ASPHALT DURABILITY CORRELATION IN IOWA

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Eight asphalt cements and paving projects using these asphalts were evaluated relative to their changes in rheological and chemical properties in pavement service for as long as 48 months. Corresponding changes in these asphalts of the same physical and chemical properties were determined during laboratory aging. The Iowa durability test is a two-stage aging process combining standard TFOT and pressure-oxidation treatment (20 atm in oxygen at 150 F) up to 1,000 hours. Good correlations between field-service aging in Iowa and laboratory aging during the Iowa durability test have been obtained. The master time-equivalency curve between the test in hours and the pavement service life in months, established by combining all asphalts (void levels) and all properties, indicates that 46 hours in test will age asphalts to the equivalent of 60 months in service. Correlation curves for different properties and different levels of pavement voids were also obtained. A tentative specification for paving asphalts, including durability requirements based on the test, is suggested in lieu of current TFOT.

•PUBLIC agencies responsible for the construction and maintenance of highways and airfield pavements and asphalt producers have been interested in the quality of paving asphalts for many years.

The interest in asphalt quality has led to a large amount of research related to asphalt durability and hardening (1, 2, 3). Most of the reported research on asphalt durability has been directed to finding mechanisms or causes of asphalt deterioration, methods for controlling or preventing undue hardening of asphalts or improving the durability of asphalts, and tests to predict the behavior and durability of an asphalt during mixing, laying, and service.

A research project was initiated in Iowa in 1966 as a long-range comprehensive program in the study of asphalt durability. Its ultimate objective was to develop a simple, rapid laboratory test that could be used by highway engineers to select paving asphalt according to quality, to identify inferior asphalts, and to reasonably predict the useful life of asphalts once they are incorporated in the pavements.

The original proposed study on asphalt durability involves work in the following phases:

1. Review of the knowledge of the durability of paving asphalts including the identification of predominant factors causing hardening during mixing, laying, and in-road service;
2. Development of an accelerated laboratory durability test to simulate changes in asphalt during both short-time production and long-term service;
3. Correlation of hardening and other changes in asphalts during the developed laboratory test and changes in the same asphalts in pavements; and
4. Establishment of durability criteria and functional approach specifications by means of established laboratory durability tests on original asphalt.

Work on phases 1 and 2 has been reported elsewhere (2, 3). This paper gives the results of 48-month laboratory-field correlations and offers suggestions as to how the

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developed durability test can be applied to realistic asphalt durability evaluation and specifications.

STUDY MATERIALS

A total of eight asphalt paving projects, selected by Iowa State Highway Commission (ISHC) engineers, were included in this study. Asphalt cements, plant mixes, and core (or slabs) samples were obtained from four paving projects during the late 1967 construction season; materials from four more paving projects were obtained during the early 1968 construction season. The locations of the eight pavement projects are given in Table 1. In addition to asphalt received from ISHC, an essentially asphaltene-free asphalt cement (asphalt concrete 5) was obtained from the ESSO Research and Engineering Co. and is included in the study to evaluate the role of asphaltenes in the performance of a paving asphalt.

Four 1-gal asphalt cement samples were taken from each project by district personnel of the ISHC just prior to the asphalt's entry into the mixer. Forty lb of plant mixtures were collected from trucks immediately after they left the mixers and are identified throughout this report as P-samples. The trucks from which the plant mixtures were sampled were tagged. Pavement cores (or slabs) of about 40 lb were cut from the newly finished pavements containing the mixtures from the same tagged trucks. Half of the cores (or slabs) were taken from the wheel track and are identified as f-0-A, and half of the cores (or slabs) were taken from between the wheel tracks and are identified in this report as f-0-B. The same amounts of field core samples were taken from the respective pavement sections every 6 months from the time the pavement was laid and are identified as f-6, -12, -18, . . ., -A, or f-6, -12, -18, . . ., -B.

Pertinent information obtained at each project site by ISHC district personnel was summarized in a standard form by research department personnel and delivered to the Bituminous Research Laboratory, Iowa State University, together with the samples. The general characteristics of the field pavement mixtures studied are given in Table 2. Specific surface, bitumen index, and film thickness were calculated based on data supplied by the project information sheets. The original properties of the nine asphalt cements studied are given in Table 3.

EXPERIMENTAL WORK

Procedures

Experimental work was carried out as shown in Figure 1. When the experimental phase of the project terminated, samples as old as 48 months were tested on six pavements, and 42-month samples were tested on two other projects.

Iowa Durability Test

An Iowa durability test (IDT) was developed (2) to simulate or reproduce the two-stage aging and hardening of the asphalt in the field. The laboratory durability test procedure finally adopted was as follows:

1. Use of BPR thin-film oven test (TFOT) on the original asphalt;
2. Application of pressure-oxidation treatment to the residue from the TFOT in a pressure vessel for as long as 1,000 hours under a film thickness of ⅛ in., a temperature of 150 F, and a pressure of 20 atm oxygen; and
3. Evaluation of the physical and chemical changes in asphalt during the artificial aging process in relation to the original properties of the asphalt.

Pressure-oxygen treatment was conducted in pressure vessels fabricated of ½-in. stainless steel. These vessels are capable of simultaneously treating 10 standard TFOT samples to a pressure of 450 psi. The interior dimensions of the vessels are 7.5 in. in diameter and 7.5 in. high. They are equipped with a pressure gauge and a relief valve.

Table 1. Pavement project locations.

Number	County	Location	Project Number	Date Laid
1	Chickasaw	On US-63 north of New Hampton	FN-63-8(1)-20-19	Nov. 1967
2	Dickinson	On Iowa 327 from Iowa 276 east and north	FN-327-1(1)-21-30	Oct. 1967
3	Harrison	On US-75 out of Mo. Valley, north into Mondamin	FN-75-2(3)-21-43	Nov. 1967
4	Story-Polk	On US-69 between Huxley and Ankeny	FN-69-5(2)	Oct. 1967
6	Monona	On US-75 from Harrison Co. line north into Ottawa 11 mi.	FN-3(2)-21-67	April 1968
7	Bremer	On Iowa 3	FN-3-6(5)-21-09	May 1968
8	Keokuk	On Iowa 92 from Sigorney east	FN-92-8(2)-21-54	May 1968
9	Jackson	On US-52 north of Maquoketa	FN-52-1(3)-21-49	June 1968

Table 2. Characteristics of field pavement mixtures.

	Asphalt							
Characteristic	1	2	3	4	6	7	8	9
Gradation, percent passing sieve								
3/4 in.					100			100
1/2 in.					94			
3/8 in.	100	100	100	100	77	100	100	78
No. 4	81	89	92	78	60	85	85	62
No. 8	62	67	58	59	43	67	63	49
No. 16	44	—	—	—	—	—	—	—
No. 30	30	34	34	31	25	35	35	23
No. 50	16	21	23	18	19	35	25	—
No. 100	12	13	13	13	9	—	13	—
No. 200	9.3	9.9	9.4	9.4	7.1	8.4	8.9	6.7
Percentage of bitumen	7.5	6.3	6.3	7.5	5.0	7.0	5.3	5.5
Specific surface[a], ft^2/lb	40.59	45.92	44.18	41.86	33.44	51.06	44.34	32.66
Bitumen index[b], $\times 10^{-3}$	1.996	1.459	1.517	1.935	1.585	1.469	1.263	1.776
Film thickness[c], μ	9.72	7.11	7.39	9.24	7.12	7.15	6.15	8.65
Laboratory design voids, percent	6.8	6.1	6.6	9.3	6.8	6.1	3.5	5.8
Hveem side pressure[d], psi	60	46	63	48	55	61	55	29
Asphalt concrete temperature, deg F	295	300	295	260	267	260	275	300
Aggregate temperature, deg F	300	320	310	310	340	310	375	305
Mix temperature, deg F	290	295	310	310	310	305	306	298
Initial field voids, percent	8.7	9.8	11.5	12.3	5.5	7.1	6.7	5.1
ADT, 1970	2,100	330	590	3,000	500	2,000	1,500	2,400
Condition after 48 months	Transverse cracks	Excellent	Excellent	Severe transverse and longitudinal centerline cracks	Good	Good, some cracks	Good to excellent	Excellent

[a] Mix Design Methods for Asphalt Concrete. The Asphalt Institute, MS-2, 1962.
[b] Percent bitumen (aggregate basic)/specific surface.
[c] Bitumen index x 4.870.
[d] At 400-psi vertical load.

Table 3. Properties of asphalt studied.

	Asphalt								
Characteristic	1	2	3	4	5	6	7	8	9
Penetration, 77/100/5	89	94	91	90	84	87	95	90	92
Specific gravity, 77/77	1.017	1.026	1.042	1.011	1.017	1.019	1.042	1.003	0.999
Viscosity									
77 F, megapoises	1.16	1.23	1.58	1.10	1.14	1.70	1.15	1.10	1.22
140 F, poises	1,356	1,086	1,316	1,106	1,781	1,455	1,316	1,922	2,060
Softening point, deg F	119.0	116.5	115.5	114.5	113.0	118.0	116.0	118.0	119.5
Flash point, COC, deg F	600	595	630	625	690	615	625	655	655
Fire point, COC, deg F	680	690	705	705	730	670	685	735	735
Microductility at 77 F, cm	63	71	66	77	82	55	68	51	63
TFOT									
Residue penetration	53	51	57	56	67	55	59	60	62
Weight loss, percent	0.02	0.16	+0.01	0.00	+0.01	0.07	0.07	0.24	0.16
Spot test	Negative	Negative	Negative	Negative	Negative	Negative	Negative	Negative	Negative
Source[a]	1	1	2	2	3	4	4	2	2

[a] 1 = blend of asphalts from Texaco at Casper, Wyoming, and American Petrofina, Big Springs, Texas. 2 = American Oil, Sugar Creek, Missouri. 3 = Esso Research and Engineering Co. 4 = American Petrofina, Big Springs, Texas.

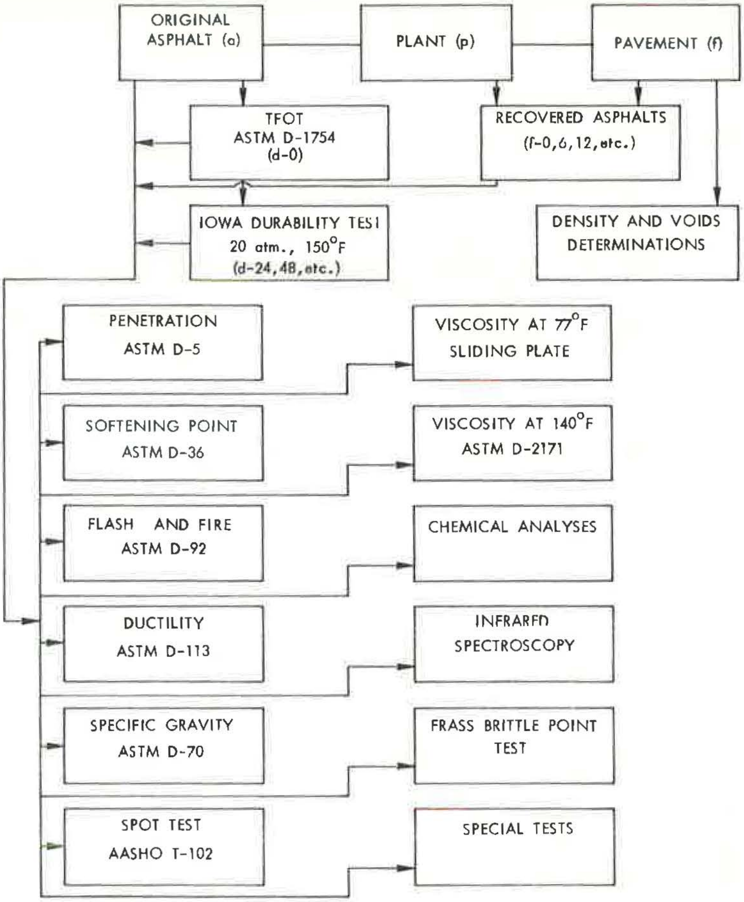


Figure 1. Flow chart of testing procedures.

Table 4. Changes in penetration during weathering.

	Asphalt Penetration								
Project Sample	1	2	3	4	5	6	7	8	9
Original	89	94	91	90	84	87	95	90	92
TFOT	53	54	57	56	67	55	59	60	62
Laboratory aging (hours)									
d-24	30	34	36	38[a]	49[a]	50	44[a]	44[a]	37
d-48	29	30	30	31	41	32	37[a]	33	27
d-96	26	25	26	25	37	27	29[a]	30	24
d-240	19	20	20	20	27	22	19[a]	26	21[a]
d-480	13[a]	17	16[a]	17[a]	20[a]	21	16[a]	22[a]	23
d-1000	11	13[a]	8	10	11	14	10	15	—
Field aging (months)									
Plant	60	72	57	67	—	71	76	74	79
f-0									
A[b]	57	67	57	62	—	—	79	71	64
B[c]	57	67	57	62	—	—	—	—	—
f-6									
A	61	56	48	57	—	39	41	43	51
B	56	58	52	62	—	40	41	43	56
f-12									
A	43	37	42	39	—	37	35	42	53
B	39	38	38	35	—	39	42	45	49
f-18									
A	41	38	40	34	—	34	35	35	39
B	43	36	30	36	—	34	35	36	41
f-24									
A	39	35	35	38	—	36	37	38	41
B	36	35	34	29	—	35	36	39	39
f-30									
A	35	33	32	30	—	33	35	35	40
B	33	31	34	32	—	34	33	35	38
f-36									
A	36	34	30	30	—	—	36	36	36
B	37	32	29	30	—	—	35	35	31
f-42									
A	37	33	31	29	—	28	—	34	—
B	39	29	32	28	—	28	—	34	—
f-48									
A	28	28	27	26	—	—	—	—	—
B	31	28	27	26	—	—	—	—	—

[a] Interpolated value. [b] A = in wheel tracks. [c] B = between wheel tracks.

Physical Tests

The physical tests selected in this study are mainly for the evaluation of changes in rheological properties of asphalt with aging or hardening and are selected based on the hypothesis that asphalt durability can be related to rheological behaviors.

Tests conducted on the original, laboratory-aged, and recovered field asphalts are shown in Figure 1. Specific gravity, penetration at 77 F (100 g, 5 sec), and ring and ball softening point were determined following standard ASTM procedures. Viscosity at 77 F was determined by the Sheel sliding-plate microviscometer. Plots of log shearing stress and log rate of shear and log viscosity and log rate of shear were made on all asphalts. Viscosities at a rate of shear of 5×10^{-2} sec^{-1}, at a constant energy input of 10^4 ergs (4), and at a constant shearing stress of 167 g/cm^2 (1.63×10^5 dyne/cm^2) were calculated (5). Unless otherwise stated, only the viscosity at the rate of shear of 5×10^{-2} sec^{-1} is reported.

The slope of the log rate of shear versus log shearing stress linear plot is defined as the degree of complex flow, commonly designated by the letter c (4). The shear index (SI) or shear susceptibility (S) is the tangent of the angle of log shear rate versus log viscosity plot (6). The rate of change in SI of various asphalts during weathering was found to be related to relative durability of asphalt (6-9).

Viscosity at 140 F was determined by Cannon-Manning vacuum viscometers following standard procedures.

Because of the limited quantity of recovered asphalts that would be available, all ductility tests were made at 77 F on ½- by ½-in. microductility molds developed by the Phillips Petroleum Co. and used in previous projects (10, 11). The use of microductility specimens also makes the differentiation among asphalts possible within the limits of the ductility machine (150 cm).

The chemical approach to durability studies of asphalts has been criticized as being premature because of a lack of definitive knowledge of chemical composition and asphalt structure. However, this is a fundamental approach. It has been proved that chemical composition does have direct effects on rheological and durability properties of asphalt, that the relation between asphalt durability and chemical composition can be established (12, 13, 14), and that the durability grouping of asphalts by chemical composition is possible (14), 15).

Asphaltene content and oxygen percentage have been used as parameters for chemical changes. Asphaltene content was determined by precipitation with a Skelly F (16), and oxygen content was determined by the combustion method using a Coleman oxygen analyzer.

Chemical analysis of asphalts 1 through 4 was also made by a method suggested by Rostler and White (13) and Halstead et al. (14) to determine the relation between asphalt durability and $(N + A_1)/(A_2 + P)$.

During the second half of this investigation, analysis of asphalts by infrared multiple internal reflection techniques was undertaken to determine the changes in infrared spectra of asphalts during field aging as well as laboratory aging and, if possible, to establish a relation between asphalt durability and its infrared spectrum. The results of infrared analyses have been reported elsewhere (17).

LABORATORY AGING

Changes in Rheological Properties

The results of penetration change with time during laboratory aging (at 77 F, 100 g, and 5 sec) in IDT are given in Table 4 and typical plots are shown in Figure 2. The results of viscosity change measured at 77 F and at 5×10^{-2} sec^{-1} with time are given in Table 5. Similar results for viscosity at 140 F are given in Table 6. Samples of log viscosity and time plots are shown in Figures 3 and 4. From viscosity at 77 F data, c and SI were calculated for all nine asphalts. Results of softening point are given in Table 7, and changes in microductility at 77 F with laboratory aging time are given in Table 8. Except in a few instances for ductility, all the preceding property changes were found to follow the hyperbolic model suggested by Brown et al. (18). This is

Figure 2. Penetration versus time of aging.

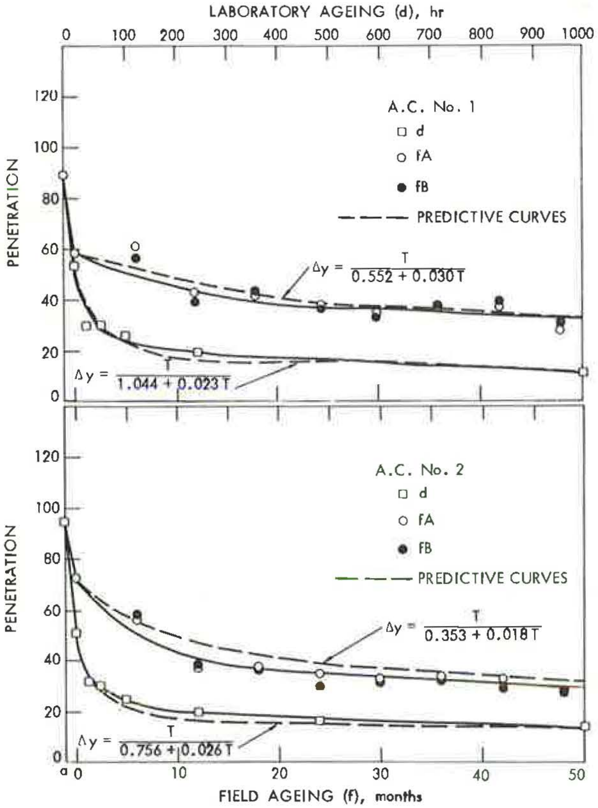


Table 5. Changes in viscosity at 77 F.

Project Sample	Asphalt Viscosity (megapoises) 1	2	3	4	5	6	7	8	9
Original	1.16	1.23	1.58	1.10	1.14	1.70	1.15	1.10	1.22
TFOT	4.22	5.35	3.70	3.09	1.68	3.80	3.90	4.15	2.86
Laboratory aging (hours)									
d-24	18.4	11.7	9.50	9.0[a]	3.50[a]	—	7.00[a]	8.30[a]	10.30
d-48	20.5	19.3	14.2	15.7	5.60	14.60	12.50[a]	12.60	12.50
d-96	23.9	24.6	19.2	22.6	7.40	21.00	22.00[a]	14.80	15.00
d-240	44.0	36.2	47.0	36.9	13.50	33.00	51.00[a]	38.00	27.50[a]
d-480	64.5[a]	38.5	76.0[a]	52.0[a]	14.70[a]	37.00	78.50	53.50[a]	45.00[a]
d-1000	89.0	—	118.0	64.0	17.30	72.00	99.20	64.00	69.00[a]
Field aging (months)									
Plant	4.30	4.70	3.40	3.09	—	2.81	2.07	3.42	2.29
f-0									
A[b]	4.87	4.60	3.39	3.01	—	—	2.25	2.14	2.61
D[c]	4.87	4.60	3.39	3.01	—	—	—	—	—
f-6									
A	4.30	5.98	3.40	3.56	—	8.58	8.30	6.40	4.90
B	5.70	5.35	3.78	3.50	—	8.70	8.74	6.40	3.90
f-12									
A	9.80	8.90	9.66	11.2	—	10.60	9.80	14.50	11.50
B	9.54	9.20	—	12.2	—	11.90	9.80	12.50	8.90
f-18									
A	12.7	8.33	12.4	13.9	—	12.10	12.80	11.50	10.50
B	11.5	10.28	12.0	15.5	—	13.80	12.00	10.90	10.50
f-24									
A	12.2	—	12.6	21.0	—	12.70	14.50	9.80	12.00
B	15.0	15.0	11.9	18.6	—	7.80	12.20	8.90	8.40
f-30									
A	14.5	18.5	17.0	20.5	—	13.50	12.00	13.50	9.68
B	18.5	19.2	13.2	21.6	—	17.50	12.00	14.00	9.10
f-36									
A	12.3	13.8	21.0	16.2	—	—	13.80	—	11.50
B	12.5	16.0	19.6	17.7	—	—	—	—	—
f-42									
A	13.4	17.8	18.8	16.2	—	17.50	—	12.50	—
B	9.5	16.5	14.0	22.2	—	—	—	—	—
f-48									
A	19.2	19.6	20.7	21.8	—	—	—	—	—
B	16.4	20.9	16.1	22.0	—	—	—	—	—

[a] Interpolated value. [b] A = in wheel tracks. [c] B = between wheel tracks.

Table 6. Changes in viscosity at 140 F.

Project Sample	Asphalt Viscosity (poises) 1	2	3	4	5	6	7	8	9
Original	1,356	1,086	1,316	1,106	1,781	1,350	1,316	1,922	2,837
TFOT	2,368	3,448	4,041	3,556	2,341	3,556	3,538	4,376	4,412
Laboratory aging (hours)									
d-24	12,094	10,849	5,812	–	–	–	7,400[a]	10,500[a]	12,558
d-48	15,248	17,022	7,979	11,830	4,891	12,457	9,000[a]	20,199	13,826
d-96	23,276	34,249	12,772	13,930	4,459	19,550	12,800[a]	24,472	23,497
d-240	81,254	89,639	28,062	23,479	7,727	33,431	26,900[a]	44,731	–
d-480	–	–	–	–	16,500[a]	52,000[a]	53,500[a]	66,000	–
d-1000	200,000	–	130,000	71,560	37,000	80,000	130,000	120,000	–
Field aging (months)									
Plant	2,182	2,045	1,913	2,136	–	2,096	2,070	2,634	3,428
f-0									
A[b]	2,294	2,931	2,122	1,781	–	–	2,130	2,456	4,001
B[c]	2,294	2,931	2,122	1,781	–	–	–	–	–
f-6									
A	2,716	3,735	2,820	2,582	–	7,546	5,506	7,762	4,824
B	3,555	3,412	3,038	2,525	–	6,227	5,737	9,292	5,852
f-12									
A	5,814	8,165	4,634	5,984	–	5,167	4,634	9,717	4,593
B	6,722	8,098	5,829	5,964	–	8,181	4,597	9,005	5,358
f-18									
A	4,733	6,964	5,331	5,077	–	9,436	6,753	13,468	6,663
B	3,717	7,806	4,799	6,178	–	–	–	–	8,109
f-24									
A	5,158	9,742	6,437	7,672	–	7,797	5,950	9,676	8,653
B	6,675	10,204	6,217	8,526	–	–	–	–	–
f-30									
A	6,710	9,341	6,229	7,960	–	9,250	6,644	13,092	9,392
B	8,506	9,588	5,593	8,605	–	8,567	–	–	–
f-36									
A	5,747	9,991	7,218	7,777	–	–	7,270	10,532	13,940
B	7,031	12,792	8,130	7,484	–	–	–	–	–
f-42									
A	6,448	12,173	6,951	7,598	–	12,384	–	12,925	–
B	4,954	10,054	9,969	–	–	–	–	–	–
f-48									
A	11,044	13,773	8,305	8,490	–	–	–	–	–
B	9,473	14,082	7,549	8,647	–	–	–	–	–

[a]Interpolated value. [b]A = in wheel tracks. [c]B = between wheel tracks.

Figure 3. Viscosity at 77 F versus time of aging.

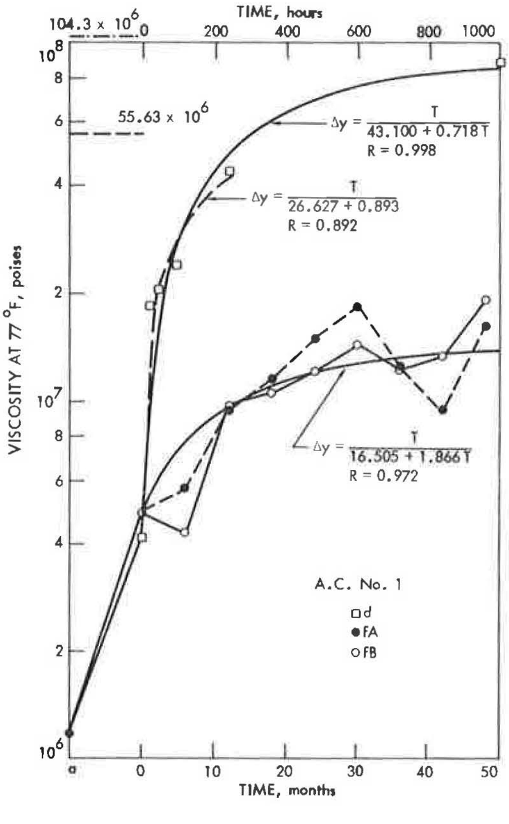


Figure 4. Viscosity at 140 F versus time of aging.

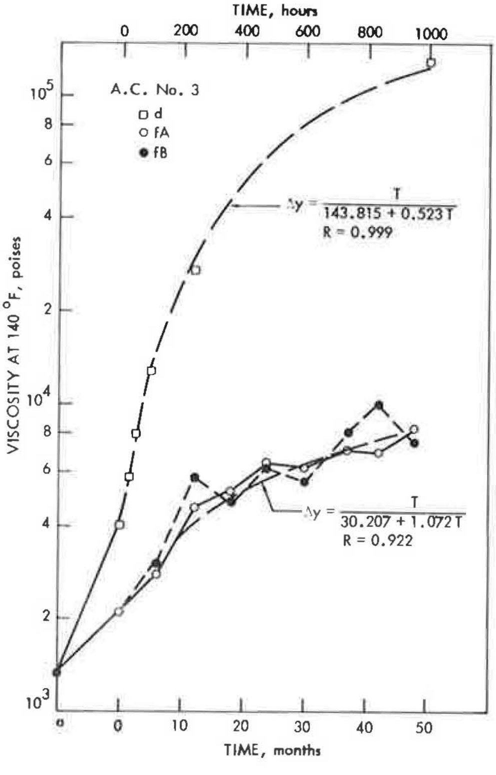


Table 7. Changes in softening point during weathering.

	Asphalt Softening Point, Ring and Ball (deg F)								
Project Sample	1	2	3	4	5	6	7	8	9
Original	119.0	116.5	115.5	114.5	113.0	118.0	116.0	118.0	119.5
TFOT	127.5	131.0	123.0	126.0	119.0	127.0	123.0	129.0	119.5
Laboratory aging (hours)									
d-24	141.0	134.0	131.0	133.5[a]	121.5[a]	—	125.5[a]	136.0[a]	132.5
d-48	140.5	143.0	138.0	138.0	126.5	140.0	128.5[a]	142.5	136.0
d-96	143.5	149.0	140.5	141.0	126.0	143.0	134.0[a]	144.5	145.5
d-240	159.0	152.5	145.0	148.5	134.0	152.0	146.6[a]	150.0	151.5[a]
d-480	168.0[a]	167.0	154.5[a]	154.5[a]	143.8[a]	163.7[a]	160.5[a]	164.0[a]	—
d-1000	175.0	170.0[a]	171.0	173.5	154.0	174.0	171.0	173.0	—
Field aging (months)									
Plant	130.5	129.0	127.5	122.5	—	118.0	120.0	124.0	116.0
f-0									
A[b]	127.5	125.0	125.0	119.0	—	—	118.0	132.0	124.0
B[c]	127.5	123.0	125.0	119.0	—	—	—	—	—
f-6									
A	124.0	128.0	122.5	120.5	—	133.5	132.0	136.0	132.0
B	125.0	120.5	125.5	120.5	—	133.0	130.0	136.0	126.0
f-12									
A	129.0	135.0	130.0	130.0	—	134.0	129.5	134.0	138.0
B	129.5	137.5	131.0	131.0	—	138.5	130.0	126.0	132.0
f-18									
A	130.0	137.0	—	134.0	—	135.0	132.8	136.4	132.0
B	132.0	136.0	128.0	134.0	—	140.0	132.8	136.0	130.0
f-24									
A	129.5	134.5	136.5	136.5	—	129.0	138.0	138.0	136.0
B	136.0	138.0	136.5	136.5	—	—	—	—	—
f-30									
A	137.0	140.0	136.5	135.5	—	140.0	137.0	141.0	136.0
B	138.0	137.0	—	136.0	—	—	—	—	—
f-36									
A	138.0	143.5	138.0	134.5	—	—	137.0	—	139.0
B	140.0	142.0	138.0	136.5	—	—	—	—	—
f-42									
A	133.0	138.0	140.0	134.5	—	142.0	—	144.0	—
B	129.0	138.2	141.0	134.6	—	—	—	—	—
f-40									
A	134.5	136.5	136.5	136.5	—	—	—	—	—
B	137.3	136.4	134.6	136.4	—	—	—	—	—

[a] Interpolated value. [b] A = in wheel tracks. [c] B = between wheel tracks.

Table 8. Changes in microductility at 77 F.

	Asphalt (cm)								
Project Sample	1	2	3	4	5	6	7	8	9
Original	63	71	72	67	81.4	53.0	68.4	51.0	63.0
TFOT	46	36	82	89	91.0	57.0	84.0	60.0	55.0
Laboratory aging (hours)									
d-24	9.2	5.4	59	82	101.0[a]	16.0[a]	70.0[a]	20.0[a]	11.0
d-48	5.0	3.0	50	41	102.6	5.1	56.0[a]	7.0	5.5
d-96	2.6	2.0	20	23	122.0	3.0	29.0[a]	4.0	6.7
d-240	2.0	1.5	5.2	4.7	115.0	0.5	8.0[a]	2.0	—
d-480	—	—	—	3.8	79.0[a]	1.0[a]	4.0[a]	1.5[a]	—
d-1000	0.5	—	0.4	1.8	-0.3	1.1	1.3	1.0	—
Field aging (months)									
Plant	48	62	87	93	—	75.0	68.0	67.0	65.0
f-0									
A[b]	69	72	78	81	—	—	60.0	67.0	79.0
B[c]	69	72	78	102	—	—	—	—	68.0
f-6									
A	87	62	102	102	—	23.0	73.0	15.0	37.0
B	87	63	95	101	—	23.0	64.5	14.6	28.0
f-12									
A	63	27	44	58	—	24.4	76.0	25.0	57.0
B	70	—	82	56	—	31.0	101.0	24.0	47.0
f-18									
A	70	33	88	84	—	—	55.5	8.5	16.5
B	76	35	79	85	—	—	80.5	11.0	16.5
f-24									
A	65	14	21	69	—	23.0	57.8	—	—
B	16	9.0	43	55	—	—	—	—	—
f-30									
A	16	7.7	84	65	—	7.2	—	5.9	—
B	17	8.0	69	74	—	—	—	—	—
f-36									
A	15	8.3	35	26	—	—	50.7	—	—
B	17	6.3	35	37	—	—	—	—	—
f-42									
A	16.5	10.0	43	37	—	4.7	—	5.0	—
B	14.0	4.0	34	12	—	—	—	—	—
f-48									
A	4.8	3.8	28	28	—	—	—	—	—
B	6.0	—	29	15	—	—	—	—	—

[a] Interpolated value. [b] A = in wheel tracks. [c] B = between wheel tracks.

significant because it agrees with reported actual field hardening in service (18-21). It also suggests that the IDT is realistic and that the correlation between field hardening and hardening of asphalt in the IDT is possible.

According to this theory, the changes in physical properties of asphalt are a hyperbolic function of time and approach a definite limit with time. Brown et al. have suggested the following equation to express the hardening of asphalts in the field:

$$\Delta Y = \frac{T}{a + bT} \qquad (1)$$

or

$$\frac{T}{\Delta Y} = a + bT \qquad (2)$$

where

ΔY = change in penetration (or softening point or ductility) with time T or the difference between the zero-life value and the value for any subsequent year;
T = time;
a = constant, the intercept of the Eq. 2 line on the ordinate;
b = slope of the Eq. 2 line; and
$1/b$ = the ultimate change (limiting value of change) of penetration at infinite time.

Note that, from the limiting values of change $1/b$, the limiting values of properties Y_u can also be calculated. Both values could be used as numerical measures for comparison of the relative performance of asphalts. Thus, an asphalt with a high value of limiting change of penetration or a low value of limiting penetration could be considered as inferior to one with a low value of limiting change of penetration or a high value of limiting penetration.

Experimental data were fitted to Eq. 2 by the least-squares linear regression methods. Predicted curves were plotted in all pertinent curves in dashed lines and with equations given. Almost without exception, the fittings, as indicated by correlation coefficients R, were excellent. It can thus be concluded that the changes of rheological properties as measured by penetration, viscosity, softening point, and ductility are a hyperbolic function of time during IDT; i.e., the penetration and ductility decrease, and the viscosity and softening point increase, with time approaching definite limiting values.

The limiting values have been suggested by Brown et al. (18) as an index in comparing performance or potential behavior of asphalts. However, as pointed out by the author (2), when it is used as the only index in asphalt durability or quality evaluation, it can be misleading. The reason is that, in reality, asphalt will most likely reach a critical value of penetration, viscosity, ductility, or other controlling property and fail before it reaches the limiting value or infinite time. Therefore, it is the critical value or values of the controlling property or properties and the time the asphalt in question takes to reach this value that are of the utmost practical concern.

From viscosity data, it is shown that aging in IDT resulted in a decrease in c and an increase in S. Here, again, the behavior of asphalts in IDT appeared to be in agreement with other reported field findings (5, 19).

Asphalt hardening can also be expressed in terms of penetration ratio (original penetration/aged penetration) or viscosity ratio (aged viscosity/original viscosity). The viscosity ratio at 77 F is often called the aging index. Results of viscosity ratio for asphalts in IDT were calculated for viscosity at 77 F and for viscosity at 140 F. Linear relations were found between log penetration ratio and log time and between log viscosity ratio and log time during IDT aging. From these plots, relative durability or hardening susceptibility of asphalts of different original penetration or viscosity can be compared.

Aging and Chemical Changes in Asphalts

In this investigation, chemical changes in asphalt during aging were measured by determining the asphaltene content, the chemical composition by the Rostler-White method, and the oxygen content and by spot testing and using IR spectroscopy.

The formation of asphaltenes that results from weathering (oxidation or polymerization or both) has long been observed. The increase in viscosity (hardening of asphalt) and the change in colloidal structure (from sol or sol-gel to gel materials), or the increase in complex flow that accompanies the increase in asphaltene content, have been postulated by many researchers as the cause for asphalt failure by cracking. Thus, the change in asphaltene content was used in this study as an important parameter in asphalt durability evaluation.

The percentage of asphaltenes as given by the Skelly F precipitation method for all asphalts studied is given in Table 9. Three important observations can be made:

1. Aging is accompanied by increase in asphaltene content.
2. Change in asphaltene content is a hyperbolic function of time. Except for asphalt concrete 5, which is an unusual asphaltene-free asphalt, regression coefficients for the plot of $T/\Delta Y$ versus T were all more than 0.90 and were all significant at the 95 percent level.
3. Rates of asphaltene content formation are different for different asphalts (a varied from 5.6 to 32.4 and b varied from 0.05 to 0.99). The ultimate change in asphaltene content varied from 9 to 20 percent.

The data on chemical compositions of asphalts by the Rostler-White method indicated, though not very consistently, general increases in A and A_2 and decreases in A_1 and P with aging in IDT. The N-fraction remained relatively constant.

The composition parameters $(N + A_1)/(A_2 + P)$, the ratios of more reactive to less reactive components, and N/P, the ratio of the most to the least reactive fractions of maltenes, were calculated. The ratio $(N + A_1)/(A_2 + P)$ has been correlated with the durability of asphalts as measured by the tendency of asphalts to harden during aging as determined by the pellet-abrasion test (13, 14). However, the pattern of change in $(N + A_1)/(A_2 + P)$ with aging for asphalts studied could not be defined. The ratios of N/P varied from 1.25 for asphalt 3 to 3.19 for asphalt 4. This parameter was suggested by Halstead et al. (15) as indicative of the quality of asphalt. The significance of this parameter is yet to be determined.

Oxygen content of asphalt and asphaltenes was determined by the combustion method; a gradual increase in oxygen content during aging (both during the durability test and the road service) was observed. The degree and rate of oxidation were also indicated by weight increase during pressure-oxidation treatment.

Data also indicated that aging not only increased asphaltene content and oxygen percentage in asphalt, but it also caused increases in oxygen percentage in asphaltenes.

Results of spot tests during laboratory aging have shown that all original asphalts showed negative spot tests, and, as asphalts aged (except for asphalt 5), all tests became positive at some time during the aging process. The border line between positive and negative spot testing appeared to be about 20 percent asphaltenes.

FIELD AGING

Density and Voids Changes of the Pavements

Changes of density and voids of asphalt pavements were studied because such changes have been found to affect the rate of asphalt hardening, fatigue resistance, and water susceptibility of the mixture. Thus, the changes and voids are two relevant factors to be considered in the final analysis of asphalt durability, correlation, and critical asphalt property values.

Bulk specific gravity d is determined by the water displacement method at 77 F. Percentage of voids V is calculated from bulk specific gravity and maximum theoretical specific gravity D data. The latter is determined following Rice's method, which is essentially that described in the ASTM D2041-64T. Changes in voids content are shown in Figure 5. When the trends are examined and compared with designed mix data, the following observations can be made:

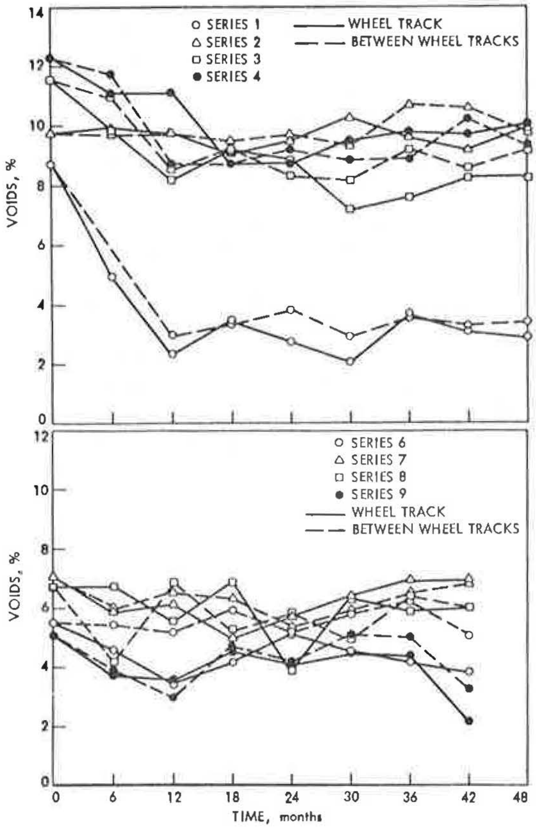
1. There were no appreciable initial differences on density-voids values between specimens in wheel tracks and specimens between wheel tracks,

Table 9. Percentage of asphaltenes.

Project Sample	Asphalt 1	2	3	4	5	6	7	8	9
Original	17.72	17.85	15.69	14.52	4.55	15.64	17.80	11.30	11.11
TFOT	20.60	21.23	19.37	18.33	5.70	19.20	20.20	14.35	14.18
Laboratory aging (hours)									
d-24	23.34	23.50	21.06	—	6.70[a]	—	22.00[a]	16.00[a]	18.55
d-48	23.50	23.85	21.67	22.14	8.07	22.30	22.80[a]	19.20	19.70
d-96	24.05	24.85	22.69	23.11	7.93	22.88	24.20[a]	19.15	19.12
d-240	27.14	26.54	24.57	26.52	10.96	27.13	26.20[a]	21.06	20.50[a]
d-480	27.60[a]	29.37	27.50[a]	29.80[a]	14.40[a]	27.35	27.50[a]	22.40[a]	22.60
d-1000	28.99	—	34.17	31.10	22.02	28.22	31.10	25.70	—
Field aging (months)									
Plant	20.26	20.04	19.04	18.83	—	19.48	20.70	13.95	11.96
f-0									
A[b]	19.96	20.75	18.22	19.10	—	—	19.30	12.35	12.82
B[c]	—	—	—	19.88	—	—	—	—	—
f-6									
A	20.11	20.87	19.84	18.38	—	20.39	20.44	17.85	14.48
B	21.31	20.11	25.97	22.56	—	21.56	20.74	—	15.51
f-12									
A	20.31	21.86	21.29	21.24	—	20.71	23.07	17.95	16.39
B	21.26	21.45	—	21.81	—	19.93	—	18.85	16.68
f-18									
A	23.21	20.69	21.40	21.45	—	23.83	24.59	19.49	18.04
B	21.68	23.12	20.00	22.20	—	24.95	23.14	19.73	18.80
f-24									
A	21.16	—	22.02	21.27	—	28.56	23.49	19.73	18.50
B	23.03	23.95	20.99	24.52	—	28.30	—	18.74	—
f-30									
A	24.02	22.78	20.99	23.66	—	24.16	24.82	20.73	19.69
B	24.71	22.85	20.65	23.94	—	—	—	—	—
f-36									
A	25.08	23.96	21.49	23.83	—	—	23.04	17.88	21.84
B	25.58	24.30	23.98	23.05	—	—	22.40	—	—
f-42									
A	24.03	24.91	24.36	23.51	—	28.00	—	21.38	—
B	—	—	—	—	—	—	—	—	—
f-48									
A	25.38	24.91	24.15	25.16	—	—	—	—	—
B	33.23	25.20	24.99	24.97	—	—	—	—	—

[a] Interpolated value. [b] A = in wheel tracks. [c] B = between wheel tracks.

Figure 5. Pavement voids versus time.



2. Pavements constructed during the second period (projects 6 to 9) of warmer weather approached higher density and lower voids relative to design density and voids than those built during the first period (projects 1 to 4),
3. Half of the projects reached design densities and voids at the end of 1 year or after one summer of traffic densification, and
4. Changes of density and voids appeared to have leveled off after 1 year of traffic compaction.

Behavior of Asphalts in the Pavements

Physical and chemical changes in asphalts in pavements were determined for 42 months on four projects and for 48 months on the other four projects. The general changes of physical and chemical properties of recovered asphalts with field aging time were found to follow the time-rate-of-change curves established in laboratory aging during IDT.

Physical Properties—All physical properties (especially rheological) that appeared to be suited to evaluating asphalt durability and that have been conducted on original and laboratory-aged asphalt were also determined on recovered asphalts from plant, p, to just compacted, f-0, and up to 48 months at 6-month intervals.

Within the range of mixing temperatures of 290 to 310 F that were recorded at the plants for the eight paving projects, no appreciable differences were detected in the hardening of asphalt as determined by increase in penetration ratio. The comparison between results of the TFOT, d, and the hardening during mixing, p and f-0, in terms of penetration, penetration ratio, viscosity at 77 and 140 F, aging index (viscosity ratio) at these two temperatures, and softening point showed slightly higher overall hardening in TFOT than in plant mixing for various asphalts used in this project. However, the close parallel between results of these two processes has reconfirmed the ability of the TFOT in simulating hardening of asphalt in an average hot mixing plant.

The changes in penetration softening point, viscosity at 77 and 140 F, and microductility at 77 F for 42 to 48 months of service life are given in Tables 4 through 8. The curves showing drop in penetration have the normally expected shapes of hyperbolic function of time, with a rather rapid rate of hardening in the first 20 months and a tendency for the rate of hardening to decrease thereafter. Hyperbolic fittings were made on all recovered asphalts (both in and between wheel tracks) for all properties between property change ΔY and T time by linear least-squares regression analysis between $T/\Delta Y$ and T. The resulting time-property change curves were indicated by dotted line curves with equations shown in terms of $\Delta Y = (T/a) + bT$. Also shown with the fitted curves is R.

The viscosity at 77 F and the 5×10^{-2} sec^{-1} increase with time also followed a hyperbolic function, as shown in Figure 3. The effects of field aging were also reflected in c and on S. The general trends of decreasing c and increasing S with field service life can be observed. A hyperbolic increase of viscosity at 140 F with field aging time is shown in Figure 4.

The microductility change with field aging time was less consistent, possibly because of the complex properties that the ductility test measures and the existence of an optimum consistency for ductility. For four of the eight asphalts (1, 3, 4, and 7), the ductility at 77 F remained high or increased up to 30 months and could not be fitted with hyperbolic curves. Only two asphalts (7 and 8) showed a marked decrease in ductility from the beginning of field aging and could be fitted with hyperbolic curves.

Chemical Properties—Changes in the percentage of asphaltenes with time of field service of recovered asphalts are given in Table 9. An increase in asphaltene content with aging or hardening is apparent. Although curve fittings were not as good as were those for rheological data, hyperbolic relations between an increase in asphaltenes and the time of field aging can be established.

Chemical analysis by the Rostler-White method was made on recovered field-aged asphalts 1 to 4. No consistent trends could be found for the two so-called quality parameters, $(N + A_1)/(A_2 + P)$ and N/P.

CORRELATIONS

The value and usefulness of any laboratory durability test depend not only on how logical or realistic the acceleration process is in the laboratory as compared with what actually occurs in the field but also on how good the correlation is between laboratory and field data. One of the major efforts in this investigation was to establish a correlation between hardening and other relevant property changes in asphalts in the developed IDT and changes in the same asphalts in the pavements in Iowa in terms of time-equivalency curves or acceleration factors between aging in IDT in hours and aging in the pavement in months. With the correlation or calibration curves and the selected durability criteria, functional approach specifications of paving asphalt can then be established, and the durability of asphalts in pavement can be predicted in more reasonably exact terms.

Time-equivalency correlation curves were established for each asphalt and for all relevant properties. Correlation curves were drawn from the property-time curves for each asphalt for a certain property. The time in hours in IDT and the equivalent time in months in the pavement required for each asphalt to reach a certain value were determined from the property curves. Seven to fifteen points were taken from each set of property-time curves for each asphalt and each property. They were plotted on semilog-scale with log laboratory time (T_1, hours) as ordinate and field service time (T_f, months) as abscissa. Sample time-equivalency correlation curves are shown in Figure 6 for penetration.

Because the majority of these curves were of hyperbolic nature, curve fittings for all time-equivalency data for all properties were attempted for all asphalts with the following model:

$$\log T_1 = \frac{T_f}{a + bT_f}$$

where

T_1 = laboratory IDT time (in hours) to reach certain property value,
T_f = equivalent field time (in months) to reach same value of same property for the same asphalt, and
a and b = constants.

In order for the time-equivalency curves to be useful, general correlation curves were established for each property by combining eight individual curves for that property. General time-equivalency curves for penetration, softening point, viscosity at 77 F, viscosity at 140 F, asphaltene content, and microductility are shown in Figure 7. Because each test determines a different asphalt property or behavior, the variation of these curves was to be expected.

Because many other variables—type of aggregate and gradation, asphalt content, mixing temperature, compaction, traffic, and voids—also influence the rate of change of asphalts in pavements, the minor variations among curves of different asphalts for the same property criterion are to be expected.

Because all pavements studied in this project were regular paving projects of the ISHC, materials and construction practices could be safely assumed to have met minimum and acceptable standards. Effects resulting from variations in mixing temperatures were not obvious, as discussed previously. Effects on hardening because of variation in asphalt content and film thickness were examined by correlating the average film thickness (6.2 to 9.7 μ) and viscosity and penetration of 42-month recovered asphalts. No relation was found. Thus, the only variable, in addition to differences among asphalts, that could affect the asphalt hardening rate was voids content. Relations between initial and final voids content and 42-month penetration and viscosity at 77 F are shown in Figure 8. No relation was found between penetration and initial voids; some general trend could be detected between penetration and final voids (correlation was not significant). Though correlations were not good, there was a linear relation between log viscosity and log void content (significant at 5 percent level for

Figure 6. Typical penetration correlation curves.

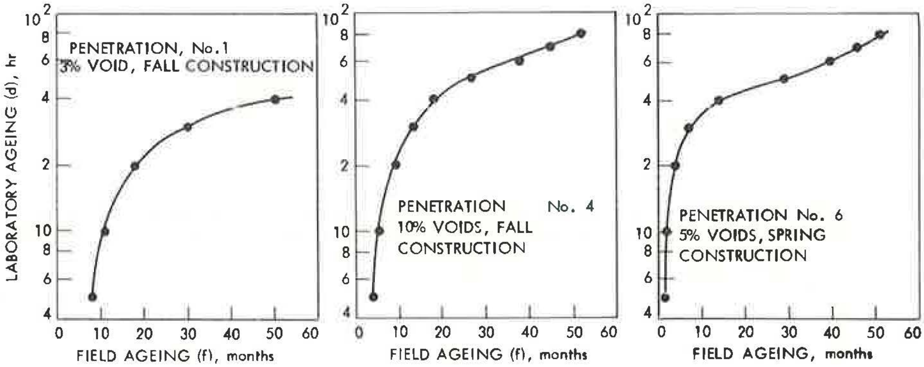
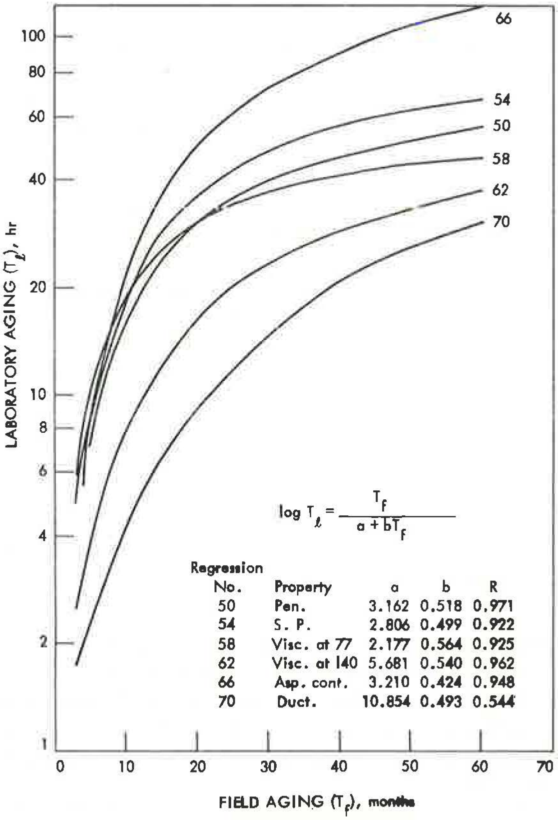


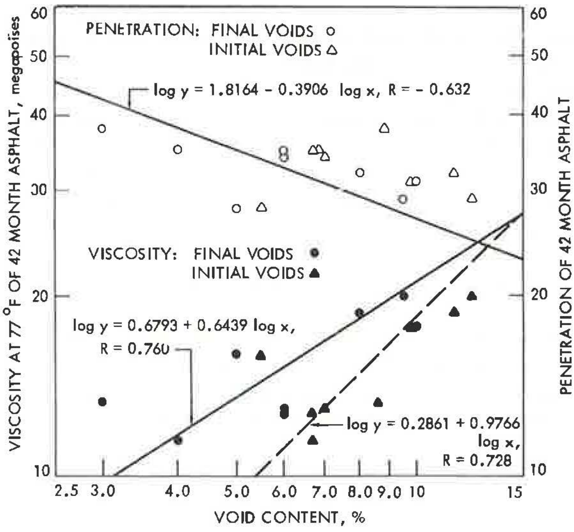
Figure 7. Time-equivalency correlation curves for various properties.



$$\log T_\ell = \frac{T_f}{a + bT_f}$$

Regression No.	Property	a	b	R
50	Pen.	3.162	0.518	0.971
54	S. P.	2.806	0.499	0.922
58	Visc. at 77	2.177	0.564	0.925
62	Visc. at 140	5.681	0.540	0.962
66	Asp. cont.	3.210	0.424	0.948
70	Duct.	10.854	0.493	0.544

Figure 8. Log viscosity (log penetration) versus log void content of 42-month field asphalts.



both initial and final voids); i.e., there is a general indication of higher viscosity for asphalts recovered from higher voids pavements.

Possible differences resulting from voids content among pavements were accounted for by establishing equations for time-equivalency correlation curves by combining asphalts of different voids level (Fig. 9). The relative positions of the curves are of significance; as percentage of voids in the pavements increases, longer laboratory IDT time is required to reach equivalent field-service hardening. Regression 74, which was obtained by combining all properties and all asphalts and which is a surprisingly good fit (linear correlation significant at 1 percent level), will be called the master time-equivalency curve. For all practical purposes, the use of the master curve for all asphalts used in all acceptable construction procedures should provide reasonable correlation and prediction for Iowa conditions. It is therefore recommended that, at least for a trial period, this curve be used for specification purposes by the IDT method. On the basis of the master curve, 46 hours of aging in IDT will result in hardening in asphalts equivalent to that attained after 60 months of service life in Iowa conditions.

APPLICATION AND ENGINEERING IMPLICATIONS OF RESULTS

It has been shown repeatedly that asphalts meeting the same present-day specifications can and do exhibit a considerable range and variety of behavior, as measured by a number of different parameters, in the field. It appears justifiable to state that, at the present time, standard test procedures and specifications provide no satisfactory means of determining whether or not asphalt will be durable.

Based on results discussed in previous sections, and with the established time-equivalency correlation curves, it is suggested that the IDT can be used to reasonably predict the changes and useful life of asphalt in Iowa pavements. If parameters, tests, and critical values of asphalts are properly selected, the results of this investigation can be applied to asphalt specification to ensure durable paving asphalts.

Selection or establishment of durability criteria and critical values of critical properties are complex problems. Relative durability of asphalts studied in this project were evaluated by using several approaches.

Limiting Values of Selected Properties

Limiting values is based on the hypothesis, which was verified in this study, that changes in asphalt, both in the laboratory IDT and in the field-service aging, are a hyperbolic function of time in the form

$$\Delta Y = \frac{T}{a + bT}$$

When a and b are determined and initial property value Y_o is known, the ultimate value Y_u can be calculated from the ultimate change

$$\Delta Y_{t \to \infty} = 1/b$$

Based on this approach, larger ultimate change (or lower ultimate penetration and higher ultimate viscosity and softening point) would be considered properties of less durable asphalts.

Predicted Time to Harden to Certain Critical Values of Selected Properties

Predicted time to critical value is also based on the hyperbolic time-property change curve model as in the preceding approach. But, instead of ultimate change or limiting value, the time it takes for a certain asphalt to harden to a critical value of a selected property is calculated from the predictive equation or from the time-property curve. Times for asphalts to harden to a critical penetration of 20, a critical softening point of 160 F, a critical viscosity at 77 F, and 0.05 sec^{-1} of 20 to 30 megapoises were

Figure 9. Time-equivalency correlation curves by voids level.

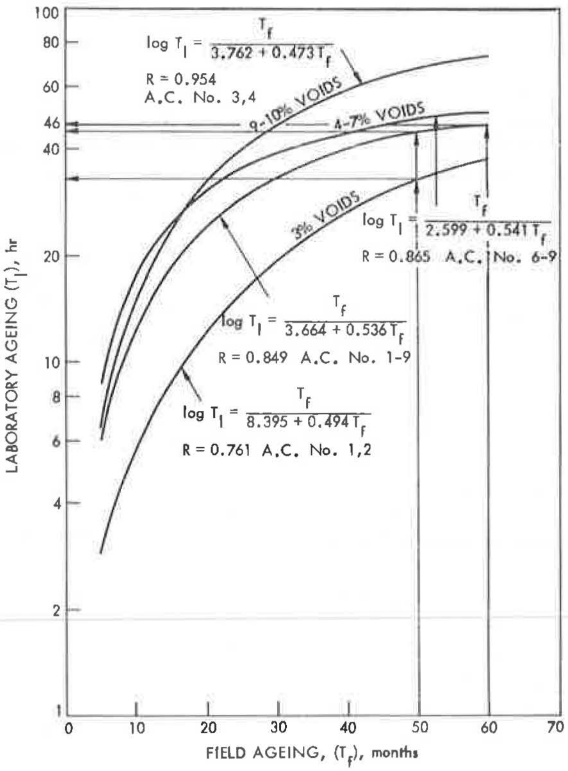


Table 10. Comparison of durability rankings based on different criteria.

	Asphalt								
Criterion	1	2	3	4	5	7	8	9	$\frac{\Sigma \lvert r_{\ell i} - r_{fi} \rvert}{n}$
Penetration ratio									
r_ℓ	4	2	8	6	5	7	3	1	2.8
r_f	4	7	6	8	3	1	2	5	
Aging index, 77 F									
r_ℓ	3	1	7	4	5	8	6	2	3.3
r_f	5	6	7	8	2	1	3	4	
Aging index, 140 F									
r_ℓ	5	7	6	8	4	2	2	1	1.5
r_f	4	8	5	7	3	1	2	6	
Limiting penetration									
r_ℓ	5	3	8	6	2	7	4	1	2.8
r_f	5	7	8	3	4	1	2	6	
Limiting viscosity, 77 F									
r_ℓ	4	6	8	5	1	3	7	2	1.5
r_f	3	8	7	6	4	2	5	1	
Limiting softening point									
r_ℓ	5	3	2	6	7	8	4	1	2.1
r_f	5	3	5	7	4	2	8	1	
Time to 20 to 30 megapoises									
r_ℓ	7	4	5	8	2	5	2	1	2.2
r_f	3	6	5	7	4	2	8	1	
Time to 20 penetration									
r_ℓ	6	7	8	5	3	4	2	1	2.2
r_f	5	4	6	8	2	3	1	7	
Time to 160-F softening point									
r_ℓ	8	7	2	3	5	4	6	1	2.2
r_f	5	4	6	8	3	2	7	1	
Total ranking									
R_ℓ	5	4	8	7	2	6	3	1	1.5
R_f	5	6	7	8	2	1	4	3	

calculated. Rankings of the eight asphalts (longer time to reach a critical value means a more durable asphalt) are given in Table 10.

Penetration Ratio Versus Time Curves

It has been established that log penetration ratio and log time of aging is linear. The slope of such plots, therefore, would be indicative of the relative rate of hardening of various asphalts with time. A small slope will indicate a more durable asphalt. Such an approach can also be applied to retained penetration data.

Aging Index Versus Time Curve

Aging index as defined by the ratio of viscosity of aged and original asphalt can be used as an index of the relative degree of hardening of asphalt. It has also been established that the log aging index and the log time of aging are linear. The slope of such a plot can then be used to indicate the relative rate of hardening of asphalt with time. A small slope will imply a more durable asphalt.

Rankings of the eight asphalts based on the preceding criteria are given in Table 10 (r_l for laboratory-aged and r_f for field-aged asphalts). It can be readily noted that rankings of asphalt durability by different criteria are not consistent, except for asphalt concrete 9, which ranked high by all criteria. The ultimate test in determining which of the criteria is most accurate and suited for Iowa conditions consists of continuing observation of the performance of the eight pavements. At this time, they are essentially all in good condition after 42 to 48 months of field service.

The laboratory- and field-durability rankings of asphalts studied were compared and the ability of various criteria to predict asphalt durability was evaluated to calculate the average laboratory- and field-durability ranking differences of the eight asphalts by each criterion. Based on this index, the aging index based on viscosity at 140 F and the limiting viscosity at 77 F seem to be most indicative of the relative aging of asphalt in the laboratory and the pavement.

The overall durability rankings of all asphalts by all criteria were calculated by totaling all nine rankings for each asphalt for both laboratory-aged and field-aged asphalts and ranked as given in Table 10. The average laboratory and field ranking difference was 1.5, which seems to indicate that the IDT can be used to evaluate and predict pavement performance of asphalts with reasonable accuracy.

Control of durability in terms of IDT can be established by incorporating in paving asphalt cement specifications the following standards: a maximum of 20 megapoises in viscosity at 77 F or a minimum penetration of 20 for residue from 46 hours of IDT or both.

CONCLUSIONS

The following conclusions are based on test data:

1. A laboratory durability method for simulating the weathering of paving asphalts during mixing and pavement service life has been developed and is being correlated with field performance under Iowa conditions.
2. The aging process of paving asphalts follows a hyperbolic function of time both in the field and in the developed IDT laboratory conditions, but at different rates.
3. Good correlations between field service aging in Iowa and laboratory aging during IDT have been obtained. The master time-equivalency curve between IDT in hours and pavement service life in months, established by combining all asphalts (void levels) and properties, indicates that 46 hours in IDT will age asphalts to the equivalent of 60 months in Iowa pavements. Correlation curves for different properties and different levels of pavement voids were also obtained.
4. A tentative specification for paving asphalt, including durability requirements based on IDT, is recommended in lieu of current TFOT.

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