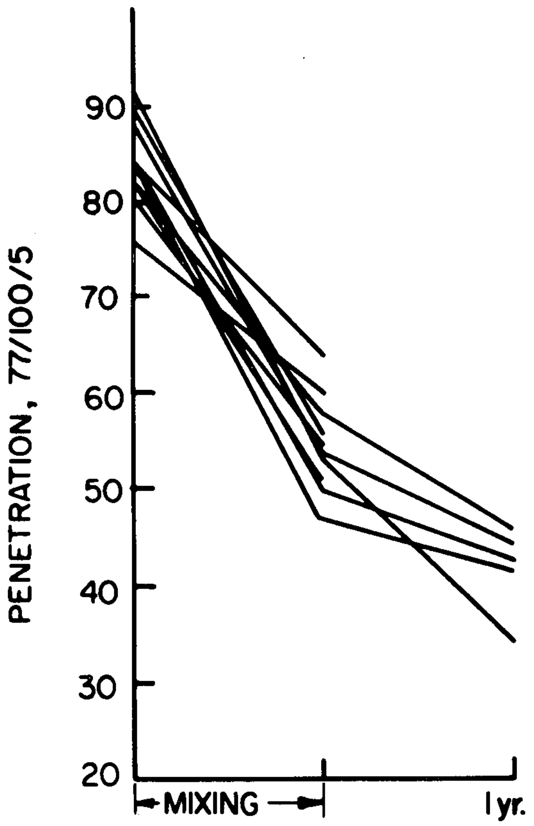

Fig. 1. Penetration vs. time

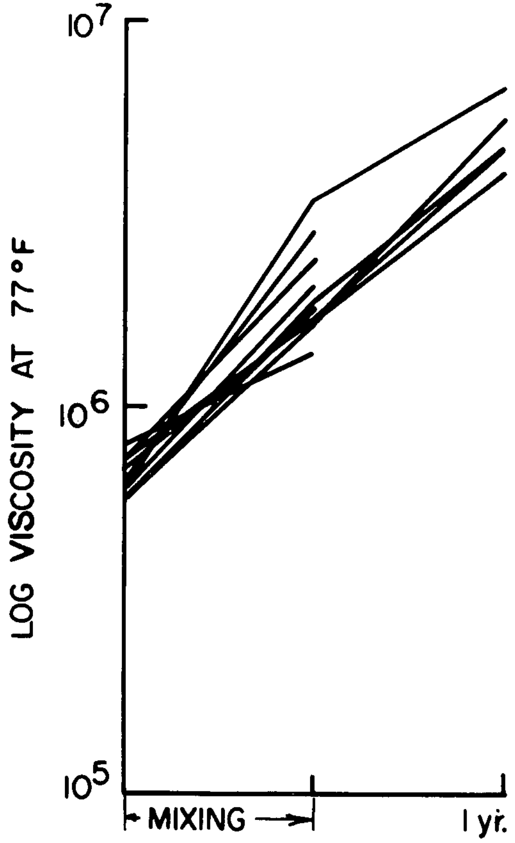

Fig. 2. Viscosity vs. time

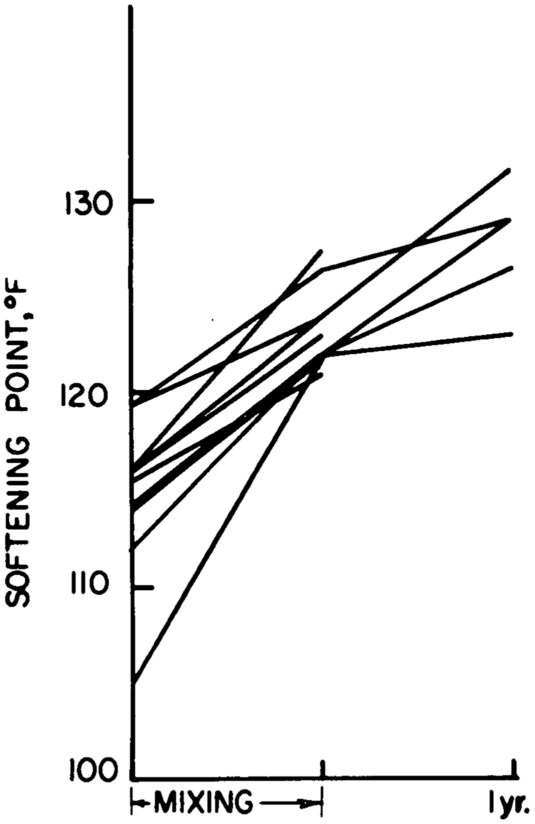

Fig. 3. Softening point vs. time

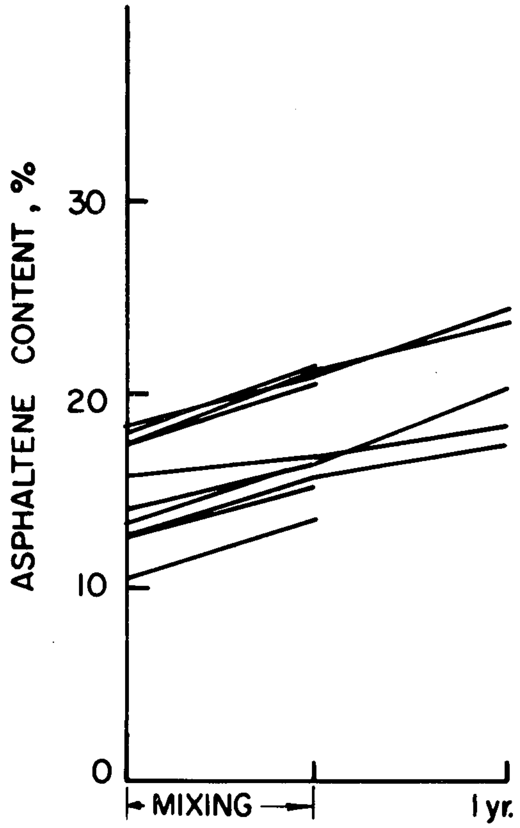

Fig. 4. Asphaltene content vs. time

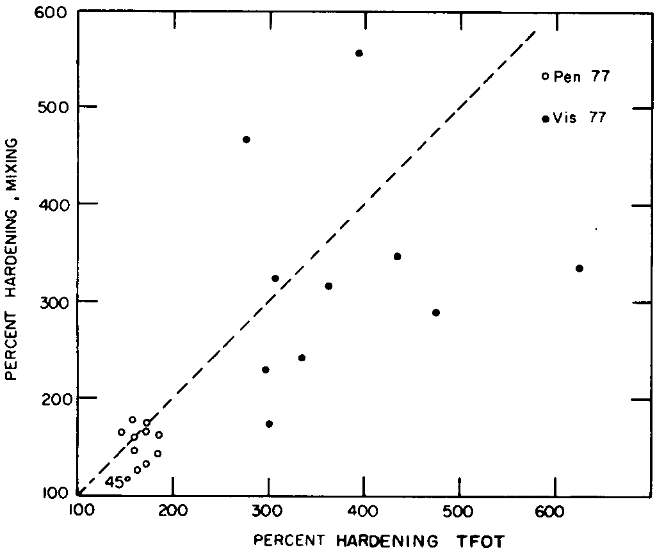

Fig. 5. Percent hardening, TFOT vs.
percent hardening, mixing

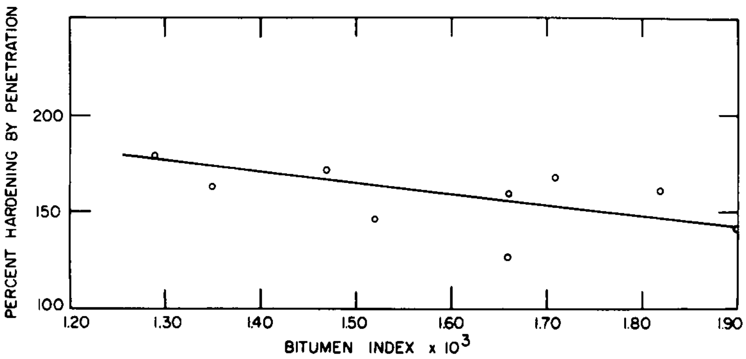

Fig. 6. Bitumen index vs.
percent hardening

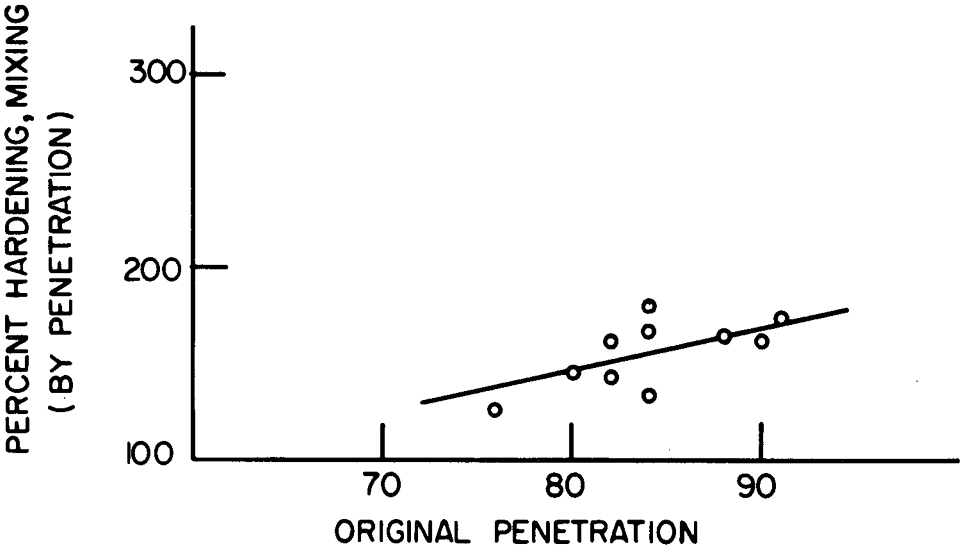

Fig. 7. Relation between original penetration and percent hardening measured by penetration

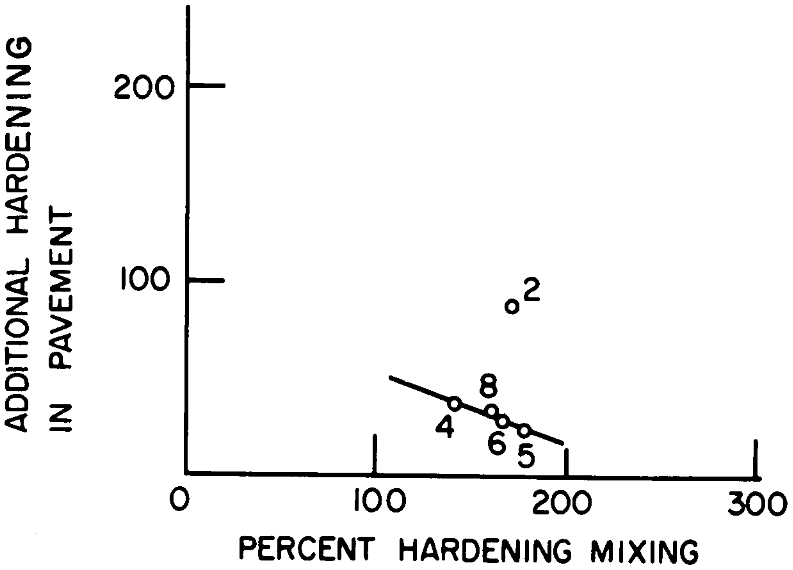

Fig. 8. Percent hardening during mixing vs. additional hardening in pavement, measured by penetration.

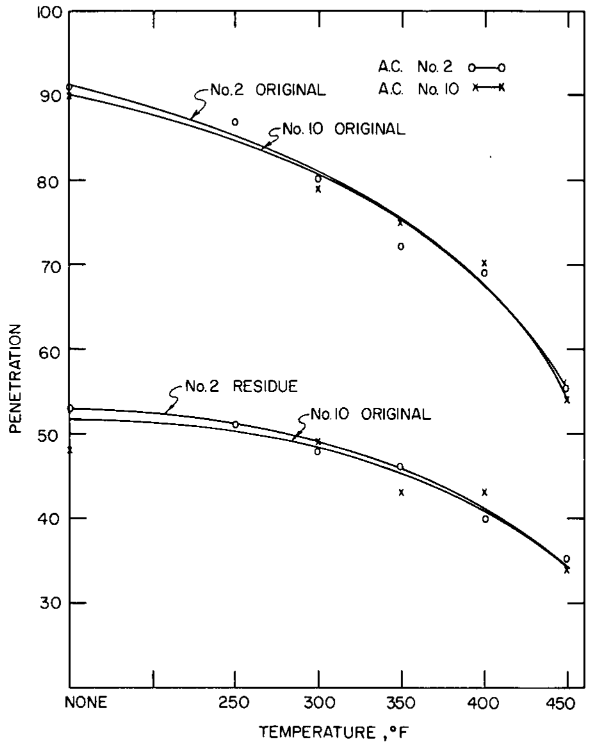

Fig. 9. Penetration vs. temperature

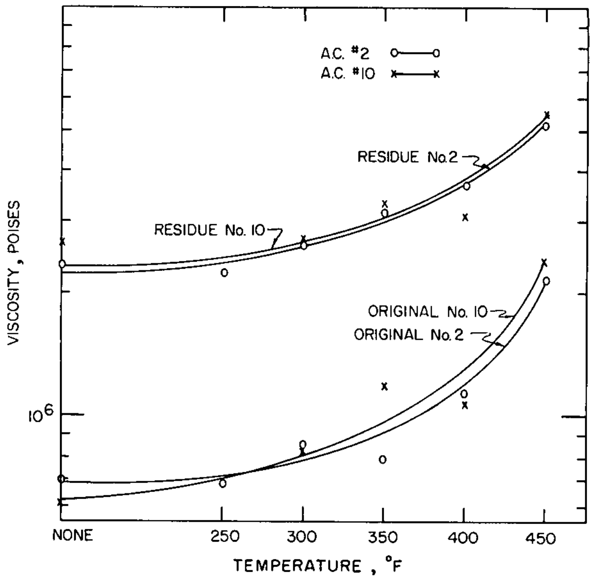

Fig. 10. Viscosity vs. temperature

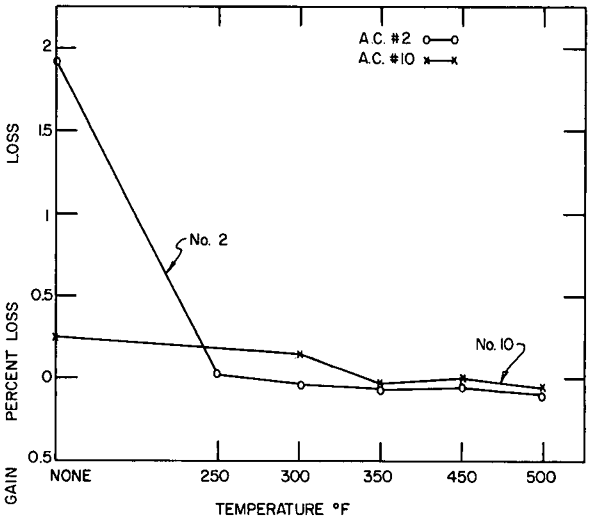

Fig. 11. Thin film oven test vs. temperature

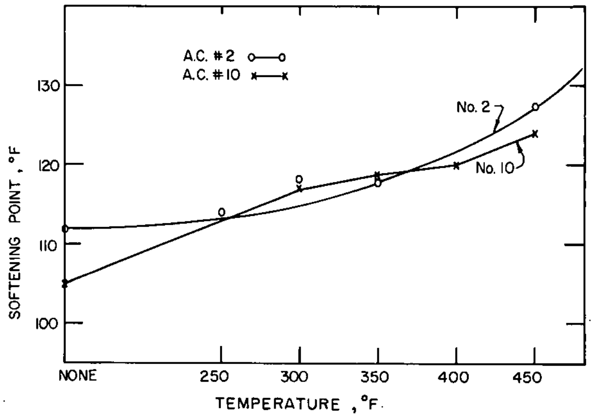

Fig. 12. Softening point vs. temperature

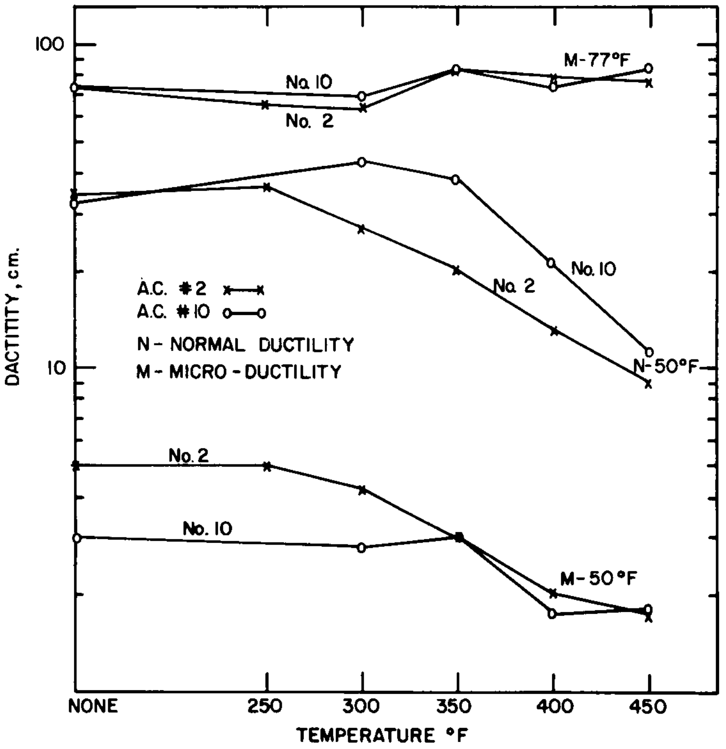

Fig. 13. Ductility vs. temperature

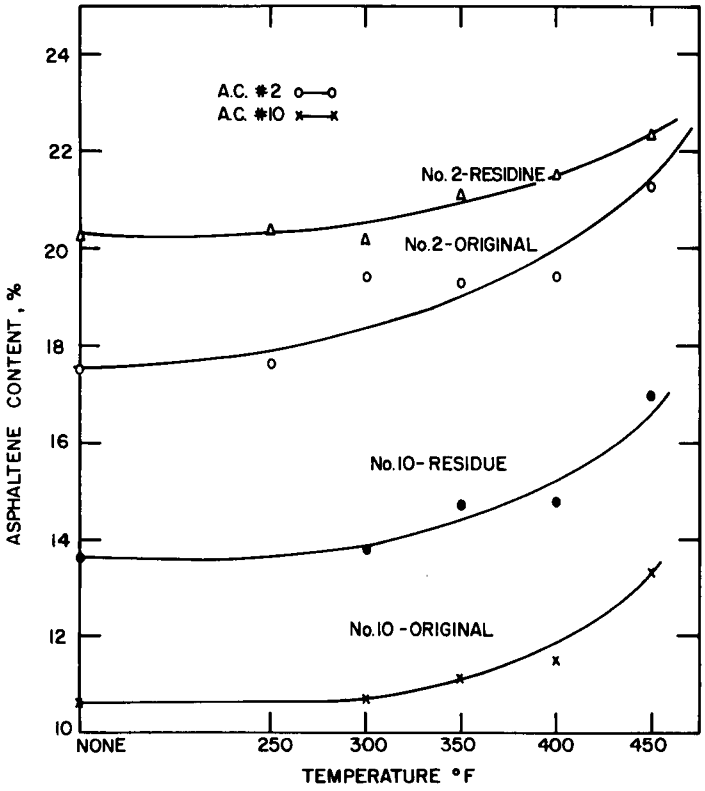

Fig. 14. Asphaltene content vs. temperature

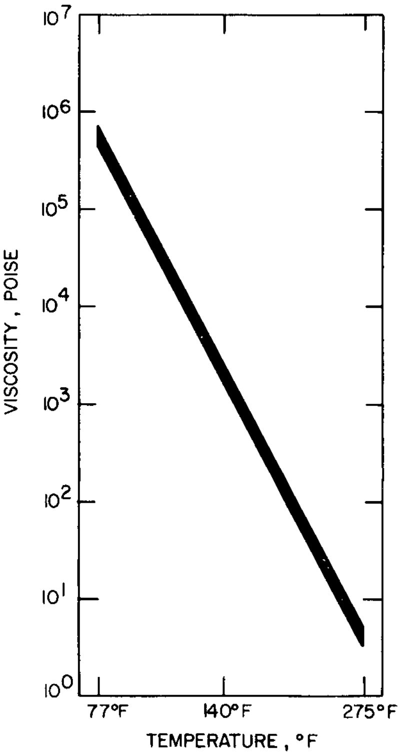

Fig. 15. Viscosity-temperature band for 10 asphalts

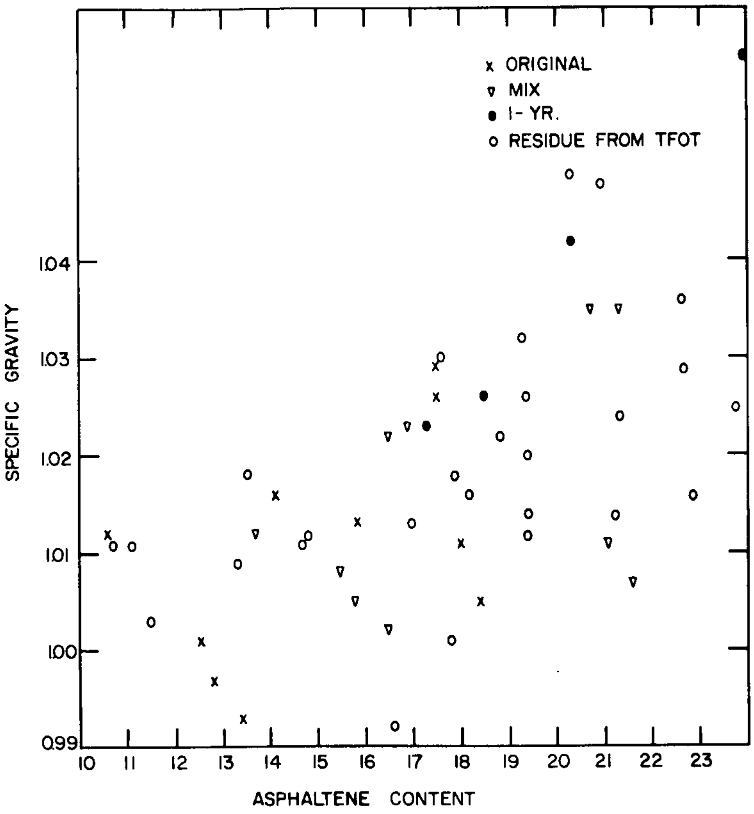

Fig. 16. Specific gravity vs. asphaltene content

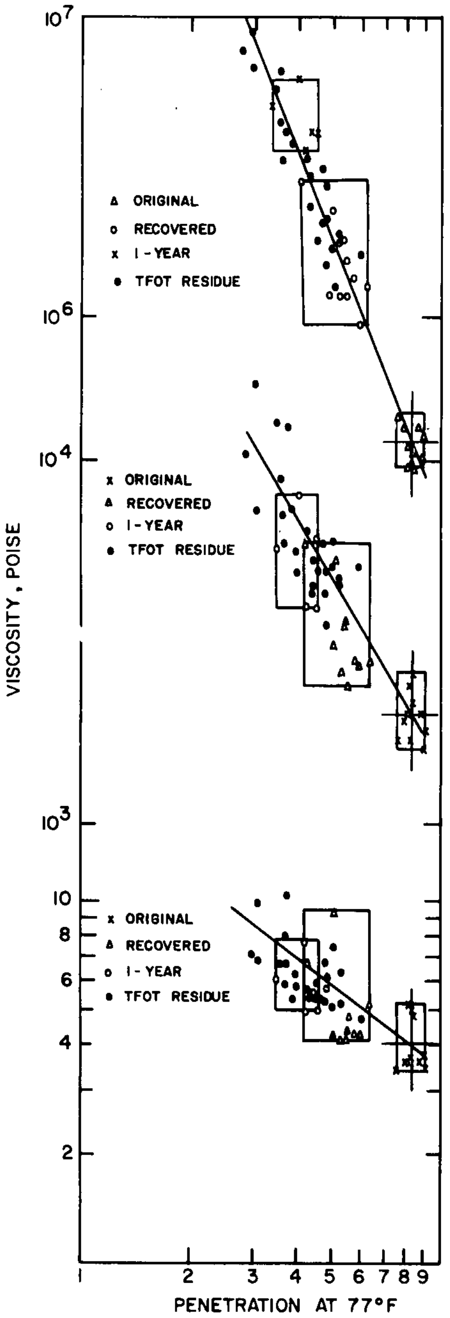

Fig. 17. Viscosity vs. penetration

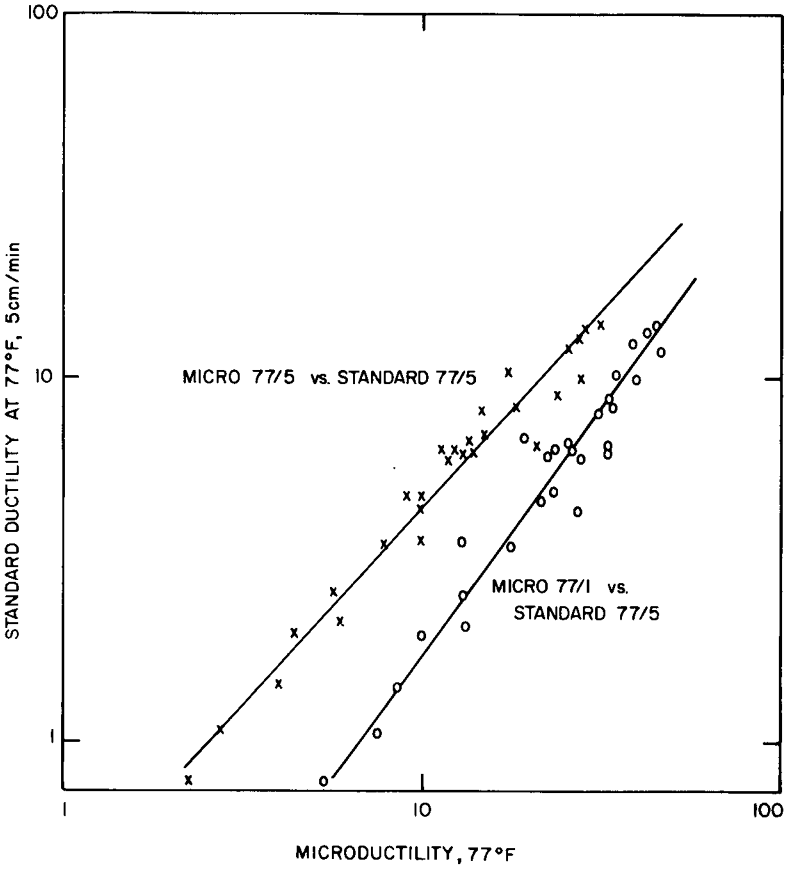

Fig. 18. Correlation between micro and standard ductility

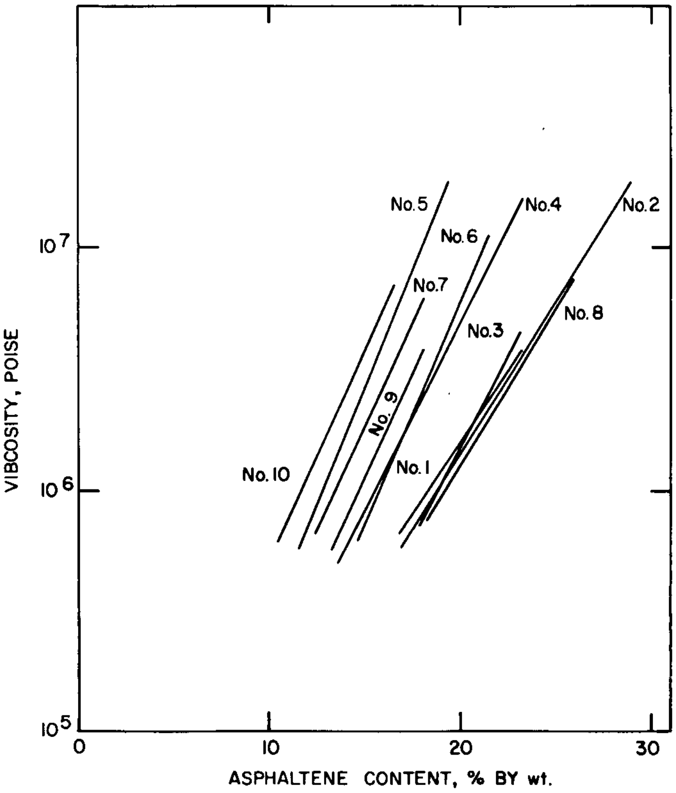

Fig. 19. Viscosity vs. asphaltene content