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IN THIS ISSUE:

Part III of the studies on properties of asphalt and a companion article on study of viscosity-graded asphalt cements aimed at establishing better specifications.

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IN THIS ISSUE

U.S. DEPARTMENT OF COMMERCE

JOHN T. CONNOR, Secretary

BUREAU OF PUBLIC ROADS

REX M. WHITTON, Administrator

Properties of Highway Asphalts—Part III, Influence of Chemical Composition

By[1] WOODROW J. HALSTEAD, Chief, Materials Division, Office of Research and Development, BUREAU OF PUBLIC ROADS; and FRITZ S. ROSTLER and RICHARD M. WHITE, Materials Research and Development[2]

Chemical analysis and laboratory abrasion tests were made on the 60–70 and 120–150 penetration grade asphalts, which are a part of the 323 samples collected in 1954 and 1955 by the Bureau of Public Roads for study. Results of other studies on these same asphalts have been reported previously. Also studied were a group of viscosity-graded asphalts now being used for research by other agencies. The Rostler-Sternberg precipitation method was used for the chemical analysis, and the pellet test developed by Rostler and White was used for the abrasion tests.

Of particular interest was the relation between the compositional parameter $(N+A_1)/(P+A_2)$ *to durability as measured by the pellet test. The influence of consistency or viscosity of the asphalts on the relationship was also determined. Results on blends of asphalts having different compositions within the same grades revealed that both viscosity of the asphalt and composition as shown by the parameter* $(N+A_1)/(P+A_2)$ *were significant factors that affected the results of the pellet abrasion test. A linear mathematical relation was derived by which abrasion resistance can be estimated from the composition parameter and the viscosity of the asphalt.*

The relation of asphalt composition to behavioral factors, other than embrittlement, as measured by the pellet abrasion tests, were not shown in these tests. But, data were obtained that can be related to on-going research by others on some of the asphalts included in the study discussed in this article.

Introduction

THIS ARTICLE is the fourth progress report of a comprehensive study of the ıysical and chemical properties of a series of phalts produced for highway purposes. A tal of 323 samples from 105 refineries were llected in 1954 and 1955 by the State highay departments and sent to the Bureau of ıblic Roads for study. The materials collected represented the greatest variety of phalts used throughout the United States, well as the greatest number of asphalts of e different consistency grades available and sted in any one investigation. The first two ticles by the Public Roads Office of Research ıd Development Staff at the Herbert S. airbank Highway Research Station included e commonly determined test characteristics the 85–100 penetration grade (*1*)[3] and the milar test characteristics of other grades—amely, 60–70, 70–85, 120–150, and 150–00 (*2*).

The third article by F. S. Rostler and R. M. Vhite involved the determination of the composition and changes in composition of the 85–100 penetration grade asphalts (*3*). The theme of the investigation was based on the axiom that the properties of any material, including asphalt, are given by its chemical composition and physical state, and that changes in properties and behavior must parallel a corresponding change in chemical composition, and that it must be possible to predict properties and changes in properties from chemical composition.

The principal finding reported was that the parameter $(N+A_1)/(P+A_2)$ expressive of the ratio of the more reactive to the less reactive chemical compounds in the asphalt, permits rating of the 85–100 penetration grade asphalts in groups of equal durability when that property is measured as the ability to cement aggregate. Nine durability groups were first proposed. Later work showed that the groups should be reduced to five (*4*).

The research reported in this article was done under Bureau of Public Roads contract by the staff of Materials Research and Development, a division of Woodward, Clyde, Sherard and Associates. The article was written by representatives of the Bureau of Public Roads and the contractor. This research was undertaken primarily to extend the composition studies described in reference (*3*) to the other penetration grade asphalts and to determine the general validity of the parameter $(N+A_1)/(P+A_2)$ as a means of estimating the quality of an asphalt from the standpoint of retention of its cementing characteristics measured by the pellet abrasion test.

The objective of this article is to present a progress report and to make available to asphalt technologists the extensive collection of data obtained in the study, as well as conclusions reached to date.

Tests Made and Materials Tested

To gather sufficient data for a realistic analysis of the importance of chemical properties of asphalts, all of the 60–70 penetration grade and 120–150 penetration grade asphalts used in previous studies (*2*) were analyzed. A group of viscosity-graded asphalts also were included in this study. They had been collected by the Bureau of Public Roads for cooperative studies with the Asphalt Institute, State highway departments, and producers of asphalt. The precipitation method of chemical analysis, as described in 1962 by Rostler and White (*3*), was used. The constituents determined in the chemical analysis and the abbreviations used in this article, as well as in previous reports are:

A = *Asphaltenes:* Constituents insoluble in n-pentane.

N = *Nitrogen bases:* Constituents precipitated by 85-percent sulfuric acid. These are the most reactive components and include substantially all the nitrogen containing compounds.

A_1 = *First Acidaffins:* Constituents precipitated by 98-percent sulfuric acid after removal of the nitrogen bases. These are essentially unsaturated resinous hydrocarbons.

A_2 = *Second Acidaffins:* Constituents removed by fuming sulfuric acid (30-percent SO_3) after removal of nitrogen bases and first acidaffins. These are slightly unsaturated hydrocarbons.

P = *Paraffins:* Constituents that are nonreactive with fuming sulfuric acid (30-percent SO_3). These are saturated hydrocarbons.

The 1962 article and the author's closure published in the 1962 *Proceedings of The Association of Asphalt Paving Technologists* provide a general summary of the significance of the chemical analysis method and its advantages and disadvantages. A further

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[1] Presented by Mr. Halstead at the annual meeting of The ssociation of Asphalt Paving Technologists, Minneapolis, Iinn., Feb. 1966.

[2] A division of Woodward, Clyde, Sherard and Associates.

[3] References indicated by italic numbers in parentheses e listed on p. 29.

Table 1.—60–70 penetration grade asphalts

Asphalt identification number	Asphalt composition, percent by weight					Paraffin fraction		Ratio,	Percent loss in pellet abrasion test at 77° F. on asphalt mixture[2]—			
	A	N	A_1	A_2	P	Wax indication[1]	Index of refraction, 77° F.	$\frac{N+A_1}{P+A_2}$	Original	Aged 3 days	Aged 7 days	Average of original and aged 7 days
120	29.9	22.1	23.1	17.7	7.2	+RT	1.4810	1.82	38	92	100(380)	69
121	32.3	16.3	23.3	20.1	8.0	+ice	1.4816	1.41	0.9	19	15	8
122	16.0	25.5	21.5	23.7	13.3	sl. RT	1.4826	1.27	2.8	11	14	8.4
123	27.2	16.9	20.8	21.5	13.6	−ice	1.4811	1.07	0.95	2.7	3.6	2.3
124	24.6	18.0	24.0	22.4	11.0	sl. RT	1.4827	1.26	3.6	35	35	19
125	24.2	14.8	23.2	22.7	15.1	sl. RT	1.4844	1.01	0.5	1.5	1.9	1.2
126	23.4	19.0	21.6	23.6	12.4	sl. ice	1.4817	1.13	0.3	1.8	4.6	2.5
127	29.6	22.8	25.1	16.4	6.1	+RT	1.4825	2.13	40	100(446)	100(391)	70
128	30.0	23.0	25.0	15.9	6.1	+RT	1.4818	2.18	30	83	100(344)	65
129	30.6	21.2	24.2	17.3	6.7	+RT	1.4811	1.89	12	58	84	48
130	23.4	22.6	20.4	22.1	11.5	sl. RT	1.4855	1.28	4.1	5.6	33	18
131	22.9	11.7	23.7	26.4	15.3	+RT	1.4838	0.85	0	0	0.1	9
132	22.1	22.7	22.0	21.9	11.3	sl. RT	1.4840	1.35	11	23	50	30
133	21.0	20.2	24.0	23.0	11.8	−ice	1.4830	1.27	3.1	1.7	3.8	3.4
134	19.1	15.0	26.7	25.2	14.0	sl. RT	1.4848	1.06	0.2	0.2	0.3	0.3
135	26.0	10.4	22.2	26.2	15.2	+RT	1.4817	0.79	0.7	1.0	0.5	0.6
136	31.0	20.4	24.7	17.3	6.6	+RT	1.4827	1.89	13	86	82	48
137	26.8	16.1	23.1	24.2	9.8	+RT	1.4819	1.15	14	41	58	36
138	22.2	23.0	21.7	22.2	10.9	sl. ice	1.4846	1.35	8	34	33	20.5
139	30.3	22.5	24.7	16.2	6.3	+RT	1.4831	2.10	39	96	94	67
140	27.4	14.0	25.6	24.2	8.8	+RT	1.4820	1.20	9	28	42	25
141	21.7	16.0	25.1	22.7	14.5	+RT	1.4869	1.11	0.3	0.2	0.2	0.3
142	18.1	19.9	28.2	23.3	10.5	sl. RT	1.4859	1.42	4.6	16	24	14
143	21.9	21.3	22.3	23.1	11.4	sl. ice	1.4836	1.26	4	7	26	15
144	21.2	23.8	21.7	23.9	9.4	+RT	1.4819	1.37	11	41	82	46
145	22.2	11.7	26.3	29.1	10.7	sl. RT	1.4833	0.96	1.0	2.2	2.8	1.9
146	23.4	21.3	21.6	21.8	11.9	+RT	1.4836	1.27	11	34	54	32
147	17.9	23.0	24.6	23.9	10.6	+RT	1.4855	1.38	26	53	78	52
148	21.8	20.1	23.8	22.3	12.0	−ice	1.4816	1.28	0.8	2.2	4.1	2.5
149	19.3	28.2	21.0	22.2	9.3	+RT	1.4847	1.56	7	33	55	31
150	20.0	15.6	23.6	26.9	13.9	+RT	1.4846	0.96	1.4	1.4	4.0	2.7
151	22.5	25.3	20.6	22.5	9.1	+RT	1.4824	1.45	13	57	76	44
152	15.0	26.4	24.7	23.3	10.6	+RT	1.4867	1.51	26	62	71	48
153	27.8	16.3	22.4	24.3	9.2	+RT	1.4811	1.16	7	15	29	18
154	20.2	20.8	23.8	26.1	9.1	+RT	1.4858	1.27	42	93	100(261)	71
155	20.0	27.6	19.8	23.1	9.5	sl. RT	1.4832	1.45	1.0	5	20	10
156	28.5	10.3	24.3	26.7	10.2	+RT	1.4816	0.94	1.8	3.2	3.2	2.5
157	5.0	25.5	32.1	25.5	11.9	sl. RT	1.4877	1.54	25	40	45	35
158	21.8	11.4	27.6	28.6	10.6	+RT	1.4826	1.00	1.4	2.1	6.0	3.7
159	28.5	19.4	14.7	20.9	16.5	sl. RT	1.4803	0.91	0.07	0.08	0.3	0
160	24.4	11.5	25.0	27.4	11.7	sl. RT	1.4798	0.93	0.12	0.1	0.08	0
161	31.4	10.8	20.0	24.3	13.5	sl. RT	1.4774	0.82	0.05	0.1	0.6	0
162	20.1	15.3	23.5	25.8	15.3	sl. RT	1.4846	0.94	1.0	0.29	0.90	1
163	31.4	11.6	19.9	24.0	13.1	+RT	1.4786	0.85	0.40	0.43	1.9	1
164	27.1	15.1	23.6	24.2	10.0	+RT	1.4822	1.13	8.0	10.0	46	27
165	24.2	21.3	16.0	23.4	15.1	+RT	1.4846	0.97	0.40	1.7	0.50	0.5
166	22.6	13.3	28.4	26.6	9.1	sl. RT	1.4815	1.17	1.75	0.24	5.4	3.6

[1] +RT represents the presence of wax at room temperature.
sl. RT represents the presence of a slight amount of wax at room temperature.
+ice represents the presence of wax when temperature was lowered by use of crushed ice.
−ice indicates that no wax was present in the paraffin fraction when temperature was lowered by use of crushed ice.
sl. ice indicates presence of a slight amount of wax when temperature was lowered by use of crushed ice.
[2] Figures in parentheses are number of revolutions to 100 percent loss.

review of the principles involved also has been published in the proceedings of the quality control conference, part II, sponsored by the Bureau of Public Roads in 1965 (*4*). In reference (*4*) details are given on the characteristics of the individual fractional components. This article is essentially a continuation of the work reported in 1962, therefore, reference should be made to the published discussion for a better understanding of the principles involved.

In addition to the Rostler-Sternberg analysis, tests were made for qualitatively determining the presence of wax in the paraffin fraction, the index of refraction of the paraffins, and the pellet abrasion test at 77° F. for specimens after mixing (6 minutes at 325° F.) and after 3 days and 7 days of aging at 140° F. Data from these tests are given in tables 1 through 3. The ranges of chemical compositions for each of the penetration grades are shown in table 4. Data for the 85–100 penetration grade previously reported in reference (*3*) are included. The content of any fractional component within each grade varied widely and, because of several interacting factors, specific relations cannot be determined by using data for single components. However, previous research had demonstrated that the parameter $(N+A_1)/(P+A_2)$, expressive of the ratio of more to less chemically reactive components, controls to a considerable degree the retention by an asphalt of its cementing quality as measured by the pellet abrasion test.

In figures 1 through 3, the average abrasion loss at 77° F. has been plotted against the ratio, $(N+A_1)/(P+A_2)$. The average of the abrasion loss immediately after mixing and after 7 days of accelerated aging was chosen as a measure of cementing quality of the asphalt. This average was chosen as it represents experimentally both the original cementing effect and the retained cementing power. The dotted line on figures 1 throug 3 indicates the position of the curve for th 85–100 grade asphalts as published by Rostl and White in 1962 (*3*). For the 60–70 grad asphalts, scatter of the data is indicated i the range of parameters between 1.0 and 1.(but a trend similar to that previously indicate for the 85–100 grade asphalts is shown. Fo the 120–150 grade asphalts the same trend apparent but the average abrasion loss much less for equal values of the paramete than indicated by the other grades. The dat in figure 3 for the viscosity graded asphal show a shot-gun pattern. This lack of tren indicates that grading an asphalt by co sistency measured at one temperature an rating its quality by performance measure at another is not a fruitful approach. A phalts graded by viscosity at 140° F., becau of large variations in temperature suscept bility, can have entirely different relati consistencies at 77° F., at which temperature t abrasion test was run. When the same series asphalts is subdivided into groups accordi to penetration or viscosity at 77° F., t viscosity graded asphalts show the same tre as the specimens of the penetration grade asphalts.

The difference shown by the various pen tration and viscosity grades of asphalts a the spread of the data within each gro indicate a complex relation that is affected other factors. One of these is obviously t consistency, or viscosity, of the asphalt. T relation will be discussed later in more deta

One of the major objectives of the stu reported here was to evaluate the influen of the ratio of the more reactive to less active maltenes constituents $(N+A_1)/(P+A$ on the cementing quality of the asph measured by the pellet abrasion test ov a wide range of consistencies. Because the many tests that would be necessary test all asphalts at several temperatur tests were considered desirable on a limit number of typical materials that would be related to a particular geographic orig To accomplish this objective, compos blends were prepared of the materials wit each penetration grade. Compositing w done on the basis of five groupings, wh composition parameters were:

- Group I, Minimum (0.54) to 1.00
- Group II, 1.01 to 1.20
- Group III, 1.21 to 1.50
- Group IV, 1.51 to 1.70
- Group V, 1.71 to maximum (2.24)

Group I

The BPR numbered asphalts of the differ penetration grades used in the blends Group I were:

60–70 penetration grade (12 asphalts): 1 135, 145, 150, 156, 158, 159, 160, 161, 1 163, and 165.

85–100 penetration grade (49 asphalts): 11, 16, 18, 19, 21, 22, 23, 26, 29, 30, 31, 32, 34, 35, 37, 41, 42, 43, 45, 46, 47, 48, 49, 51, 55, 56, 57, 58, 60, 61, 62, 63, 64, 65, 66, 68, 72, 73, 75, 76, 77, 78, 79, 80, and 83.

120–150 penetration grade (16 asphal 204, 209, 215, 225, 228, 230, 231, 232, 2 234, 235, 239, 240, 242, 244, and 245.

Table 2.—120–150 penetration grade asphalts

Asphalt identification number	Asphalt composition, percent by weight: A	N	A_1	A_2	P	Paraffin fraction: Wax indication [1]	Index of refraction, 77° F.	Ratio, $\frac{N+A_1}{P+A_2}$	Percent loss in pellet abrasion test at 77° F. on asphalt mixture—: Original	Aged 3 days	Aged 7 days	Average of original and aged 7 days
196	28.1	17.8	23.5	21.1	9.5	−ice	1.4806	1.35	0.35	0.32	0.60	0.5
197	26.0	24.4	25.6	16.8	7.2	+RT	1.4791	2.08	2.0	43	55	28
198	12.9	25.1	22.1	23.9	16.0	sl. RT	1.4823	1.18	0.3	0.3	0.6	0.4
199	19.2	21.1	25.6	24.0	10.1	+RT	1.4808	1.37	4.0	4.0	24	14
200	26.6	23.4	25.8	16.6	7.6	+RT	1.4771	2.03	0.9	7	55	28
201	25.7	27.4	21.4	16.3	9.2	+RT	1.4819	1.91	4.1	17	51	28
202	27.2	22.4	24.9	17.7	7.8	+RT	1.4780	1.85	1.7	25	41	21
203	19.5	23.2	21.2	23.3	12.8	sl. ice	1.4838	1.23	0.4	0.7	13	6.7
204	18.9	12.6	25.6	27.1	15.8	+RT	1.4822	0.89	0.1	0.03	0	0
205	20.4	18.0	22.3	24.8	14.5	sl. ice	1.4815	1.03	0.1	0.1	0.2	0.1
206	19.0	19.3	24.1	25.0	12.6	−ice	1.4824	1.15	0.12	1.7	0.20	0.2
207	27.6	22.7	25.5	17.1	7.1	+RT	1.4762	1.99	1.90	20	55	28
208	16.1	20.4	24.1	24.6	14.8	+RT	1.4828	1.13	0.05	0.05	0.12	0.1
209	18.4	23.5	16.7	27.5	13.9	+RT	1.4827	0.97	0.08	0.08	0.22	0.10
210	20.7	21.9	22.9	23.7	10.8	+RT	1.4788	1.30	0.7	8	7	3.8
211	19.2	22.7	20.5	24.5	13.1	+RT	1.4804	1.15	0.20	2	2	1.1
212	18.2	17.2	23.8	25.4	15.4	+RT	1.4822	1.01	0	0	0.1	0
213	15.5	23.6	22.6	25.8	12.5	+RT	1.4815	1.21	2.1	3.9	9	5.5
214	14.4	23.6	25.0	26.2	10.8	+RT	1.4841	1.31	3.5	11	20	12
215	17.6	15.8	23.2	28.0	15.4	+RT	1.4815	0.90	0.12	0	0.05	0.1
216	15.9	21.1	23.1	24.8	15.1	+RT	1.4820	1.11	0	0.12	0.05	0
217	21.8	24.0	22.1	21.6	10.5	+RT	1.4781	1.44	0.60	2.7	17	8.8
218	20.5	19.3	22.6	26.4	11.2	+RT	1.4793	1.11	1.3	1.7	3.8	2.5
219	19.6	19.6	22.0	26.8	12.0	+RT	1.4798	1.07	0.40	0.15	1.07	0.74
220	19.7	23.7	22.4	23.6	10.6	+RT	1.4786	1.35	1.1	9	15	8.0
221	20.4	25.6	23.1	21.3	9.6	+RT	1.4791	1.58	5.5	31	50	28
222	17.7	25.1	21.1	24.0	12.1	+RT	1.4814	1.28	2.8	9	20	11
223	21.7	24.7	22.4	21.0	10.2	+RT	1.4784	1.51	1.3	8	31	16
224	24.2	14.9	24.0	25.8	11.1	+RT	1.4785	1.05	0.22	0.15	2.9	1.6
225	19.5	19.0	20.8	23.9	16.8	+RT	1.4807	0.98	0.02	0.08	0.80	0.4
226	17.4	19.5	23.8	28.7	10.6	+RT	1.4815	1.10	1.9	10	48	25
227	15.6	29.9	19.4	24.6	10.5	sl. RT	1.4822	1.41	0.47	0.50	3.0	1.7
228	25.7	10.3	23.5	28.1	12.4	+RT	1.4769	0.83	0.12	0.05	0.10	0.10
229	5.0	18.2	38.4	26.0	12.4	+RT	1.4854	1.47	0.20	0.34	1.3	0.7
230	19.2	12.5	26.3	29.7	12.3	+RT	1.4797	0.92	0	0.08	0.30	0.15
231	24.1	21.4	15.4	22.3	16.8	+ice	1.4805	0.94	0.08	0.02	0.02	0
232	19.1	13.3	25.6	30.6	11.4	+RT	1.4799	0.93	0.02	0.05	0.20	0.10
233	29.5	10.5	19.8	25.3	14.9	+RT	1.4770	0.75	0	0.2	0.2	0.10
234	19.8	12.9	21.6	26.8	18.9	+RT	1.4802	0.76	0.02	0.10	0.05	0
235	28.1	10.6	20.2	26.5	14.6	+RT	1.4764	0.75	0	0.02	0.08	0
236	6.1	51.2	51.2	35.2	7.5	+RT	1.4822	1.20	0.12	0.08	0.49	0.30
237	20.3	16.9	27.6	19.2	16.0	+RT	1.4930	1.26	1.9	14	25	13
238	21.4	15.1	25.3	27.0	11.2	sl. RT	1.4801	1.06	1.8	1.1	4.8	3.2
239	13.9	19.5	15.2	29.0	22.4	−ice	1.4970	0.67	0.84	1.3	1.3	1.1
240	18.2	17.2	21.7	25.0	17.9	+RT	1.4803	0.91	0.12	0	0.05	0.08
241	13.0	26.5	28.7	23.7	8.1	sl. RT	1.4846	1.74	0.59	2.0	5.4	3.0
242	20.5	22.0	15.7	26.2	15.6	+RT	1.4843	0.90	0.22	0.08	0.34	0.28
243	15.1	17.5	29.1	26.0	12.3	+RT	1.4827	1.22	0.15	0.10	0.10	0.12
244	18.6	15.1	25.4	30.8	10.1	+RT	1.4806	0.99	0.10	0.08	0.08	0.10
245	21.9	13.2	23.7	29.6	11.6	+RT	1.4790	0.90	0.15	0.15	0.19	0.17
246	27.8	27.0	20.9	12.6	11.7	+RT	1.4792	1.97	1.2	21	51	26
247	8.1	39.6	16.3	22.8	13.2	−ice	1.4860	1.55	1.7	5.6	4.7	3.2
248	18.0	37.0	16.5	16.0	12.5	+RT	1.4843	1.88	15	49	56	35.5
249	9.8	38.9	15.2	21.8	14.3	−ice	1.4857	1.50	3	13	32	17.5
250	29.4	26.4	22.4	12.4	9.4	+RT	1.4770	2.24	2.0	22	54	28
251	29.1	28.4	20.6	12.5	9.4	+RT	1.4775	2.24	2.3	44	54	28

[1] +RT represents the presence of wax at room temperature.
sl. RT represents the presence of a slight amount of wax at room temperature.
−ice indicates that no wax was present in the paraffin fraction when temperature was lowered by use of crushed ice.
sl. ice indicates presence of a slight amount of wax when temperature was lowered by use of crushed ice.

Table 3.—Asphalts graded by viscosity at 140° F.

Asphalt code number	Asphalt composition, percent by weight: A	N	A_1	A_2	P	Paraffin fraction: Wax indication [1]	Index of refraction, 77° F.	Ratio, $\frac{N+A_1}{P+A_2}$	Percent loss in pellet abrasion test at 77° F. on asphalt mixture [2]—: Original	Aged 3 days	Aged 7 days	Average of original and aged 7 days
A–5	19.0	19.0	21.7	27.2	13.1	+RT	1.4827	1.01	0.1	1.5	2.8	1.5
A–10	20.5	19.4	21.6	25.5	13.0	+RT	1.4826	1.07	2.2	3.1	15	8.6
A–20	21.6	20.1	21.7	23.8	12.8	+RT	1.4817	1.14	3.2	24	44	23.6
B–5	14.0	18.6	28.0	26.3	13.1	+RT	1.4839	1.18	0.2	0.25	0.4	0.3
B–10	15.5	18.0	29.4	24.8	12.3	+RT	1.4837	1.28	1.2	1.9	5	3.1
B–20	18.1	18.5	28.6	22.8	12.0	+RT	1.4844	1.35	7	43	49	28
C–5	25.2	10.6	23.9	26.4	13.9	+RT	1.4766	0.86	0	0	0.2	0.1
C–10	27.4	13.1	24.1	24.4	11.0	+RT	1.4775	1.05	0.05	0.5	1.8	0.9
C-20	27.9	12.0	24.4	25.6	10.1	+RT	1.4775	1.02	3.0	6	19	11
D-5	19.3	19.0	21.0	25.4	15.3	sl. RT	1.4815	0.98	0.02	0.32	0.08	0.05
D-10	20.2	17.7	23.5	24.6	14.0	sl. ice	1.4819	1.07	0.10	0.10	0.24	0.17
D–20	21 6	19.4	22.3	24.2	12.5	sl. RT	1.4822	1.14	1.5	1.7	1.1	1.3
E–5	16.6	13.0	30.8	23.4	16.2	+RT	1.4839	1.11	7	7	9	8
E–10	16.5	13.6	33.0	22.6	14.3	+RT	1.4851	1.26	61	63	87	74
F-5	14.3	19.7	25.4	25.8	14.8	+RT	1.4836	1.11	0.22	0.02	0.17	0.20
F–10	17.8	16.7	26.2	24.3	15.0	+RT	1.4833	1.09	0.25	0.08	0.24	0.24
F–20	20.1	13.0	27.8	24.3	14.8	+RT	1.4813	1.04	0.70	0.02	0.20	0.45
G–5	19.1	14.4	26.5	27.4	12.6	+RT	1.4805	1.02	0.12	0.15	0.98	0.55
G–10	20.8	15.2	26.0	26.7	11.3	+RT	1.4810	1.08	1.3	2.4	6.2	3.8
G–20	21.6	15.9	27.1	25.2	10.2	+RT	1.4814	1.21	5.6	19	42	24
H–5	19.5	16.8	21.3	28.2	14.2	+RT	1.4806	0.90	0.34	0.32	0.84	0.59
H-10	21.2	18.4	20.0	26.8	13.6	+RT	1.4806	0.95	0.6	1.1	6.0	3.3
H–20	23.3	19.7	19.9	25.2	11.9	+RT	1.4812	1.07	10	52	52	31
I–5	14.8	16.4	26.9	31.1	10.8	+RT	1.4825	1.03	0.30	0.4	1.3	0.80
I–10	16.7	17.1	26.9	29.6	9.7	+RT	1.4827	1.12	5.2	22	28	17
I–20	18.3	17.2	26.7	29.0	8.8	+RT	1.4828	1.16	62	91	93	78
J–5	24.5	23.3	24.5	17.8	9.9	+RT	1.4770	1.73	0.10	0.12	18	9.0
J–10	26.1	24.5	24.4	16.9	8.1	+RT	1.4769	1.96	0.80	12	53	27
J–20	27.6	24.4	24.4	16.3	7.3	+RT	1.4773	2.07	12	43	74	43
J–40	28.9	25.0	24.1	15.5	6.5	+RT	1.4786	2.23	32	79	98	65
K–5	19.5	18.3	23.3	18.4	20.5	+RT	1.4790	1.07	1.0	0.4	2.1	1.5
K–10	19.2	20.3	25.4	18.5	16.6	+RT	1.4805	1.30	29	24	55	42
K–20	19.2	21.0	27.3	18.3	14.2	+RT	1.4806	1.49	83	80	100(385)	92
K–40	18.7	22.7	29.4	16.5	12.7	+RT	1.4826	1.78	100	100(197)	100(114)	100
L–5	22.4	13.3	23.4	27.4	13.5	+RT	1.4790	0.90	0.10	0.10	0.12	0.11
L–10	23.6	13.7	24.6	25.8	12.3	+RT	1.4791	1.01	0.70	1.6	18	9.4
L–20	25.3	14.6	24.1	25.0	11.0	+RT	1.4800	1.08	4.4	8	28	16
L–40	26.7	15.0	24.2	24.3	9.8	+RT	1.4810	1.15	25	60	87	56
M–5	17.3	30.8	15.3	20.3	16.3	sl. RT	1.4851	1.26	0.60	1.6	7	3.8
M–10	18.6	30.4	15.4	20.4	15.2	sl. RT	1.4850	1.29	11	23	39	25
M–20	19.7	31.5	14.5	19.9	14.4	+RT	1.4842	1.34	21	27	44	32.5
N–5	18.1	34.8	14.1	18.0	15.0	−ice	1.4890	1.48	1.0	1.3	7	4.0
N–10	18.6	35.2	15.1	17.2	13.9	−ice	1.4897	1.62	3.2	12	49	26
N–20	19.9	37.2	13.5	16.7	12.7	−ice	1.4904	1.72	30	53	100(355)	65
O–5	9.7	38.7	16.3	20.2	15.1	−ice	1.4863	1.56	1.1	2.0	14	7.6
O–10	11.0	40.5	15.7	19.9	12.9	−ice	1.4867	1.71	19	37	60	39
O–20	12.2	42.0	15.8	18.4	11.6	−ice	1.4868	1.93	70	90	100(312)	85
O–40	13.5	42.9	15.1	18.2	10.3	−ice	1.4872	2.04	100(390)	100(185)	100(94)	100

[1] +RT represents the presence of wax at room temperature.
sl. RT represents the presence of a slight amount of wax at room temperature.
−ice indicates that no wax was present in the paraffin fraction when temperature was lowered by use of crushed ice.
sl. ice indicates presence of a slight amount of wax when temperature was lowered by use of crushed ice.
[2] Figures in parentheses are number of revolutions to 100 percent loss.

roup II

The BPR numbered asphalts of the different enetration grades used in the blends for roup II were:

60–70 penetration grade (10 asphalts): 123, 25, 126, 134, 137, 140, 141, 153, 164, and 166.

85–100 penetration grade (16 asphalts): 3, 7, 8, 9, 12, 17, 20, 27, 28, 38, 39, 50, 59, 13, and 117.

120–150 penetration grade (11 asphalts): 98, 205, 206, 208, 211, 212, 216, 218, 219, 24, and 238.

roup III

The BPR numbered asphalts of the different enetration grades used in the blends for roup III were:

60–70 penetration grade (14 asphalts): 121, 122, 124, 130, 132, 133, 138, 142, 143, 144, 146, 147, 148, and 151.

85–100 penetration grade (11 asphalts): 1, 15, 25, 52, 71, 93, 104, 105, 110, 114, and 118.

120–150 penetration grade (14 asphalts): 196, 199, 203, 210, 213, 214, 217, 220, 222, 227, 229, 237, 243, and 249.

Group IV

The BPR numbered asphalts of the different penetration grades used in the blends for Group IV were:

60–70 penetration grade (3 asphalts): 149, 152, and 157.

85–100 penetration grade (6 asphalts): 5, 14, 24, 91, 106, and 108.

120–150 penetration grade (3 asphalts): 221, 223, and 247.

Group V

The BPR numbered asphalts of the different penetration grades used in the blends for Group V were:

60–70 penetration grade (6 asphalts): 120, 127, 128, 129, 136, and 139.

85–100 penetration grade (6 asphalts): 90, 92, 94, 95, 96, and 99.

120–150 penetration grade (10 asphalts): 197, 200, 201, 202, 207, 241, 246, 248, 250, and 251.

As typical behavior was desired, those asphalts that had shown anomalous behavior in the previous research of Rostler and White

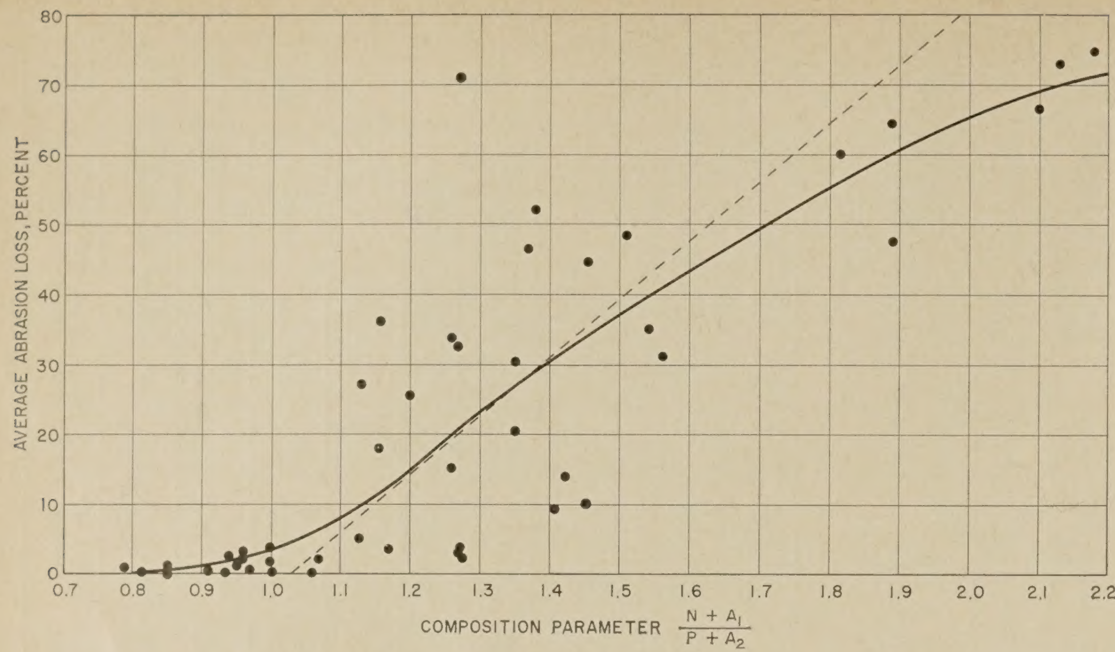


Figure 1.—Relation of average abrasion loss to composition parameter for 60–70 penetration grade asphalts.

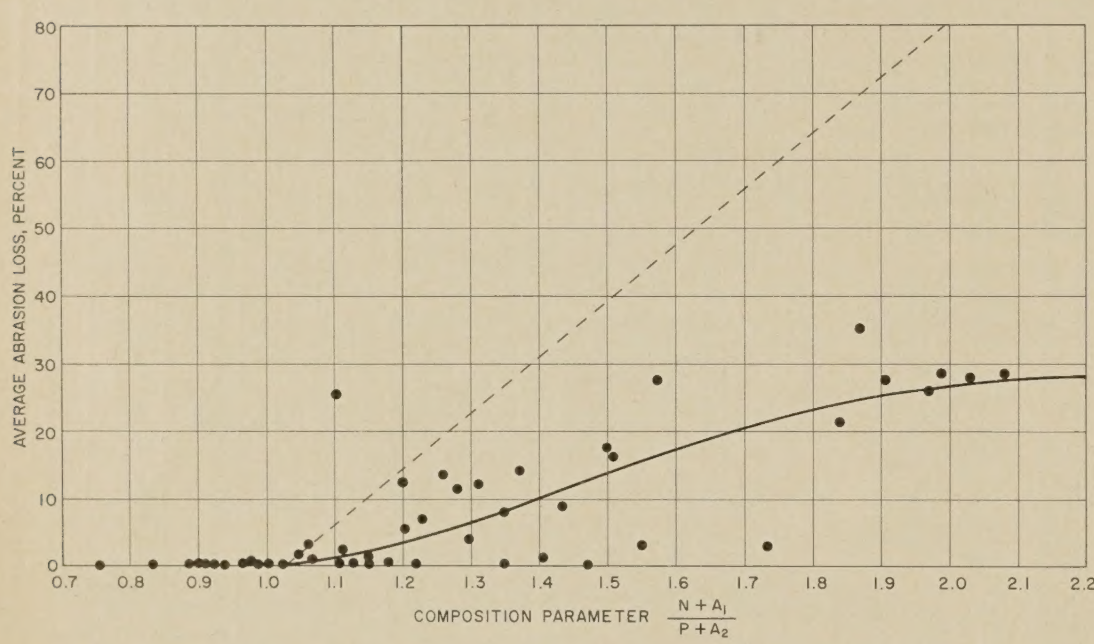


Figure 2.—Relation of average abrasion loss to composition parameter for 120–150 penetration grade asphalts.

Table 4.—Smallest and largest amount each component present in individu asphalts

	Asphalt number and smallest amount		Asphalt number and largest amount	
60–70 PENETRATION GRADE				
	No.	*Amt.*	*No.*	*Amt.*
Components:				
A	157	5.0	121	32.3
N	156	10.3	149	28.2
A_1	159	14.7	157	32.1
A_2	128	15.9	145	29.1
P	127 and 128	6.1	159	16.5
$\frac{N + A_1}{P + A_2}$	135	0.79	128	2.18
85–100 PENETRATION GRADE				
Components:				
A	93	11.4	103	35.9
N	37	6.6	96	41.9
A_1	97	13.1	71	28.3
A_2	103	12.4	60	33.0
P	13	6.8	84	23.6
$\frac{N + A_1}{P + A_2}$	84	0.54	100	2.06
120–150 PENETRATION GRADE				
Components:				
A	229	5.0	233	29.5
N	228	10.3	247	39.6
A_1	239 and 249	15.2	229	38.4
A_2	250	12.4	244	30.8
P	207	7.1	239	22.4
$\frac{N + A_1}{P + A_2}$	239	0.67	250 and 251	2.24
ASPHALTS GRADED BY VISCOSITY AT 140° F.				
Components:				
A	O–5	9.7	J–40	28.9
N	C–5	10.6	O–40	42.9
A_1	N–20	13.5	E–10	33.0
A_2	J–40	15.5	I–5	31.1
P	J–40	6.5	K–5	20.5
$\frac{N + A_1}{P + A_2}$	C–5	0.86	J–40	2.23

(*3*) were not included in the composite blends. Also, because of the large number of 85–100 grade asphalts that fell in Group I, some of these asphalts were not included in this composite. The groupings listed in the preceding paragraphs were selected after preliminary studies of blends of the 85–100 penetration grade asphalts. Blends made on the basis of durability as defined in reference (*3*) gave a reasonable relation between composition and abrasion resistance. However, these preliminary results indicated that the relative differences in asphalts measured by the pellet abrasion test did not justify nine groupings. It was also decided that groupings by chemical composition provided a more precise classification and was the more direct approach to testing the influence of composition on performance. On the basis of previous study of data in which composition was related to durability measured as loss of cementing power, it was postulated that the abrasion resistance would decrease as the group number increased.

Precipitation Analysis

One of the major advantages of the precipitation method of analysis is that the results are contingent on the reactivity of the component groups, and independent of interactions or equilibrium considerations between different components. Good evidence supporting this fact is shown by the data given in tables 5, 6, and 7. These tables compare the analytically determined composition of the composites for each penetration grade with the average calculated from the data on the individual asphalts included in the composites. The measured penetrations at 77° F. (tables 5, 6, and 7) for a number of the blends are slightly outside the limits the grade represented. This difference caused by heating the samples during blending process, as well as the fact that blends were made with material remain after most of the other tests had been co pleted. As the purpose of these tests was compare relative behavior, the deviations fr grade are of no consequence.

The original chemical properties of blends for each group within the 60– 85–100, and 120–150 asphalt penetra grades are shown in table 8. This ta also shows the same properties for thin-film residues and for asphalt recove from the abrasion test mixture immedia after mixing and after 7 days of aging. chemical properties shown include data o qualitative test for wax and the index refraction for the paraffins. The ratios highly reactive to less reactive compone $(N+A_1)/(P+A_2)$ are also given.

Fractional Composition

Figure 4 depicts, in the form of two set bar graphs, the results of the fractic analysis of the composite blends of the th penetration grades of asphalt. The lower of bars shows the asphaltenes content ble 5.—Comparison of test result and calculated result for percentage of components in blends of 60–70 penetration grade asphalts

	Group I, blend of 12 asphalts		Group II, blend of 10 asphalts		Group III, blend of 14 asphalts		Group IV, blend of 3 asphalts		Group V, blend of 6 asphalts	
	Test result	Calculated result	Test result	Calculated result	Test result	Calculated result	Test result	Calculated result	Test result	Calculated result
Components:										
A..........pct. by wt..	24.8	25.2	24.2	24.7	21.8	22.0	14.9	13.1	27.9	30.2
N..........do....	14.4	13.4	17.0	15.7	23.0	21.7	26.5	26.7	24.7	22.0
A_1..........do....	21.1	22.2	22.8	24.0	21.1	22.8	24.9	25.9	23.5	24.5
A_2..........do....	26.1	25.8	24.2	23.9	23.2	22.6	23.3	23.7	17.2	16.8
P..........do....	13.6	13.4	11.8	11.7	10.9	10.9	10.4	10.6	6.7	6.5
$\frac{N+A_1}{P+A_2}$..........	0.89	0.91	1.11	1.12	1.29	1.33	1.53	1.53	2.02	2.00
Penetration of original...	58	61	58	60	60	61	67	64	61	63
Thin-film oven test [1] pct. loss..	0.14	0.08	0.09	0.05	0.11	0.05	+0.01	0.00	0.38	0.27
Residue:										
Penetration at 77° F.	43	43	41	41	41	40	47	44	40	40
Percent of original penetration........	74	70	71	68	68	66	70	69	66	63
Percent loss in pellet abrasion test at 77° F. on—										
Original mix..........	0.35	0.7	1.1	4.2	3.6	7.4	17	19	33	29
Mix aged 3 days.......	0.5	0.9	1.1	10.1	9	22	49	45	74	86
Mix aged 7 days.......	2.4	1.7	13	19.1	45	40	62	57	96	93
Average loss on original mix and mix aged 7 days.	1.4	1.4	7.1	11.7	24	24	39.5	38	64.5	61

[1] Residue from thin-film oven test ⅛-in. film, 5 hours at 325° F.

Table 6.—Comparison of test result and calculated result for percentage of components in blends of 85–100 penetration grade asphalts

	Group I, blend of 49 asphalts		Group II, blend of 16 asphalts		Group III, blend of 11 asphalts		Group IV, blend of 6 asphalts		Group V, blend of 6 asphalts	
	Test result	Calculated result	Test result	Calculated result	Test result	Calculated result	Test result	Calculated result	Test result	Calculated result
Components:										
A..........pct. by wt..	22.6	23.3	20.4	21.1	20.6	22.4	24.7	23.7	24.7	25.4
N..........do....	15.4	13.0	22.1	18.4	24.9	22.1	25.5	24.6	31.4	28.1
A_1..........do....	20.5	21.6	21.0	22.7	21.4	22.1	21.3	22.2	17.6	20.0
A_2..........do....	27.5	28.3	24.8	26.1	23.5	23.9	20.2	20.6	16.2	16.5
P..........do....	14.0	13.8	11.7	11.7	9.6	9.5	8.3	8.9	10.1	10.0
$\frac{N+A_1}{P+A_2}$..........	0.87	0.82	1.18	1.09	1.40	1.32	1.64	1.59	1.86	1.82
Penetration of original...	78	89	84	90	84	89	81	91	81	90
Thin-film oven test [1] pct. loss..	0.13	0.04	0.22	0.08	0.19	0.04	0.44	0.08	0.62	0.11
Residue:										
Penetration at 77° F.	55	56	56	55	52	52	48	54	52	51
Percent of original penetration........	70	63	67	61	62	58	59	59	64	57
Percent loss in pellet abrasion test at 77° F. on—										
Original mix..........	0.3	1.6	0.7	2.4	10.0	9.4	22	9.5	29	22
Mix aged 7 days.......	0.9	5.1	6.0	8.9	53.0	38.5	69	81.2	96	99
Average loss on original mix and mix aged 7 days.	0.6	3.3	3.4	5.6	31.5	24	45.5	45.4	62.5	60.5

[1] Residue from thin-film oven test ⅛-in. film, 5 hours at 325° F.

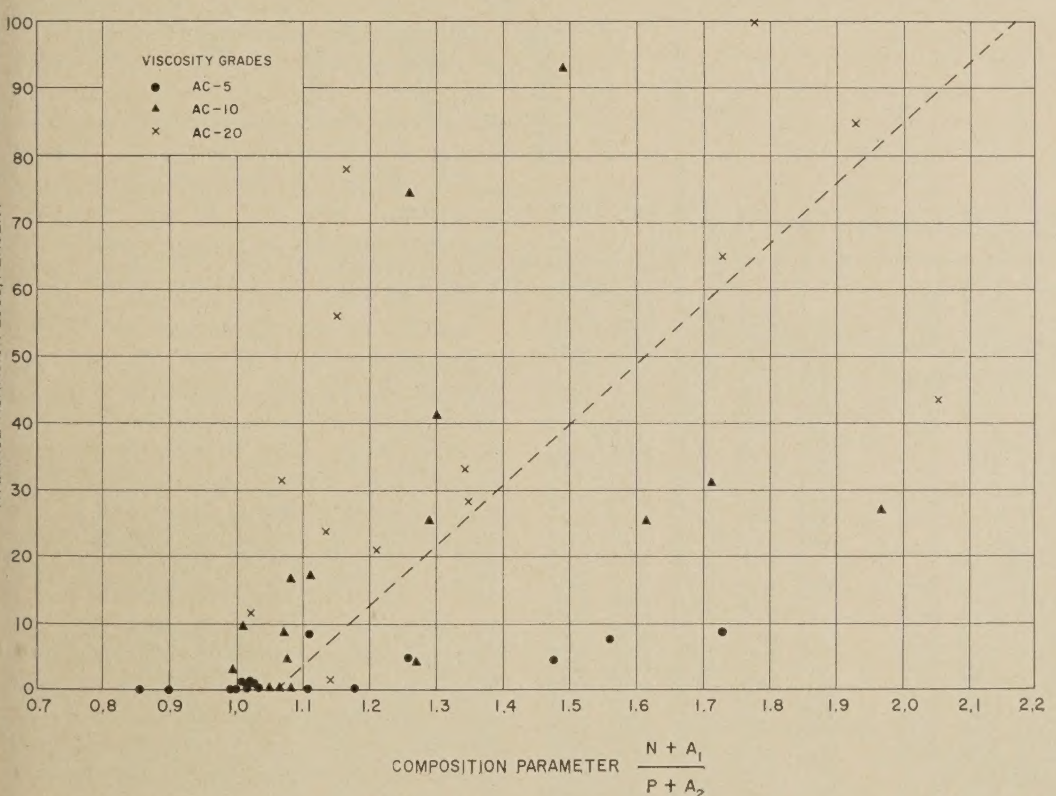


Figure 3.—Relation of average abrasion loss to composition parameter for viscosity graded asphalts.

ercent of asphalt. As shown, asphaltenes ntent varies without definite pattern from end to blend. This is true because the nount of asphaltenes present in an asphalt governed primarily by the amount and the scosity of the other components, which epends on manufacturing procedures aimed producing an asphalt of the specified nsistency.

Because of the variation in asphaltenes content, the balance of the components are graphed in the upper set of bars as a percent of maltenes—total asphalt minus asphaltenes—rather than as percent of the total asphalt. This plot of the data shows that in all three penetration grades the nitrogen bases increased significantly from Group I to Group V; whereas, first acidaffins were relatively constant. The increase in the ($N + A_1$) portion from group to group was therefore primarily an increase in nitrogen bases. Both second acidaffins (A_2) and paraffins (P) decreased from Group I to Group V, so the decrease in the ($P + A_2$) portion from group to group was the result of a decrease in both constituents.

The bars in figure 5 illustrate the changes in chemical composition during mixing and during aging for 7 days. Although no attempt was made to determine definitely how much of the changes was caused by volatility and how much by chemical reaction during mixing or aging, the close agreement between the compositions of the residues from the thin-film oven test and the residue after mixing, as shown by data in table 8 indicates that much of the change was caused by chemical reaction. This agreement of results is also indicative that the conditions chosen for the mixing in the pellet abrasion test, 6 minutes at 325° F., approximate the effect of mixing in commercial hot mix plants.

For most asphalt blends the amounts of constituents, other than asphaltenes, either decreased or underwent no significant change during mixing and aging. The increases in asphaltenes therefore approximated the sum of changes in all other constituents. Generally the largest decreases were in the first acidaffins. Usually only small changes occurred in the second acidaffins fraction, and paraffins essentially were unchanged for all blends. The content of nitrogen bases increased for some blends and decreased for others. This suggests that some of the reaction products from changes in other constituents are reactive with 85-percent sulfuric acid. Thus, the analytical result would be the net effect of two opposite changes. The general trend shown is for the total changes in composition to increase as the group number increases—the most significant changes

Table 7.—Comparison of test result and calculated result for percentage of components in blends of 120–150 penetration grade asphalts

	Group I, blend of 16 asphalts		Group II, blend of 11 asphalts		Group III, blend of 14 asphalts		Group IV, blend of 3 asphalts		Group V, blend of 10 asphalts	
	Test result	Calculated result	Test result	Calculated result	Test result	Calculated result	Test result	Calculated result	Test result	Calculated result
Composition:										
A.........pct. by wt..	21.2	20.8	19.3	18.8	17.9	17.3	16.9	16.7	24.8	25.0
N..............do....	16.1	15.6	20.0	19.3	24.8	23.3	31.3	30.0	28.4	26.6
A_1..............do....	20.8	21.3	21.6	23.1	22.1	24.0	19.2	20.6	21.4	23.2
A_2..............do....	26.8	27.3	25.7	25.4	23.3	23.6	21.4	21.7	16.3	16.2
P..............do....	15.1	15.0	13.4	13.4	11.9	11.8	11.2	11.0	9.1	9.0
$\frac{N+A_1}{P+A_2}$..................	0.88	0.87	1.06	1.09	1.33	1.33	1.55	1.55	1.96	1.98
Penetration of original...	133	130	139	137	137	130	131	127	127	132
Thin-film oven test[1] pct. loss..	0.20	0.13	0.09	0.05	0.27	0.20	0.31	0.21	0.74	0.81
Residue:										
Penetration at 77° F.	84	79	85	82	83	76	79	78	77	67
Percent of originial penetration........	63	61	61	60	61	58	60	61	61	51
Percent loss in pellet abrasion test at 77° F. on—										
Original mix...........	0.15	0.12	0.1	0.4	0.2	1.5	0.9	2.8	0.9	3.2
Mix aged 3 days.......	0.25	0.14	1.1	0.7	1.4	10.6	18	15	15	25
Mix aged 7 days.......	0.10	0.24	0	1.4	2.1	13.4	29	29	48	48
Average loss on original mix and mix aged 7 days.	0.13	0.18	0	0.9	1.2	7.4	15	16	24.5	25.5

[1] Residue from thin-film oven test ⅛-in. film, 5 hours at 325° F.

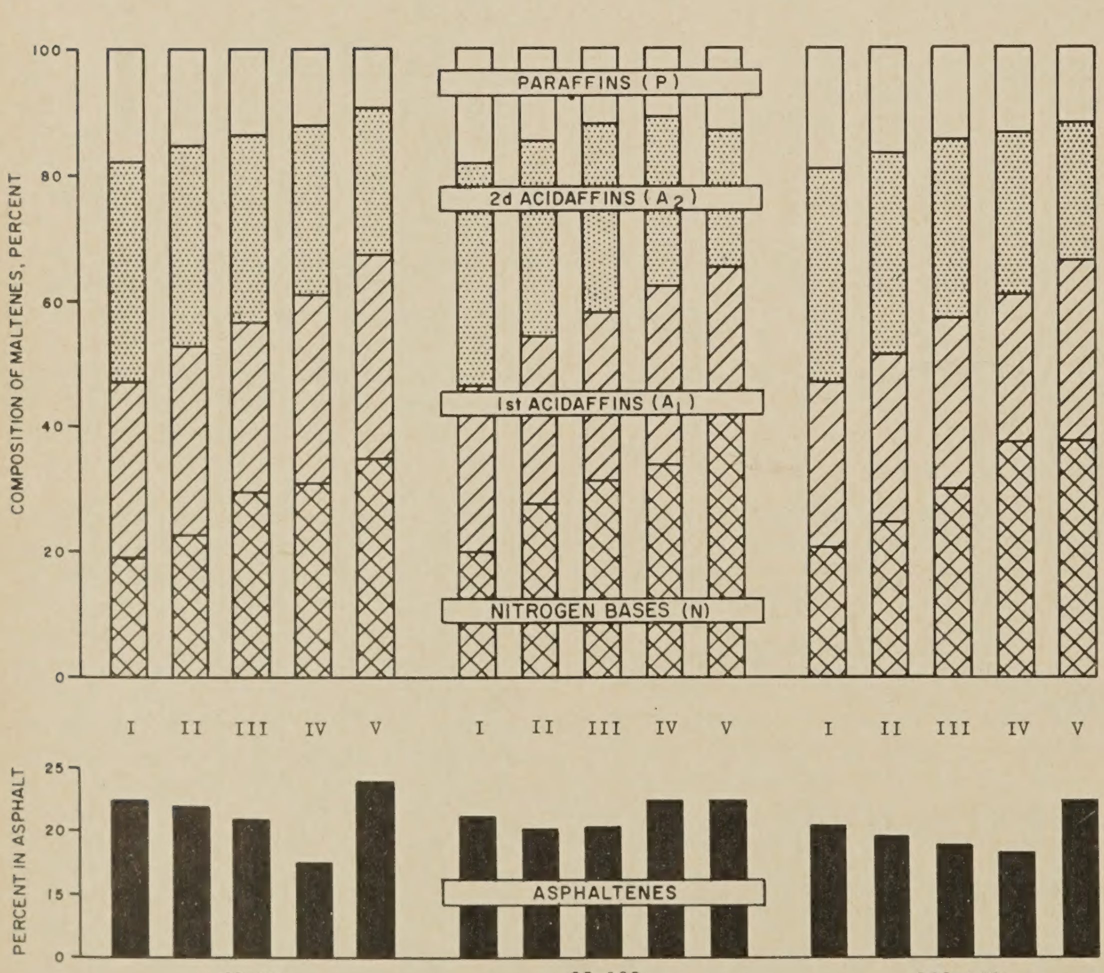


Figure 4.—Composition of asphalt blends shown by percent of asphaltenes in the blend and by composition of maltenes.

being the decreases in the sums of nitrog bases and first acidaffins. However, t blends of the 85–100 grade showed almo uniform changes for all groups.

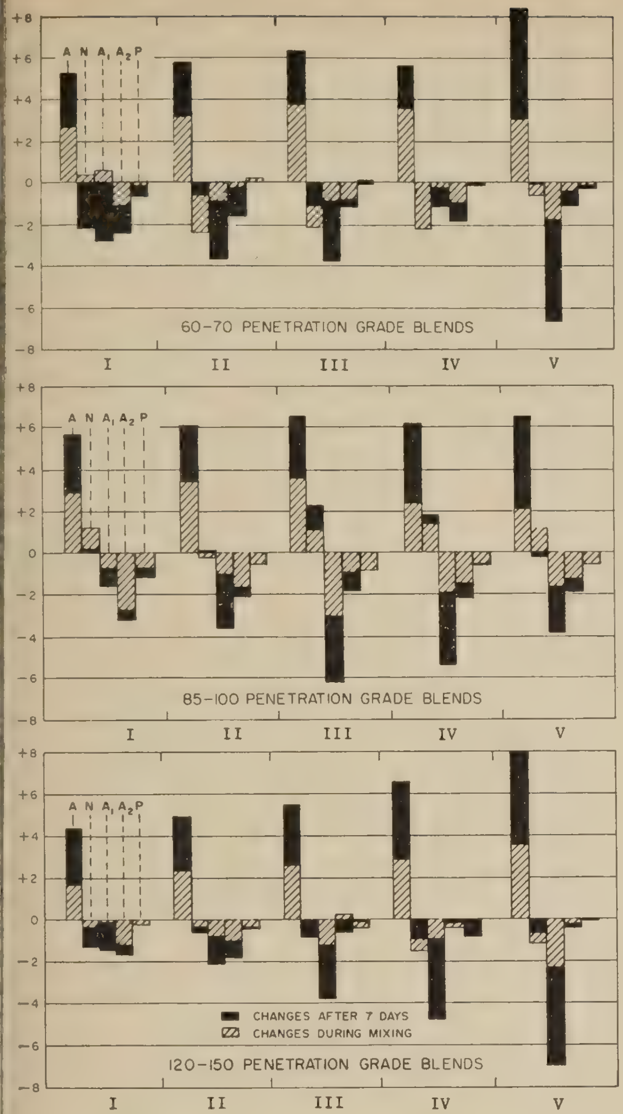
Pellet Abrasion Test

The pellet abrasion test, described pre ously (*3*), was used to measure the relati cementing quality of the asphalts. Te temperature was more exactly controlled the study reported here. Also, tests we made over a range of temperatures from 40° to 90° F. A detailed description of the pell abrasion test and the apparatus used is giv in a paragraph near the end of this article.

Results of the abrasion tests, over the ran of temperatures from 40° F. to 90° F. are giv in table 9 for each of the three penetrati grade blends. Data are included on tes made immediately after mixing, after 3 da aging of the mixture at 140° F., and after days of aging at 140° F. The test resul indicate the influence of consistency of t asphalt on the abrasion test results. Abrasi loss varied from 0 to 100 over a relative narrow temperature range. Figure 6 ill trates the average abrasion loss for t unaged specimens and the specimens after days of aging plotted against the ra $(N+A_1)/(P+A_2)$ for each of the asphalt pen tration grades at each temperature. Becau of the sensitivity of asphalt consistency temperature, only the pellet abrasion tests 65° F. and 77° F. gave sufficient data betwe 0 and 100 percent to be useful. Therefo the results at 77° F. were used for furth evaluation. Also 77° F. was used as t standard temperature for the abrasion evalu tion for continuity with the previous work which this temperature was used.

Because of the significant dependence abrasion resistance on the viscosity of t asphalt, the viscosities of the blends at diff ent temperatures were determined for a ran of shear rates. The viscosity data are giv in table 10. Figure 7 shows the square ro of the average abrasion loss at 77° F. plott against the viscosity of the residues from t thin-film oven test loss at a shear rate of 0. sec.$^{-1}$ The trial and error method was us to determine that the square root of t abrasion data gave better indication of relati abrasion resistance than did the percenta loss. Also because the characteristics of t thin-film residue are known to approxim closely the characteristics of the asphalts the abrasion specimen prior to aging, the th film residue viscosities provide a more accur comparison than do the viscosities of t original blends. However, the general tre indicated by data in figure 7 also are shown figure 8 in which the abrasion data are plott against viscosities of the original blends. T significant difference between data is a grea separation of the curves for Group IV and asphalts in figure 8 than in figure 7.

The relations indicated by data in figure and 8 demonstrate that for asphalts of eq viscosities the ratio $(N + A_1)/(P + A_2)$ ha significant effect on the cementing quality an asphalt when the asphaltenes are relativ constant. The effects of variations in t



gure 5.—Changes in composition of asphalt blends during mixing and after 7 days of aging at 140° F.

ɪount of asphaltenes or the average molecu- weights of either the maltenes constituents asphaltenes have not been evaluated by ese tests as these properties did not vary bstantially in the series of specimens tested. ictors such as those mentioned most likely ve an important effect on the overall havior of an asphalt as a binder in a pave- ent.

The points represented by open circles on gure 8 are for the asphalts graded by viscosity 140° F. These data are for the same phalts as in figure 3, which showed no lationship between abrasion loss and value the compositional ratio $(N + A_1)/(P + A_2)$. gure 8 data show that the lack of correlation as a result of widely different viscosities at ° F. When the abrasion loss was measured temperatures at which the asphalts had the me viscosity and was plotted against the mposition parameter, good correlation was tained.

Analyses of Data

As part of the contract under which the search discussed here was performed, some

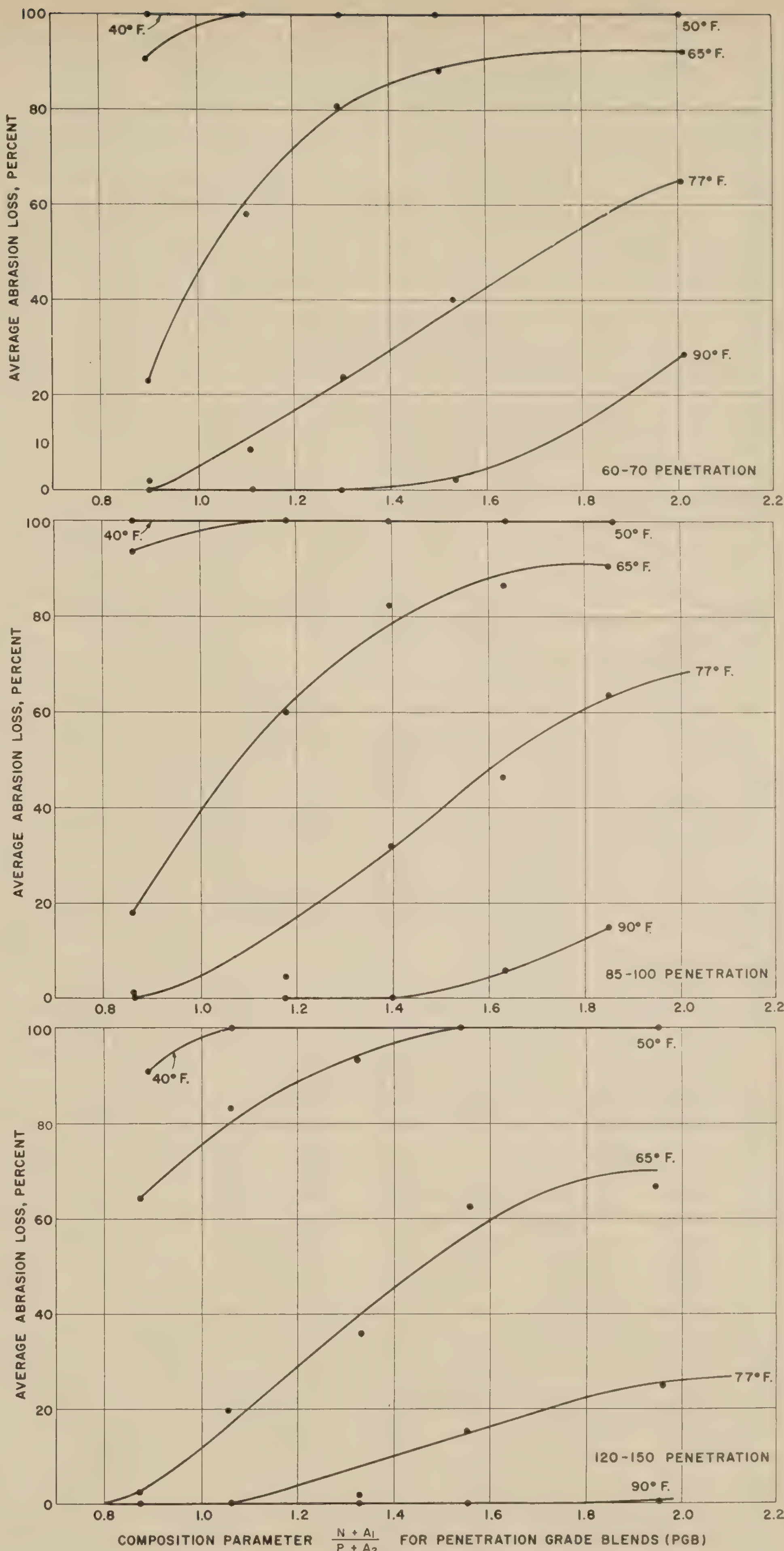


Figure 6.—Relation of average abrasion loss at different temperatures to composition parameter for blends of indicated penetration grades of asphalts.

Table 8.—Components and chemical properties of asphalt blends

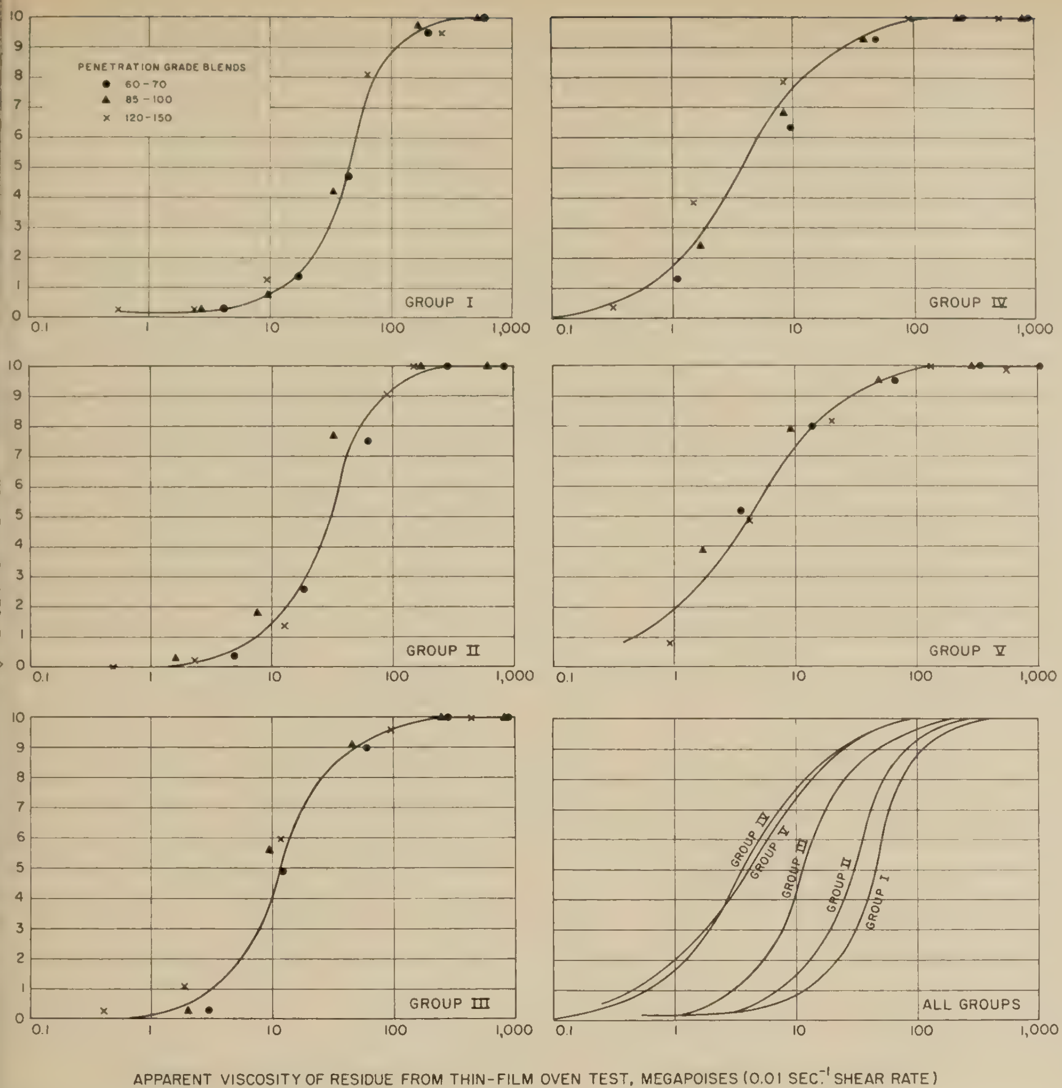
	Group I				Group II				Group III				Group IV				Group V			
	Blend	Thin-film oven test residue	Asphalt recovered from— Original mix	Asphalt recovered from— Mix aged 7 days	Blend	Thin-film oven test residue	Asphalt recovered from— Original mix	Asphalt recovered from— Mix aged 7 days	Blend	Thin-film oven test residue	Asphalt recovered from— Original mix	Asphalt recovered from— Mix aged 7 days	Blend	Thin-film oven test residue	Asphalt recovered from— Original mix	Asphalt recovered from— Mix aged 7 days	Blend	Thin-film oven test residue	Asphalt recovered from— Original mix	Asphalt recovered from— Mix aged 7 days
60–70 PENETRATION GRADE BLENDS																				
Components:																				
A pct. by wt.	24.8	27.1	27.5	30.1	24.2	26.9	27.4	30.0	21.8	24.0	25.5	28.1	14.9	17.6	18.4	20.5	27.9	31.1	30.9	36.2
N do	14.4	13.1	12.2	14.8	17.0	15.8	14.7	16.5	23.0	22.0	20.9	21.8	26.5	25.1	24.3	24.2	24.7	24.0	24.0	24.6
A_1 do	21.1	20.9	21.8	18.4	22.8	21.4	22.0	19.1	21.1	20.0	20.2	17.3	24.9	24.0	24.6	23.7	23.5	21.4	21.7	16.7
A_2 do	26.1	25.4	25.0	23.7	24.2	24.4	24.0	22.6	23.2	23.2	22.4	22.0	23.3	23.1	22.3	21.4	17.2	17.1	16.8	16.1
P do	13.6	13.5	13.5	13.0	11.8	11.5	11.9	11.8	10.9	10.8	11.0	10.8	10.4	10.2	10.4	10.2	6.7	6.4	6.6	6.4
$\frac{N+A_1}{P+A_2}$	0.89	0.87	0.88	0.90	1.11	1.04	1.02	1.03	1.29	1.24	1.23	1.19	1.53	1.47	1.50	1.52	2.02	1.93	1.95	1.84
Paraffin fraction:																				
Wax indication [1]	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT
Index of refraction	1.4812	1.4817	1.4813	1.4808	1.4815	1.4821	1.4826	1.4824	1.4826	1.4829	1.4833	1.4832	1.4849	1.4844	1.4843	1.4844	1.4812	1.4810	1.4812	1.4809
85–100 PENETRATION GRADE BLENDS																				
Components:																				
A pct. by wt.	22.6	25.3	25.5	28.3	20.4	23.7	23.8	26.5	20.6	23.8	24.2	27.1	24.7	27.2	27.1	30.9	24.7	26.9	26.8	31.2
N do	15.4	16.1	16.6	15.6	22.1	21.7	21.9	22.2	24.9	26.2	26.0	27.2	25.5	27.4	26.9	27.3	31.4	32.6	32.6	31.2
A_1 do	20.5	20.3	19.8	18.9	21.0	20.0	20.0	17.4	21.4	18.9	18.4	15.2	21.3	18.6	19.4	16.0	17.6	15.9	16.0	13.7
A_2 do	27.5	24.7	24.8	24.3	24.8	22.9	23.2	22.8	23.5	21.9	22.6	21.7	20.2	19.0	18.8	18.1	16.2	15.0	15.0	14.3
P do	14.0	13.6	13.3	12.9	11.7	11.7	11.1	11.1	9.6	9.2	8.8	8.8	8.3	7.8	7.8	7.7	10.1	9.6	9.6	9.6
$\frac{N+A_1}{P+A_2}$	0.87	0.95	0.96	0.93	1.18	1.21	1.22	1.17	1.40	1.45	1.41	1.39	1.64	1.72	1.74	1.68	1.86	1.97	1.98	1.88
Paraffin fraction:																				
Wax indication	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT
Index of refraction	1.4814	1.4815	1.4814	1.4822	1.4825	1.4830	1.4833	1.4833	1.4823	1.4817	1.4821	1.4822	1.4810	1.4816	1.4810	1.4815	1.4823	1.4830	1.4829	1.482
120–150 PENETRATION GRADE BLENDS																				
Components:																				
A pct. by wt.	21.2	23.0	22.9	25.6	19.3	21.2	21.7	24.2	17.9	19.7	20.2	23.4	16.9	19.4	19.8	23.5	24.8	27.5	28.4	32.8
N do	16.1	15.9	15.8	14.9	20.0	19.0	19.7	19.4	24.8	24.0	23.8	23.9	31.3	30.4	29.8	30.4	28.4	27.3	27.2	27.8
A_1 do	20.8	20.7	20.7	19.4	21.6	21.0	20.8	19.5	22.1	22.1	20.9	18.2	19.2	18.1	18.3	14.4	21.4	19.8	19.1	14.4
A_2 do	26.8	25.1	25.7	25.2	25.7	24.9	24.7	23.9	23.3	22.4	23.6	22.7	21.4	21.0	21.0	21.3	16.3	16.3	16.2	16.0
P do	15.1	15.3	14.9	14.9	13.4	13.9	13.1	13.0	11.9	11.8	11.5	11.8	11.2	11.1	11.1	10.4	9.1	9.1	9.1	9.0
$\frac{N+A_1}{P+A_2}$	0.88	0.91	0.90	0.86	1.06	1.03	1.07	1.05	1.33	1.35	1.27	1.22	1.55	1.51	1.50	1.41	1.96	1.85	1.83	1.69
Paraffin fraction:																				
Wax indication [1]	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT	+RT
Index of refraction	1.4822	1.4828	1.4820	1.4822	1.4816	1.4825	1.4816	1.4816	1.4836	1.4831	1.4840	1.4834	1.4828	1.4830	1.4824	1.4827	1.4804	1.4812	1.4802	1.4801

[1] +RT represents the presence of wax at room temperature.

Table 9.—Abrasion characteristics shown by pellet abrasion tests on asphalt blends [1]

Pellet abrasion test temperature, ° F.	Group I, percent loss in test				Group II, percent loss in test				Group III, percent loss in test				Group IV, percent loss in test				Group V, percent loss in test			
	Original mix	Mix aged 3 days	Mix aged 7 days	Average, original mix and mix aged 7 days	Original mix	Mix aged 3 days	Mix aged 7 days	Average, original mix and mix aged 7 days	Original mix	Mix aged 3 days	Mix aged 7 days	Average, original mix and mix aged 7 days	Original mix	Mix aged 3 days	Mix aged 7 days	Average, original mix and mix aged 7 days	Original mix	Mix aged 3 days	Mix aged 7 days	Average, original mix and mix aged 7 days
60–70 PENETRATION GRADE BLENDS																				
40	100(278)	100(264)	100(249)	100	100	100(198)	100(105)	100	100	100(150)	100(103)	100	100	100(118)	100(110)	100	100	100(72)	100(93)	100
50	79	100(416)	100(303)	90+	100(323)	100(223)	100(195)	100	100(191)	100(143)	100(165)	100	100(154)	100(165)	100(126)	100	100(280)	100(158)	100(88)	100
65	9	13	36	22.5	34	67	80	57	61	87	100(441)	81+	73	100(440)	100(418)	87+	81	100(279)	100(211)	91+
77	0.35	0.5	2.4	1.9	1.1	1.1	13.0	7.0	3.6	9	45	24	17	49	62	40	33	74	96	65
90	0.12	0.0	0.05	0.1	0.12	0.12	0.20	0.2	0.05	0.18	0.80	0.4	0.45	0.7	2.7	1.6	1.1	12	53	27
85–100 PENETRATION GRADE BLENDS																				
40	100(347)	100(260)	100(184)	100	100(282)	100(130)	100(112)	100	100(174)	100(80)	100(63)	100	100(170)	100(91)	100(70)	100	100(125)	100(80)	100(43)	100
50	87	93	100(410)	94+	99	100(240)	100(200)	100	100(250)	100(171)	100(100)	100	100(246)	100(142)	100(115)	100	100(246)	100(134)	100(94)	100
65	7	24	29	18	33	65	87	60	64	96	100(395)	82	72	98	100(310)	86+	79	100(283)	100(94)	90+
77	0.3	0.6	0.9	0.6	0.7	2.1	6.0	3.4	10	27	53	31	22	49	69	46	29	77	96	63
90	0	0.1	0.3	0.1	0	0.2	0.1	0.1	0	0.7	0.2	0.1	0.3	1.6	11	5.6	0.4	8.7	29	15
120–150 PENETRATION GRADE BLENDS																				
40	81	100(338)	100(302)	91+	100(399)	100(235)	100(216)	100	100(375)	100(224)	100(173)	100	100(326)	100(208)	100(140)	100	96	100(127)	100(96)	98+
50	43	66	86	65	66	99	100(440)	83	86	100(253)	100(318)	93+	100(418)	100(227)	100(203)	100	100(485)	100(315)	100(215)	100
65	0.3	2.2	3.4	1.8	4.6	22	34	19	12	39	61	36	35	69	90	62	34	76	100(403)	67
77	0.15	0.25	0.1	0.12	0.1	1.1	0	0.1	0.2	1.4	2.1	1.2	0.9	18	29	15	0.9	15	48	24
90	0.02	0.02	0.10	0.06	0	0.02	0.02	0	0.02	0.10	0.10	0.06	0.05	0.5	0.4	0.22	0.15	0.5	1.3	0.72

[1] Figures in parentheses are the number of revolutions to 100 percent loss.



gure 7.—Relation of abrasion loss to viscosity of thin-film oven test residue at abrasion test temperature.

alyses of data were conducted that have t been reported in detail. One of these was computer analysis of the data to determine nether a more significant relation between e abrasion resistance and composition could obtained mathematically, rather than perimentally. Relations with single con-ituents or ratios of single constituents were plored. Results showed that the ratio N/P dicated the best correlation for single con-ituents and corresponded closely to results otained by use of $(N+A_1)/(P+A_2)$ with e latter ratio being slightly superior. he effect of changing coefficients for $N+A_1$ nd $P+A_2$ was also explored, but no improve-ent over the 1 to 1 ratio was obtained. An tempt to find mathematically the best fit r the data by calculating a power index gave e form:

$$\text{Power index} = K\frac{(N/P+8)^{4.82}(A_1/N-0.7)^{0.14}}{(A_2/P)^{0.24}}$$

bviously such an expression has no practical gnificance nor is it theoretically founded. n any event, plotting this parameter and hers obtained by computer analyses showed o advantage over the parameter $(N+A_1)/(P+A_2)$ arrived at from chemical considera-ons. The exploratory computer analysis onducted was concerned only with relations the different fractions in the maltenes to abrasion resistance measured by the pellet abrasion test. Consideration was not given, in the study reported here, to the relation of chemical constitution to other characteristics of the asphalt or the effects of asphaltenes.

Another analysis of the data involved the computation of a general linear equation to calculate abrasion loss as a function of viscosity and composition. The data measured on the composite blends was the basis of the computations. Calculations were made using the portion of the *S*-curve for square root of average abrasion loss related to viscosity in poises at 0.05/sec. shear rate, which approximated a straight line—the portion between 1 and 99 percent. Using the least squares method for obtaining the best fit, separate curves for each group of asphalts were calculated as follows:

Group I:

$$\sqrt{\text{abrasion loss}} = 6.74 \log \eta - 42.6$$

Group II:

$$\sqrt{\text{average abrasion loss}} = 5.95 \log \eta - 34.8$$

Group III:

$$\sqrt{\text{average abrasion loss}} = 4.68 \log \eta - 24.6$$

Group IV:

$$\sqrt{\text{average abrasion loss}} = 4.93 \log \eta - 24.9$$

Group V:

$$\sqrt{\text{average abrasion loss}} = 3.67 \log \eta - 16.1$$

It is apparent from these equations that the slope of the line and its relative location is a function of the value of the ratio $(N+A_1)/(P+A_2)$, as this is the difference between the groups. When the slopes and constants were plotted against the value of the ratio for each blend, a general relation was obtained by which the five equations could be reduced to a single equation.

$$\sqrt{\text{Average abrasion loss}} = \log \eta \left(9 - 2.75\frac{N+A_1}{P+A_2}\right) + 24\left(\frac{N+A_1}{P+A_2}\right) - 61.5$$

This equation provides a means for predicting the abrasion resistance when the composition and viscosity of an asphalt are known. Comparisons of measured data with calculated data showed that for the blends most results agreed to within ± 15 percent, and for the viscosity graded asphalts result agreements were within the band of ± 20 percent. Figures 9 and 10, respectively, show these two relationships. Although calculated results greater than 100 percent or less than zero have no true significance, these results are shown in figures 9 and 10 for comparison. This degree of agreement between calculated and measured results suggests that an alternate procedure for measuring abrasion resistance could be devised that would permit better overall evaluation. Some preliminary studies were conducted using the weight loss per revolution for such an evaluation. This approach eliminates the zero and 100 percent loss figures and provides characteristic values for all asphalts.

Figure 11 data are an example of the improvement in test results available by use of this refinement in the abrasion test. The curves show percent average abrasion loss per revolution against the parameter $(N+A_1)/(P+A_2)$ for the 120–150 penetration grade composite blends. The individual curves are for the different temperatures at which the tests were run. The improvement obtained by this approach to measuring abrasion resistance is strikingly brought out by the fact that all data above the line of 0.2 percent loss per revolution were previously reported as 100 percent loss (fig. 6). The same general pattern was shown by data from other penetration grades.

Chemical Composition Related to Physical Characteristics

The relationship between the ratio $(N+A_1)/(P+A_2)$ and the durability of an asphalt as a cementing agent was originally postulated on the basis of the logical assumption that durability must be related to a parameter expressive of the ratio of reactive to nonreactive components. The product is less durable and more susceptible to embrittlement as more of the reactive components $(N+A_1)$ are present in an asphalt. It was neither postulated nor assumed that the parameter $(N+A_1)/(P+A_2)$, should be or could be indicative of any property of asphalts except one that logically can be related to chemical reactivity. No attempt was made, therefore, in the study reported here

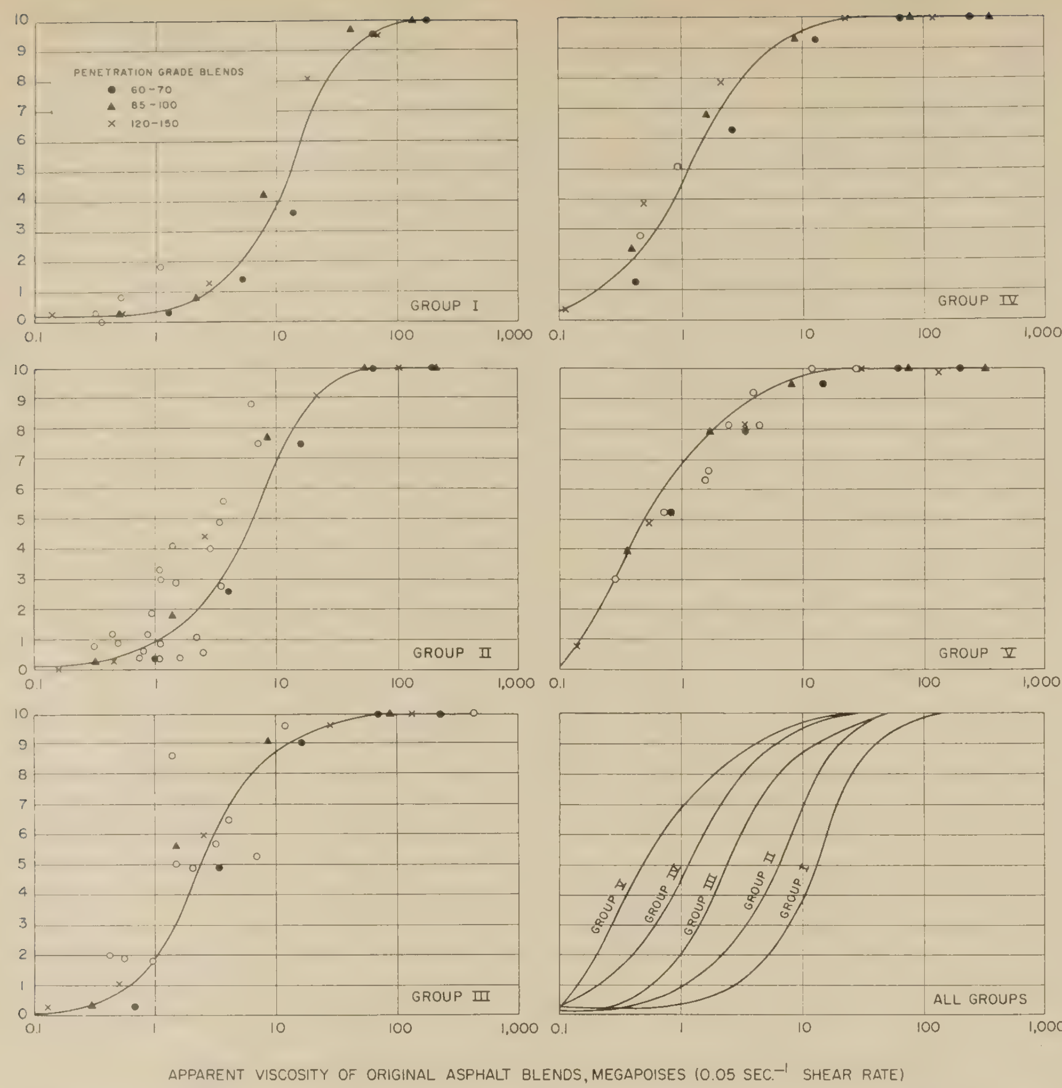


Figure 8.—Relation of abrasion loss to original asphalt viscosity at abrasion test temperatures.

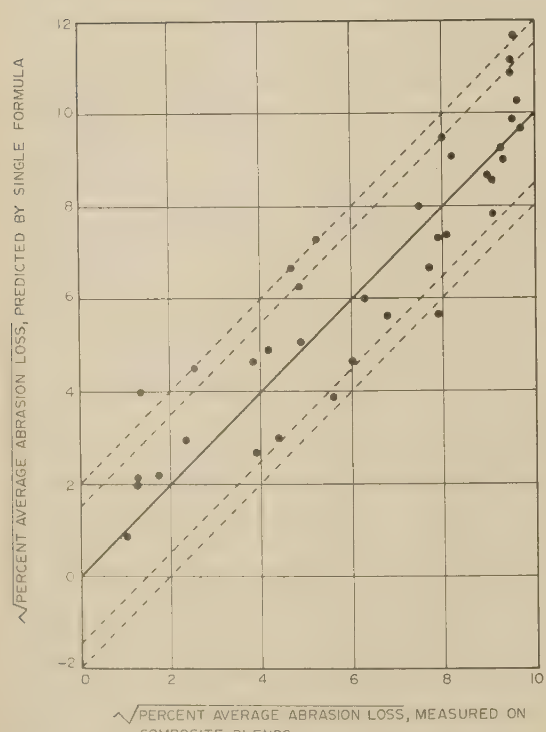


Figure 9.—Relation of abrasion loss predicted from single formula to measured abrasion loss of blends of penetration grade asphalts.

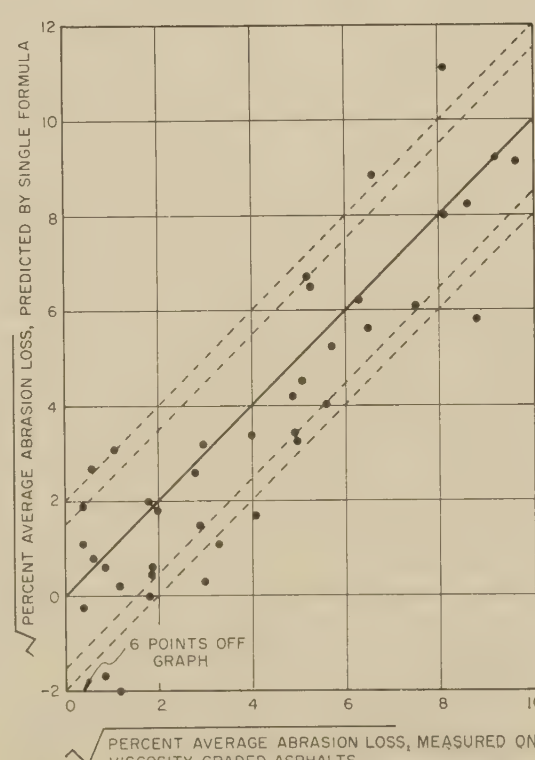


Figure 10.—Relation of abrasion loss predicted from single formula to measured abrasion loss of viscosity graded asphalts.

to correlate this parameter with any prope other than embrittlement.

It can, however, be expected that param ters also can be developed to relate ot properties, such as viscosity characterist to composition of the asphalt. A parame for viscosity characteristics logically wo have to be based on viscosity characteris of the individual components. It can postulated that in a parameter relat viscosity characteristics to composition components, A, P, and N and their molecu weights should have significant effects on relation. The data in this article prov some of the measured values that can be u in such further research, but they are sufficient for determining the specific relati that might exist.

The data presented for the viscosity gra asphalts provide information on the chem reactivity of the components of these asph and are available for comparison with ot data now being developed by other research These other data include chromatograp separations, molecular weights, and inte tions with aggregates. Hopefully, the ad tional information will permit a sorting of all important relations so that a cl understanding of the role of chemical co position on the performance of asph eventually can be attained.

Summary

A significant effect of asphalt composit was determined, by the precipitation met of fractional analysis for asphalts, from d collected in the study discussed here. viscosity of the asphalt significantly affec the results of the pellet abrasion test but co parisons made on the basis of the same asph viscosity also showed that abrasion resista decreased as the value of the param $(N+A_1)/(P+A_2)$ increased from a minim of about 0.5 to the maximum measured this study, 2.24. In other work by Ros and White they have reported that for s thetic asphalts abrasion resistance increa rapidly as the ratio falls below 0.4 because excess of saturated or nearly saturated co ponents tends to destroy the cohesive fo within the asphalt. Similarly, very p abrasion resistance is the result of an ex of highly reactive components that degr rapidly.

Data are not now sufficient to estab exact limits for the parameter $(N+A$ $(P+A_2)$, that will provide for acceptable f performance of an asphalt as a highw binder. However, evidence indicates tha ratio within a range of 0.8 to 1.5 produ materials of good original and retained ceme ing quality. The spread of results for ab sion resistance for asphalts having eq viscosities and equal values of the parame as well as a lack of general correlation parameter value with other physical characteristics of the asphalts, emphasizes role of factors not measured by these test such factors as the quantitative amount asphaltenes and the molecular weights of constituents.

An equation, taking into account, both nsistency and chemical composition of the phalt has been developed. This equation presents a first approach to a generally plicable mathematical expression for deter-ining the inherent susceptibility of an phalt to embrittlement. The fact that ta obtained on asphalts of widely different igin, consistency, and composition could fitted into a reasonably narrow band ustrated the dependence of durability on th composition and viscosity.

Physical and chemical data believed to be aracteristic of present day asphalts have en measured on a large collection of asphalt mples. These data provide an extensive cumulation of figures that can be further alyzed and compared with findings of her workers in the field.

ASPHALT IDENTIFICATION

For the convenience of researchers who may ish to compare data from this study with ta from other studies, a cross-reference for e different identification numbers of the scosity graded asphalts is shown in the llowing tabulation. The original Bureau of iblic Roads numbers and the numbers signed by The Asphalt Institute are shown.

Asphalt code number	*BPR laboratory number*	*The Asphalt Institute number*
A-5	B-2908	3
B-5	B-2920	31
C-5	B-2958	4
D-5	B-2962	33
E-5	B-2974	1
F-5	B-3008	2
G-5	B-3012	13
H-5	B-3028	35
I-5	B-3037	37
J-5	B-3050	22
K-5	B-3054	23
L-5	B-3058	28
M-5	B-3108	39
N-5	B-3578	46
O-5	B-3601	49
A-10	B-2909	7
B-10	B-2921	14
C-10	B-2959	8
D-10	B-2963	21
E-10	B-2975	5
F-10	B-3009	6
G-10	B-3013	20
H-10	B-3029	19
I-10	B-3036	15
J-10	B-3051	16
K-10	B-3055	17
L-10	B-3059	18
M-10	B-3109	40
N-10	B-3579	47
O-10	B-3602	50
A-20	B-2910	11
B-20	B-2922	32
C-20	B-2960	12
D-20	B-2964	34
F-20	B-3010	10
G-20	B-3014	38
H-20	B-3030	9
I-20	B-3035	36
J-20	B-3052	24
K-20	B-3056	25
L-20	B-3060	29
M-20	B-3110	41
N-20	B-3580	48
O-20	B-3603	51
P-20	B-3039	43
J-40	B-3053	26
K-40	B-3057	27
L-40	B-3061	30
O-40	B-3604	52
P-40	B-3040	44

Table 10.—Viscosity of asphalt blends at different temperatures and shear rates

Temperature, ° F.	Shear rate sec.$^{-1}$	Viscosity, megapoises									
		Group I		Group II		Group III		Group IV		Group V	
		Blend	Thin-film residue [1]	Blend	Thin-film residue [1]	Blend	Thin-film residue [1]	Blend	Thin-film residue [1]	Blend	Thin-film residue [1]
60–70 PENETRATION GRADE ASPHALT BLENDS											
90	0.1	1.23	2.57	0.98	3.48	0.63	2.45	0.43	1.10	0.70	2.55
	0.05	1.32	2.97	1.02	3.85	0.68	2.62	0.42	1.10	0.78	2.82
	0.01	1.60	4.20	1.09	4.80	0.69	3.05	0.40	1.10	0.97	3.50
	0.001	2.08	6.85	1.22	6.60	0.72	3.78	0.38	1.10	1.33	4.85
77	0.1	5.15	9.24	3.90	8.50	3.30	8.95	2.66	9.2	3.15	8.60
	0.05	5.35	11.1	4.10	10.6	3.45	10.0	2.67	9.3	3.45	9.90
	0.01	5.70	16.7	4.70	17.9	3.88	12.5	2.69	9.6	4.25	13.5
	0.001	6.35	30.0	5.70	37.5	4.55	17.5	2.70	10.0	5.70	21.1
65	0.1	12.1	18.3	14.3	31.3	14.8	36.2	12.0	28.6	13.7	50.0
	0.05	14.3	24.0	16.5	38.5	16.5	62.0	12.8	33.5	15.0	55.0
	0.01	21.4	44.5	23.8	42.0	20.5	60.0	15.0	48.0	18.5	67.5
	0.001	37.3	108	39.5	123	28.1	100	18.8	80.5	25.0	91.0
39.2	0.1	122	158	138	255	169	279	174	300	141	353
	0.05	172	232	195	370	227	390	237	420	198	495
	0.01	380	580	430	830	450	855	485	910	430	1,080
	0.001	1,200	2,150	1,360	2,725	1,200	2,650	1,340	2,780	1,320	3,275
85–100 PENETRATION GRADE ASPHALT BLENDS											
90	0.1	0.48	1.87	0.30	1.20	0.30	1.55	0.36	1.37	0.33	1.52
	0.05	0.50	2.10	0.32	1.32	0.30	1.67	0.39	1.44	0.36	1.57
	0.01	0.55	2.70	0.36	1.64	0.30	1.98	0.47	1.70	0.43	1.70
	0.001	0.63	3.90	0.44	2.23	0.31	2.53	0.62	1.90	0.55	1.90
77	0.1	2.02	5.35	1.38	5.10	1.47	7.20	1.57	6.05	1.64	7.20
	0.05	2.20	6.35	1.38	5.75	1.47	7.80	1.65	6.65	1.71	7.80
	0.01	2.65	9.55	1.38	7.65	1.47	9.35	1.83	8.30	1.93	9.45
	0.001	3.50	17.2	1.38	11.5	1.47	12.1	2.12	11.3	2.29	12.3
65	0.1	7.30	13.8	8.00	20.0	8.35	31.3	8.05	29.6	7.60	36.2
	0.05	7.80	17.8	8.35	23.2	8.70	35.2	8.65	31.7	8.00	40.0
	0.01	9.15	32.0	9.05	32.5	9.55	46.0	10.2	37.5	8.95	50.5
	0.001	11.50	73.5	10.3	52.5	11.0	68.5	12.8	47.5	10.5	70.5
39.2	0.1	96.0	153	163	202	375	310	292	315	259	435
	0.05	135	222	205	280	435	420	345	420	318	570
	0.01	280	525	350	600	615	840	505	825	510	1,070
	0.001	800	1,800	745	1,800	1,010	2,280	885	2,160	1,020	2,620
120–150 PENETRATION GRADE ASPHALT BLENDS											
90	0.1	0.13	0.54	0.15	0.46	0.12	0.37	0.11	0.28	0.13	0.82
	0.05	0.15	0.54	0.16	0.47	0.13	0.38	0.11	0.29	0.14	0.85
	0.01	0.18	0.56	0.18	0.49	0.17	0.41	0.11	0.32	0.16	0.94
	0.001	0.24	0.59	0.23	0.53	0.24	0.43	0.11	0.36	0.21	1.09
77	0.1	0.53	1.86	0.44	1.90	0.47	1.90	0.49	1.44	0.53	3.10
	0.05	0.55	2.00	0.46	2.00	0.50	1.90	0.50	1.47	0.56	3.40
	0.01	0.59	2.41	0.50	2.26	0.57	1.90	0.52	1.53	0.63	4.20
	0.001	0.65	3.12	0.58	2.70	0.69	1.90	0.56	1.62	0.76	5.70
65	0.1	2.65	5.08	2.60	7.55	2.46	9.48	2.14	8.40	3.38	12.3
	0.05	2.75	6.15	2.62	8.95	2.57	10.2	2.16	8.40	3.38	14.2
	0.01	3.02	9.55	2.70	13.1	2.88	12.1	2.22	8.40	3.62	20.3
	0.001	3.45	18.1	2.82	22.5	3.37	15.3	2.30	8.40	4.02	33.5
39.2	0.1	56.7	94	88.5	152	113	180	108	310	118	240
	0.05	69.5	128	105	200	132	236	120	362	135	308
	0.01	112	260	153	380	190	435	153	510	182	555
	0.001	216	715	265	960	317	1,040	215	850	276	1,300

[1] Residue from thin-film oven test, ⅛-in. film, 5 hours at 325° F.

TEST PROCEDURES

To maintain the continuity of the work, the test procedures used in the research reported here were basically the same used in the previous investigations. The refinements and improvements employed are described in the following paragraphs.

Chemical

The chemical composition of the asphalts was determined by the precipitation method described in detail in reference *3*. The only change in the procedure was that the time between treatment of the sample with 97- to 98-percent H_2SO_4 and the following step of decanting and neutralizing the solution was limited to a maximum of 3 hours. The improvement brought about by this refinement has been explained previously *(6)*.

Preparation of Ottawa sand and asphalt mixtures

The procedure described in reference *(7)* was used in the preparation of Ottawa sand and asphalt mixture, except that the batch size was larger, namely, 300 grams of sand and 6 grams of asphalt.

Aging sand-asphalt mixtures

For aging the sand-asphalt mixtures, a larger cabinet and slightly different pans for

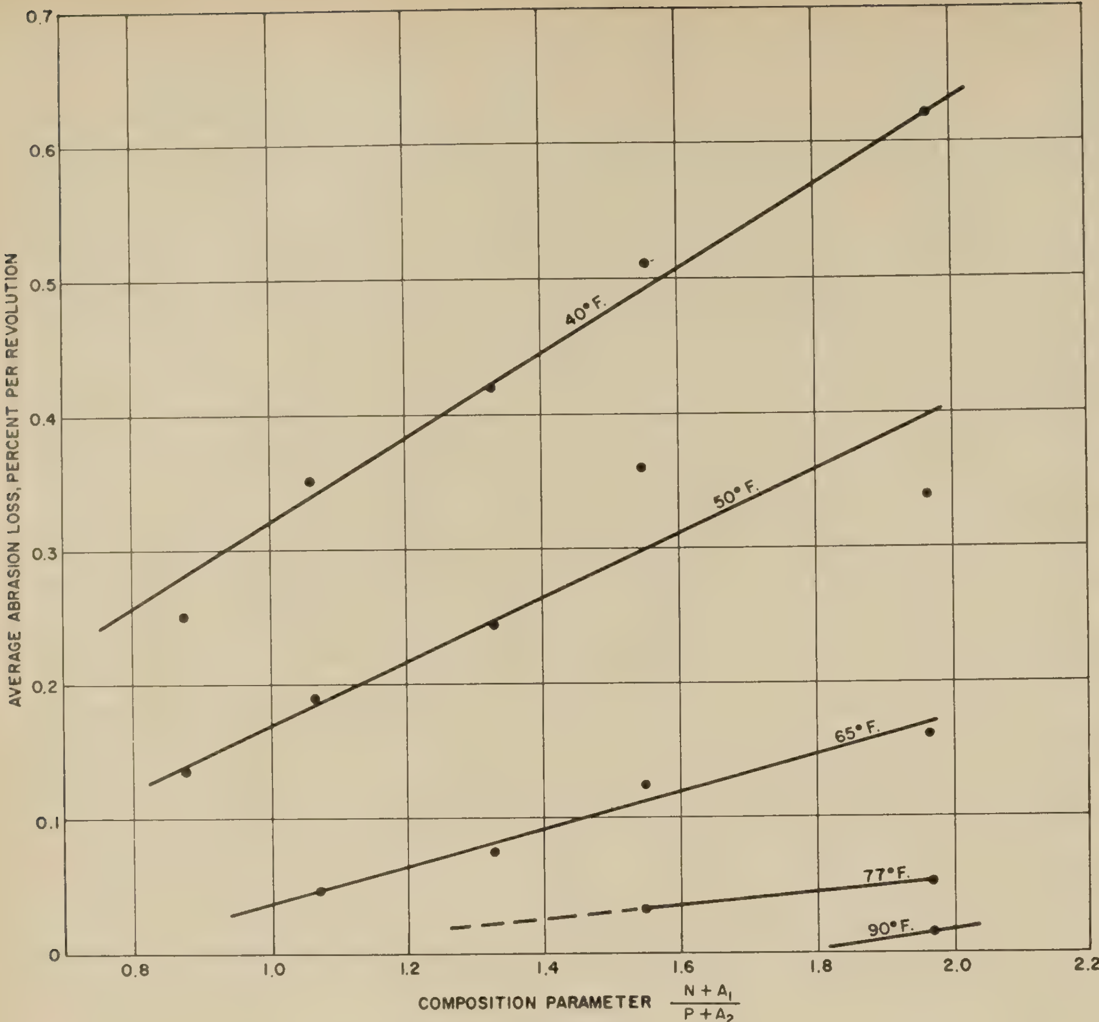


Figure 11.—Relation of average abrasion loss in percent per revolution of test device to composition parameter at different test temperatures for 120–150 penetration grade blends.

holding the specimen were used than described in reference (7). A photograph of the cabinet is shown in figure 12. The cabinet was designed to give aging effects identical to those obtained in the cabinet used previously. In calibrating the cabinet, a number of parallel aging tests were performed and the openings regulating air circulation were adjusted until the conditions represented identical aging environments in the test cabinets.

The apparatus and procedure outlined for use by laboratory technicians is as follows:

Aging cabinet. Steel, 28 by 28 by 36 inches high, containing a 25-inch diameter turntable rotating 6 r.p.m., and four 250-watt infrared reflector lamps thermostatically controlled to maintain sand-asphalt mixture at a temperature of 140±2° F.

Sample pans. Aluminum, 97 mm. in diameter and 15 mm. deep.

Thermometers. Dial, 1¾-inch diameter having a 5-inch stem and a temperature range of 0° to 180° F., with the stem painted dull black. Two or three aging pans should be fitted with these thermometers. The stem of the thermometer should be inserted through a ⅛-inch diameter hole drilled in the side, ¼ inch above the bottom of the pan, with the end of the stem supported in a depression made by denting the side of the pan diametrically opposite the hole. Epoxy cement should be used for fastening the thermometers in place.

Calibration

For proper calibration, the aging cabinet must be operated where the room temperature can be maintained at 77±4° F.—a location away from windows, free from drafts and from direct sunlight.

To complete the calibration procedure, load the turntable with 15 aging sample pans each containing 60 grams of Ottawa sand-asphalt mix. A full load of samples is necessary to ensure correct equilibrium between radiant heat absorbed and heat lost from all causes. Two or three of the pans should have dial thermometers. Hang the thermometer dials over the edge of the turntable in a proper position to avoid striking the walls as the table turns. Adjust the variable transformer so that the three lamps controlled by it will maintain a temperature of about 130° F. in the pans; then adjust the thermostat so that the fourth lamp, operating intermittently, maintains the temperature at 140±2° F.

Procedure

Procedure for completing the testing is to: Preheat the aging cabinet at least 1 hour. Weigh 60±0.2 grams Ottawa sand-asphalt mixture into an identified aging sample pan, trowelling the surface reasonably smooth with a warm spatula. Place the sample pans on the turntable, between 7½ and 12 inches from the center. If less than 15 specimens are

Figure 12.—Infrared aging oven.

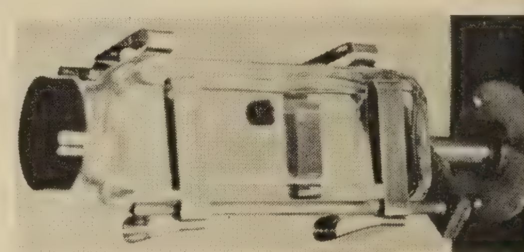


Figure 13.—Spring-clip bottle holder.

tested, ballast the turntable with extra pa[ns] of sand-asphalt mix to be kept on hand for t[his] purpose. If some specimens are removed [at] intervals during the aging period, repla[ce] them with extra pans of mix so that there a[re] always 15 pans of mix on the table. Do n[ot] stir or remove any portion of a specimen durin[g] the aging period. At the end of the agin[g] period, remove the pan, mix the conten[ts] gently with a spatula for 30 seconds a[nd] transfer them to an airtight container.

Pellet Abrasion Test

The apparatus used for the pellet abrasi[on] test for Ottawa sand-asphalt mixtures [at] different temperatures, was as follows:

Mold, from pellet press.

Carver laboratory press.

Force gage, proving ring, and other attac[h]ments, used on Carver press permitting acc[u]rate gage reading in the range used, includi[ng] that produced by a force of 200 pounds on t[he] pellet ram.

Bottle, wide-mouth French square, 16-oun[ce] capacity, with screw cap, see figure 13.

Universal timer, Gralab, laboratory mod[el].

Weighing dishes, disposable aluminum.

Analytical balance.

Thermometer, range dependent on test te[m]perature.

Temperature-controlled cabinet, 8- by 8-in[ch] multipane window in front, access port in si[de,] circulating fan, and 75-watt incandesce[nt] light, figure 14.

Bottle rotating device, a spring-clip bot[tle] holder mounted on shaft extending throu[gh] access port to externally mounted Bost[on] gear ratiomotor, VMB 5820-S, 87.5 r.p.[m.,] figure 13.

libration

'or proper calibration, determine the time uired for the bottle rotating device to ate 500 ± 10 revolutions. One hour before ting, set the temperature control to main- the desired temperature in the cabinet .° F. Use a 75-watt incandescent light b to maintain close temperature control l to provide sufficient heat for operating ve room temperature up to 90° F. If her temperatures are required, an addi- nal heat source is required.

ocedure

Procedure for this pellet abrasion test is to igh out two, 2 ± 0.1-gram portions of speci- l Ottawa sand-asphalt mixture, or measure tions using 7/16-inch I.D. arch-punch fitted h sliding piston and adjustable stop cali- ted to deliver a 2 ± 0.1-gram portion of x, figure 15. Mold each portion into a let, maintaining for 1 minute a force of 200 unds on the pellet ram, equivalent to 00 p.s.i. on the ½-inch diameter pellet. ow pellets to rest at least one-half hour ore abrading. Pellets not abraded the ne day should be discarded or broken up d returned to sealed sample cans for later lding.

Veigh each pellet, in an aluminum dish, the nearest 0.001 gram. Carefully place e pellet in a square bottle that is in a hori- tal position. Use long-handled spoon ed-tea spoon) for inserting and removing lets. Close the bottle and allow to remain test temperature for one-half hour (omit iting period for tests made at room tem- rature). Place the bottle in the holding vice; check temperature and allow it to bilize again if necessary. Set the timer to rotate the bottle for 500 revolutions; observe through the viewing window to be sure that the pellet is free to tumble, that is, not stuck to bottle. At the end of the tumbling period, carefully remove the largest remaining piece of the pellet, place it in the aluminum dish and weigh it to the nearest 0.001 gram. If the pellet disintegrates completely before the end of the test, stop the rotation and record the elapsed time.

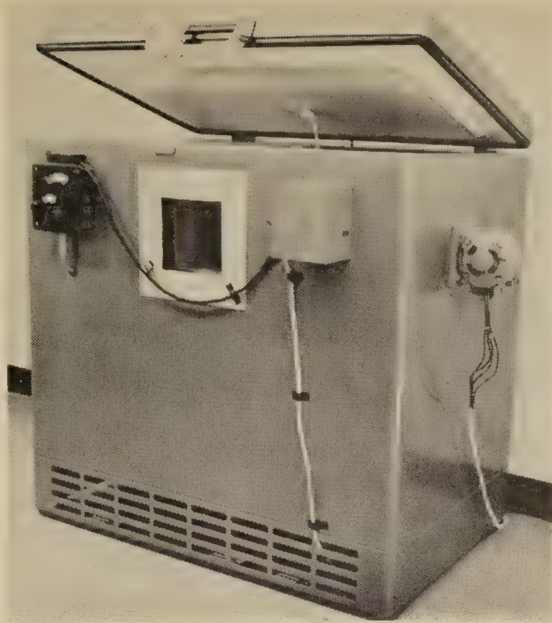


Figure 14.—Temperature-controlled (cold) cabinet.

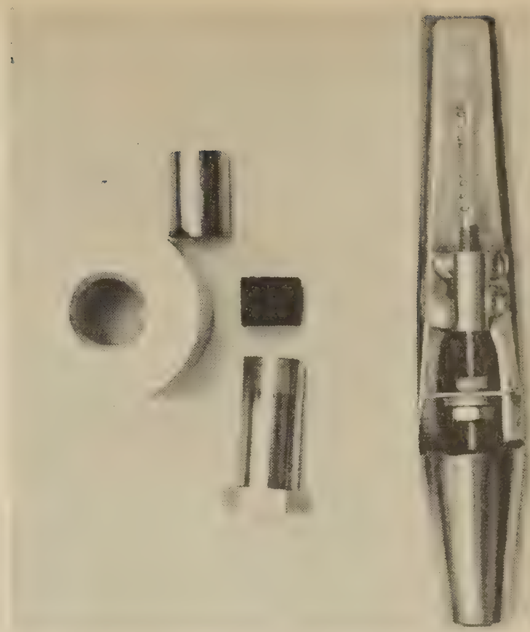


Figure 15.—Mold and arch punch.

Report

For report on this pellet abrasion test, record sample identification and history (aging, etc.), test temperature, pellet weight before and after abrasion. Calculate abrasion loss as weight and as a percent of original weight of pellet. When test results for duplicate pellets do not check within 0.010 gram or 10 percent, whichever is larger, two more pellets should be molded and tested. When pellets disintegrate completely before the end of the test, calculate from the elapsed time the number of revolutions to 100 percent abrasion loss. Also, report whether, in the operator's judgment, the pellet disintegrated because of brittleness or excessive softness and lack of cohesion.

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A Study of

Viscosity-Graded Asphalt Cements

*BY THE OFFICE OF
RESEARCH AND DEVELOPMENT
BUREAU OF PUBLIC ROADS*

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As part of a national effort to improve the quality of highway structures, the Bureau of Public Roads has initiated a comprehensive research program directed toward the development and use of fundamental knowledge to define the essential functional properties of asphalt and to recommend realistic tests and material requirements to specification writers. This article concerns a laboratory study of asphalt cements representing a broad range of sources that were collected by the Bureau of Public Roads to investigate the feasibility of grading and specifying asphalts by viscosity at 140° F. in lieu of penetration at 77° F. A secondary purpose for this article is to disseminate the test data to other researchers, who are using the same asphalts in their work.

Among other findings, the results indicate that when asphalt is graded by viscosity at 140° F. resultant materials will have more uniform within-grade consistency at temperatures of 140° F. and higher than materials obtained by use of the present system of grading asphalts by penetration at 77° F. However, the wide range in viscosity at temperatures of 77° F. and below recorded in tests during this research indicates a need for a requirement to control asphalt consistency at low temperatures. No evidence was noted during the tests reported here that viscosity grading caused any significant change in temperature susceptibility or resistance to hardening from changes previously noted for penetration graded asphalts.

Although some of the information reported here can be applied in the development of better specifications to define and control the essential functional properties of asphalt, the authors believe that additional research is needed to evaluate the binder rheology with that of paving mixtures, including the influence of mixture design, temperature, and aging. The authors recommend that this research be directed toward development of information from pavements in service and from carefully designed experiments in which the asphalts will be described on the basis of fundamental properties.

Introduction

ASPHALTIC materials are of prime economic importance in the construction and maintenance of the National highway system. Many thousands of miles of asphalt pavements—from low cost secondary to the highest type Interstate roads—have been constructed. An ever increasing demand is being made for better materials and construction methods that will provide higher quality and more durable pavements to carry modern and future traffic. A need also exists for a reduction in the cost of highway construction. Such goals can be met only by innovations in technology of structural design, construction practices, and maintenance operations. Better utilization of current materials and the development of new materials capable of producing lower cost, longer life, and superior performance will be required in the future.

In 1965 the Bureau of Public Roads promulgated a National Program of Research and Development to provide the knowledge of methods and materials to increase highway engineering productivity. As a beginning, the need for a better understanding of the properties of asphalt materials, especially those properties that affect the performance of pavements in service, is evident.

Thus, as part of the national effort, the Bureau of Public Roads has initiated a comprehensive research program directed toward the development and use of fundamental knowledge to define the essential functional properties of asphalt and to recommend realistic tests and material requirements to specification writers. Because of the greatly accelerated interest in asphalt research by the States, Federal Government, universities, industry, and other groups, it is essential that the national coordination of the overall effort be stressed. Such a program was outlined and discussed as part of a 3-day conference in Washington, D.C., April 7, 1965, on qualit control and acceptance specifications (*1*)[2]. I the session on asphalt technology, representatives from the asphalt industry, the pavin contractors, and the consumer interests expressed the need for: (1) better tests that wil measure and control consistency, (2) tests tha will predict durability in service, (3) specification requirements that will recognize variability that is the result of manufacturing sampling, and testing, and (4) specification that will provide requirements that wil assure the proper balance of engineerin properties.

To acquire the information desired, th Bureau of Public Roads is stressing the nee for a coordinated research program for th development of instrumentation and tech niques to measure and define the fundament properties of asphalt binders that are relate to rheology, durability, and chemistry, an to determine the relation of these properti to mixture design, asphalt-aggregate system and pavement performance.

The need for fundamental research on th properties of asphalt is not new and man reports and discussions have been written o different aspects of the subject. Howeve it was not until about 1960 that serious con sideration actually was given to the funda mental aspects of the problem. Becaus consistency was believed to be of primar importance, the research effort was concen trated on the development of tests to measu viscosity in fundamental units and to dete mine the relation of these fundamental prop erties to mixture design and pavement pe formance.

In 1962 the Bureau of Public Road published a report (*2*) speculating on the u of absolute and kinematic viscosity to contr the consistency of asphaltic materials. I this article the possible advantages and di advantages of such an approach for speci cation purposes were pointed out. The considerable evidence showed that the appl cation of fundamental viscosity measuremen to specifications for liquid asphalts of th cutback and slow curing types was practicabl Since then standard test methods have bee

[1] Presented at the annual meeting of The Association of Asphalt Paving Technologists, Minneapolis, Minn., Feb. 1966.

[2] Italic numbers in parentheses indicate the referenc listed on page 41.

eloped and the adoption of specifications ıg these methods has become a reality. major national specifications and a ority of the State highway departments grade liquid asphalts by kinematic osity at 140° F. There is evidence that grade limits may need some adjustment the basic principle of using fundamental s to measure consistency has proved kable.

n 1963 a concerted effort was made to elerate the study to determine the significe of using absolute and kinematic visity to measure the consistency and control characteristics of asphalt cements at peratures encountered in construction and he resultant asphalt pavements in service. application of fundamental viscosity asurements over such a range in temperaes presented some complex problems. table test methods were needed to measure cosity at temperatures below 100° F. h methods would have to be reliable and ple to use. Also, asphalt cements from rces normally being used were known to er greatly in viscosity-temperature susptibility and to exhibit varying degrees of nplex flow at low temperatures. The nificance of these differences in terms of vement performance would have to be ermined before optimum specifications ıld be written. Continued research on se problems was supported by a recomndation of the Highway Research Board ecial Committee No. 5 for Research Probns of Mutual Interest and Concern to Users d Producers of Asphaltic Materials. The jor points in the Committee's recomndations were that instrumentation and t methods should be developed for measur viscosity at low temperatures and that aracteristics of asphalt cements at the low nperatures be studied.

Findings

The intent of the study reported here was to esent and evaluate the physical properties a series of asphalt cements prepared to meet specification using viscosity grading at 0° F. Particular emphasis was given to the aracteristics of the asphalts at temperatures sociated with pavements in service. The incipal findings are summarized as follows r the asphalts included in this study:

- Asphalt cements graded on the basis of scosity at 140° F. have more uniform contency within grade at temperatures above 0° F. than asphalts graded by penetration 77° F.
- Viscosity grading at 140° F. provides a der range in asphalt consistency at temperares below 77° F. than is obtainable for phalts controlled by penetration at 77° F. hus, there is an apparent need for a specifition requirement to control low-temperature operties of asphalts graded by viscosity at 0° F.
- The range in viscosity-temperature susptibility between 140° and 275° F. is similar the range for penetration graded asphalts.
- The sliding plate viscometer, using controlled rates of shear, is a satisfactory method for determining viscosities at low temperatures over a wide range of shear rates.
- Varying degrees of deviation from a straight line occurred in the viscosity-temperature relations below 140° F. when data were plotted on the Walther chart.
- Essentially straight line relations were shown when the log of the limiting viscosity and temperature in the relatively narrow range between 39.2° and 60° F. were plotted.
- Viscosity data obtained with two viscosity methods at several test temperatures and rates of shear, when plotted, superposed to a single flow diagram for each asphalt at a single test temperature. This superposition substantiates previous findings that the superpositioning technique can be used to evaluate rheological properties of viscosity-graded asphalts.
- A good correlation was obtained between log viscosity at 0.05 $sec.^{-1}$ rate of shear and log penetration at 60° and 77° F.
- A good correlation was obtained between shear susceptibility and log ductility at 60° F. on the original asphalts and thin-film residues, indicating the possibility of the use of a test for shear susceptibility in place of a ductility test.

The data presented in this report for viscosity-graded asphalts provide fundamental information that can be applied to the development of optimum specifications to define and control the essential functional properties of asphalt. However, the significance of some of the rheological properties of asphalts indicated by fundamental viscosity measurements must be studied further before requirements can be recommended for use in standard specifications. Research needs to be continued to evaluate the binder rheology with that of paving mixtures, including the influence of factors induced by mixture design, temperature, and aging. More knowledge is needed to correlate pavement performance adequately with asphalt properties measured by empirical tests presently in use and by tests related to the fundamental characteristics. This research should be directed toward development of information from pavements in service and from carefully designed experimental projects in which the asphalts used will be described on the basis of fundamental properties.

Study Specifications of The Asphalt Institute

One of the steps taken to accomplish the recommendations of the committee was the development of study specifications by The Asphalt Institute, College Park, Md., 1963. The requirements included in these specifications are set forth in table 1. The major element of the asphalt specifications is that of absolute viscosity measurements at 140° F. The primary advantage of such a specification is that the consistency of all asphaltic road binders would be graded at the temperature associated with maximum pavement temperature and the temperature used in some mixture design methods. It was also believed that such control would tend to eliminate some of the nonuniformity in asphalt cements and some of the variations in behavior encountered in construction and at high temperatures of pavement in service. Previous study (*3*) by the Bureau of Public Roads, using penetration grade asphalts from many different sources in paving mixtures made with crushed stone, gravel and sand, and sand alone, showed that compressive strength was dependent on the viscosity of the contained asphalt, as well as the type of aggregate used in the mixture. These findings supported the idea that good results could be obtained by grading asphalts on the basis of viscosity at 140° F., the approximate temperature at which the stability or instability of paving mixtures in the pavement is most critical.

In addition to the control of asphalt grades by viscosity at 140° F., The Asphalt Institute study specifications call for information for a minimum viscosity requirement at 275° F. and a provision to control hardening, using the ratio of viscosity at 140° F. after and before the thin-film oven test. Other proposed requirements cover ductility, flash point, and solubility in CCl_4 on the original asphalt.

Asphalts Studied

The viscosity-graded asphalts used in the study reported here were collected by the coordinated effort of The Asphalt Institute and the Bureau of Public Roads. The selection of the sources of production was based on the knowledge of the viscosity-temperature relationships of penetration-grade asphalts reported in previous studies of highway asphalts produced and used in the United States (*4*, *5*).

Samples, totalling 25 gallons, of each grade of asphalt were obtained directly from asphalt producers and are believed to have been a fair sample of total production in the United States. Asphalts of AC-5 and AC-10 grades produced to meet the viscosity ranges at 140° F. under The Asphalt Institute study specifications were obtained from 15 sources. The AC-20 and AC-40 grades were obtained from 14 and 4 of these sources, respectively.

Table 1.—Asphalt study specification requirements

Properties	Viscosity graded asphalts			
	AC-5	AC-10	AC-20	AC-40
Viscosity at:				
140° F___poises	500-750	1,000-1,500	2,000-3,000	4,000-6,000
275° F., centistokes	150+	200+	300+	400+
Ductility at:				
77° F_______cm	------	100+	100+	100+
60° F_______cm	60+	------	------	-----
Solubility in CCl_4, pct	99.5+	99.5+	99.5+	99.5+
Flash point, C.O.C.[1], ° F	375+	425+	450+	450+
Thin-film oven test—viscosity ratio [2]	5	5	5	5

[1] Cleveland open cup test.
[2] Viscosity of residue at 140° F./viscosity of original asphalt at 140° F.

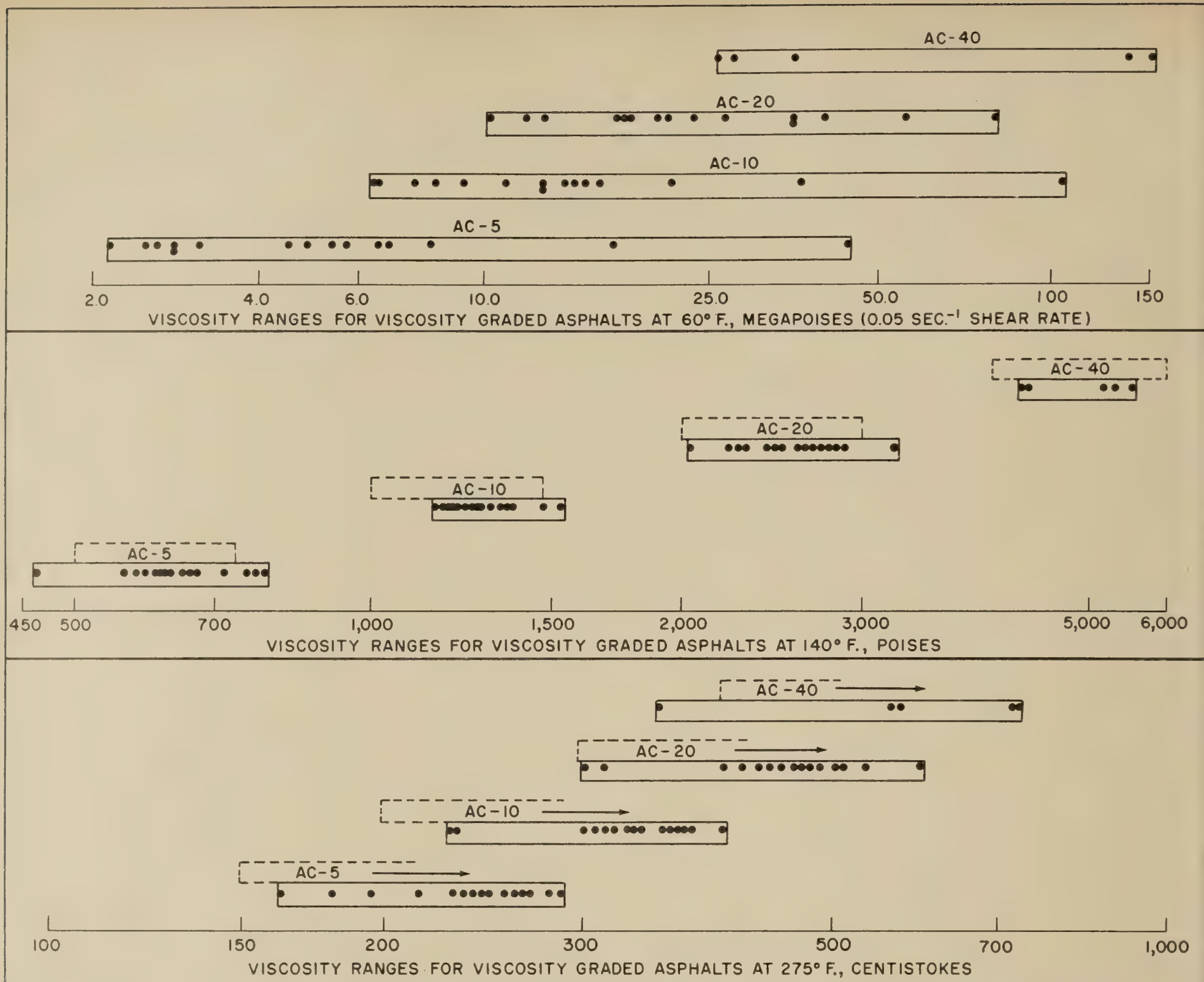

Figure 1.—Ranges and distributions of viscosity test results by viscosity grade of asphalt cements at different temperatures.

Asphalts from one other source that met the viscosity limits for AC-20 and AC-40 grades, submitted as penetration grade materials, also were included in the study. Some of the asphalts furnished were special products and, except for the source of the base products, do not necessarily represent commercial products based on present penetration grade specifications. They may not represent regular production that would be available under viscosity-grade specifications.

The samples were collected by the Bureau of Public Roads and were divided with The Asphalt Institute, which in turn provided samples for some of its company members. Public Roads in turn furnished samples to several State highway departments and to universities conducting research for the States. Some of the asphalts were or are being used in research projects initiated by the States and supported by Federal funds. Also, in accordance with the Public Roads effort to coordinate research efforts under the National program, the materials were made available to contractors in the National Cooperative Highway Research Program and to the Bureau of Mines for inclusion in their fundamental studies of asphalt.

Test Methods

Except for low temperature viscosity tests and a minor modification in the ductility tests, standard ASTM test procedures generally were used. For ductility tests, single specimens were used rather than the three prescribed specimens. Four different types of viscometers were used to cover adequately the temperature range over which viscosity determinations were made. The viscometers, applicable test method, and the test temperature at which they were used, are described in the following paragraphs.

- Zeitfuchs Cross-Arm Capillary Viscometer, ASTM Designation: D–2170–63T, "Tentative Method of Test for Kinematic Viscosity of Asphalts," 275° and 210° F.

- Cannon-Manning Viscometer, AST Designation: D–2171–63T, "Tentative Me od of Test for Absolute Viscosity of Asphalt 140° and 120° F.

- Sliding Plate Microviscometer, in acco ance with the method described by Fink Heithaus (*6*), 77° and 100° F.

- Sliding Plate Viscometer, in accorda with "Proposed Method of Test for Visco of Asphalt with a Sliding Plate Viscomete Controlled Rates of Shear" (*7*) 60°, 45°, 39.2° F. This viscometer and method, wh were developed in the Public Roads laborat by the authors, are described briefly late this article.

The precision of the capillary and slid plate microviscometer test methods have b established by usual interlaboratory rou robin tests and are given in the respective methods. The precision of the sliding pl viscometer, in which controlled rates of sh are used, was estimated from tests made 60° F. in the Public Roads laboratory.

Table 2.—Statistical summary of precision data for repeatability of viscosity determinations at 60° F.

Asphalt code number and statistics	Replicates	Thickness of specimens	Viscosity, at shear rates of— 0.1 sec.$^{-1}$	0.05 sec.$^{-1}$	0.01 sec.$^{-1}$	0.005 sec.$^{-1}$	0.001 sec.$^{-1}$
	No.	*Microns*	*Megapoises*	*Megapoises*	*Megapoises*	*Megapoises*	*Megapoises*
C-5:							
Average	5	468.8	2.252	2.386			
Range	5	35	0.09	0.20			
Standard deviation	5	15	0.044	0.091			
Coefficient of variation ... pct	5	3.20	1.92	3.81			
B-10:							
Average	5	471.0	12.70	14.12	17.84	18.58	18.70
Range	5	157	1.1	0.1	1.7	1.3	1.3
Standard deviation	5	124	.418	0.050	0.634	0.605	0.660
Coefficient of variation ... pct	5	26.3	3.29	0.35	3.55	3.26	3.53
I-10:							
Average	5	452.2	14.50	15.56	16.82	16.98	16.98
Range	5	90	0.5	1.0	1.6	1.5	1.5
Standard deviation	5	35	0.187	0.403	0.657	0.605	0.605
Coefficient of variation ... pct	5	7.74	1.29	2.59	3.91	3.56	3.56
D-20:							
Average	5	478.6	15.58	17.75	21.74	22.28	22.40
Range	5	71	0.8	0.2	1.4	1.3	1.0
Standard deviation	5	30	.303	0.100	.630	0.668	0.547
Coefficient of variation ... pct	5	6.26	1.94	0.56	2.90	3.00	2.44
F-20:							
Average	5	488.4	12.80	15.64	24.40	28.80	31.35
Range	5	155	1.0	0.8	0.9	3.3	1.2
Standard deviation	5	131	0.400	0.320	0.424	1.31	0.900
Coefficient of variation ... pct	5	26.8	3.12	2.05	1.74	4.55	2.87
O-40:							
Average	5	564.4	119.0	156.2	212.2	215.4	215.4
Range	5	384	10	13	8	10	10
Standard deviation	5	162	4.30	4.60	4.38	4.98	4.98
Coefficient of variation ... pct	5	28.7	3.61	2.94	2.06	2.31	2.31
Pooled:							
Coefficient of variation ... pct			2.53	2.05	2.83	3.34	2.94
Repeatability ... do			7.34	5.95	8.23	9.72	8.56

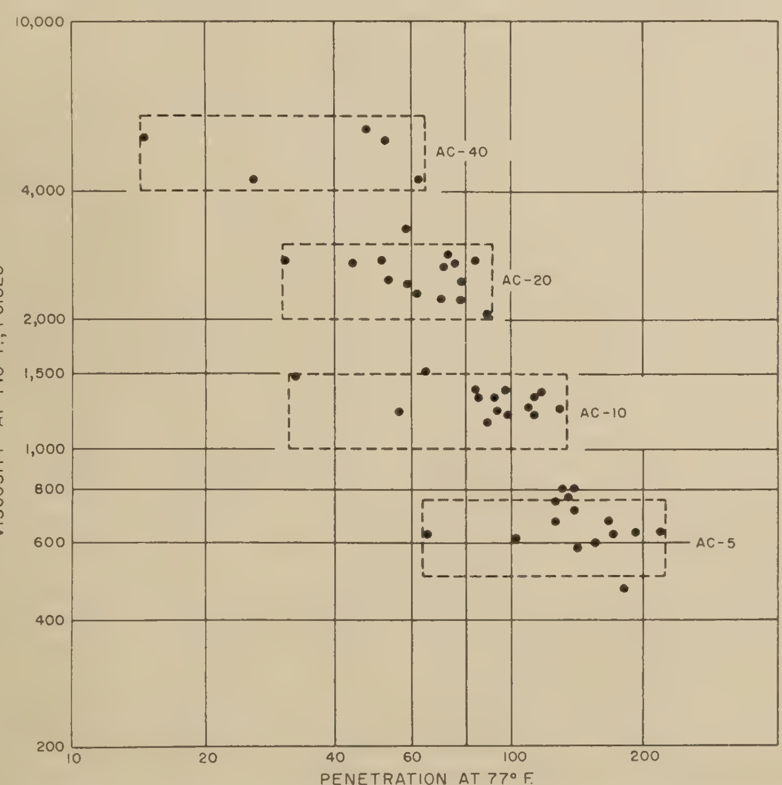

Figure 2.—Results of viscosity tests at 140° F. and penetration at 77° F. for the four viscosity graded asphalt cements.

Table 3.—Precision of viscosity test methods

Method or instrument	Repeatability,[1] 95-percent confidence level	Reproducibility,[2] 95-percent confidence level
	Pct. of mean	*Pct. of mean*
ASTM D-2170-63T	1.8	8.8
ASTM D-2171-63T	7	10
Microviscometer [3]	13	26
Controlled shear rate [4]	8	

[1] Duplicate results obtained by the same operator.
[2] Single results from each of two laboratories.
[3] At 0.05 sec.$^{-1}$ shear rate. 77° F.
[4] Pooled data from table 2, 0.1 to 0.001 sec.$^{-1}$ shear rate, 60° F.

tests consisted of five replicate determinations made on different days by one operator on six of the asphalts selected to obtain three different levels of viscosity and three different levels of shear susceptibility. A statistical summary of the test results is given in table 2. For comparison, table 3 contains lists of the precisions for the four viscosity methods used in the study reported here. The test data are given in terms of the percentage of the average of two tests, and they reflect the manner of expressing test method precision used by the ASTM Committee D-4, namely, the maximum difference between two test results that may be expected at the 95-percent confidence level.

The precision for repeatability of the method, when controlled shear rates were used, was 8 percent and this is comparable to the precision obtained for the absolute viscosity method, ASTM D-2171-63T. However, this precision was based on tests made in one laboratory and may differ from that based on interlaboratory tests. Further work is needed to establish both repeatability and reproducibility for the low temperature tests involving the sliding plate and possibly other methods. Further work also is needed to develop more rapid methods. Results obtained late in the study reported in this article show that comparable results were obtained when the time of room conditioning was reduced from 1 to 1½ hours to 15 minutes and the time of bath conditioning was reduced from 25 minutes to 15 minutes, thus reducing total time of preparation and testing from 2 hours to 1 hour.

Test Results

The test results on the viscosity-graded asphalts are given in tables 4, 5, and 6. Two identification numbers are given, an asphalt code number and the corresponding Bureau of Public Roads laboratory number. The asphalt code number consists of a letter followed by a number. The letter serves to identify the refinery and the number identifies the viscosity grade. The laboratory number provides sample identification for other investigators and the cooperators who have included these asphalts in their studies.

Viscosity

In figure 1 the range and distribution of the viscosity data are summarized within each of the four study specification grades at the two test temperatures specified and at 60° F. and 0.05 sec.$^{-1}$ rate of shear. The boxes formed

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Table 4.—Characteristics of viscosity-graded asphalt cements

Asphalt code number	BPR laboratory number	Viscosity		Penetration 100 g., 5 sec.			Ductility				Specific gravity, 77°/77° F.	Flash point	
							1 cm./min.	5 cm./min.					
		140° F.	275° F.	45° F.	60° F.	77° F.	45° F.	45° F.	60° F.	77° F.		C.O.C.[2]	P-M.[3]
		Poises	*Centistokes*				*Cm.*	*Cm.*	*Cm.*	*Cm.*		*° F.*	*° F.*
A-5	B-2908	754	257	17	42	125	126	31	215	130	1.004	600	500
B-5	B-2920	773	289	12	40	134	150+	31	250+	181	1.001	670	415
C-5	B-2958	662	264	32	68	180	150+	116	225	148	1.023	505	515
D-5	B-2962	642	231	28	70	192	150+	150+	250+	155	1.010	540	515
E-5	B-2974	627	246	6	16	64	3.5	3	16	152	0.999	645	345
F-5	B-3008	602	247	19	46	154	150+	59	250+	139	0.991	670	520
G-5	B-3012	669	282	22	60	175	150+	150+	250+	177	1.018	610	555
H-5	B-3028	459	195	26	65	191	171	71	250+	151	1.011	575	515
I-5	B-3037	586	240	13	40	139	175+	179	250+	172	1.022	640	585
J-5	B-3050	636	267	30	75	216	150+	150+	250+	154	1.021	460	460
K-5	B-3054	610	215	10	30	101	21	6	129	163	1.008	515	310
L-5	B-3058	632	267	23	58	169	150+	150+	250+	140	1.021	550	465
M-5	B-3108	791	238	15	43	136	175+	244	250+	167	1.011	515	460
N-5	B-3578	719	181	16	42	137	175+	150+	250+	205	1.015	465	455
O-5	B-3601	674	160	11	35	125	250+	250+	250+	171	1.011	580	525
A-10	B-2909	1,367	335	14	30	83	39	9	192	221	1.007	610	520
B-10	B-2921	1,152	339	11	28	88	29	8	243	250+	1.004	680	420
C-10	B-2959	1,352	401	20	45	115	116	22	177	157	1.031	530	485
D-10	B-2963	1,227	315	18	43	114	150+	150+	250+	250+	1.015	570	545
E-10	B-2975	1,484	355	4	9	32	(1)	(1)	5	215	1.005	670	605
F-10	B-3009	1,361	367	15	36	96	33	12	170	230	0.994	660	560
G-10	B-3013	1,209	376	15	37	112	150+	150+	250+	245	1.021	600	525
H-10	B-3029	1,208	309	14	35	97	91	16	250+	190	1.022	590	500
I-10	B-3036	1,268	333	9	26	84	141	11	250+	210	1.026	650	460
J-10	B-3051	1,255	374	18	46	128	150+	124	250+	210	1.028	480	455
K-10	B-3055	1,233	302	6	15	55	6	3	32	206	1.016	530	500
L-10	B-3099	1,257	362	16	39	108	84	33	250+	200	1.025	565	480
M-10	B-3109	1,317	322	10	28	91	175+	19	250+	250+	1.014	535	455
N-10	B-3579	1,208	227	10	27	94	250+	150+	250+	245	1.016	510	455
O-10	B-3602	1,529	233	5	18	64	250+	12	250+	250+	1.016	580	535
A-20	B-2910	2,340	417	10	22	61	9	9	47	210	1.012	600	510
B-20	B-2922	2,497	464	6	16	52	6	(1)	17	250+	1.007	655	430
C-20	B-2960	2,060	482	14	32	87	62	11	161	160	1.034	560	505
D-20	B-2964	2,696	452	10	25	70	175+	10	250+	241	1.021	590	555
F-20	B-3010	2,861	490	12	27	72	10	7	24	205	0.995	635	580
G-20	B-3014	2,261	506	11	26	76	175+	14	250+	250+	1.025	625	515
H-20	B-3030	3,286	467	8	20	57	11	5	88	250+	1.028	570	490
I-20	B-3035	2,786	606	6	16	50	8	4.5	250+	250+	1.034	640	475
J-20	B-3052	2,743	534	11	28	82	118	18	250+	250+	1.033	495	470
K-20	B-3056	2,684	430	3	11	30	3.5	3	10	250+	1.020	545	515
L-20	B-3060	2,741	513	12	27	74	45	8	250+	250+	1.030	585	480
M-20	B-3110	2,261	401	8	23	69	120	9	250+	250+	1.018	535	485
N-20	B-3580	2,461	314	6	16	57	243	4	250+	250+	1.022	490	470
O-20	B-3603	2,729	301	4	12	43	72	(1)	250+	250+	1.021	585	505
P-20	B 3039	2,485	442	12	30	77	11	7	47	250+	1.004	635	450
J-40	B-3053	5,266	745	7	20	51	13	6.5	193	250+	1.035	510	480
K-40	B-3057	5,217	574	2	6	14	(1)	(1)	3	231	1.025	570	515
L-40	B-3061	5,537	742	6	17	46	8	5	58	250+	1.038	615	485
O-40	B-3604	4,286	353	2	7	25	(1)	(1)	35	250+	1.025	620	555
P-40	B-3040	4,286	567	10	23	60	7	4	18	230	1.006	665	515

[1] Fracture.
[2] Cleveland open cup test.
[3] Pensky-Martens test.

by the solid lines show the ranges in viscosities for each grade. The dots within the boxes represent the viscosities obtained for each asphalt and show the distribution of results obtained for each viscosity grade. The broken line boxes show the study specification requirements at 140° and 275° F. for each grade. The figure shows that viscosity test results outside the study specification limits at 140° F. were obtained on 6 of the 50 asphalts: 5 results exceeded the maximum limits and one was below the minimum limit. Some of the asphalts furnished for the study represented special production and the noncompliance with specification limits may not be typical of regular production. However, caution should be used in adjusting specification limits so that production and testing variability and the criticalness of the requirements in use and performance will be recognized. The Bureau of Public Roads is concerned about such adjustments and has recommended that, when possible, specification requirements be based on targets having optimum tolerances. For example, viscosity requirements comparable to those in the study specifications would be specified as 600±150, 1,200±300, 2,400±600, and 4,800±1,200. This would provide a general recognition that materials should be furnished in the center of the grades and also would provide a better basis for statistical evaluation.

Also, figure 1 data show that test results for viscosity at 275° F. were above the minimum specified for each grade, except for asphalt sample O-40. The results for other grades from the same source, as well as those from producer N were near the minimum requirement. The location of viscosity results at 275° F. for the different grades of asphalt from the same source show that more attention should be given to setting the viscosity limits to account for a change in grade of asphalt. For example, the viscosity of asphalt O-40 is below the minimum limit; the vis cosity of asphalt O-20 is slightly above th minimum limit, and the viscosities of asphalts O-10 and O-5 are appreciably above th minimum limit. Setting limits for other re quirements applicable to specifications for two or more asphalt grades also should be considered.

As shown by comparison of the ranges in viscosity at different temperatures in figure 1, on the basis of grading at 140° F., extensive overlapping occurred in the results obtained at 60° F. (0.05 sec.$^{-1}$ shear rate) and 275° F on asphalts of the four grades. As is wel known, overlapping of consistency measurements at temperatures other than the grading temperature also occurs in the penetration grading system presently in use. This overlapping is caused by the differences in temperature susceptibility of asphalts. In th temperature interval of 140° F. to 275° F. temperature susceptibilities ranged from abou −3.4 to −3.9 for the asphalts having th lowest susceptibility and the highest suscepti bility, respectively, within each grade. These results were determined from the Walther re lation, as follows:

Viscosity-temperature susceptibility

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

Where,

η_1 = Viscosity in centipoises at 275° F.
η_2 = Viscosity in centipoises at 140° F.
$T_1 = (275+459)$
$T_2 = (140+459)$

Previous studies have shown that asphalt supplied under the present penetration gradin system range in susceptibility from abou −3.1 to about −3.9, which is comparable t the range determined in the study for th viscosity-graded asphalts.

Within-grade uniformity

As indicated previously, one of the advan tages to be expected when grading aspha cements on the basis of absolute viscosity a 140° F. is that better uniformity in withi grade consistency would be obtained at con struction temperature than is now bein obtained by penetration grading at 77° F This expectation is a logical consequence o shifting the grading control point from 77° F to 140° F. That this expectation was reason able can be seen from an examination of th results in figure 1 showing about a twofol spread in within-grade viscosity at 275° F This is less than the threefold spread previous tests for penetration graded asphal (*5*).

Penetration for Viscosity-Graded Asphalts

Much of the early work done to develo specifications based on viscosity grading a 140° F. was concerned with the effect of suc a system on penetration (*2*). Accordingl estimates were made of the ranges in pen tration at 77° F. that could be expected b specifying asphalt cements by viscosity a

0° F. with no other requirements to control mperature susceptibility. These estimates ere based on extrapolations that assumed a raight line relation between viscosity and mperature over the full 77° F. to 275° F. nge on Walther charts and slopes of −3.1 d −3.9 for the lowest and highest susceptilities. The penetration ranges estimated on is basis for the AC-5, AC-10, AC-20, and C-40 asphalt grades were 140 to 400, 87 to 0, 60 to 150, and 34 to 85. As shown in gure 2 and table 4 penetration at 77° F. nged from 64 to 216, 32 to 128, 30 to 93, d 14 to 60 for the asphalts included in the ur grades used for the study reported here. hese results are appreciably lower than had en estimated.

One reason for the discrepancy between the netrations actually obtained and those iginally estimated can be seen in figure 3, hich shows plots of the viscosity data for ur asphalts on a Walther-type chart over e temperature range 39.2° F. to 275° F. hese asphalts were selected because they present the extremes in viscosity below ° F. at 0.05 sec.⁻¹ for the AC-5 and AC-10 ades. None of the four asphalts produced a raight line over the full temperature range vered and the curves show distinct deirture from linearity in the 39.2° to 77° F. mperature range. The actual curves at e lower temperatures are above the projecon of the straight lines drawn between the 75° F. and the 140° F. points. This deirture, or offset, occurred in most of the phalts and the amount of offset varied acording to the asphalt in relation to its source. metimes, such as for the J asphalts marked figure 3, the offset was relatively slight. or a few asphalts, such as the E asphalts, the fset was comparatively large. For other sphalts the amount of offset was somewhere etween these extremes. Changes in rheogical responses in this area have been noted y other investigators (*8*, *9*) on penetrationraded asphalts. They theorized that the oftening point is a region of transition where sphalts change rapidly in physical structure, hich causes changes in the asphalts temerature susceptibility and rheological aracter.

In previous discussion (*2*) of the feasibility f using viscosity at 140° F. for grading sphalt cements, it was pointed out that the esult of control at one temperature could ossibly be greater differences between maerials of the same grade than occur with use f the present penetration grading and conols. It was also indicated that control at wo or more temperatures should be considered efore viscosity grading is adopted. The nge in results shown in figure 1 for viscosity t 60° F. supports these contentions. The anges in viscosity for each grade are extremely rge at this temperature and it is evident that w temperature requirements are necessary. However, continued research is necessary to stablish the optimum limits for such a requireent. These should be based on fundamental roperties of mixtures and closely related to erformance in layered pavement systems, cluding the effects of aging.

Table 5.—Characteristics of residues from thin-film oven test

Asphalt code number	Change in weight	Tests on residue: Penetration, 77° F.	Ductility, 5 cm./min.: 77° F.	Ductility, 5 cm./min.: 60° F.	Viscosity: 140° F.	Viscosity: 275° F.	Viscosity at 60° F., at shear rates of—: 0.001 sec.⁻¹	0.005 sec.⁻¹	0.01 sec.⁻¹	0.05 sec.⁻¹	0.10 sec.⁻¹	Retained penetration	Viscosity ratio at 140° F.	Viscosity ratio at 275° F.	Shear susceptibility, 60° F.[1]
	Pct.		*Cm.*	*Cm.*	*Poises*	*Centistokes*	*Megapoises*	*Megapoises*	*Megapoises*	*Megapoises*	*Megapoises*	*Pct.*			
A-5	+0.02	74	185	50	1,943	371	28	28	27	18	14	59.2	2.58	1.44	0.27
B-5	−.06	77	216	63	1,743	390	21	21	21	15	13	55.2	2.25	1.35	.21
C-5	−.17	101	220	35	1,882	405	18	18	12	11	10	56.1	2.84	1.53	.23
D-5	−.03	112	220+	250+	1,508	334	15	13	12	9	8	58.3	2.35	1.45	.15
E-5	−.09	38	68	4	1,709	347	320	180	127	56	39	59.4	2.73	1.41	.51
F-5	+.12	90	230	73	1,504	347	17	17	16	11	10	58.4	2.50	1.40	.25
G-5	+.10	108	228	243	1,157	353	10	10	10	8	7.5	65.1	1.73	1.25	.13
H-5	−.05	92	225	85	1,532	316	27	27	24	18	15	48.2	3.34	1.62	.22
I-5	+.07	96	250+	250+	1,027	301	12	12	12	11	11	69.1	1.75	1.25	.02
J-5	−.79	103	225+	140	2,212	474	8	8.0	7.6	6.7	6.3	47.7	3.48	1.78	.08
K-5	−.29	54	193	13	1,514	297	92	69	57	33	26	53.5	2.48	1.38	.34
L-5	−.22	115	220+	141	1,443	368	12	12	11	9	8	68.0	2.28	1.38	.12
M-5	−.57	74	234	168	2,092	364	30	30	28	22	19	54.4	2.64	1.53	.17
N-5	−.87	72	250+	250+	1,904	293	44	39	37	32	30	52.6	2.65	1.62	.09
O-5	+.07	94	250+	250+	999	191	11	11	11	11	11	75.2	1.48	1.19	.00
A-10	+.01	51	201	11	3,908	497	84	73	63	35	27	61.4	2.86	1.48	.37
B-10	−.11	54	250+	19	3,054	506	75	61	51	30	24	61.4	2.65	1.49	.32
C-10	−.22	70	170	23	4,039	634	35	34	32	21	17	60.9	2.99	1.58	.28
D-10	+.04	71	250+	94	3,135	465	33	29	26	19	16	62.3	2.56	1.48	.21
E-10	+.10	23	24	3	3,735	490	1,140	520	353	141	95	70.8	2.52	1.38	.57
F-10	+.10	61	213	10	4,089	508	48	44	38	23	17	63.5	3.00	1.38	.36
G-10	+.04	77	250+	191	2,316	493	25	25	25	20	18	68.8	1.92	1.31	.15
H-10	+.03	60	250+	15	3,497	463	58	56	50	30	24	61.9	2.89	1.50	.32
I-10	+.11	56	250+	118	2,360	441	37	37	36	29	27	66.3	1.86	1.32	.14
J-10	−.69	75	220+	61	3,826	634	32	30	27	21	18	58.6	3.05	1.70	.17
K-10	−.12	35	180	7	2,568	397	206	161	130	67	50	63.6	2.08	1.31	.42
L-10	−.15	70	250+	32	2,954	509	36	35	32	22	19	64.8	2.35	1.41	.24
M-10	−.31	55	250+	52	3,397	486	59	58	53	37	32	60.4	2.58	1.51	.22
N-10	−.68	53	250+	250+	2,971	350	50	50	48	42	39	56.4	2.46	1.54	.09
O-10	+.08	51	250+	250+	2,235	275	41	41	40	38	37	79.7	1.46	1.18	.04
A-20	−.02	39	148	6	7,047	640	176	138	106	55	42	63.9	3.01	1.77	.40
B-20	−.05	34	156	6	7,038	678	285	182	136	69	52	65.4	2.82	1.46	.42
C-20	−.11	56	159	15	5,479	749	75	62	53	32	26	64.4	2.66	1.55	.31
D-20	+.09	47	250+	35	6,311	649	71	67	62	37	29	67.1	2.34	1.44	.36
F-20	+.12	50	102	8	9,293	735	95	68	55	29	22	69.4	3.25	1.50	.41
G-20	−.01	53	250+	61	4,331	671	50	50	47	36	32	69.7	1.92	1.33	.17
H-20	.00	37	168	8	9,703	750	182	143	113	56	41	64.9	2.95	1.61	.46
I-20	+.11	33	225+	21	5,404	624	140	131	117	68	58	66.0	1.94	1.03	.31
J-20	−.51	50	250+	29	7,853	903	63	60	54	37	31	61.0	2.86	1.69	.25
K-20	−.05	24	137	4	5,300	564	590	359	265	115	82	80.0	1.97	1.31	.51
L-20	−.12	45	250	13	7,153	750	94	86	74	43	34	60.8	2.61	1.46	.33
M-20	−.24	41	213	21	6,424	637	108	102	88	57	47	59.4	2.84	1.59	.28
N-20	−.45	32	250+	150	5,627	479	115	115	113	84	70	56.1	2.29	1.53	.25
O-20	+.08	32	250+	37	4,210	365	170	170	168	115	95	74.4	1.54	1.21	.28
P-20	−.04	49	73	8	11,046	812	122	84	66	34	25	63.6	4.45	1.84	.42
J-40	−.46	29	119	7	16,143	1,278	135	123	107	63	50	56.9	3.07	1.72	.33
K-40	−.07	9	49	0	10,451	761	1,530	780	535	210	139	64.3	2.00	1.33	.59
L-40	−.06	28	250+	6	14,539	1,055	277	185	146	81	63	60.9	2.63	1.42	.37
O-40	+.09	19	250+	0	5,786	515	400	390	342	205	157	76.0	1.35	1.46	.40
P-40	+.06	43	72	6	14,267	900	182	120	90	41	30	71.7	3.33	1.59	.48

[1] Tangent of viscosity—rate of shear curve between 0.05 $sec.^{-1}$ and 0.10 $sec.^{-1}$

Limiting Viscosity

Other researchers have used limiting or initial viscosity in studying the rheological behavior of asphalts. This is the viscosity obtained when the material is behaving in a Newtonian fashion and is independent of the rate of shear. It occurs in asphalts at low shear stresses or low rates of shear and the viscosities obtained are higher than those in the shear-dependent or non-Newtonian region. Limiting viscosity was determined for all of the asphalts included in the study reported here and are given in table 7. The viscosity-temperature relations are shown in figure 4 for the same asphalts as those depicted in figure 3, but limiting viscosity rather than apparent viscosity at 0.05 $sec.^{-1}$ shear rate is plotted against temperature on a Walther-type chart. Comparison of data in figures 3 and 4 will show the difference between limiting viscosity and viscosity determined in the shear-dependent region. The curves in figure 4 are straighter and the asphalt viscosities are higher than shown by curves in figure 3.

To explore the low temperature properties of the asphalts the limiting viscosities were plotted using the ordinates of log viscosity in poises and temperature in degrees Fahrenheit. This relation for AC-10 grade asphalts is represented by essentially straight lines in figure 5. Similar relations existed for the other grades. Recognizing that the temperature range of 39.2° to 60° F. is relatively narrow, these relations are possibilities that should be considered in further evaluation of both the level of viscosity and temperature susceptibility of asphalt.

Viscosity Data Reduced to Master Curves

Because the microviscometer and the controlled rate of shear viscometer were used to determine viscosities at the temperatures below 140° F., study was made to determine whether the two instruments gave concordant results and also to indicate the general rheological character of the asphalts as affected by temperature and shear rate. The asphalts selected for the special study were A-5, E-5, B-10, and I-10. The viscosity results obtained at different rates of shear at test temperatures of 39.2°, 45°, 60°, 77°, 100°, and 120° F. are given in table 8.

All four asphalts produced flow diagrams as illustrated in figure 6 for asphalt A-5. The curves are similar to those obtained by Brodnyan (*10*) with penetration-graded asphalts and subsequently by others. It is interesting that the curves approach zero slope at the lower shear rates. As mentioned before, viscosity in this area is the limiting viscosity and it is independent of rate of shear. Curves for each of the four asphalts were superposed by the method described in reference (*11*) to a single master curve at a reference temperature of 60° F., as shown in figure 7. The amount of horizontal shifts (a_T) required to effect the smooth, reduced curves shown in the figure are given in table 9 and shown in figure 8. As will be noted, these factors permit obtaining viscosity at a single temperature over a much wider range of shear rates, approximately 6 decades in figure 7, than is now practicable with present viscometers. Furthermore the factors are considered (*10*) to be an indication of the temperature dependence of limiting viscosity and, as such, are useful in comparing asphalts as to temperature susceptibility.

The close conformance of the data points to the master curves in figure 7 indicates that the viscosities measured by the controlled shear rate viscometer at 39.2°, 45°, and 60° F. are substantially in agreement with those measured by the standard microviscometer at 77° and 100° F. The general shape of the curves also indicates that at these test temperatures the viscosity-graded asphalts appear to be similar, but the level of viscosity and the influence of this difference on the rheological properties of paving mixtures before and after aging needs further study.

Table 6.—Viscosity at different rates of shear and temperatures

Asphalt code number	Viscosity, megapoises at shear rate and temperature of—																	Shear susceptibility [1] at temperatures of—		
	0.1 sec.$^{-1}$			0.05 sec.$^{-1}$				0.01 sec.$^{-1}$			0.005 sec.$^{-1}$			0.001 sec.$^{-1}$					
	39.2° F.	45° F.	60° F.	39.2° F.	45° F.	60° F.	77° F.	39.2° F.	45 F.	60° F.	39.2° F.	45° F.	60° F.	39.2° F.	45° F.	60° F.	39.2° F.	45° F.	60° F.
A-5	68	38	6.4	87	45	6.7	0.46	153	67	7.6	196	79	8.0	250	96	[2] 9.0	0.36	0.25	0.08
B-5	62	46	7.2	84	56	8.0	.81	171	91	9.7	209	111	[2] 9.7	343	147	[2] 9.7	.44	.30	.14
C-5	25	18	2.5	31	21	2.6	.48	49	30	3.0	56	30	[2] 3.2	64	30	[2] 3.6	.29	.26	.08
D-5	26	17	2.5	30	19	2.5	.36	42	26	2.5	46	28	[2] 2.5	51	[2] 32	[2] 2.5	.21	.18	.00
E-5	197	129	33.9	298	184	44.0	3.50	775	414	82.5	1,180	585	103.0	3,100	1,300	137.0	.59	.50	.39
F-5	37	23	4.2	52	29	4.5	1.12	103	51	5.5	131	60	[2] 6.0	177	[2] 62	[2] 7.4	.47	.35	.12
G-5	37	23	2.8	45	25	2.8	.32	68	27	2.9	70	27	[2] 2.9	70	[2] 27	[2] 3.0	.28	.11	.02
H-5	30	14	2.4	37	18	2.8	.52	60	27	3.0	70	29	[2] 3.0	70	29	[2] 3.0	.30	.29	.23
I-5	79	48	6.2	102	54	6.5	.49	166	76	7.0	194	82	7.0	232	86	7.0	.34	.23	.06
J-5	33	16	2.2	40	18	2.2	.29	56	22	2.3	60	25	[2] 2.3	[2] 64	26	[2] 2.3	.24	.15	.04
K-5	92	72	14.0	130	96	16.8	.87	290	195	25.5	410	264	28.0	700	410	29.5	.50	.43	.27
L-5	28	21	3.1	35	23	3.1	.32	50	28	3.1	54	30	[2] 3.1	[2] 65	30	[2] 3.1	.31	.12	.00
M-5	70	40	5.5	82	46	5.6	.57	119	62	6.0	142	66	6.2	150	66	[2] 6.4	.23	.19	.04
N-5	90	42	4.8	105	48	4.8	.42	146	58	4.8	146	58	[2] 4.8	146	58	[2] 4.8	.21	.15	.00
O-5	126	67	5.3	153	74	5.3	.46	239	80	5.3	239	80	[2] 5.3	239	80	[2] 5.3	.29	.16	.00
A-10	100	58	14.4	130	74	16.0	1.49	247	134	20.2	323	170	21.5	540	227	[2] 22.3	.39	.36	.16
B-10	141	78	13.1	188	99	15.1	.96	370	174	19.2	495	215	19.4	920	250	[2] 20.0	.42	.35	.25
C-10	47	30	7.6	59	35	8.1	1.08	99	54	9.2	120	60	9.8	148	73	[2] 11.0	.32	.26	.08
D-10	62	36	6.4	78	42	6.5	.75	129	57	6.8	147	60	7.0	170	65	[2] 7.2	.31	.21	.02
E-10	310	268	78.0	487	360	109.0	13.5	1,400	990	237.0	2,200	1,530	330.0	5,770	3,850	625.0	.66	.63	.48
F-10	79	42	11.0	103	54	12.7	1.58	203	96	17.8	272	124	19.7	385	180	[2] 22.2	.41	.36	.21
G-10	81	44	7.5	106	50	7.5	.95	161	65	7.5	181	70	7.5	217	82	[2] 7.5	.32	.17	.00
H-10	88	52	11.1	105	65	12.7	1.14	230	112	13.4	310	137	13.8	470	174	[2] 14.7	.43	.34	.19
I-10	161	94	12.7	215	117	13.8	1.35	412	186	14.5	545	215	15.0	770	250	[1] 15.8	.42	.29	.09
J-10	56	33	6.4	68	37	6.4	.72	103	46	6.4	123	49	[2] 6.4	145	50	[2] 6.4	.18	.15	.00
K-10	188	113	28.4	293	165	36.5	4.08	815	395	63.0	1,270	575	73.5	3,100	1,080	90.0	.64	.54	.35
L-10	66	42	8.4	85	52	9.1	1.08	147	85	12.0	186	94	13.3	220	94	[2] 13.3	.34	.30	.14
M-10	101	68	13.7	135	90	14.7	1.53	267	150	17.7	327	183	18.6	395	215	[2] 19.0	.43	.35	.11
N-10	155	86	10.5	203	94	10.8	.95	333	109	12.0	360	109	12.6	380	109	[2] 13.0	.40	.14	.06
O-10	243	150	21.5	341	190	21.5	1.58	715	293	21.5	849	305	21.5	950	314	[2] 21.5	.50	.36	.00
A-20	124	70	17.7	177	101	21.5	3.40	400	233	32.2	560	317	35.0	975	405	[2] 35.0	.51	.53	.28
B-20	204	133	28.8	313	190	36.0	6.99	860	435	57.5	1,250	625	67.0	2,740	1,225	69.7	.62	.51	.33
C-20	79	44	9.3	106	57	10.5	1.41	209	101	13.1	272	123	13.5	419	153	[2] 13.7	.42	.37	.16
D-20	117	84	18.4	158	112	20.6	2.25	320	210	26.0	423	255	27.3	630	295	[2] 28.5	.44	.40	.16
F-20	90	44	14.8	127	62	18.5	2.49	278	132	30.6	385	183	36.1	760	345	38.0	.49	.47	.38
G-20	133	68	12.4	176	90	13.0	2.14	325	158	14.2	425	179	15.0	630	200	[2] 16.9	.39	.39	.07
H-20	148	93	21.9	220	131	27.2	3.68	555	283	42.0	780	363	46.1	1,620	600	[2] 48.0	.58	.49	.31
I-20	217	160	33.5	330	219	41.0	6.20	850	460	58.1	1,210	595	63.0	2,190	870	[2] 67.0	.59	.46	.28
J-20	108	67	11.2	143	86	12.1	1.73	287	143	14.3	360	168	15.0	460	202	[2] 15.4	.42	.35	.14
K-20	[2] 320	262	57.5	[2] 495	394	82.0	12.5	1,400	1,025	185.0	2,170	1,550	233.0	6,150	3,460	300.0	.64	.59	.50
L-20	110	73	18.9	149	94	23.8	2.93	300	185	30.1	387	232	32.4	465	238	[2] 32.7	.44	.41	.20
M-20	117	82	16.4	181	110	18.3	3.22	430	213	24.0	575	277	26.4	860	340	[2] 26.5	.54	.41	.17
N-20	273	160	34.6	375	200	36.0	2.52	775	320	38.5	1,040	339	39.8	1,300	350	[2] 41.5	.45	.31	.05
O-20	342	267	57.0	535	375	57.3	3.90	1,470	800	57.8	2,040	1,000	58.0	3,000	1,180	58.7	.65	.49	.01
P-20	89	45	14.7	126	62	17.7	3.18	282	136	27.9	400	178	33.7	700	280	[2] 44.0	.50	.48	.28
J-40	171	100	24.0	238	133	26.7	4.36	520	257	34.5	690	317	37.5	1,120	400	42.0	.48	.42	.16
K-40	426	297	96.0	710	505	138.0	27.7	2,279	1,630	323.0	3,571	2,700	435.0	10,445	6,900	690.0	.73	.73	.53
L-40	180	120	28.7	269	165	36.2	7.25	650	344	58.0	920	460	63.5	1,700	695	65.0	.56	.46	.32
O-40	[2] 500	365	125.0	[2] 890	520	154.0	12.4	1,640	1,170	217.0	2,000	1,650	217.0	2,740	2,600	220.0	.60	.51	.35
P-40	105	77	21.6	153	107	28.2	3.15	372	230	51.2	550	322	62.0	1,090	670	79.0	.55	.48	.46

[1] Tangent of viscosity—rate of shear curve between 0.05 sec.$^{-1}$ and 0.1 sec.$^{-1}$.
[2] Values obtained by extrapolation from viscosity—rate of shear curve.

Relation of Viscosity and Empirical Tests

The primary interest in studying the use of fundamental properties of asphalts is to determine whether they can be related to the fundamental properties of paving mixtures and whether they will ultimately provide a better basis for improved specifications. Also, of interest is a comparison of the results of fundamental properties to the characteristics measured by conventional empirical methods. So a part of the study reported here was devoted to examining the relation of viscosity data to penetration, ductility, and durability.

Penetration

The relation of penetration to viscosity detailed in tables 4 and 6, at 60° and 77° F., is shown in figures 9 and 10, respectively. As shown in the figures, good correlations of penetration and viscosity were obtained at

Table 7.—Limiting viscosities of asphalt cements, by viscosity grades

Asphalt code	Limiting viscosities, megapoises											
	AC-5			AC-10			AC-20			AC-40		
	39.2° F.	45° F.	60° F.	39.2° F.	34° F.	60° F.	39.2° F.	45° F.	60° F.	39.2° F.	45° F.	60° F.
A	250	97.0	9.50	[1] 625	240	23.0	[1] 1,300	[1] 510	35.0	-------	-------	-------
B	[1] 400	150	9.70	[1] 730	250	20.0	[1] 3,900	[1] 1,250	69.0	-------	-------	-------
C	64.0	30.5	4.00	150	77.0	11.3	[1] 435	153	13.6	-------	-------	-------
D	54.0	34.0	2.50	170	67.0	7.40	650	290	28.6	-------	-------	-------
E	[1] 15,000	[1] 4,400	137	[1] 36,000	[1] 12,000	[1] 860	-------	-------	-------	-------	-------	-------
F	180	62.0	4.30	[1] 450	[1] 210	23.0	[1] 940	[1] 360	38.0	-------	-------	-------
G	70.0	27.0	3.00	225	87.0	7.50	630	210	17.5	-------	-------	-------
H	70.0	29.0	3.00	[1] 500	175	15.0	[1] 2,100	[1] 630	48.5	-------	-------	---
I	235	85.0	7.00	[1] 800	250	16.0	[1] 2,700	[1] 920	67.0	-------	-------	---
J	64.0	25.7	2.30	130	50.5	5.50	470	202	15.5	[1] 1,160	420	42.0
K	[1] 1,090	[1] 410	30.0	[1] 4,000	[1] 1,220	[1] 93.0	[1] 15,000	[1] 4,500	[1] 310	[1] 21,400	[1] 8,200	[1] 720
L	70.0	29.5	3.15	222	93.6	12.0	470	238	33.0	[1] 2,150	[1] 730	64.0
M	155	66.0	6.80	520	215	19.2	900	350	26.5	-------	-------	---
N	146	60.0	4.93	380	130	13.1	1,290	450	41.5	-------	-------	---
O	239	80.0	5.32	950	315	22.0	[1] 3,200	1,200	58.7	[1] 6,500	[1] 2,700	240
P	-------	-------	-------	-------	-------	-------	[1] 700	[1] 360	[1] 45.0	[1] 2,600	[1] 1,020	[1] 79.5

[1] Values obtained by extrapolation from viscosity—rate of shear curve.

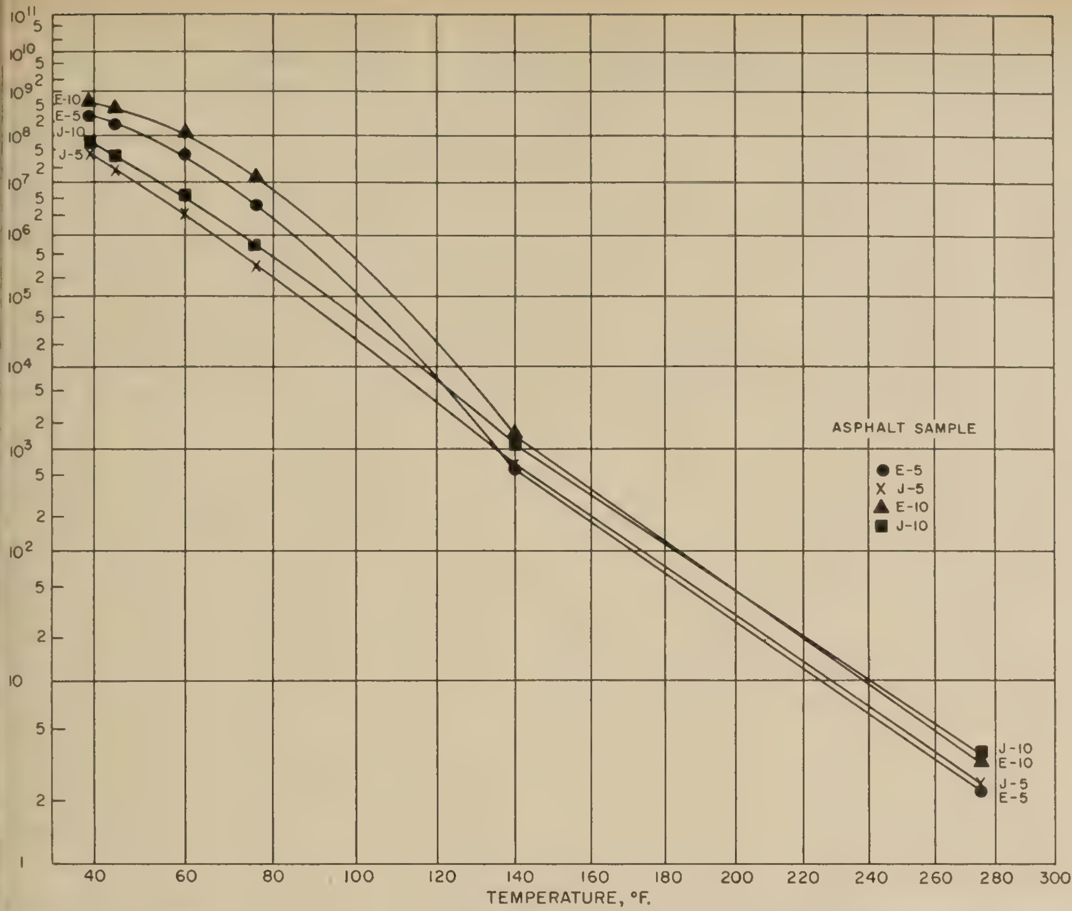


Figure 3.—Viscosity (0.05 sec.$^{-1}$ shear rate) and temperature relation for selected asphalt cements.

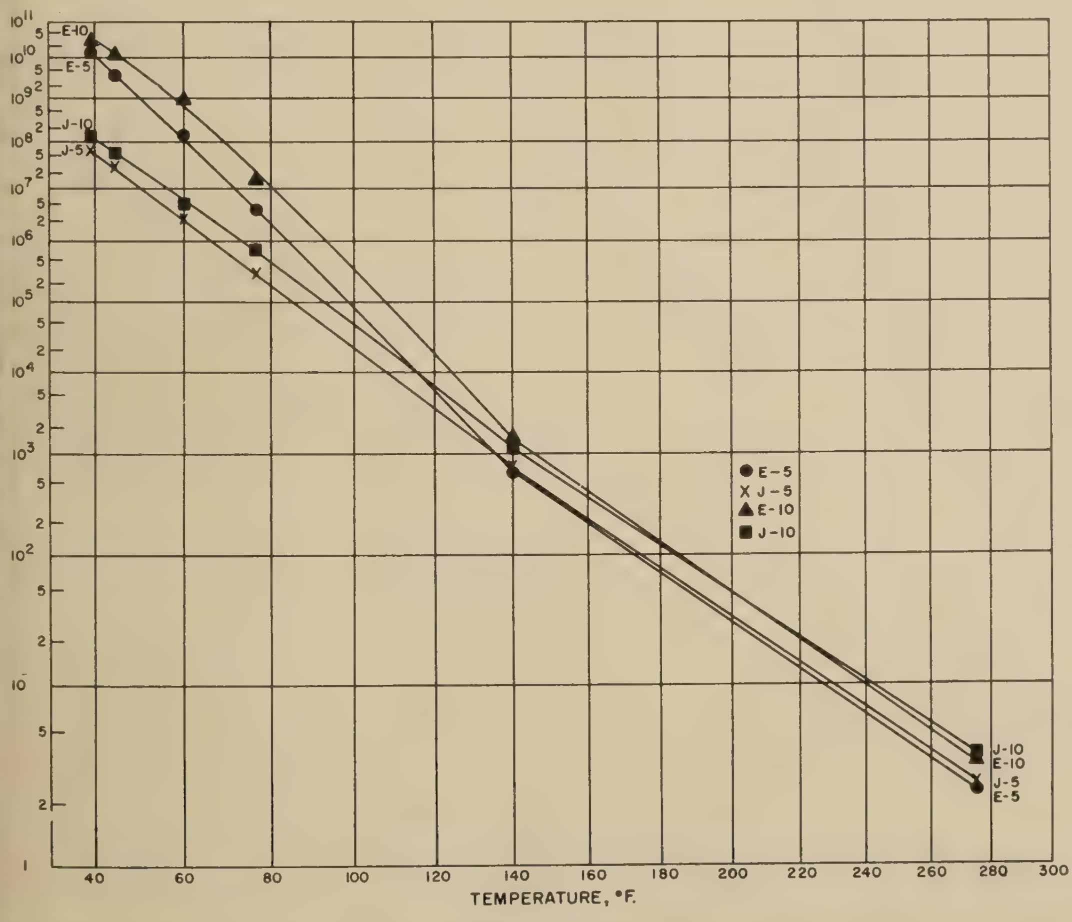


Figure 4.—Limiting viscosity and temperature relation for selected asphalt cements.

both test temperatures, but the correlation obtained at the 60° F. test temperature seems to have been somewhat better than that obtained at 77° F. The equations derived by the method of least squares for the relation between log viscosity and log penetration at each temperature are:

At 60° F.,

$$\text{log viscosity (megapoises)} = 3.54 - 1.67 \text{ log penetration.}$$

At 77° F.,

$$\text{log viscosity (megapoises)} = 3.86 - 1.89 \text{ log penetration.}$$

Ductility

The value of a ductility requirement in specifications for asphalts has been the subject of debate among asphalt technologists since its introduction in the early part of this century. Some technologists are of the opinion that ductility, under the present standard test method, is of little value as an indicator of asphalt quality. Others believe that the ductile properties of asphalt give an asphalt pavement its quality of flexibility—the ability to conform tc moderate deflections or changes in supporting layers without permanent cracking or disintegration. Some believe that ductility is related to stickiness or ability to adhere to aggregate and other surfaces. Regardless of the merits of the various arguments, some studies (*12, 13*) have related ductility to pavement performance.

The ductility requirements proposed in the study specifications were a minimum of 60 cm. at 60° F. for grade AC-5 and a minimum of 100 cm. at 77° F. for grades AC-10, AC-20, and AC-40, respectively. The results of ductility tests, table 4, at these temperatures show that, except for asphalt E-5, all asphalts were well above the proposed requirements for their respective grades. On the whole, these results are similar to the results obtained on penetration-graded asphalts (*4, 5*), thus indicating that viscosity grading did not materially affect ductility characteristics as measured by present specified standards for ductility at 77° F.

Inspection of the ductility results at temperatures of 45° F. for the AC-5 grade asphalts and at 45° and 60° F. for the other grades shows large differences for the asphalts from different sources. To explore what relations might exist between the viscosity data and ductility, several correlations were tried at 45° and 60° F. A good relation between ductility and viscosity existed among asphalts from the same source but none among asphalts from different sources. However, good correlations existed between ductility and shear susceptibility at 45° and 60° F. for all the asphalts tested, regardless of source. The equation derived by the method of least squares for the relation shown in figure 11 between log ductility and shear susceptibility at 60° F. is:

$$\text{log ductility} = 3.19 - 4.88 \text{ shear susceptibility}$$

The shear susceptibility values were calculated from the tangent drawn between 0.05

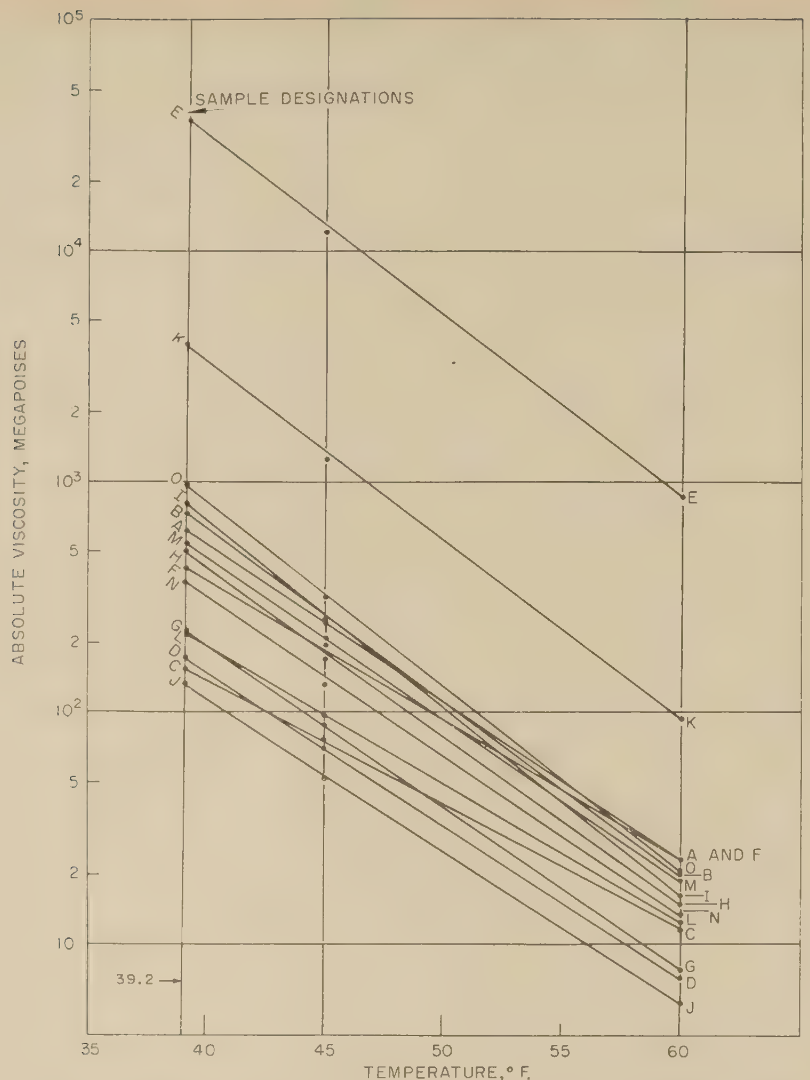


Figure 5.—Limiting viscosity of AC–10 viscosity graded asphalt cements at low temperatures.

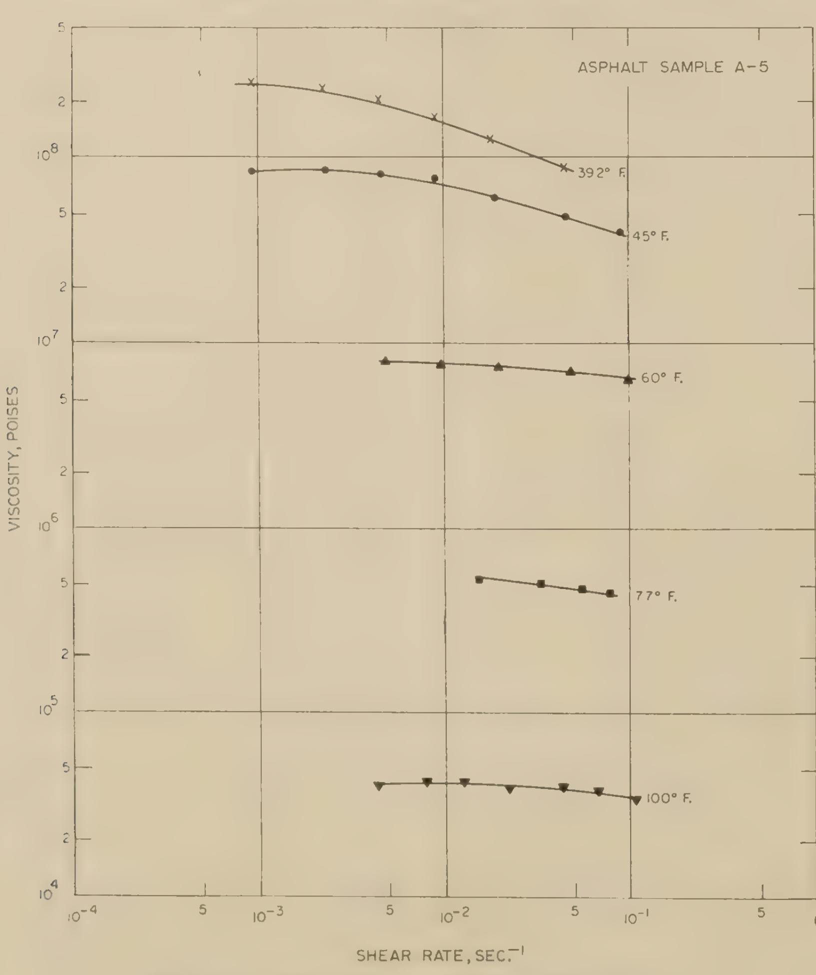


Figure 6.—Flow diagrams for asphalt A–5.

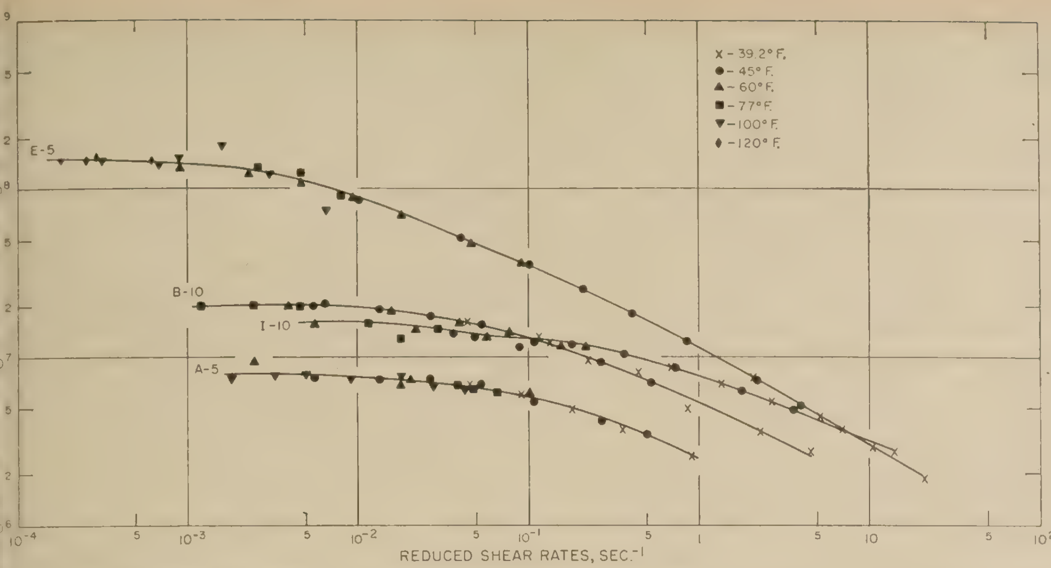
sec.$^{-1}$ and 0.10 sec.$^{-1}$ rates of shear on th viscosity-rate of shear curves obtained in th viscosity determinations. Except for aspha I-20, those asphalts having a ductility of mo than 150 cm. had shear susceptibilities le than 0.25. It is evident that this relatic between ductility and shear susceptibilit could provide a basis for using shear suscept bility rather than the present ductility r quirements and possibly could effect a economy in testing in viscosity-graded spec fications. The low temperature viscosit determination of shear susceptibility involvir a simple calculation could be obtained in th viscosity test.

Durability

Starting about 1955, many specificatio for asphalt cements incorporated requir ments for the thin-film oven test to provi more assurance of durability, particular resistance to hardening during hot mixing a in service. The thin-film oven test w proposed in the study specifications but viscosity ratio based on viscosities at 140° before and after heating was used in pla of the percent of retained penetration in t penetration grade specifications. The resul of the thin-film tests on the viscosity-grad asphalts are given in table 5. To provi additional information for comparative pu poses the tests made on the residues cover considerably more than was required in t study specifications.

The viscosity ratios at 140° F. were w under 5, the ratio proposed. Actually, ratios, except that shown for asphalt P-2, were less than 4. Also, all the asphalts we within the maxima specified for perce retained penetration in both the prese ASTM and AASHO specifications for aspha cements. This would indicate that, for t asphalts studied, the proposed maximu viscosity ratio at 140° F. was either unnec sarily liberal or that borderline materials we not included in the tests. The viscosity rat for asphalts of different grades from the sa source did not differ significantly. This is contrast to experience with penetration gra asphalts in which the percent retained pe tration usually decreases with an increase penetration.

Because the thin-film test had been d veloped and used on the basis of penetratic at 77° F., and the study proposal us viscosities at 140° F. as criteria, a determi tion was made as to whether the propos criteria were satisfactory or whether viscosit at different temperatures would provide better evaluation. Accordingly, viscosity tios at both 140° F. and 60° F. were plott against the percent of retained penetration 77° F. for each grade, as shown for the AC- asphalts in figure 12. The 60° F. viscos ratios are given at three different shear ra because at this temperature shear suscep bility could affect the results. The fig shows that good correlations were not tained. This result is in contrast to t correlation obtained between viscosity ra



ure 7.—Composite master curves for reduced shear and viscosity at reference temperature (T_o) of 60° F. (288.7 Kelvin) for selected asphalt cements.

retained penetration, both determined at F., for a selected group of 85–100 pene-ion grade asphalts (*14*). A control ...ed at some temperature, such as 60° or F. would provide a better correlation. ...s is another indication of the need for a low ...perature control.

...When the thin-film test was first proposed, ...ductility requirement for the residue was recommended because some asphalts showed an abnormally large loss in ductility during heating. As indicated previously, there is evidence that low ductility, caused by hardening occurring in hot mixing or in service, is associated with poor performance. Accordingly, Public Roads, AASHO, and many State specifications include a requirement for minimum ductility on the thin-film residue. However, the present ASTM specification and the proposed study specification do not include this requirement. The ductility characteristics of the thin-film residues of the asphalts are given in table 5.

Using the penetration of the original asphalt as a basis for comparison, the results at 77° F. show that the asphalts met the AASHO requirements for ductility of thin-film residue for the respective penetration grades. There is generally a substantial decrease in ductility at the 60° F. test temperature, and a specification requirement at this or a lower temperature might provide better criteria. No correlation was present between ductility and viscosity at 60° F. However, a relatively good correlation between ductility and shear susceptibility at 60° F. was obtained for all asphalts, as shown in figure 13. The equation derived by the method of least squares for the relation between log ductility and shear susceptibility of the thin-film residue at 60° F. is:

$$\text{log ductility} = 2.66 - 4.19 \text{ shear susceptibility}$$

This supports the previous finding on the original asphalts that shear susceptibility may be useful as a specification requirement in place of the ductility test. It is pointed out that each value for shear susceptibility and ductility used in this correlation was obtained by single determination.

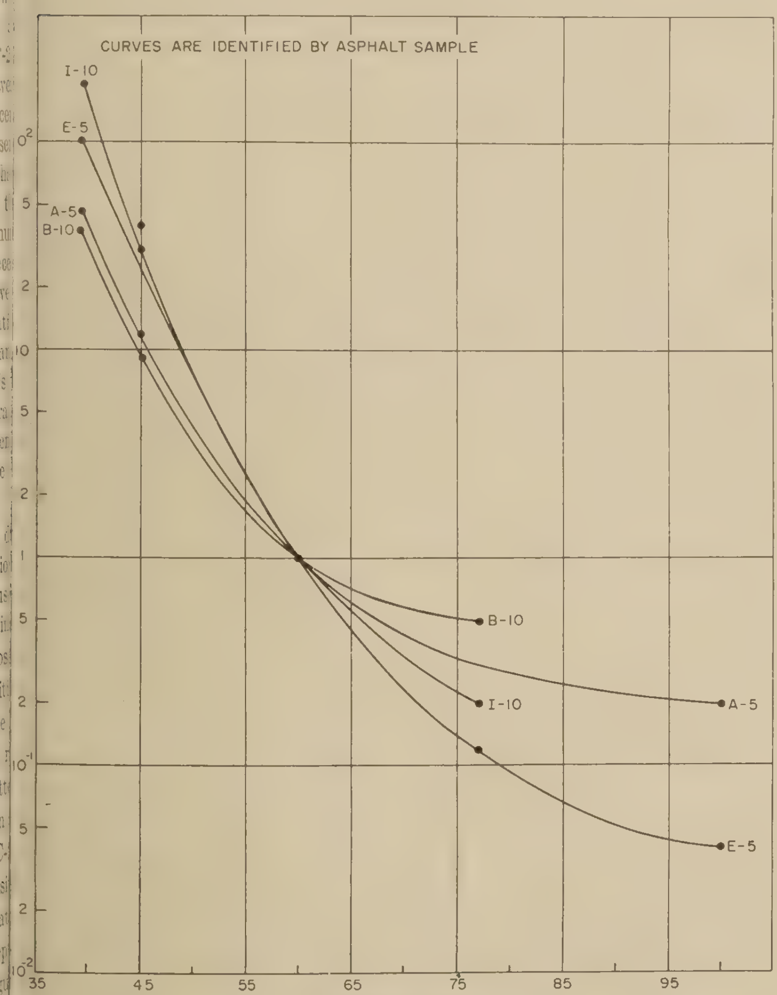


Figure 8.—Horizontal shift factors (a_T) for selected asphalt cements.

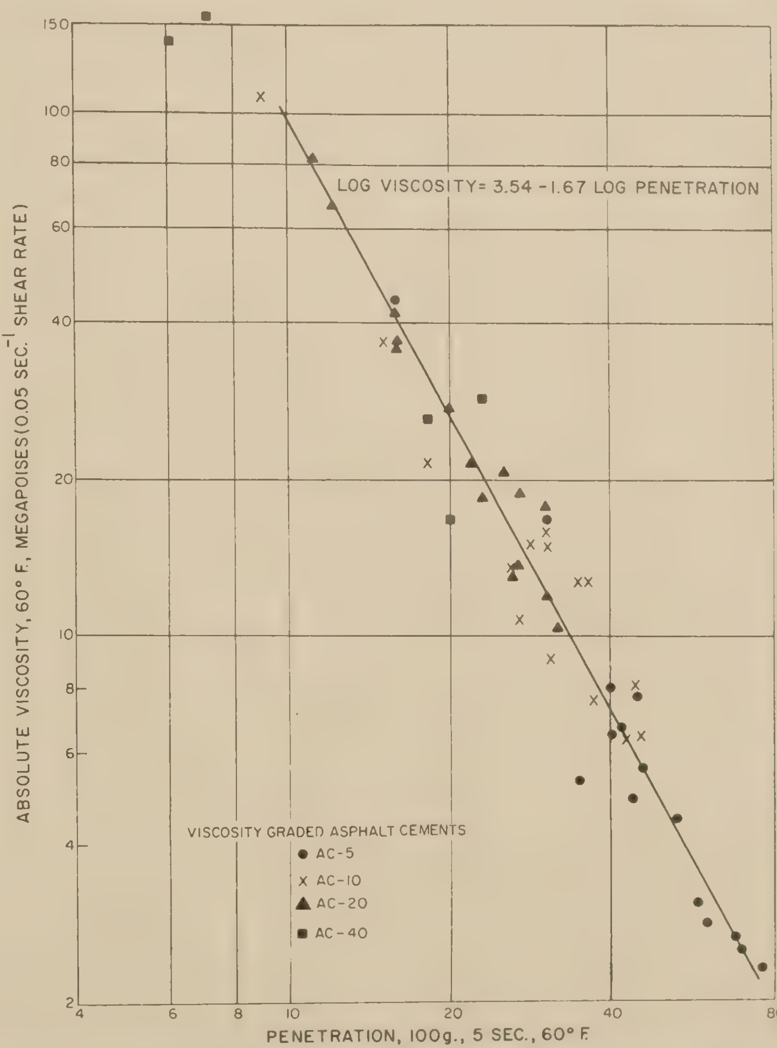


Figure 9.—Relation between penetration at 60° F. and absolute viscosity at 60° F. (0.05 sec.$^{-1}$ shear rate).

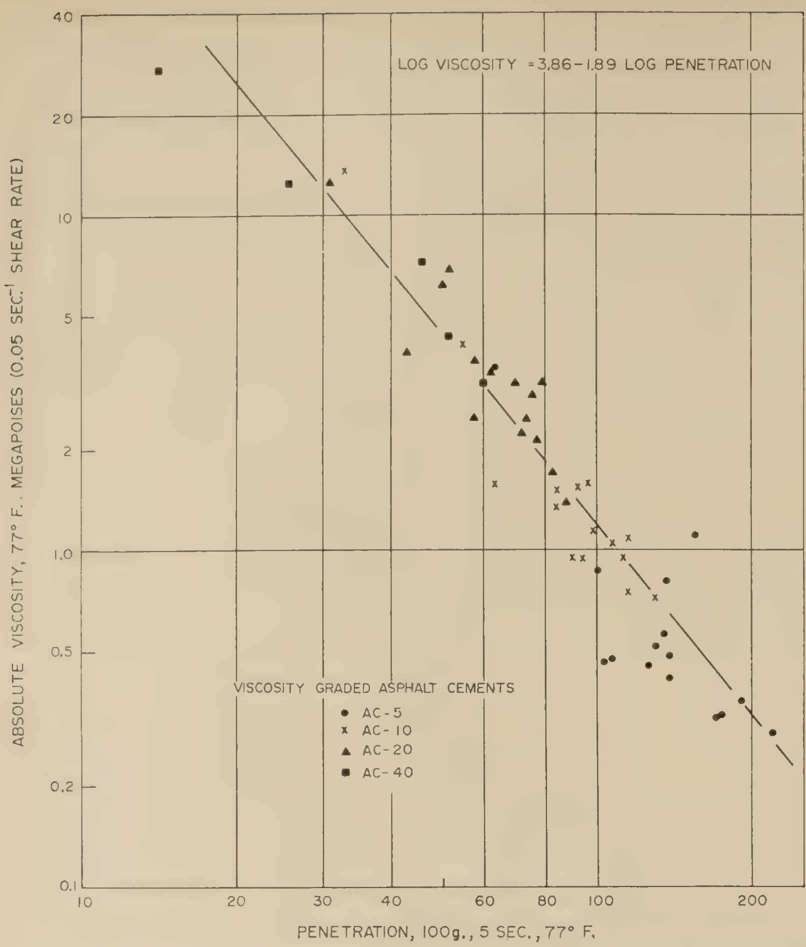


Figure 10.—Relation between penetration at 77° F. and viscosity at 77° F. (0.05 sec.$^{-1}$ shear rate).

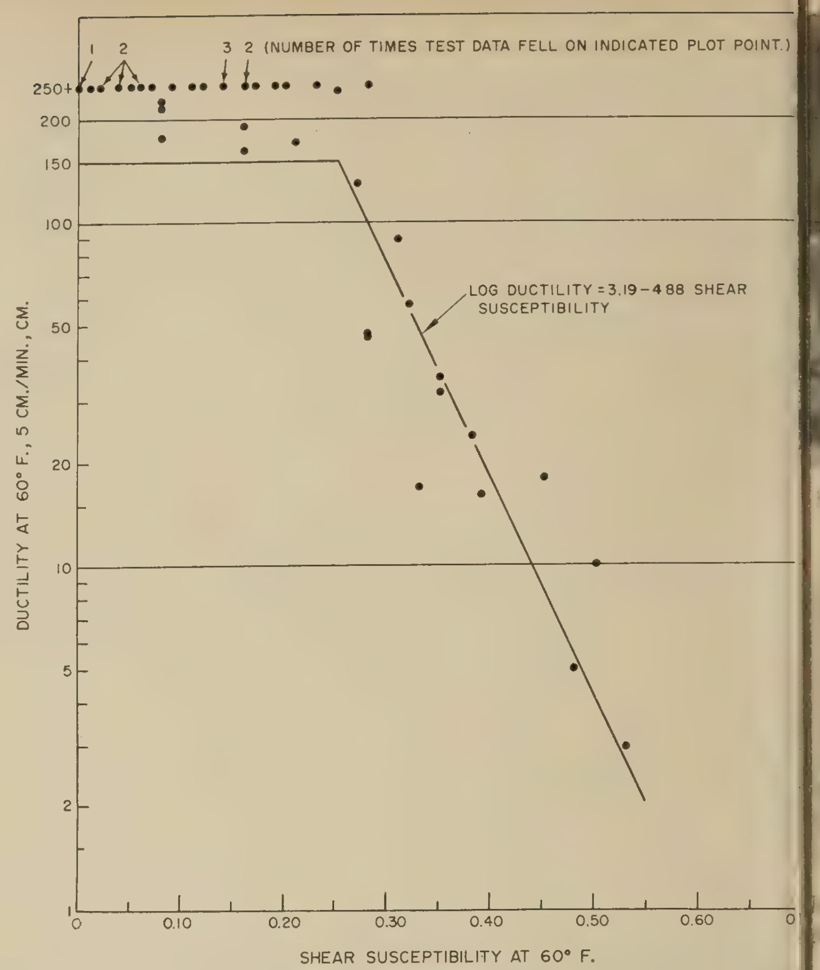


Figure 11.—Relation of ductility and shear susceptibility at 60° of all asphalts tested.

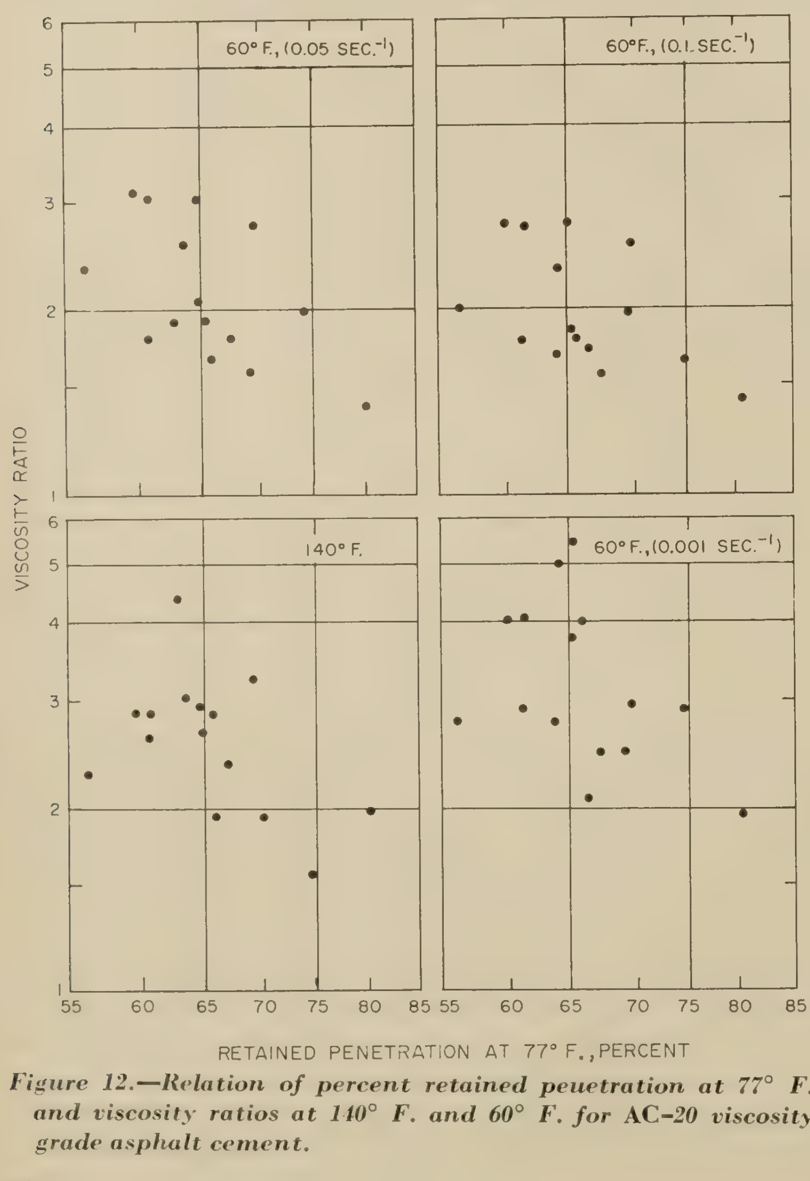


Figure 12.—Relation of percent retained penetration at 77° F. and viscosity ratios at 140° F. and 60° F. for AC–20 viscosity grade asphalt cement.

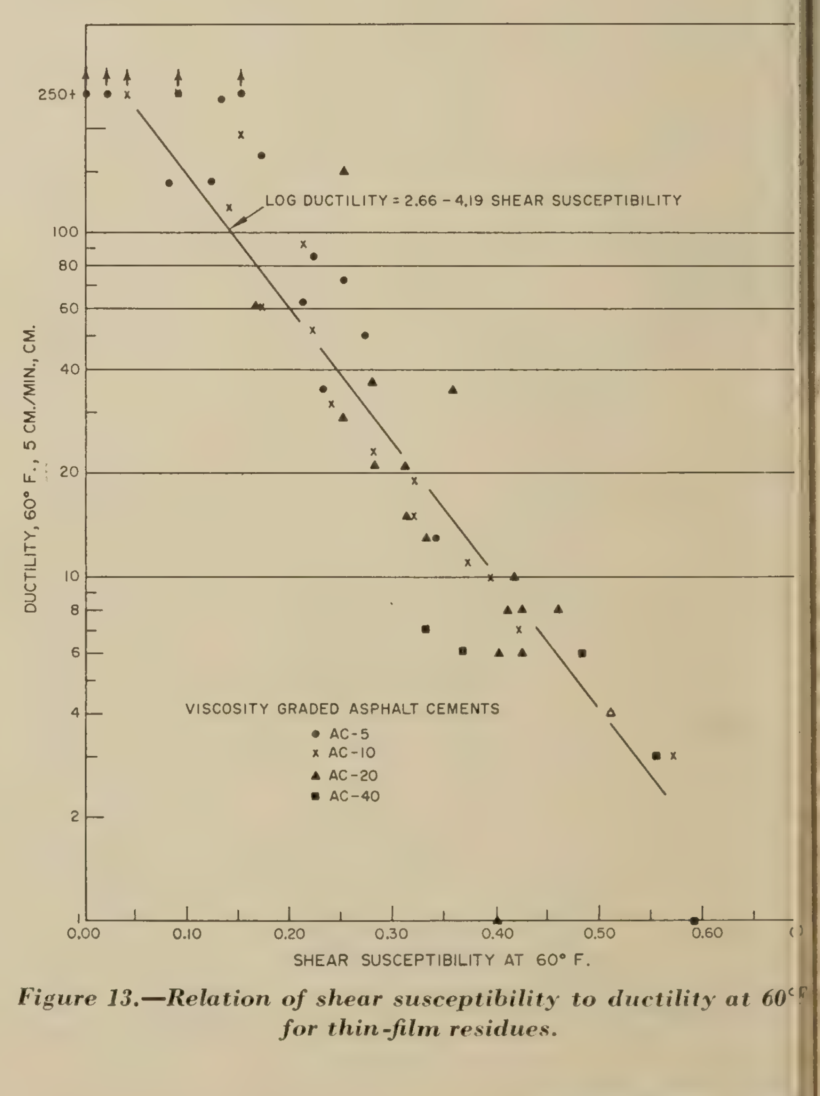


Figure 13.—Relation of shear susceptibility to ductility at 60° F. for thin-film residues.

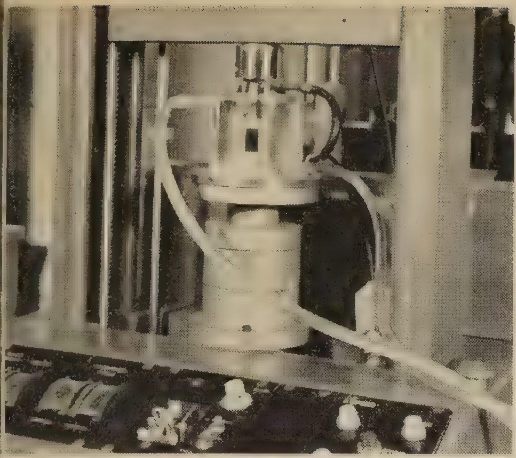
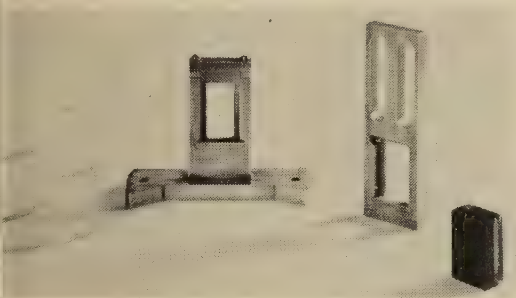
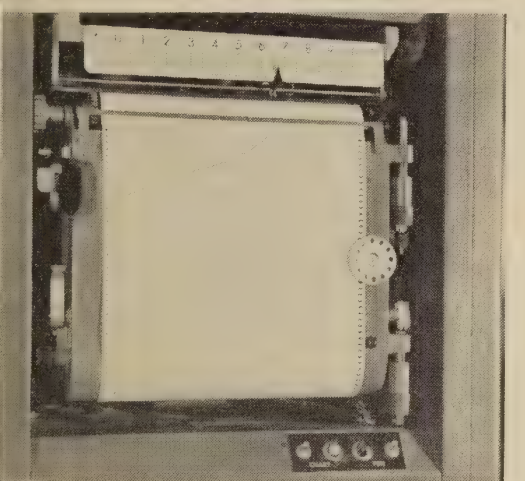


Figure 14.—Viscometer assembly during test run.



igure 15.—Viscometer clamps, matched ass plates, and prepared test specimen.



igure 16.—Recorder, showing load trace.

Table 8.—Viscosity results at low temperatures for selected asphalts

Temperature, ° F., and asphalt code number	Rate of shear	Viscosity
	Sec.$^{-1}$	*Megapoises*
39.2: A-5	4.39×10^{-2}	86.8
	1.76×10^{-2}	122
	8.78×10^{-3}	162
	4.39×10^{-3}	204
	2.20×10^{-3}	234
	8.78×10^{-4}	250
E-5	1.04×10^{-1}	188
	5.21×10^{-2}	290
	2.09×10^{-2}	509
	1.04×10^{-2}	760
	5.21×10^{-3}	1,160
	2.61×10^{-3}	1,740
	1.04×10^{-3}	2,950
B-10	6.41×10^{-2}	173
	3.21×10^{-2}	230
	1.28×10^{-2}	311
	6.41×10^{-3}	516
	3.21×10^{-3}	599
	1.60×10^{-3}	819
	6.41×10^{-4}	993
I-10	9.10×10^{-2}	167
	4.55×10^{-2}	224
	1.82×10^{-2}	335
	9.10×10^{-3}	444
	4.55×10^{-3}	540
	2.28×10^{-3}	666
	9.10×10^{-4}	778
45: A-5	8.78×10^{-2}	38.9
	4.39×10^{-2}	45.9
	1.76×10^{-2}	59.4
	8.78×10^{-3}	78.4
	4.39×10^{-3}	81.2
	2.20×10^{-3}	81.9
	8.78×10^{-4}	95.5
E-5	1.04×10^{-1}	124
	5.21×10^{-2}	176
	2.09×10^{-2}	293
	1.04×10^{-2}	428
	5.21×10^{-3}	614
	2.61×10^{-3}	828
	1.04×10^{-3}	1,250
B-10	6.41×10^{-2}	91.4
	3.21×10^{-2}	117
	1.28×10^{-2}	159
	6.41×10^{-3}	205
	3.21×10^{-3}	231
	1.60×10^{-3}	252
	6.41×10^{-4}	241
I-10	9.10×10^{-2}	94.2
	4.55×10^{-2}	122
	1.82×10^{-2}	161
	9.10×10^{-3}	187
	4.55×10^{-3}	213
	2.28×10^{-3}	209
	9.10×10^{-4}	250
60: A-5	9.46×10^{-2}	6.35
	Sec.$^{-1}$	*Megapoises*
60: A-5	4.73×10^{-2}	6.79
	1.89×10^{-2}	7.25
	9.46×10^{-3}	7.59
	4.73×10^{-3}	7.88
E-5	9.09×10^{-2}	35.8
	4.54×10^{-2}	46.8
	1.82×10^{-2}	67.6
	9.09×10^{-3}	87.0
	4.54×10^{-3}	109
	2.27×10^{-3}	124
	9.09×10^{-4}	136
B-10	1.54×10^{-1}	11.7
	7.72×10^{-2}	14.0
	3.86×10^{-2}	15.9
	1.54×10^{-2}	18.9
	3.86×10^{-3}	19.6
I-10	2.19×10^{-1}	11.5
	1.09×10^{-1}	12.5
	5.47×10^{-2}	13.6
	2.19×10^{-2}	14.1
	5.47×10^{-3}	14.8
77: A-5	7.41×10^{-2}	.439
	5.32×10^{-2}	.460
	3.20×10^{-2}	.509
	1.51×10^{-2}	.536
E-5	6.60×10^{-2}	3.00
	5.40×10^{-2}	3.10
	3.10×10^{-2}	4.20
	1.75×10^{-2}	4.60
B-10	1.14×10^{-1}	.730
	2.95×10^{-2}	1.10
	1.55×10^{-2}	1.10
I-10	1.00×10^{-1}	1.15
	6.00×10^{-2}	1.35
	2.40×10^{-2}	1.35
100: A-5	9.79×10^{-2}	.033
	6.40×10^{-2}	.038
	4.07×10^{-2}	.040
	2.14×10^{-2}	.038
	1.17×10^{-2}	.042
	7.71×10^{-3}	.042
	4.22×10^{-3}	.039
E-5	1.58×10^{-1}	.052
	7.45×10^{-2}	.088
	3.88×10^{-2}	.126
	2.34×10^{-2}	.105
	1.66×10^{-2}	.098
	7.77×10^{-3}	.105
120: E-5	2.79×10^{-1}	.0058
	1.34×10^{-1}	.0061
	1.15×10^{-1}	.0057
	8.62×10^{-2}	.0057
	6.81×10^{-2}	.0048
	3.67×10^{-2}	.0044

Controlled Shear Rate Viscometer Test Method

The method for the determination of the scosity of paving grade asphalt by use of a ding plate viscometer at controlled rates of ear is applicable to materials having vissities in the range of 10^5 to 10^{10} poises and is erefore suitable for use at temperatures 4.0° C., 15.6° C., and so on, where viscosity in the range indicated. Its use also is itable for determinations on materials havg either Newtonian or non-Newtonian flow operties. Shear susceptibility may also be termined. The details of the method of st are given in reference (*7*).

An asphalt film of known thickness is formed tween matched pairs of aluminum or glass ates. One plate is clamped in a fixed posin, the other is displaced at constant, eselected velocities, and the constant shearing force is measured. Rate of shear, shear stress, and viscosity are calculated from the dimensions of the specimen, displacement velocity, and the shearing force developed in the test. When several displacement velocities are used, shear susceptibilities may also be determined for non-Newtonian materials. A non-Newtonian complex liquid is a liquid in which the rate of shear is not proportional to the shearing stress. This method measures the viscous flow behavior of asphalt at relatively low shearing rates (1 to 10^{-4} sec.$^{-1}$) and low temperature ranges (15.6° C. and below).

Table 9.—Horizontal shift factors (a_T) for different temperatures

Temperature	Asphalt code number			
	A-5	E-5	B-10	I-10
° *F.*	a_T	a_T	a_T	a_T
39.2	4.6×10	1.0×10^2	3.7×10	1.9×10^2
45	1.2×10	3.0×10	9.0×1	4.0×10
60	1.0×1	1.0×1	1.0×1	1.0×1
77	1.4×1	1.2×10^{-1}	5.0×10^{-1}	2.0×10^{-1}
100	2.0×10^{-1}	4.0×10^{-2}	----------	----------
120	----------	4.0×10^{-3}	----------	----------

A sliding plate viscometer is shown in figure 14 and the clamps, matched glass plates, and a test specimen are shown in figure 15. A load trace on the recorder is shown in figure 16.

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A Comparative Evaluation of Trip Distribution Procedures

Y THE OFFICE OF PLANNING
UREAU OF PUBLIC ROADS

Reported by[1] KEVIN E. HEANUE, Highway Engineer, Urban Planning Division, and CLYDE E. PYERS[2]

The results of a research project designed to test, evaluate, and compare four major trip distribution techniques are presented in this article. These techniques are the Fratar growth factor procedures as developed by Thomas J. Fratar and utilized for many transportation studies; the so-called gravity model, currently the most widely used of the mathematical travel formulas; the intervening opportunities model developed by Morton Schneider of the Chicago Area Transportation Study (CATS) and since then utilized for several other major studies; and the competing opportunities model suggested by Anthony Tomazinis of the Penn-Jersey Transportation Study (P-J), but as yet not utilized in an operational study.

These techniques present interesting contrasts in their approach to the trip distribution problem. People as social beings do not order their lives according to strict physical or mathematical laws and no single model could ever be expected to perfectly match reality; however, some theories can be expected to be more explanatory than others. In this article an attempt has been made to give the potential user of trip distribution models insight into the theoretical differences underlying the models, as well as knowledge of some of their advantages and disadvantages in a practical application. The validity of these models as forecasting tools is also presented in an analysis of the accuracy of model forecasts made for a 7-year historical period for Washington, D.C.

Introduction

THE RAPID evolution of computer-oriented trip distribution techniques coupled ith the pressing deadlines of the major urban ansportation studies has made it difficult start a comprehensive program for testing ıd evaluating the most widely used trip stribution techniques. Individual applicaons of trip distribution models often have volved a certain amount of research, and a byproduct of these applications, revisions ıd improvements in each of the techniques ıve been made. However, since about)63, the rate of evolutionary development ıs slackened to the extent that most of the chniques are now considered to be mature.

This article is a report on the results of a search project conducted by the Urban lanning Division of the Bureau of Public oads to test, evaluate, and compare four ajor trip distribution techniques. These e the Fratar growth factor procedures as eveloped by Thomas J. Fratar and utilized r many transportation studies (*1*)[3]; the solled gravity model, currently the most idely used of the mathematical travel rmulas (*2*); the intervening opportunities odel developed by Morton Schneider of the Chicago Area Transportation Study (CATS) and since then utilized for several other major studies (*3*); and the competing opportunities model suggested by Anthony Tomazinis of the Penn-Jersey Transportation Study (P-J), but as yet not utilized in an operational study (*4*).

The mathematical model techniques differ in the approach to the trip distribution problem. These models can be classified into two categories: growth factor procedures and interarea travel formulas. For the growth factor procedures, growth factors that reflect land-use changes in the zones are used to expand a known travel pattern to some future year. The interarea travel formulas simulate travel distributions by relating them to characteristics of the land-use pattern and of the transportation system. The interarea travel formulas require calibration; that is, a determination of the effect of spatial separation on travel, prior to their actual application as forecasting tools.

Conclusions

On the basis of the research reported in this article, it is concluded that the gravity model and the intervening opportunities model had about equal reliability and utility in simulating the 1948 and 1955 trip distributions for Washington, D.C. Although use of the Fratar growth factor procedure correctly expanded trips for stable areas, this procedure had significant weaknesses when applied to areas undergoing land use changes.

The competing opportunities model, in exploratory work in the Penn-Jersey study at a district level (grouping of zones), offered promise as a useful tool. However, it is concluded that this procedure may not be useful for determining trip distributions between traffic zones as small as the Washington, D.C. zones.

Study Procedures

For the study reported here, an attempt was made to establish a standard set of test conditions for evaluating the four procedures. It was not possible always to adhere to strictly comparable conditions but each variation from a common base is fully discussed.

Basic data sources for the analysis were the 1948 and 1955 home interview travel surveys conducted in Washington, D.C. The 1948 survey covered 5 percent of the dwelling units in the metropolitan area. In 1955 a repeat survey was conducted. In the repeat survey, occupants of 3 percent of the dwelling units were interviewed within the District of Columbia. Elsewhere in the area, occupants of 10 percent of the dwelling units were interviewed. Figure 1 is a map of the study area.

The boundaries of the 1948 and the 1955 study areas were not exactly matched. Every attempt was made, however, to make the 1948 and 1955 analysis zones compatible. This was not a critical problem when the interarea travel formulas were used, as the only variable projected directly is the effect of spatial separation on trip making. This variable is independent of zone configuration. The Fratar procedure, however, requires compatible zones for base and projection years. For the Fratar analysis it was necessary to reduce the 400 zones used in the standard analysis to 362 units that were comparable. Mostly, this involved eliminating zones that were external to the 1948 study area but internal to the 1955 study area and thus had zero trip ends in 1948. Certain irregularities in zonal boundaries still were present; however, their effect was not serious. Because of changes in the location of external cordon stations between 1948 and 1955, all trips crossing the cordon—external trips—were omitted from the analysis. The basic trips considered were the total person trips by all modes expanded from the home interview surveys. Trips recorded in the special truck and taxi surveys were not included.

Although the test period covered by this analysis was only 7 years, the characteristics of the area changed significantly in this time.

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[1] Presented at the 44th annual meeting of the Highway esearch Board, Washington, D.C., Jan. 1965.
[2] Mr. Pyers is presently Assistant Director of the Cleveland ven County Land Use Transportation Study; formerly was a Highway Engineer, Urban Planning Division.
[3] Numbers in parentheses identify references listed on page

Figure 1.—Study area for O-D surveys, Washington, D.C., 1948 and 1955.

The population increased 38 percent to almost 1.5 million; the number of person trips increased by more than 42 percent; and the number of passenger cars owned by residents increased 96 percent, almost double. Probably the most significant change in the study area, during the 7-year period, was the decentralization of many activities. Residential, employment, and shopping activities all were relatively less oriented to the central business district (CBD) in 1955 than in 1948 (*5*). Total trips to the CBD decreased relatively from 28 percent to 21 percent of the total person trips.

The study reported here was designed so that the 1948 survey data would be used as the base year travel pattern for the Fratar procedure and as a calibration source for the interarea travel formulas. The 1955 travel survey data were used as a control against which all forecasts were checked. To establish the Fratar growth factors, trip ends reflecting the 1955 characteristics were taken directly from the 1955 O–D survey trip ends. Also, these trip ends were used directly as producing and attracting powers of the zones when the synthetic distributions were calculated with the interarea travel formulas. The 1955 trip ends were used rather than estimates developed in a land use and trip generation analysis, to restrict the possible sources of error to those inherent within each of the distribution procedures.

Fratar Procedure

The Fratar procedure has been proved to be computationally the most efficient of the growth factor techniques (*6*). The basic premise of the Fratar procedure is that, the distribution of trips from a zone is proportional to the present movements out of the zone modified by the growth factor of the zone to which the trips are attracted. The future volume of trips out of a zone is determined from the present trips out of the zone and the growth factors developed for the zone. In previous applications of the Fratar procedure, generally only one trip purpose had been used. The Urban Planning Division of the Bureau of Public Roads, in 1962, developed a Fratar procedure that uses up to 10 trip purposes. This program also permits the application of growth factors by mode, time of day, or for trips entering or leaving a zone. The basic formula for the directional purpose Fratar procedure is:

$$T_{ij} = t_{ij}G_iG_j\left(\frac{L_i + L_j}{2}\right)$$

Where,

T_{ij} = Future year trips from zone i to zone j with a given purpose at zone i and a given purpose at zone j.

t_{ij} = Base year trips between zone i and zone j with a given purpose at zone i and a given purpose at zone j.

G_i = Growth factor for zone i for a given purpose.

L_i = Locational factor

$$= \frac{t_i}{\sum_{j=1}^{n} t_{ij}F_i}$$

t_i = Base year trip ends at zone i for a given purpose.

The directional purpose Fratar allows th procedure to be sensitive to the type of lan use changes that are occurring in a given zone For example, work trips can be expanded as function of employment changes only. Prio to the development of the new compute program, all trips regardless of purpose wer expanded by a measure of the overall growt of the zone.

Gravity Model

The gravity model is the most thoroughl documented of the trip distribution technique (*7*, *8*, *9*, and *10*). This technique, loosel paralleling Newton's gravitational law, based upon the assumption that all trip starting from a given zone are attracted b the different traffic generators and that th attraction is in direct proportion to the siz of the generator and in inverse proportion t the spatial separation between the area The Public Roads computer battery gravit model program was used in the research r ported here. The basic gravity model formu lation is:

$$T_{ij} = \frac{P_iA_jF_{ij}K_{ij}}{\sum_{j=1}^{n} A_jF_{ij}K_{ij}}$$

Where,

T_{ij}= Trips produced in zone i and attract to zone j.

P_i= Trips produced in zone i.

A_j= Trips attracted to zone j.

F_{ij}= Empirically derived traveltime facto (one factor for each 1-minute incr ment of traveltime) that are a fun tion of the spatial separation betwe the zones. These factors expre the average areawide effect of sp tial separation on trip interchang

K_{ij}= Specific zone-to-zone adjustment fa tor to allow for the incorporation the effect on travel patterns of d fined social or economic linkages n otherwise accounted for in the gra ity model formulation.

The traveltime factors are developed in iterative procedure that is continued until t synthetic trips calculated for each trip-leng interval closely match the surveyed trips ported for the same intervals. Any convenie set of traveltime factors may be used to st the iteration procedure.

Intervening Opportunities Model

For the intervening opportunities moc a probability concept is used that in esse requires a trip to remain as short as possi and to be lengthened only when a pr destination is not acceptable. An eq areawide probability of acceptance for a origin is defined for all destinations in a giv category. In use of this model, all t destinations (opportunities) are conside in sequence by traveltime from zone of orig The first destination considered is the

sest to the origin of the trip and its accept-
ce has the stated areawide probability of
eptance. The same basic probability of
eptance exists for the next opportunity but
actual probability of its being accepted
decreased by the possibility of the trip-
ker having accepted the first opportunity
his destination. The procedure is applied
each successive destination from point of
gin but, for each successive opportunity,
actual probability of its being accepted
reases. Thus, spatial separation for the
ervening opportunities model is measured
terms of the number of intervening desti-
ions rather than in terms of the absolute
veltime, cost, or distance between one
e and the other. The intervening oppor-
ities are determined by arraying the
ilable destinations in all zones by traveltime
m the zone of origin. The formulation
the procedure is:

$$T_{ij}=O_i[e^{-LD}-e^{-L(D+D_j)}]$$

here,

T_{ij} = Trips originating in zone i with destinations in zone j.

O_i = Trip origins in zone i.

D = Trip destinations considered prior to zone j.

D_j = Trip destinations in zone j.

L = Measure of probability that a random destination will satisfy the needs of a particular trip. It is an empirically derived function that describes the rate of trip decay with increasing trip destinations and increasing length of trip.

e = Base of natural logarithms (2.71828).

his model is calibrated by varying the prob-
ility values until the simulated trip distri-
tion reproduces the person hours of travel
d percent intrazonal trips of the surveyed
p distribution.

Competing Opportunities Model

Essentially the basic concept of the com-
ting opportunities model is that opportuni-
es or destinations compete for trips within
ual traveltime, travel distance, or travel
st bands as measured from the zone of
igin. Within a given band, each destina-
on has an equal probability of acceptance.
he probability that trips will be distributed
a certain zone is the product of two inde-
ndent probabilities. The first, called the
obability of satisfaction, reflects the chances
at a trip will be of a particular length and is
function of the destinations at a greater
stance than the time band under considera-
on. The determination of the specific
stination within this time band is quantified
a probability of attraction, which is
lated to the available opportunities that fall
ithin the area up to and including the time
nd considered. The mathematical formu-
tion for this procedure is:

$$T_{ij}=O_i\rho_{a_j}\rho_{s_j}$$

Where,

T_{ij} = Trips produced in zone i and attracted to zone j.

O_i = Trip origins in zone i.

ρ_{a_j} = Probability of attraction

= destination available in zone j divided by sum of destinations available in time bands up to and including band m.

$$=\frac{D_j}{\sum_{k=0}^{m} D_k}$$

ρ_{s_j} = Probability of satisfaction

= 1 minus the sum of the destinations available in time bands up to and including band m divided by the sum of total destinations in study area.

$$=1-\frac{\sum_{k=0}^{m} D_k}{\sum_{k=0}^{n} D_k}$$

k = Any time band.

m = Time band into which zone j falls.

D_k = Destinations available in time band k.

n = Last time band as measured from origin zone i.

D_j = Destinations available in zone j.

This model is calibrated by varying the width of the attracting bands until the trip length characteristics of the synthetic trips correspond to the trip length characteristics of the surveyed trips.

Basic Tests

Four basic tests were used to measure the ability of the different procedures to reproduce the total person trip movements of the known travel patterns. These tests evaluated the procedures as to: (1) ability to match the trip length frequency distribution from the O–D survey; (2) ability to produce river crossing volumes that matched O–D survey volumes; (3) ability to match O–D survey trip movements by corridor to and from the CBD, and (4) accuracy of model as measured by statistical comparison of O–D survey trips and model trips assigned to a spider network.

The Fratar procedure could not be tested against 1948 data because its base is the survey data. However, some validation for the other travel formulas was accomplished against base conditions. Such validation is an essential part of calibrating the models before they are used for projection. The accuracy of this base year simulation is typically the most important check in the calibration procedure. This check is based on the fact that the calibrated travel model must accurately simulate the base year travel pattern before the same model can be expected to simulate accurately a travel pattern for a future year.

The trip length frequency comparisons were made by 1-minute time intervals. A comparison of the O–D and model trip-length frequency curves and mean trip lengths provides a measure of the accuracy of the estimate of person hours of travel for the total area. Such a comparison also provides an indication of the accuracy of the trip distribution.

The river crossing tests were made on the basis of screenlines set up on the Potomac and Anacostia Rivers. Because of the trip definition, the base screenline values were the O–D survey person movements rather than actual vehicle counts. The analysis of movements by corridor to and from the CBD was designed to detect any bias in the estimated travel patterns. The gravity model computer program provides for the use of adjustment factors to correct for bias. When the other techniques are used, it is usually assumed that the procedure adequately distributes trips and that adjustment factors are not needed.

The statistical analysis of trips assigned to a spider network was used as the fourth test on the procedures. A spider network consists of airline distance connections between adjacent zone centroids. The resultant differences between the O–D and model assignments were arrayed by volume group and the root mean square error was calculated. This test provides a measure of the overall accuracy of the final trip distribution.

Calibration of Interarea Travel Formulas

Gravity model

In previous research with the gravity model, the Washington, D.C., 1955 O–D data were used as a calibration base rather than the 1948 data (*7*, *8*). The model parameters were in effect forecast backward from 1955 to 1948. For the research reported here, the gravity model was recalibrated and the 1948 O–D data were used as a base. These 1948 model parameters were used to forecast 1955 travel patterns. The research results showed that the same traveltime factors held for both 1948 and 1955 and that the K factors (socioeconomic adjustment factors) also had the same relation with average family income by district for both periods. Some doubt existed as to whether the river crossing time impedances could have been properly forecast without the knowledge gained from the former research, but for comparisons made in the study reported here it was assumed that the river barriers could be properly forecast. The impedances varied from 5 and 3 minutes for work and nonwork trips in 1948, to 6 and 5 minutes in 1955, respectively. The 1955 river crossings were forecast from 1948 on the basis of the relative congestion levels for the 2 years (*8*, p. 26). The traveltime factors for each of the six trip purposes used for both 1948 and 1955 are shown in table 1.

Intervening opportunities model

Several methods of calibration of the intervening opportunities model were tried for the 1948 Washington area data. The best procedures and the final calibration parameters were incorporated into the study discussed here. The several methods of calibration and the resultant findings are documented in

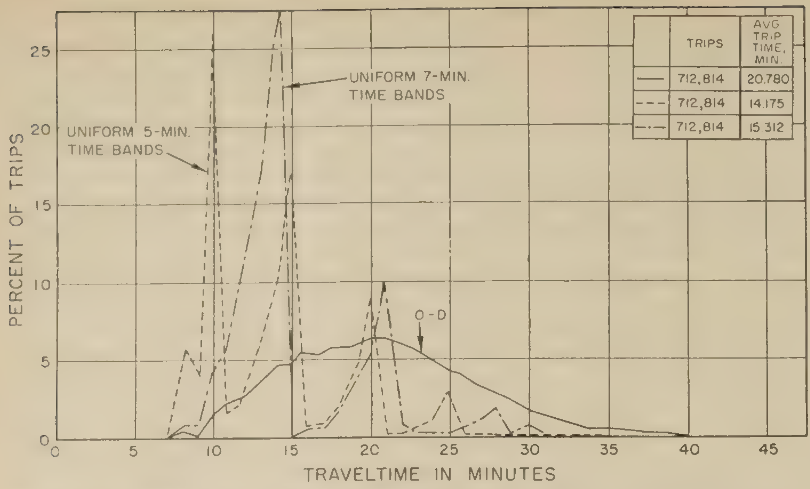


Figure 2.—Work trip length distribution in uniform time bands from O–D survey and competing opportunities model, Washington, D.C., 1948.

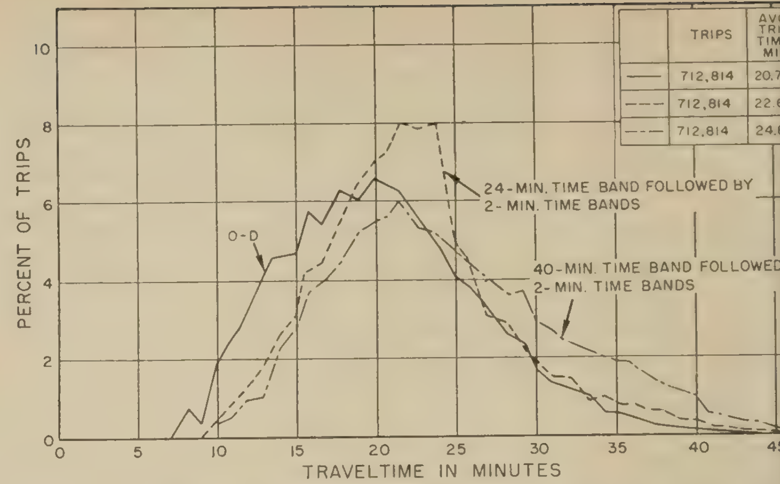


Figure 3.—Work trip length distribution in different time bar from O–D survey and competing opportunities model, Wa ington, D.C., 1948.

reference (*11*). The methods of calibration and forecasting of the model examined are very olose to those used previously in Chicago and elsewhere except that procedures were developed to ensure that the model would both send and attract approximately the correct number of trips for each zone in the study area. Without these adjustments, only 84 percent of the total trips were distributed and trips to the CBD were overestimated by 20 percent.

Trip ends were stratified into long residential, long nonresidential, and short. Both long and short L values were developed through an iterative process to ensure that, when the final L values were applied to the appropriate trip ends, a satisfactory average trip length, trip length frequency curve, and number of intrazonal trips would be obtained for the total trips—all three trip types combined.

The river crossing time impedance was needed for the intervening opportunities model as well as for the gravity model. The additional bridge crossing time required for the 1948 intervening opportunities model calibration was 5 minutes. The use of procedures developed in the gravity model research to forecast the impedance for the intervening opportunities model estimated that an 8-minute impedance was required for 1955 data. Although use of this 8-minute forecast time penalty did materially improve model accuracy, estimated Potomac River crossings by the intervening opportunities model were approximately 16 percent high. The differences in forecast time penalty by the gravity model and the intervening opportunities model were caused by the different trip purpose categories, which required different weighting of peak hour trips. The basic structure of the models also made it necessary to use different impedances for 1948 data.

An increase in the total number of trip destinations or opportunities requires that the probability of any one of these destinations being accepted for any given origin be reduced. Because of the growth in total and intrazonal trips in the study area, the 1948 L (probability) values required reduction for use in 1955 forecasts. The final 1948 long and short L values were 2.50×10^{-6} and 13.00×10^{-6}, respectively, and they were reduced to 1.65×10^{-6} and 10.80×10^{-6} for the 1955 forecasts. These adjustments were made on the basis of the actual growth in total destinations between 1948 and 1955 (*11*).

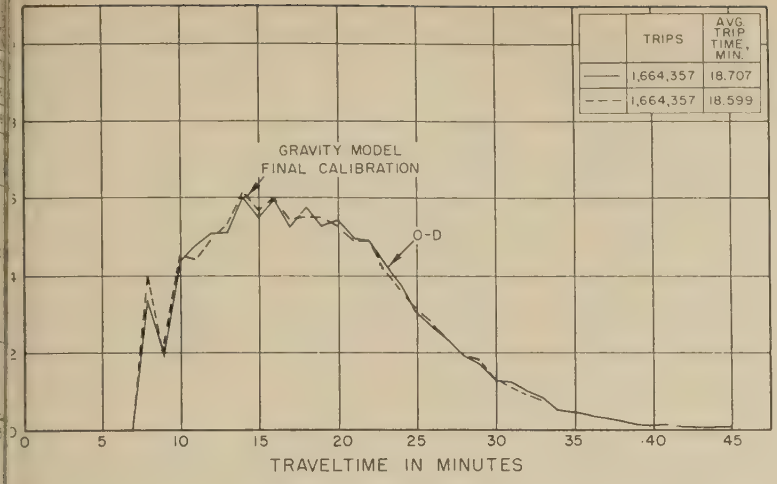
Competing opportunities model

The competing opportunities model proved to be very difficult to calibrate. Because no systematic calibration procedures were available, many alternate approaches were tried. Initially, equal time bands were used for work trips but this was not successful, as shown in figure 2. Time bands of different widths were utilized and the results became more meaningful. It seemed that the best simulation for work trips was obtained when the first time band incorporated the majority of the opportunities in the study area. This broad band was followed by equal 2-minute bands. Even with this approach, however, it was impossible to obtain a trip length frequency distribution that approached the O–D trip length frequency. As shown in figure 3, for a 24-minute time band the peaks of the curve are too high and the curve for the 40-minute time band, which is similar in shape to the O–D curve, is offset approximately 4 minutes to the right. No grouping of time bands that would fit the O–D curve could be determined. The calibration attempts were stopped at this point.

The calibration of the competing opportunities model in the Penn–Jersey (*4*) area involved a district rather than zonal analysis. This in effect restructured the grouping of opportunities by greatly increasing the number of intrazonal trips. To date a calibration at the zonal level has not been attempted in the Penn–Jersey study. For purposes of the research reported here, the authors believe that the model would have to prove operational at the zonal level to be of universal value. District analysis was not attempted as a part of the subject research. The only other difference from the Penn–Jersey application involved the measure of spatial separation. Because of the grossness of the measure, particularly of the first opportunity band, where all trips in a ±20-minute time band would be treated equally, the use of

Table 1.—Traveltime factors by trip purpo Washington, D.C., 1948 and 1955

Travel-time, minutes	Traveltime factors for— Home based trips, by purpose: Work	Shopping	Social and recreational	School	Miscellaneous	Non-home based trips
1	1,000	8,700	2,000	4,200	2,600	1,600
2	1,000	8,700	2,000	4,200	2,600	1,600
3	1,000	8,700	2,000	4,200	2,600	1,600
4	1,000	8,700	2,000	4,200	2,600	1,600
5	1,000	8,700	2,000	4,200	2,600	1,600
6	1,000	8,700	2,000	4,200	2,600	1,600
7	1,000	8,700	2,000	4,200	2,600	1,600
8	1,000	8,700	2,000	4,200	2,600	1,600
9	680	5,400	1,475	2,800	1,700	1,100
10	500	3,600	1,100	2,000	1,200	780
11	400	2,300	820	1,475	875	580
12	320	1,600	640	1,075	650	440
13	270	1,120	500	800	500	340
14	235	800	400	625	390	265
15	205	580	320	480	300	215
16	180	420	260	370	235	170
17	160	310	220	280	190	140
18	145	235	180	215	150	110
19	130	180	152	165	125	92
20	120	140	130	135	105	78
21	110	105	110	110	87	[illegible]
22	100	95	95	90	72	54
23	93	70	82	70	60	[illegible]
24	87	58	72	57	51	[illegible]
25	82	45	64	47	43	[illegible]
26	77	38	56	40	38	[illegible]
27	70	32	49	32	32	[illegible]
28	63	26	42	26	28	[illegible]
29	58	21	38	22	24	[illegible]
30	53	17	34	18	21	[illegible]
31	49	13	30	15	18	[illegible]
32	44	10	27	12	15	[illegible]
33	40	8	24	10	13	[illegible]
34	37	6	21	9	12	[illegible]
35	34	5	19	7	10	[illegible]
36	29	4	17	6	8	[illegible]
37	27	3	15	5	7	[illegible]
38	24	2	13	4	6	[illegible]
39	22	2	11	4	5	[illegible]
40	19	1	10	3	4	[illegible]
41	17	0	8	3	3	[illegible]
42	15	0	7	2	3	[illegible]
43	13	0	6	2	2	[illegible]
44	11	0	5	2	1	[illegible]
45	9	0	4	1	1	[illegible]
46	7	0	3	1	0	[illegible]
47	6	0	3	1	0	[illegible]
48	5	0	2	1	0	[illegible]
49	4	0	1	0	0	[illegible]
50	3	0	1	0	0	[illegible]
51	3	0	0	0	0	[illegible]
52	2	0	0	0	0	[illegible]
53	2	0	0	0	0	[illegible]
54	1	0	0	0	0	[illegible]
55	1	0	0	0	0	[illegible]



...ure 4.—Trip length distribution for total trips for all purposes ...rom O-D survey and final calibration of gravity model, Wash...ngton, D.C., 1948.

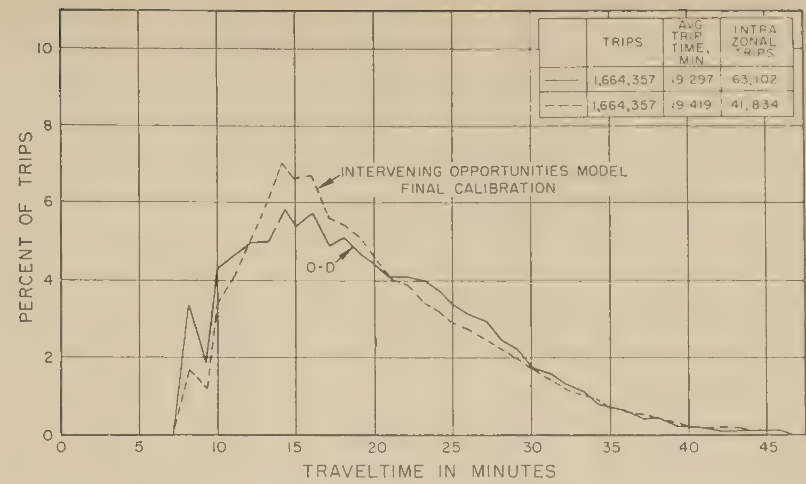


Figure 5.—Trip length distribution for total trips for all purposes from O-D survey and final calibration of intervening opportunities model, Washington, D.C., 1948.

...veltime rather than travel costs as the ...asure of spatial separation seems justified.

Analytical Tests

...he analytical tests considered as a group ...w the measures of accuracy of the different ...cedures as well as providing data that ...mit insight into the theoretical differences ...lerlying the techniques. Some of the ques...ns that can be considered are: (1) Do ...an residents maintain a continuum of ...vel patterns over time modified only by ... growth of the area as reflected in the ...tar procedure; (2) or, when considering ...king a trip, do residents follow gravitational ...cepts weighing all attractors in direct ...portion to the size of the attractors and in ...erse proportion to the spatial separation ...measured by the traveltime between the ...es; (3) or can travel patterns be best ...lained by opportunity concepts in the ...ervening opportunities model that assumes ...ople do not consider time directly but ...her consider opportunities in sequence by ...veltime and proceed on to any specific ...portunity only after having considered and ...ected all closer opportunities; (4) or does a ...rson consider all opportunities in rather ...ad time or cost bands with all opportunities ...a given band having an equal probability of ...eptance as in the competing opportunities ...del.

...eople as social beings do not order their ...s according to strict physical or mathe...tical laws and no single model could ever ...expected to perfectly match reality; how...r, some theories can be expected to be more ...planatory than others. The tests and ...ults of use of the different models should ...n be analyzed as to whether (1) the par...ular procedure is rational; (2) the applica...n is simple enough so that the procedure ...y be applied in urban planning studies by ...se who lack detailed experience in the ...cedure gained by research or earlier appli...ions, (3) the specific procedure fits the ...an area to be studied, for example, where ...re are local conditions such as relatively ...w or rapid growth, inherent socio-economic trip linkages, large analysis units, that might make one or more of the procedures more applicable. Some underlying differences in the procedures are described in the following paragraphs. One of the most relevant differences is the weight placed on the role of traveltime as an influence on trip distribution.

In use of the Fratar growth factors procedures, the existing travel patterns are expanded by considering growth in each portion of the study area without any specific consideration of the transportation network. Should changes in the traveltime between zones be sufficient to cause a change in travel patterns in the forecast year, the Fratar or any other growth factor technique would not reflect the change in travel patterns. However, each of the interarea travel formulas studied—gravity, intervening opportunities, and competing opportunities uses time separation as a key variable. Thus changes in the transportation system and the concomitant changes in accessibility between certain portions of the study area are directly reflected in the models.

The gravity model uses a traveltime factor for each 1-minute increment and, therefore, makes the most explicit use of absolute traveltime of any of the procedures. These traveltime factors are adjusted in the calibration process until there is close agreement between the estimated trip length frequency curve and the actual curve at all increments of traveltime. These factors, or relative weights of making trips of certain lengths, are then usually assumed to remain constant over the forecast period.

In contrast to the gravity model, the intervening opportunities model does not make such explicit use of absolute traveltime. Traveltime is used instead to rank all possible destination zones from a particular origin zone. This ranking then is used to determine the number of intervening opportunities; that is, the number of destinations already considered before a particular destination zone is considered. Changes in the transportation system and accessibility between zones over the forecast period are thus reflected in the forecasting model. Two probability factors generally described as the long and short L values are used in conjunction with the intervening opportunities model to determine trip interchanges between zone pairs. The procedure of ranking used in the intervening opportunities model does cause situations unique to this model. For example, those traveling from zones in the developed area and not finding a suitable destination would ignore time gaps and immediately consider opportunities in a fringe community. In effect, any separation, or gap, would be ignored in use of the intervening opportunities model. But, when the gravity model is used, these separations are considered and the possibility of a trip crossing a gap is decreased.

The competing opportunities model is somewhat unique: results from its use approach those of the gravity model if small time bands are used but when large time bands are used, the model tends to ignore spatial separation.

In evaluating and comparing the results of the tests, consideration should be given to the formulation and parameter makeup of each of the procedures. The amount of the actual O-D data used for the base calibration and the number of parameters requiring forecasting are important in weighing the results of one model against results of others. For the Fratar procedure, all of the base year travel data from the home interview survey were used. The travel models all required less O-D data than the Fratar procedure; however, the amount of data used, as well as the number of parameters used to represent these data, varied to a considerable degree between the travel models tested.

Trip Length Frequency

Base year

Comparisons of the final calibrated model trip length frequency curves with actual trip length frequency curves: for the gravity model, the intervening opportunities model, and the competing opportunities model can be made from data shown in figures 4–6. Each of these plots is on a slightly different basis because of the way in which the research was carried out. However, each is compatible with the survey data with which it is shown.

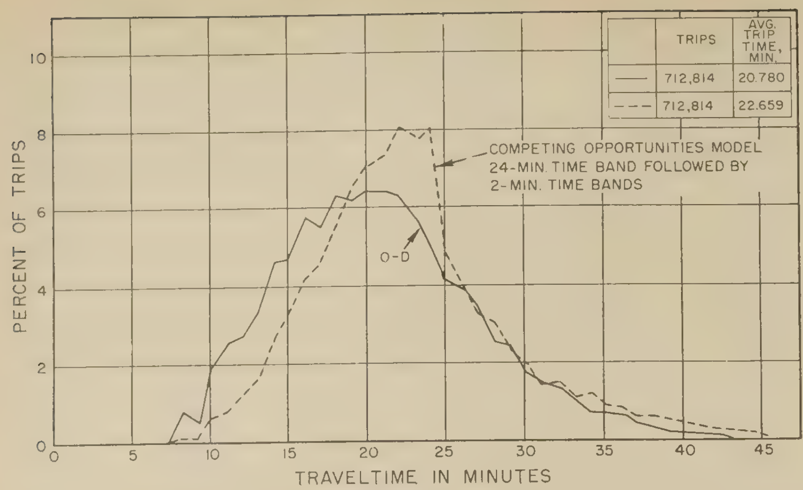


Figure 6.—Work trip length distribution from O-D survey and best calibration of competing opportunities model, Washington, D.C., 1948.

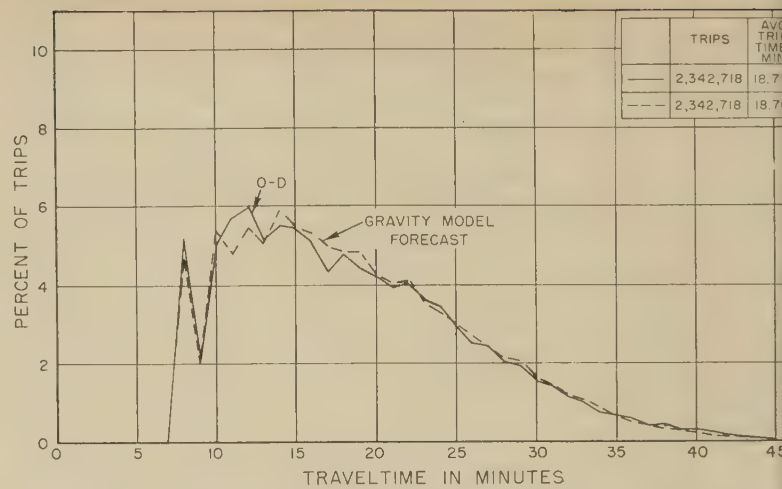


Figure 8.—Trip length distribution for total trips for all purpo from O-D survey and gravity model, Washington, D.C., 195

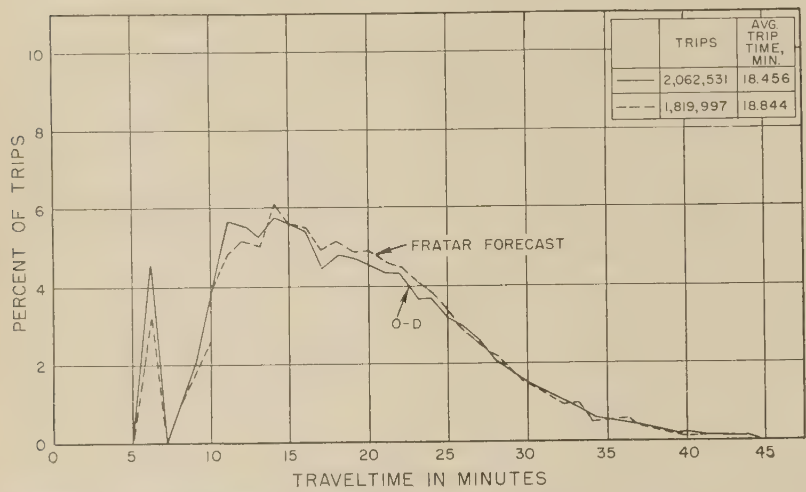


Figure 7.—Trip length distribution for total trips from O-D survey and Fratar model, Washington, D.C., 1955.

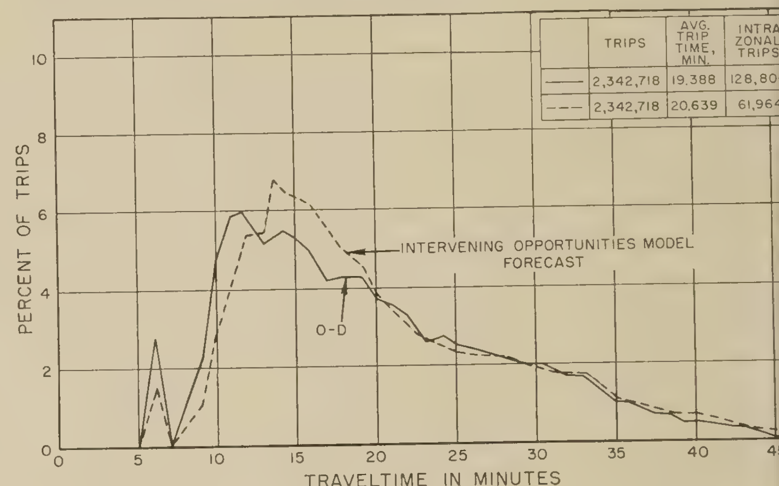


Figure 9.—Trip length distribution for total trips for all purpo from O-D survey and intervening opportunities model, Wa ington, D.C., 1955.

The curves in figure 6 for the competing opportunities model are for work trips only. A full analysis of this procedure could not be made because of calibration problems. The information in figure 6 represents the best calibration achieved with this procedure.

As expected, the gravity model had the best agreement through most portions of the trip length frequency curves because of the refined degree of adjustment made during the calibration phase. Both the gravity and intervening opportunities models produced good duplication of the total hours of travel and average trip length.

Even though the two curves for the competing opportunity model (fig. 6) have some agreement, no rational method could be found to adjust toward a more satisfactory model.

Forecast year

The trip length frequency curves from the travel patterns as estimated by each of the procedures are shown for comparison to the appropriate O–D information in figures 7–9. No forecast was made for the competing opportunities model.

The Fratar procedures provided a good duplication of average trip length for 1955 as shown in figure 7, although approximately 195,000 trips out of the total available 2,012,947 trips were not distributed because of zero trip ends for certain purposes in particular zones in 1948. The average trip length of the expanded patterns for 1955 of 18.8 minutes compares favorably with that of 18.5 minutes obtained from the surveyed information.

Travel patterns forecast with the gravity model likewise provided an extremely good duplication of the average trip length, as well as close agreement with the trip length frequency curve (fig. 8). The average traveltime for the forecast gravity model results of 18.8 minutes compared very well with the 18.7 minutes from the surveyed data. The intervening opportunities model forecast is shown in figure 9. The average traveltime (driving time plus terminal times) of 20.6 compared well with the actual traveltime of 19.4. These figures included the use of a river impedance.

River crossings

The tests of estimated river crossings made on the different model results were developed because of definite bias in the simulated trip distributions of two of the models, which became apparent during the calibration stage of model development. The use of time penalties on the Potomac River in the base year and in the forecast year was required for both the gravity model and the intervening opportunities model. Different impedar were required for the two models. The gr ity model research was completed first procedures to forecast these time penal were developed at that time. When th procedures were applied during the interven opportunities research, the error in the fo cast year was reduced substantially but completely. The penalties required in gravity model and intervening opportuni model were different. The different meth required to forecast the time penalties probably related to the different manne which time is used by each model. Of cou the effect of the impedance to free trave the form of the Potomac River bridges present in the 1948 surveyed trip crossi which were expanded to 1955 by the Fr procedures. Table 2 data show the rela accuracies of river crossing estimates for Potomac and Anacostia Rivers for each of models for both the calibration and forecas phases. The effect of the use of time in dances for the gravity and interve opportunities model is included.

Movements by Corridor

A test on the movements by corridor to from the CBD was developed to isolate geographical bias present in model res The incorporation and need for adjustment

le 2.—Total trips crossing the Potomac nd Anacostia Rivers for comparison of ata from Washington, D.C., O–D surveys, nd models

Data source	Potomac River		Anacostia River	
	Trips	Difference from O–D data [1]	Trips	Difference from O–D data [1]
	Number	*Percent*	*Number*	*Percent*
948:				
O–D survey	196, 255	NA	183, 696	NA
Gravity model	202, 237	+3. 05	184, 188	+0. 27
Intervening opportunities model	188, 134	−4. 14	193, 398	+5. 28
955:				
O–D survey	246, 268	NA	287, 452	NA
Fratar model [2]	279, 055	+13. 31	281, 881	−1. 94
Gravity model	230, 949	−6. 22	296, 830	+3. 26
Intervening opportunities model	287, 447	+16. 72	318, 269	+10. 72

Survey data used as base.
Adjusted to common O–D survey base.

le 3.—Calibration accuracy of different athematical models, Washington, D.C., 948

Sector	Travel between zero sector and sector number				
	O–D survey trips	Gravity model [1]		Intervening opportunities model [2]	
		Trips	Difference from O–D data	Trips	Difference from O–D data
Number	*Number*	*Number*	*Percent*	*Number*	*Percent*
0	134, 951	141, 105	+4. 56	142, 595	+5. 66
1	44, 771	46, 110	+2. 99	45, 407	+1. 42
2	72, 206	66, 494	−7. 91	59, 710	−17. 31
3	195, 114	181, 860	−6. 79	184, 815	−5. 28
4	93, 542	92, 027	−1. 62	94, 923	+1. 48
5	62, 484	58, 550	−6. 30	64, 999	+4. 02
6	80, 275	83, 684	+4. 25	91, 174	+13, 58
7	67, 835	68, 898	+1. 57	58, 299	−14. 06
8	42, 833	43, 505	+1. 57	36, 297	−15. 26
TOTAL	794, 011	782, 233	−1. 48	778, 219	−1. 99

[1] Includes K factors.
[2] Does not include K factors.

Table 4.—Forecasting accuracy of different mathematical models in duplicating home interview data, Washington, D.C., 1955

Sector	Travel between zero sector and sector number							
	O–D survey trips	Gravity model [1]		Intervening opportunities model [2]		O–D survey trips [3]	Fratar model [3]	
		Trips	Difference from O–D data	Trips	Difference from O–D data		Trips	Difference from O–D data
Number	*Number*	*Number*	*Percent*	*Number*	*Percent*	*Number*	*Number*	*Percent*
0	112, 471	123, 243	+9. 58	119, 613	+6. 35	112, 007	113, 972	+1. 75
1	52, 391	53, 830	+2. 75	53, 680	+2. 46	52, 213	47, 485	−9. 06
2	100, 710	87, 896	−12. 72	82, 498	−18. 08	88, 865	79, 388	−10. 66
3	197, 167	182, 558	−7. 41	187, 026	−5. 14	191, 362	181, 933	−4. 93
4	102, 384	105, 943	+3. 48	108, 668	+6. 14	97, 906	98, 860	+0. 97
5	64, 788	62, 019	−4. 27	70, 485	+8. 79	64, 623	63, 348	−1. 97
6	95, 461	100, 579	+5. 36	107, 037	+12. 13	92, 087	84, 960	−7. 74
7	69, 221	64, 911	−6. 23	66, 541	−3. 87	62, 125	62, 161	+0. 06
8	57, 847	54, 652	−5. 52	53, 258	−7. 93	51, 154	49, 653	−2. 93
TOTAL	852, 440	835, 631	−1. 97	848, 806	−0. 43	812, 342	781, 760	−3. 76

[1] Includes K factors.
[2] Does not include K factors.
[3] Contains information from 362 zones only, as used in Fratar model.

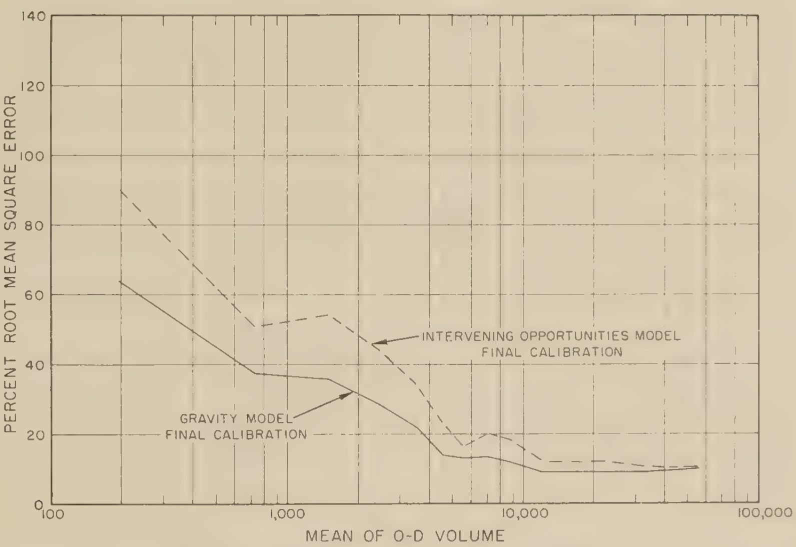


Figure 10.—RMSE for total trips for all purposes by volume groups from final calibration of gravity model and intervening opportunities model, Washington, D.C., 1948.

ographical bias has been shown for the vity model through the use of K factors. such adjustments were used in the Fratar intervening opportunities procedures. bles 3 and 4 contain information to relate estimated patterns to and from the CBD, corridor, to the actual patterns obtained m the O–D surveys for 1948 and 1955. In gravity model, factors to adjust for ographical bias were for the work trips to CBD.

atistical Analysis of Assigned Trips

As a common measure of the accuracy of h of the model distributions, the total rson trip output for the calibration and ecast runs of each model were assigned to pider network and compared by link with O–D survey assigned to the same netrk. All trips were defined as going from gin zone to destination zone. To achieve iformity, the gravity model trips were refined. Standard gravity model procedures were used to adjust the production to attraction trip tables to true origin to destination trip tables for directional assignments. To do this a 50–50 split of all production to attraction zone-to-zone transfers was assumed to get back to true origin to destination tables. For example, in determining the number of trip productions and trip attractions in any zone, the home end of any home based trip is always called the production and the nonhome end is always called the attraction. All trips with the general purpose of work would be considered as going from home to work, the work to home portions being reversed. After the model simulates trips by this definition, again assuming work trips, all home based trips are then converted to directional volumes by assuming 50 percent are trips from work to home.

Comparisons were made of directional link volumes assigned to a spider network and the differences recorded by volume group. Statistical analyses were made of these comparisons with the RMSE calculated for each model for each O–D volume group. The results of these analyses for the calibration of base year gravity and intervening opportunities models are shown in figure 10. Each model output includes the river time penalties. In the gravity model, K factors were used to adjust the work trips to the CBD. Next, RMSE by volume group for the forecast travel patterns for each of the models is shown in figure 11. The Fratar output is shown in relation to the O–D from only the 362 zones where compatibility for 1948 and 1955 could be achieved.

The analyses showed that the gravity model forecasts were closest to the O–D data in most volume groups up to 1,500 trips; the Fratar procedure and the intervening opportunities model had slightly better agreement in the very highest volume groups. River impedances were used with both the gravity and intervening opportunities models. However, the opportunities model could not be adjusted as closely as the gravity model to actual river crossings.

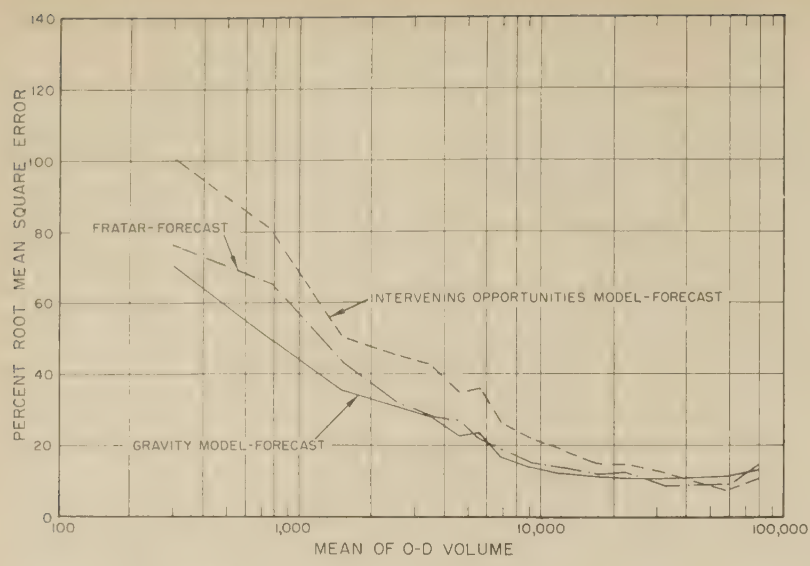


Figure 11.—RMSE for total trips for all purposes by volume groups forecast by Fratar, gravity, and intervening opportunities models, Washington, D.C., 1955.

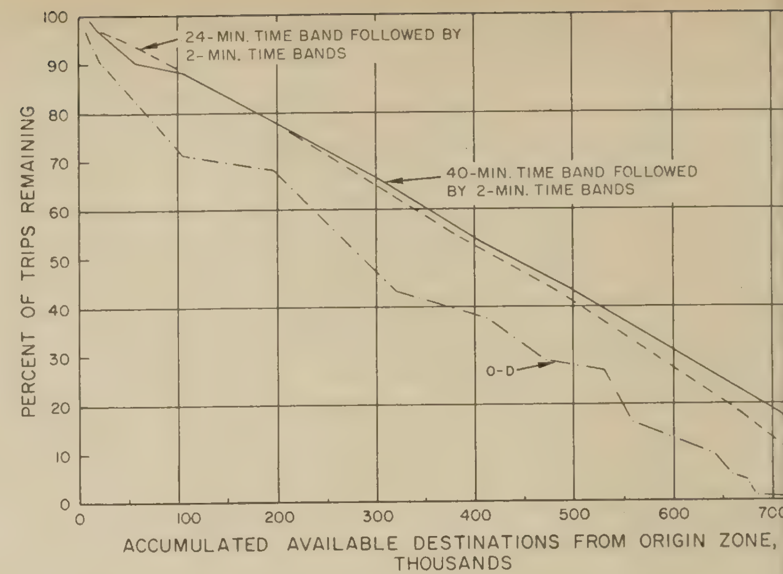


Figure 12.—Distribution of 10,687 home based work trips fr zone 48 from O-D survey and by time bands from compet opportunities model, Washington, D.C., 1948.

The results of trip distributions by the Fratar procedure were biased in that 195,000 trips, for one cause or another, could not be expanded. It might be expected that the Fratar procedures would produce results that would have increasing error as the forecast period was lengthened and land use changes increased in significance but, even over such a relatively short time as 7 years, the Fratar forecasts were not significantly better than the other model results.

Analysis

An attempt was made to test on a common basis the four procedures being used to distribute and forecast urban travel patterns. When large masses of data and a series of formulations requiring different definitions and calibration procedures are used, variations in the base conditions occur. These variations in the test conditions did not seriously detract from the analysis of the relative merits and weaknesses of each of the procedures.

Fratar procedure

The Fratar procedure requires no calibration and performed essentially as expected. Six trip purposes were used: home, work, shop, social-recreational, school, and miscellaneous. Over the 7-year period, the results from the Fratar procedure had a high level of accuracy in all analytical tests. However, the Fratar procedure was not tested specifically in a most critical area—the correct expansion of trips from zones that are changing from essentially undeveloped rural land uses to full urban development. Most zones in this class had to be eliminated from the analysis because of the incompatibility of 1948 and 1955 zone boundaries. The model by its nature does not require any type of adjustment because of the socio-economic trip linkages inherent in the travel patterns expanded. It was surprising that the Fratar procedure was only moderately better, in estimating trips to and from each of the eight sectors and the CBD, than the gravity and intervening opportunities models. This particular test is the most sensitive indicator of socio-economic bias.

The multipurpose Fratar procedure has some distinct advantages in the proper expansion of trips by purpose but also has certain drawbacks when compared with a single purpose Fratar. By expanding the number of trip categories to six, the possibility of zero volumes in the trip tables increases. In the Washington area, 195,000 trips were lost in the expansion because no trips had been made in 1948 in certain zones and certain trip categories. But in 1955, in the same zones and for the same trip purposes, 195,000 trips were made. This amounted to almost 10 percent of the 1955 trips. Had it been possible to include all fringe area zones in the analysis, the magnitude of the problem would have been much more serious. Again the most serious problems in forecasting occur for the urban fringe areas where, for example, shopping centers and golf courses are developed on farm or vacant land. It is not possible to achieve correct trip distributions for such areas unless base year trips are first synthesized for these areas with an interarea travel formula and then artificially superimposed on the base year travel pattern before the Fratar expansion is made.

Gravity model

The gravity model proved adequate in most respects. The calibration phases are particularly strong. Its orderly procedure allowed fine adjustments in the traveltime factors and the direct adjustment for socio-economic or geographic bias. The traveltime factors were stable over the 7-year period. One problem inherent in the gravity control procedure was the necessity for socio-economic adjustment factors—34 adjustment factors ranging from 2.23 to 0.29 were utilized. Developing relations between these factors and characteristics of the districts of residence or attraction can present problems in forecasting these characteristics. In Washington, D.C., the factors used to adjust work trips to the CBD were related to the average incomes of the residence zones. Another problem in use of the gravity model is the necessity for forecasting river impedan These topographical impedances, which probably related to historical deficiencie capacity that include the complete lack facilities, can be projected on the basis present and projected volume-capacity ra River barriers are a problem because t require a detailed, though not com analysis, and because they relate to suc critical area in terms of the analysis of fu transportation system needs.

Intervening opportunities model

The intervening opportunities model, though not previously utilized operation by the researchers, provided very good sults. Several methods of calibration tried and, after selection of the best pr dures, the model was calibrated with l difficulty. No socio-economic adjustment tors were used. The trip purposes defined by the intervening opportun model so that directional trips were m tained at all times. Fairly large river pedances were required and, as with gravity model, their projection was stra forward although detailed analysis was quired. However, even with the proje river impedance of 8 minutes, this m overestimated the 1955 Potomac River c ings. Examination of the results and skim trees indicated that very little additi improvement could have been made with a higher impedance value. A draw in the use of this model is the fact that t values change with time. In the ana reported here the change in L value forecast as a function of the change in number of trips. Refinement in methoc forecasting these L values will require finements in methods to project future lengths. Such a projection was not attem in the application reported here. Cons able research is currently underway on length trends. The University of Pen vania, Institute for Urban Studies in coo ation with the Urban Planning Divisio the Bureau of Public Roads has rec ıpleted a research project, *Trip Length* *ꞌiations among Urban Activities* and is ꞌently undertaking a second project, *p Length Variations among Urban Areas.*

.n additional point for consideration is the ; that in the calibration phase, the interꞌing opportunities models for the individual ꞌ purposes do not necessarily reproduce the ꞌ length frequency characteristics of the ꞌesponding O–D trips. When the indiꞌual purposes are summed to a total purpose trip length frequency characteristics are d because of compensating deviations in individual trip purposes. The explana- ı given for this situation is that in the ꞌortunities model, trip purposes per se ꞌe not used but the survey trip purposes ꞌe used as a convenient way of grouping ꞌ ends to apply individual L values. ꞌblems may arise when trips are distributed purpose; for example, when performing a ꞌdal split analysis. The L value derived ꞌreat a single purpose would differ from the ꞌalue used if the trip purpose were to be ꞌbined with others to form a total trip ꞌribution. In essence, the trip distributions purpose were meaningful only when ꞌımed to a total trip purpose distribution.

ꞌnpeting opportunities model

ꞌhe fact that the competing opportunities ꞌdel could not be calibrated with the ꞌshington, D.C., O–D data and on a zonal ꞌis was disappointing. Time bands of ꞌform width were not applicable and no ꞌple procedure could be derived for select- nonuniform time bands. Many different ꞌbinations of time bands were tried before ꞌset was obtained that even approached ꞌviding correct trip length characteristics. ꞌen the different trial and error approaches arriving at appropriate time bands proved ꞌile, a theoretical approach to the problem ꞌs attempted. The required type of probꞌlity curve for selected Washington, D.C. ꞌes was derived. It was a plot of the ꞌcent of trips remaining to be distributed ꞌted to the accumulated available opporꞌities. Working within the framework of model, it was not possible to duplicate the ꞌbability curve derived from the selected ꞌal O–D data. Figure 12 illustrates the ꞌree to which two different time band ꞌupings approach the actual O–D probꞌlity groupings.

ture research

Several areas for future research were ꞌermined when the models were analyzed a common basis. The use of different ꞌp purpose categories as input to the gravity ꞌdel trip distribution procedure should be ꞌplored as a means of eliminating the socioꞌnomic adjustment factors. As a first empt, a five-purpose, true origin and destination purpose definition model consisting of (1) home to work trips, (2) work to home trips, (3) home to other trips, (4) other to home trips, and (5) nonhome based trips should be tried.

Research is needed to develop more sophisticated procedures to adjust the base year L values to the future year for the intervening opportunities model. Certainly, better information on future trip length in terms of either miles or minutes would be very helpful. Also, some work is required to test the effect of the trip universe used on accuracy and the need to make adjustments to force all the trips to be sent. For example, the inclusion or exclusion of the external trip ends creates a slightly different set of intervening opportunities for any given origin zone.

Additional research is also needed in which the impedance effect on travel of physical or topographical features would be studied. More insight into basic causes of the impedance is essential for the development of comprehensive techniques for projecting the impedance. The advantages of the purpose Fratar model, that is the more direct consideration of land use changes, must be investigated in relation to the resultant and very significant loss in expanded trips. Finally research is required to develop calibration procedures for the competing opportunities model.

Summary

The overall accuracy of the gravity model was slightly better than the accuracy of the intervening opportunities model in base year simulation and in forecasting. But more parameters were used in the gravity model calibration. When socio-economic adjustment factors were used, the gravity model test results had less error than the intervening opportunities model when trips by sector to the CBD were examined. However, better results were obtained from the opportunities model than from the unadjusted gravity model. The cause of this difference in results from the two models is not definite but may have been either the conceptual basis of the models or the trip purpose stratifications used. The intervening opportunities model was slightly less difficult to calibrate than the gravity model because fewer parameters were used. However, adjustments required for future L values reduced this advantage in making the forecasts. The gravity and intervening opportunities models proved to be about equal in reliability and utility in simulating the 1948 and 1955 trip distributions for Washington, D.C.

The Fratar growth factor procedure was useful in correctly expanding trips for stable areas but had significant weaknesses related to areas undergoing land use changes. The concentration of error for areas experiencing growth in trips emphasizes the need for supplemental procedures to provide a base year synthesized trip pattern for such areas. The magnitude of this problem in relation to the favorable results attained with the gravity and intervening opportunities models indicates that the use of a travel model provides a more direct and efficient approach to trip distribution for growing urban areas. It was not possible to adequately calibrate the competing opportunities model for use in determining trip distributions between areas as small as the traffic zones used in Washington, D.C.

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