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DESIGNING CONCRETE MIXTURES FOR PAVEMENTS

BY THE DIVISION OF TESTS, PUBLIC ROADS ADMINISTRATION

Reported by W. F. KELLERMANN, Materials Engineer

THE PURPOSE of this report is to describe a method of investigating the flexural strength of concrete in connection with the problem of designing concrete mixtures for pavements and to present the results of a series of laboratory tests which demonstrate how flexural strength may vary over a wide range due to the characteristics of the aggregates employed.

All pavement concrete, particularly that laid in the Northern States, must be designed so as to afford maximum resistance to weathering agencies. Assuming that the constituent materials are durable, it is generally agreed that this may be accomplished either by placing a maximum limit on the water-cement ratio or by requiring a cement content sufficiently high to insure that the maximum allowable water content will not be exceeded. The necessity for limiting the water-cement ratio to insure durability applies to all concrete exposed to the weather.

Insofar as strength characteristics are concerned, concrete for most purposes need only be investigated for compressive strength. However, compressive strength is not of primary importance in concrete for pavement slabs because of the character of the stresses to which such slabs are subjected. Live loads and changes in temperature and moisture, either alone or in combination, produce tensile and flexural stresses which pavements must resist in order to perform the function for which they are designed. Of the two, the flexural stresses are the more important. For this reason, flexural or bending stresses rather than compressive stresses become critical in cases where the concrete mixture is to be designed for use in highway pavements. Therefore the designer of concrete paving mixtures must give consideration not only to the factors that affect durability but also to those variables that affect flexural strength.

TESTS MADE TO DETERMINE CEMENT FACTOR FOR VARIOUS COMBINATIONS OF AGGREGATES

The specifications for pavement concrete of the American Association of State Highway Officials specify that the proportions shall be based on laboratory tests and shall be such that, in the judgment of the engineer, they will assure durable concrete of the plasticity and workability required, and which will attain at the age of 14 days a modulus of rupture not less than 550 pounds per square inch when tested by the third point method of loading. In order to assure durability it is further specified that the net water-cement ratio shall in no case exceed 0.80 by volume (6.0 gallons per sack of cement).

The tests reported in this paper were made in an investigation of the design of concrete mixtures in which 25 different combinations of fine and coarse aggregate were used, the requirement being compliance with the above specifications. The work was done in the laboratory of the Public Roads Administration during 1936 at the request of the State Highway and Public Works Commission of North Carolina. The purpose was to establish the cement factor required for various combinations of available aggregates, the information thus obtained to be used as the basis for bidding. Seven sands and 13 coarse aggregates, all commercially available in North Carolina, were investigated. The 25 combinations of materials were selected on the basis of economic availability and represented practically all combinations of aggregates that were likely to be encountered in practice in that State.

As will be noted from table 1 the sands varied in grading over a wide range, the fineness modulus of the finest being 2.12 and that of the coarsest, 3.37. All coarse aggregates were separated into three sizes and recombined for test in accordance with the grading shown in table 2, the maximum size being 2 inches. This table also gives the mineral composition of both the fine and coarse aggregates as well as their physical properties. One lot of cement, meeting all A. S. T. M. requirements, was used throughout.

In order to determine the required cement content for each combination of materials it was decided to establish directly the relation between cement content and flexural strength at 14 days, using mixtures with five different cement factors as follows: 4.4, 5.2, 6.0, 6.8, and 7.2 sacks of cement per cubic yard of concrete. This procedure also afforded an opportunity to establish the corresponding relations between water-cement ratio and flexural strength.

TABLE 1.—*Sieve analysis of fine aggregates for concrete mixes using North Carolina aggregates*

Fine aggregate	Percentage retained on sieve no.—						Fineness modulus
	4	8	16	30	50	100	
1	0	0	2.8	35.8	77.3	95.9	2.12
2	0	0	5.3	42.8	79.4	94.4	2.22
3	.5	4.0	19.6	58.0	93.1	99.4	2.75
4	.2	4.1	21.2	63.2	93.2	99.0	2.81
5	0	7.3	26.8	62.1	89.3	97.2	2.83
6	.1	7.1	30.4	68.3	91.0	98.4	2.95
7	.3	14.6	44.2	81.2	97.6	99.4	3.37

The decision to design the mixes on the basis of a fixed cement factor rather than by the use of fixed water-cement ratios was made because of the fact that in the North Carolina specifications the final proportions are stated in terms of a fixed cement factor for each aggregate combination. The problem, therefore, resolved itself into one of designing 125 different concrete mixes: Five cement contents with each of the 25 combinations of aggregates. The problem was complicated by the fact that both angular and rounded coarse aggregates were used in combination with sands graded from extremely fine to extremely coarse.

In keeping with North Carolina practice the different mixes were designed with a view to maintaining a minimum of sand consistent with satisfactory workability at a consistency corresponding to a slump of 2½ inches. This was accomplished by making numerous trial batches, the ratio of fine to coarse aggregate

TABLE 2.—*Physical properties of aggregates for concrete mixes using North Carolina aggregates*

Aggregate	Type	Bulk specific gravity	Weight per cu. ft.[1]		Voids		Absorption	Abrasion loss	
			Dry rodded	Dry loose	Dry rodded	Dry loose		Los Angeles[2]	Deval[3]
STONE									
			Pounds	*Pounds*	*Percent*	*Percent*	*Percent*	*Percent*	*Percent*
1	Dolomite	2.85	105	97	41	45	0.27	30.4	4.3
2	do	2.82	103	93	42	47	.56	33.0	5.0
3	Limestone	2.79	102	92	41	47	.44	21.1	2.6
4	Granite	2.69	101	91	40	46	.46	51.1	4.0
5	do	2.65	102	93	38	44	.46	53.5	2.6
6	do	2.64	102	92	38	44	.58	37.9	2.4
7	do	2.63	100	91	39	44	.52	58.4	3.9
8	do	2.62	95	87	42	47	.28	30.1	2.0
9	do	2.62	100	90	39	45	.44	41.9	3.6
GRAVEL									
10	Gneiss	2.67	106	98	36	41	1.19	47.9	18.5
11	Quartz	2.63	111	103	32	37	.22	53.7	14.6
12	do	2.63	109	103	34	37	.28	40.9	8.2
13	do	2.63	111	104	32	37	.32	54.9	19.4
SAND									
1	Quartz	2.64	98	91	40	45	0.40		
2	do	2.63	100	93	39	43	.50		
3	do	2.63	98	93	40	43	.40		
4	do	2.64	98	92	40	44	.40		
5	do	2.66	103	97	38	42	.35		
6	do	2.64	101	94	39	43	.32		
7	do	2.60	99	94	39	42	.70		

[1] All coarse aggregates proportioned to give following grading in concrete. Unit weights determined for this grading:

	Percent
Total retained on 2-inch sieve	0
Total retained on 1½-inch sieve	15
Total retained on ¾-inch sieve	70
Total retained on No. 4 sieve	100
Fineness modulus	7.75

[2] Grading A used with both stone and gravel.

[3] Grading A used with gravel. Stone sample consisted of 50 pieces weighing 5 kilograms.

being adjusted, in each case, until, in the opinion of the operator, the minimum sand content was reached.

The final proportions for each of the 5 cement factors and for each of the 25 aggregate combinations are shown in table 3. This table includes, in addition to the mix proportions by weight, the water-cement ratio by volume, the value of W_c, that is, the volume of water in a unit volume of concrete, the ratio b/b_0 as defined by Talbot and Richart,[1] the mortar voids ratio,[2] the percentage of sand by weight, the fineness modulus of the combined aggregate, and the resulting slump in inches.

SEVERAL THEORIES OF MIX DESIGN TRIED

In view of the fact that it was necessary to design 25 different mixes for each cement content, attempts were made to apply certain theories of mix design to the problem of determining the proper percentage of sand to use in each case. An attempt to use the fineness modulus theory of Abrams[3] proved unsuccessful due to the fact that a fixed value for maximum permissible fineness modulus could not be used, even in the case of a given sand combined with several coarse aggregates of the same general particle shape.

Next, an attempt was made to design on the basis of a fixed value for the mortar voids ratio, that is, a constant excess of mortar over the amount necessary to fill the voids in the coarse aggregate. This was found satisfactory so long as particle shape remained reasonably constant. However, as will be noted in table 3, a

TABLE 3.—*Data on concrete mixes using North Carolina aggregates*

CEMENT FACTOR—4.4 SACKS PER CUBIC YARD

Aggregate		Proportions by weight	Water-cement ratio by volume	W_c[1]	b/b_0	Mortar voids ratio	Sand to total aggregate by weight	Fineness modulus of combined aggregate	Slump
Fine	Coarse								
		Pounds					*Percent*		*Inches*
1	1	94:254:548	1.04	0.169	0.920	1.19	31.7	5.88	2.4
	2	94:264:524	1.08	.176	.920	1.18	33.5	5.79	2.3
	3	94:267:519	1.06	.173	.920	1.18	34.0	5.77	2.3
	10	94:226:553	.97	.158	.920	1.21	29.0	6.11	2.5
2	4	94:256:514	1.04	.169	.920	1.19	33.2	5.88	2.5
	5	94:240:526	1.02	.166	.920	1.20	31.3	6.01	2.7
	6	94:245:520	1.01	.164	.920	1.20	32.0	5.98	2.5
	7	94:246:515	1.02	.166	.920	1.20	32.3	5.96	2.4
	8	94:263:492	1.05	.171	.920	1.19	34.8	5.83	2.6
	9	94:251:508	1.02	.166	.920	1.19	33.1	5.93	2.4
	11	94:205:583	.86	.140	.920	1.23	26.0	6.31	2.6
	13	94:200:587	.86	.140	.920	1.24	25.4	6.35	2.5
3	4	94:272:492	1.07	.174	.880	1.30	35.6	5.94	2.4
	5	94:263:501	1.03	.168	.880	1.31	34.4	6.02	2.6
	6	94:263:497	1.04	.169	.880	1.31	34.6	6.02	2.5
	7	94:267:492	1.03	.168	.880	1.31	35.2	5.99	2.4
	9	94:272:486	1.03	.168	.880	1.30	35.9	5.96	2.5
4	13	94:224:550	.95	.155	.860	1.45	28.9	6.32	2.6
5	7	94:274:492	1.01	.164	.880	1.31	35.8	6.00	2.5
	9	94:276:486	1.03	.168	.880	1.30	36.2	5.98	2.5
6	4	94:280:480	1.10	.179	.860	1.36	36.8	5.96	2.4
	6	94:277:486	1.03	.168	.860	1.37	36.3	6.01	2.4
	11	94:237:545	.90	.147	.860	1.44	30.3	6.30	2.6
7	7	94:297:458	1.04	.169	.820	1.50	39.3	6.02	2.3
	12	94:261:519	.89	.145	.820	1.59	33.5	6.27	2.4

[1] Volume of water per unit volume of concrete.

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[1] A. N. Talbot and F. E. Richart, University of Illinois Engineering Experiment Station Bulletin 137. The term b/b_0 is defined as the ratio of the absolute volume of coarse aggregate in a unit volume of concrete (b) to the absolute volume of coarse aggregate in a unit volume of coarse aggregate (b_0). Stated in different terms, it is the apparent volume of coarse aggregate in a unit volume of concrete. The values given in table 3 are on a dry-loose basis.

[2] The ratio of the volume of mortar in a unit volume of concrete to the volume of the voids in the coarse aggregate, determined in a dry-loose condition.

[3] The Design of Concrete Mixtures, by D. A. Abrams. Bulletin No. 1, Structural Materials Research Laboratory, Lewis Institute.

TABLE 3.—*Data on concrete mixes using North Carolina aggregates*—Continued

Aggregate: Fine	Aggregate: Coarse	Proportions by weight	Water-cement ratio by volume	W_c[1]	b/b_0	Mortar voids ratio	Sand to total aggregate by weight	Fineness modulus of combined aggregate	Slump
CEMENT FACTOR—5.2 SACKS PER CUBIC YARD									
		Pounds					*Percent*		*Inches*
1	1	94:208:459	0.87	0.168	0.910	1.22	31.2	5.90	2.5
	2	94:216:438	.91	.175	.910	1.21	33.0	5.81	2.6
	3	94:217:434	.90	.173	.910	1.21	33.3	5.80	2.5
	10	94:183:463	.82	.158	.910	1.24	28.3	6.15	2.6
2	4	94:207:430	.89	.171	.910	1.22	32.5	5.93	2.6
	5	94:199:438	.85	.164	.910	1.23	31.2	6.02	2.6
	6	94:199:435	.86	.166	.910	1.23	31.4	6.01	2.6
	7	94:202:430	.86	.166	.910	1.22	32.0	5.99	2.5
	8	94:215:410	.89	.171	.910	1.21	34.4	5.85	2.5
	9	94:205:425	.86	.166	.910	1.22	32.5	5.95	2.6
	11	94:169:486	.72	.139	.910	1.27	25.8	6.32	2.5
	13	94:162:491	.73	.141	.910	1.27	24.8	6.37	2.5
3	4	94:225:411	.89	.171	.870	1.32	35.4	5.96	2.5
	5	94:217:420	.85	.164	.870	1.34	34.1	6.04	2.6
	6	94:218:417	.85	.164	.870	1.34	34.3	6.02	2.6
	7	94:218:412	.87	.168	.870	1.33	34.6	6.02	2.5
	9	94:222:407	.87	.168	.870	1.33	35.3	5.99	2.6
4	13	94:184:459	.79	.152	.850	1.48	28.6	6.34	2.6
5	7	94:224:412	.85	.164	.870	1.33	35.2	6.03	2.6
	9	94:224:407	.87	.168	.870	1.33	35.5	6.02	2.6
6	4	94:231:401	.92	.177	.850	1.39	36.6	5.98	2.7
	6	94:224:407	.88	.170	.850	1.40	35.5	6.05	2.6
	11	94:194:455	.76	.146	.850	1.48	29.9	6.31	2.6
7	7	94:243:382	.88	.170	.810	1.53	38.9	6.03	2.5
	12	94:212:433	.76	.146	.810	1.63	32.9	6.30	2.5
CEMENT FACTOR—6.0 SACKS PER CUBIC YARD									
1	1	94:173:393	0.76	0.169	0.900	1.24	30.6	5.94	2.5
	2	94:181:377	.78	.173	.900	1.24	32.4	5.84	2.6
	3	94:181:373	.78	.173	.900	1.24	32.7	5.84	2.7
	10	94:153:397	.71	.158	.900	1.27	27.8	6.17	2.6
2	4	94:174:369	.76	.169	.900	1.24	32.0	5.95	2.5
	5	94:162:377	.75	.167	.900	1.25	30.1	6.07	2.6
	6	94:166:372	.75	.167	.900	1.25	30.9	6.04	2.5
	7	94:167:369	.75	.167	.900	1.25	31.2	6.02	2.6
	8	94:181:352	.77	.171	.900	1.24	34.0	5.88	2.5
	9	94:167:365	.77	.171	.900	1.25	31.4	6.01	2.6
	11	94:138:417	.64	.142	.900	1.30	24.9	6.37	2.5
	13	94:133:422	.64	.142	.900	1.30	24.0	6.42	2.4
3	4	94:189:353	.77	.171	.860	1.36	34.9	5.98	2.7
	5	94:182:359	.74	.164	.860	1.37	33.6	6.06	2.7
	6	94:184:356	.74	.164	.860	1.37	34.1	6.04	2.6
	7	94:185:353	.74	.164	.860	1.37	34.4	6.02	2.4
	9	94:187:348	.75	.167	.860	1.36	35.0	6.00	2.7
4	13	94:155:394	.68	.151	.840	1.52	28.2	6.36	2.5
5	7	94:189:353	.73	.162	.860	1.37	34.9	6.04	2.6
	9	94:191:348	.74	.164	.860	1.36	35.4	6.02	2.6
6	4	94:196:344	.78	.173	.840	1.42	36.3	5.99	2.5
	6	94:191:348	.75	.167	.840	1.43	35.4	6.05	2.4
	11	94:165:389	.65	.144	.840	1.51	29.8	6.32	2.3
7	7	94:206:328	.75	.167	.800	1.56	38.6	6.05	2.4
	12	94:178:371	.66	.147	.800	1.67	32.4	6.32	2.5
CEMENT FACTOR—6.8 SACKS PER CUBIC YARD									
1	1	94:150:343	0.65	0.164	0.890	1.28	30.4	5.95	2.3
	2	94:156:327	.68	.171	.890	1.26	32.3	5.85	2.6
	3	94:158:324	.67	.169	.890	1.26	32.8	5.84	2.6
	10	94:128:347	.63	.159	.890	1.30	26.9	6.21	2.6
2	4	94:148:321	.68	.171	.890	1.27	31.6	5.98	2.5
	5	94:139:327	.66	.166	.890	1.28	29.8	6.09	2.6
	6	94:143:324	.65	.164	.890	1.28	30.6	6.06	2.5
	7	94:141:322	.67	.169	.890	1.28	30.5	6.06	2.6
	8	94:153:307	.68	.171	.890	1.27	33.3	5.92	2.6
	9	94:144:317	.67	.169	.890	1.28	31.2	6.02	2.6
	11	94:115:364	.57	.144	.890	1.34	24.0	6.42	2.5
	13	94:110:368	.58	.146	.890	1.34	23.0	6.48	2.5
3	4	94:164:307	.66	.166	.850	1.39	34.8	5.98	2.5
	5	94:156:313	.65	.164	.850	1.41	33.3	6.08	2.6
	6	94:159:310	.64	.161	.850	1.40	33.9	6.05	2.5
	7	94:159:307	.65	.164	.850	1.40	34.1	6.04	2.6
	9	94:161:302	.66	.166	.850	1.39	34.8	6.02	2.6

TABLE 3.—*Data on concrete mixes using North Carolina aggregates*—Continued

Aggregate: Fine	Aggregate: Coarse	Proportions by weight	Water-cement ratio by volume	W_c[1]	b/b_0	Mortar voids ratio	Sand to total aggregate by weight	Fineness modulus of combined aggregate	Slump
CEMENT FACTOR—6.8 SACKS PER CUBIC YARD—Continued									
		Pounds					*Percent*		*Inches*
4	13	94:130:343	.61	.154	.830	1.55	27.5	6.40	2.6
5	7	94:161:307	.65	.164	.850	1.40	34.4	6.07	2.6
	9	94:164:302	.65	.164	.850	1.39	35.2	6.03	2.7
6	4	94:165:301	.70	.176	.830	1.44	35.4	6.03	2.5
	6	94:161:303	.67	.169	.830	1.46	34.7	6.08	2.6
	11	94:137:340	.59	.149	.830	1.54	28.7	6.38	2.5
7	7	94:178:286	.65	.164	.790	1.59	38.4	6.05	2.5
	12	94:152:323	.58	.146	.790	1.71	32.0	6.34	2.4
CEMENT FACTOR—7.2 SACKS PER CUBIC YARD									
1	1	94:137:322	0.63	0.168	0.885	1.28	29.8	5.98	2.6
	2	94:143:308	.65	.173	.885	1.27	31.7	5.88	2.6
	3	94:145:305	.64	.171	.885	1.27	32.2	5.86	2.5
	10	94:119:325	.60	.160	.885	1.31	26.8	6.23	2.6
2	4	94:136:302	.64	.171	.885	1.28	31.1	6.00	2.5
	5	94:128:309	.62	.165	.885	1.30	29.3	6.12	2.5
	6	94:130:306	.62	.165	.885	1.29	29.8	6.10	2.5
	7	94:133:302	.62	.165	.885	1.29	30.6	6.06	2.4
	8	94:141:289	.64	.171	.885	1.28	32.8	5.94	2.4
	9	94:135:299	.62	.165	.885	1.29	31.1	6.04	2.4
	11	94:105:341	.55	.147	.885	1.35	23.5	6.45	2.5
	13	94:102:345	.55	.147	.885	1.35	22.8	6.49	2.4
3	4	94:151:289	.63	.168	.845	1.40	34.3	6.01	2.6
	5	94:144:294	.61	.163	.845	1.42	32.9	6.10	2.6
	6	94:146:292	.61	.163	.845	1.41	33.3	6.08	2.6
	7	94:146:289	.62	.165	.845	1.41	33.6	6.07	2.6
	9	94:149:284	.62	.165	.845	1.41	34.4	6.04	2.6
4	13	94:120:322	.58	.155	.825	1.58	27.1	6.41	2.5
5	7	94:149:289	.61	.163	.845	1.41	34.0	6.09	2.6
	9	94:151:285	.62	.165	.845	1.41	34.6	6.06	2.5
6	4	94:155:280	.66	.176	.825	1.46	35.6	6.02	2.5
	6	94:150:285	.63	.168	825	1.49	34.5	6.09	2.4
	11	94:127:318	.56	.149	.825	1.57	28.5	6.39	2.5
7	7	94:165:267	.62	.165	.785	1.62	38.2	6.06	2.5
	12	94:141:304	.55	.147	.785	1.74	31.7	6.35	2.5

change from angular to rounded coarse aggregate resulted in an increase in the value of this ratio. (Compare combinations 2–4 to 2–9, inclusive, with combinations 2–11 and 2–13.)

This particular difficulty was overcome by using a fixed value of b/b_0 in place of a constant mortar voids ratio. After making many trial batches it was found that, for a given cement content and a given sand, a constant value of b/b_0 could be used irrespective of type of coarse aggregate. (See table 3.) It was noted, furthermore, that certain consistent changes in b/b_0 resulted from changing the cement factor and sand grading. Thus, for a given sand, table 3 shows that an increase in the cement factor of 0.8 sack resulted in a decrease of 0.01 in b/b_0 for equal workability. Furthermore, as the sand used became coarser, it was found necessary to reduce the value of b/b_0. Thus at 6.0 sacks per cubic yard the value of this ratio decreased from 0.90 for sand No. 1 (F. M.=2.12) to 0.80 for sand No. 7 (F. M.=3.37).

It is believed that the systematic variation in b/b_0 with changes in cement content revealed by these tests together with the principle stated by Lyse[4] in 1932 to the effect that, for a given combination of materials

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[4] Inge Lyse, Tests of Consistency and Strength of Concrete Having Constant Water Content. Proceedings A. S. T. M., vol. 32, pt. II, 1932.

and a given consistency, the total quantity of water per unit of volume of concrete (W_c) is constant regardless of the cement content, makes it possible to simplify considerably the problem of designing mixtures of varying cement content. Having established by trial the proper value of b/b_0 to use with given aggregates and with a given cement factor, the proportions required for the same consistency with any other cement factor may be obtained by computation, provided the aggregates have the same gradations as those used in the trial batch. This will be illustrated by an example.

Given a mix having:

The proportions 94:274:492 by weight.
Water-cement ratio 1.01 by volume.
Specific gravities of materials: Cement, 3.16; fine aggregate, 2.66; coarse aggregate, 2.63.

Percentage of voids in coarse aggregate (dry–loose), 44.5, the corresponding solid volumes per 1-sack batch would be as follows:

		Cu. ft.
Cement	$\frac{94}{62.4\times3.16}$	=0.48
Fine aggregate	$\frac{274}{62.4\times2.66}$	=1.65
Coarse aggregate	$\frac{492}{62.4\times2.63}$	=3.00
Water *(W/C)*		=1.01
Yield		=6.14

$$\text{Cement factor}=\frac{27}{6.14}=4.4 \text{ sacks per cubic yard.}$$

$$\text{Bulk volume of coarse aggregate}=\frac{3.00}{1.00-0.445}=5.41 \text{ cubic feet.}$$

$$\text{Then } b/b_0=\frac{5.41}{6.14}=0.88.$$

$$\text{Water per unit volume of concrete } (W_c)=\frac{1.01}{6.14}=0.164.$$

Having analyzed the above mix and determined the values of b/b_0 and W_c as 0.88 and 0.164, respectively, another mix will be designed with the same materials but with a cement factor of 6.8 sacks of cement per cubic yard of concrete, an increase of 2.4 sacks per cubic yard.

Following the procedure outlined, the value for W_c for the new mix would remain constant at 0.164. The new value for b/b_0 is determined as follows: For each increase of 0.8 sack per cubic yard in cement factor, b/b_0 is decreased 0.01. Therefore, the new value of b/b_0 is $0.88-\frac{2.4}{0.8}\times0.01=0.85$.

The yield per 1-sack batch for the new mix would be $\frac{27}{6.8}=3.97$ cubic feet and the apparent or bulk volume of coarse aggregate would be $3.97\times0.85=3.37$ cubic feet. The corresponding solid volume of coarse aggregate $(b)=3.37\times(1-0.445)=1.87$ cubic feet; the solid volume of cement $(c)=0.48$ cubic feet; and the volume of water $(W/C)=3.97\times0.164=0.65$ cubic feet; making a total of 3.00 cubic feet. The only unknown quantity remaining is the volume of fine aggregate, which is determined by subtracting the sum of the solid volumes of coarse aggregate, cement, and water from the total yield. Therefore the solid volume of fine aggregate $=3.97-3.00=0.97$ cubic feet. The complete proportions per 1-sack batch for the new mix would be as follows:

	Cu. ft.
Cement (solid)	0.48
Fine aggregate (solid)	0.97
Coarse aggregate (solid)	1.87
Water *(W/C)*	0.65
Total (solid)	3.97

Multiplying the above by 62.4 times the appropriate values for specific gravity gives the following:

Weight proportions=94:161:307
$W/C=0.65$ (by volume).

LOW WATER-CEMENT RATIO MAINTAINED USING FINE SANDS

By this procedure any mix, within a reasonable range, can readily be calculated provided the proper values of b/b_0 and W_c have been predetermined on the materials under investigation and, further, provided the slump is to remain constant. As can be seen from the example given above, the only unknown quantity in the mix is the amount of sand and this is determined by simple calculation. In these tests the water-cement ratio determined by calculation from the law of constant water per unit volume of concrete for a constant slump was not always the exact value needed to obtain the proper slump. However, it was possible in all cases to make the proper adjustment by slight changes in the ratio of water to sand, keeping the sum of the absolute volumes of the two ingredients constant. Even though the general law did not hold precisely in all individual cases, that is, to the third decimal, the following tabulation, which gives average values for the 25 combinations, will illustrate its accuracy.

Cement factor, sacks per cubic yard:	W_c
4.4	0.164
5.2	.163
6.0	.163
6.8	.163
7.2	.163

In connection with the procedure employed, that is, the use of the highest value of b/b_0 compatible with workability, it is interesting to note that for a given coarse aggregate and a given cement factor it was possible to use approximately the same water-cement ratio irrespective of whether a coarse or fine sand was used. For instance, in table 3, using a cement factor of 6.0 sacks per cubic yard, coarse aggregate No. 7 was used with sands 2, 3, 5, and 7. These sands varied in fineness modulus from 2.22 to 3.37. However, the total range in water-cement ratio was only 0.02 (from 0.73 to 0.75), demonstrating that, by proper proportioning, it is possible to maintain a low water-cement ratio when using fine sands.

The concrete was mixed in a laboratory mixer of the type shown in figure 1. In order to approximate field conditions, the coarse aggregate was handled in a saturated surface-dry condition and the sand in a wet condition, correction for the free water in the sand being made when computing the water-cement ratio. Test specimens consisted of 6- by 6-inch beams, 21 inches long. In all, 625 specimens—25 combinations of material, times 5 mixes, times 5 specimens per mix made on each of 5 different working days—were fabricated. All strength tests were made at 14 days, the specimens being tested by the third point method

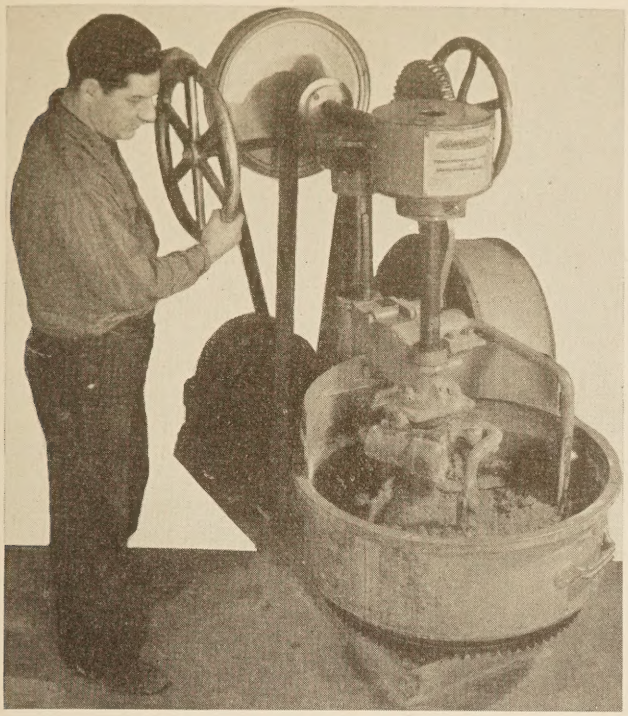


Figure 1.—Laboratory Mixer Used in Preparing Test Mixtures.

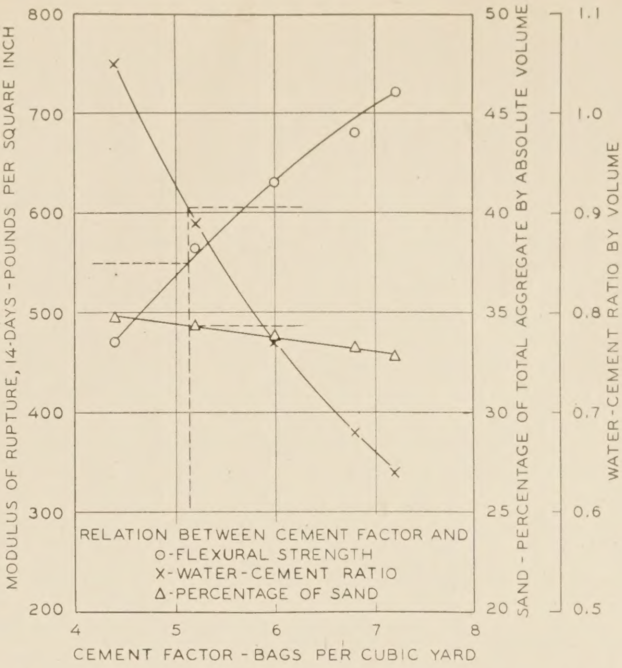
in accordance with A. S. T. M. Method C 78–39. The specimens were placed in the testing machine with the side, as molded, in tension.

The average flexural strengths for each combination of materials for each of the five different proportions are given in table 4. In discussing these results the various combinations of materials will be referred to by number. Thus, combination 2–4 refers to sand No. 2 combined with coarse aggregate No. 4. In order to illustrate the method of plotting the results for the purpose of determining the required cement factor for a specified modulus of rupture, two examples will be given.

CHART ENABLES COMPUTATION OF MIX DESIGN

Figure 2 shows a typical chart giving the relations between modulus of rupture and cement factor, water-cement ratio and cement factor, and percentage of sand and cement factor. Considering first the strength-cement factor relationship, it will be noted from the curve that the required amount of cement to produce a modulus of rupture of 550 pounds per square inch was 5.1 sacks per cubic yard. The corresponding water-cement ratio was 0.91 and the percentage of sand 34. From this type of chart a complete mix design could be computed for any strength specified within the range covered. In figure 2 for instance, the range in strength would be from about 500 to 700 pounds per square inch.

Frequently specifications for concrete contain a limiting value for water-cement ratio in order to assure durability. Assuming a maximum allowable value of 6 gallons per sack ($W/C=$ 0.80 by volume), it will be observed from figure 2 that the required strength was obtained with a water-cement ratio of 0.91, which is more than allowable. From the water-cement ratio–cement factor curve it is seen that, in order to keep within the limits dictated by durability considerations, it would be necessary to use a cement factor of 5.8 sacks per cubic yard instead of 5.1 sacks, the resulting flexural strength being in excess of 600 pounds per square inch.



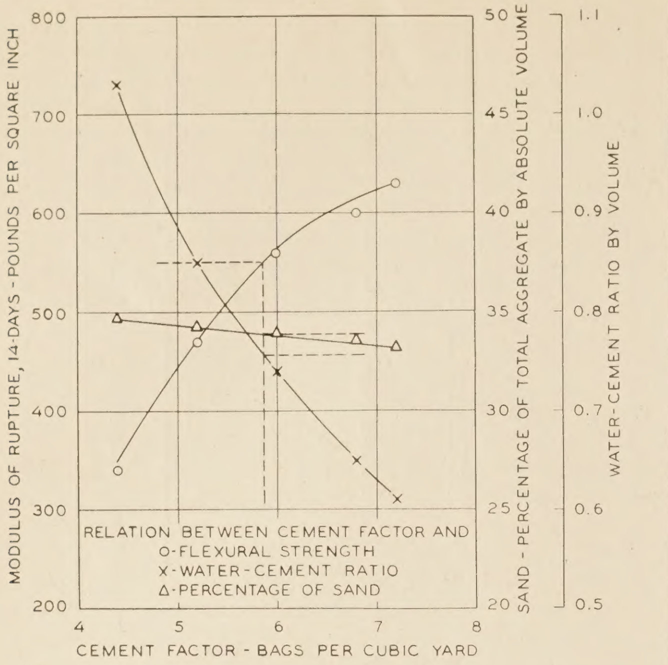
AGGREGATE	NUMBER	TYPE	SP. GR.	PERCENT ABS.	F.M.
FINE	2	SAND	2.63	0.50	2.22
COARSE	8	GRANITE	2.62	0.28	7.75

Figure 2.—Concrete Mix Design Chart for Combination 2–8.

Table 4.—*Average flexural strength, 14 days, of 6- by 6-inch beams tested on 18-inch span with third-point loading, for concrete mixes using North Carolina aggregates*

Aggregate		Modulus of rupture [1] for cement factor (sacks per cubic yard) of—				
Fine	Coarse	4.4	5.2	6.0	6.8	7.2
		Lb. per sq. in.	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*	*Lb. per sq. in.*
1	1	470	615	655	795	765
	2	460	575	655	695	755
	3	435	570	715	730	745
	10	380	425	510	535	545
2	4	455	510	540	630	655
	5	430	505	575	635	630
	6	475	570	620	640	615
	7	440	505	555	610	640
	8	470	565	630	680	720
	9	470	565	600	665	680
	11	490	500	545	635	635
	13	430	485	535	560	615
3	4	350	470	570	600	610
	5	340	470	560	600	630
	6	355	470	565	645	630
	7	365	445	575	610	625
	9	390	495	620	665	660
4	13	430	485	510	585	585
5	7	395	490	565	610	670
	9	395	510	615	675	695
6	4	425	490	530	630	620
	6	465	545	585	685	670
	11	480	515	575	635	655
7	7	395	490	565	630	620
	12	505	555	630	675	685
Average		428	513	584	642	654

[1] Each value is average of 5 tests.



AGGREGATE	NUMBER	TYPE	SP. GR.	PERCENT ABS.	F. M.
FINE	3	SAND	2.63	0.40	2.75
COARSE	5	GRANITE	2.65	0.46	7.75

Figure 3.—Concrete Mix Design Chart for Combination 3–5.

Figure 3 gives the same type of data for a different combination of materials. The required cement factor as determined from the curve is 5.9 sacks, with a corresponding water-cement ratio of 0.75. In this case the strength is the governing factor while in the former case the maximum allowable water-cement ratio governs.

Charts similar to figures 2 and 3 were drawn for each of the 25 combinations of materials and the required cement factors obtained from the strength curves as illustrated. These cement factors are enumerated in table 5 and show values ranging from 4.9 sacks for combination 1–1, to 7.1 sacks for combination 1–10, or, for all practical purposes, from 5 to 7 sacks. In view of the fact that the same sand was used in both combinations, the strength differential in this case is a direct function of the concrete-making properties of the two coarse aggregates.

Table 5.—*Cement factor required for 550 pounds per square inch modulus of rupture, third point loading, for concrete mixes using North Carolina aggregates*

Fine aggregate	Coarse aggregate	Cement factor
		Sacks per cubic yard
1	1	4.9
	2	5.1
	3	5.1
	10	7.1
2	4	5.8
	5	5.7
	6	5.1
	7	6.0
	8	5.1
	9	5.0
	11	5.8
	13	6.2
3	4	5.8
	5	5.9
	6	5.9
	7	6.1
	9	5.5
4	13	6.4
5	7	5.9
	9	5.5
6	4	6.0
	6	5.3
	11	5.6
7	7	5.9
	12	5.0

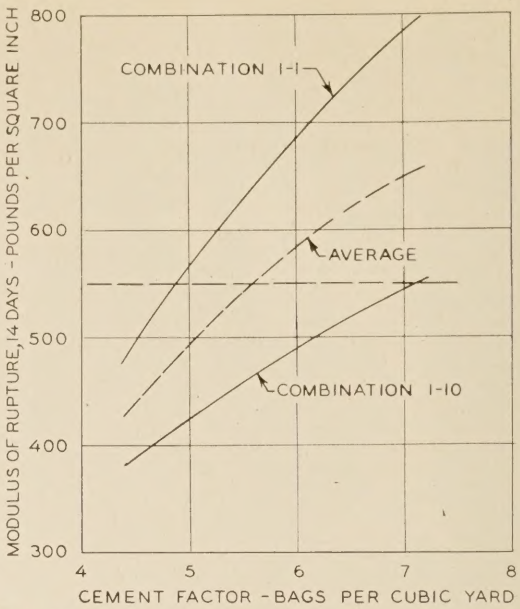


Figure 4.—Relation Between Cement Factor and Flexural Strength of Concrete. (Average Curve and Maximum Range.)

In order to illustrate better the effect of aggregate characteristics upon flexural strength, figure 4 is shown. Three flexural strength-cement factor curves are given, one for combination 1–1, one for combination 1–10, and one for the average of all 25 combinations of materials, thus representing the average and the extreme ranges for the entire series of tests. From the shapes of the two extreme curves it is seen that they tend to converge at the lower cement factors. This is to be expected because of the fact that for very lean mixes the strength of the mortar determines the flexural strength of the concrete. However, as the cement content is increased and the mortar becomes stronger, the quality of the coarse aggregate and the bond between mortar and coarse aggregate become important factors.

Coarse aggregate number 1 was a dolomite of excellent quality having a surface texture which gave good bond with the mortar. With this aggregate, the full strength of the mortar appeared to have been developed up to a cement factor of 7 sacks per cubic yard. Aggregate number 10 was a structurally weaker material so that the full strength of the mortar was not developed. If the water-cement ratio was the only controlling factor, the strengths of combination 1–10 should have been greater than those developed by combination 1–1 because of the fact that lower water-cement ratios were used (table 3). Notwithstanding this fact, combination 1–1 gave 26 percent greater strength for the leanest mix and 44 percent greater strength for the richest mix. At a cement factor of 6 sacks per cubic yard, one commonly used for pavement mixes, combination 1–1 gave 40 percent greater strength than combination 1–10. While in this particular instance the low strength was probably due to structurally poor material, this is not always the case. Frequently aggregates which are structurally strong give comparatively low flexural strengths in concrete because of the fact that the surface texture does not permit of sufficient bond to develop the full strength of the mortar.

(*Continued on p. 138*)

DETERMINATION OF THE KINEMATIC VISCOSITY OF PETROLEUM ASPHALTS WITH A CAPILLARY TUBE VISCOSIMETER

BY THE DIVISION OF TESTS, PUBLIC ROADS ADMINISTRATION

Reported by **R. H. LEWIS**, Chemist, and **W. J. HALSTEAD**, Junior Chemist

IN many research investigations of bituminous materials the determination of consistency in poises or stokes is desirable since fundamental units give an accurate basis of comparison for different types of materials. Accurate comparisons are often very difficult to make from test values obtained by the use of empirical methods. In 1935, Messrs. Rhodes, Volkmann, and Barker[1] reported the development of a new viscosimeter of the capillary tube type for the determination of the consistency of bitumens. They found that this instrument could be used to measure, at the same temperature, the absolute viscosity of all grades of road tars. Since its introduction, this instrument has been used in several investigations. Reports of these investigations [2] [3] indicate that the instrument is useful and gives very accurate results.

A study of the viscosimeter, the data of which are given in this report, was made to ascertain the accuracy and the scope of this instrument for determining the kinematic viscosity of asphaltic materials, more especially petroleum asphalts of the 50–60 and 85–100 penetration grades. The value of these results for determining the viscosity-temperature susceptibility was also studied. Since at the present time there is much interest in these problems, the results of this investigation are reported in detail for the benefit of those actively engaged in the testing of bituminous materials.

INSTRUMENT USES PRINCIPLE OF CAPILLARITY

The operation of the viscosimeter is described by Rhodes, Volkmann, and Barker[1], as follows:

> With this new instrument, viscosity is determined by timing the flow of the material under test through a capillary tube. Contrary to the classical method of Ostwald, which utilizes gravitation as the driving force, the material is made to ascend through the capillary tube. This is accomplished by immersing in the sample to be tested the lower end of a capillary tube, the upper end of which is connected with a partly evacuated reservoir. Two fixed points are chosen on the capillary tube and the time required for the passage of the air-sample interface between these points is noted. From the time, vacuum applied, the distance between points, and the radius of the bore of the capillary tube, the viscosity of the sample can be calculated.

The equation for calculating the viscosity from the observed data was derived by Volkmann, Rhodes, and Work[2] from Poiseuilles' equation for viscosity by capillary flow. This equation is:

$$\frac{\nu}{\Delta t}=\frac{gr^2}{8\left[\left(\frac{h}{\rho}+\lambda\right)\times\log_e\left[\frac{\left(\frac{h}{\rho}+\lambda\right)-l_1}{\left(\frac{h}{\rho}+\lambda\right)-l_2}\right]-(l_2-l_1)\right]} \text{ - - - - (1)}$$

where

ν = kinematic viscosity in stokes,
g = acceleration due to gravity (980 cm. per sec.^{2}),
r = radius of capillary bore (cm.),
h = vacuum in centimeters of water,
λ = length of capillary submerged in sample (cm.),
l_1 = length of capillary filled with liquid at start of time interval (cm.),
l_2 = length of capillary filled with liquid at end of time interval (cm.),
ρ = density of sample at test temperature (gm. per cm.^{3}), and
Δt = time of rise between l_1 and l_2 (sec.).

As explained by the earlier authors, [1] this equation is very difficult to use for extremely low values of the logarithmic expression. For this reason, they expanded the logarithmic expression into a series and obtained the equation in the following form:

$$\frac{\nu}{\Delta t}=\frac{gr^2}{8\left[\frac{l_2^2-l_1^2}{2\left(\frac{h}{\rho}+\lambda\right)}+\frac{l_2^3-l_1^3}{3\left(\frac{h}{\rho}+\lambda\right)^2}+\frac{l_2^4-l_1^4}{4\left(\frac{h}{\rho}+\lambda\right)^3}\right]} \text{ - - - - (2)}$$

In this study equation 2 has been simplified by neglecting all but the first two terms of the series in the denominator. Since λ is always controlled at 1.0 centimeter, the value $\lambda=1$ is used and the equation reduces to the following form:

$$\frac{\nu}{\Delta t}=\frac{gr^2}{4(l_2^2-l_1^2)}\left[\frac{h}{\rho}+1-\frac{2(l_2^2+l_2l_1+l_1^2)}{3(l_2+l_1)}+\frac{\left[\frac{2(l_2^2+l_2l_1+l_1^2)}{3(l_2+l_1)}\right]^2}{\frac{h}{\rho}+1+\frac{2(l_2^2+l_2l_1+l_1^2)}{3(l_2+l_1)}}\right] \text{ - - (3)}$$

A further approximation may be made by neglecting the last term in equation 3. The equation then becomes:

$$\frac{\nu}{\Delta t}=\frac{gr^2}{4(l_2^2-l_1^2)}\left[\frac{h}{\rho}+1-\frac{2(l_2^2+l_2l_1+l_1^2)}{3(l_2+l_1)}\right] \text{ - - - - - - (4)}$$

This equation may be expressed in the following form:

$$\frac{\nu_a}{\Delta t}=K\left(\frac{H}{\rho}\right)+C \text{ - - - - - - - - - - - - - - - - (5)}$$

where

ν_a = kinematic viscosity in centistokes,
H = vacuum in centimeters of mercury, and
K, C = constants for chosen values of l_1 and l_2.

The constants K and C include all instrumental constants and conversion factors as shown in table 1. This

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[1] New Viscosimeter for Bitumens Has Extended Range. Engineering News-Record, vol. 115, Nov. 21, 1935.

[2] Physical Properties of Coal Tars, by Volkmann, Rhodes, and Work. Industrial and Engineering Chemistry, vol. 28, June 1936.

[3] Consistency Measurements in the Coal Tar Industry, by Rhodes, Volkmann, and Barker. Symposium on Consistency, A. S. T. M., June 1937.

table also shows values of K and C for the various height intervals used in this report.

APPROXIMATE EQUATIONS MAKE POSSIBLE USE OF VARIOUS VALUES FOR l_1 AND l_2

The two approximations that have been made in deriving equation 4 have opposite effects. The omission of all but the first two terms of the series in the denominator of equation 2 tends to increase the computed values of $\nu/\Delta t$, while the omission of the last term in equation 3 tends to decrease these values. The increase in computed values caused by the first approximation will be greater for large values of l_2 and small values of l_1. For a given value of l_2, the decrease caused by the second approximation will be least for small values of l_1. Therefore, the greatest error caused by the use of the approximate equation 4 will result when the value of l_2 is large and that of l_1 is small.

TABLE 1.—*Equations for calculating viscosity, and values of* K *and* C *for various values of* l_1 *and* l_2

$$\frac{\nu}{\Delta t}=\frac{gr^2}{4(l_2^2-l_1^2)}\left[\frac{h}{\rho}+1-\frac{2(l_2^2+l_2l_1+l_1^2)}{3(l_1+l_2)}\right] \text{--------}(4)$$

or:

$$\frac{\nu_a}{\Delta t}=K\left(\frac{H}{\rho}\right)+C \text{------------------}(5)$$

where:

Length of capillary submerged in sample = 1.0 cm.

$$K=\frac{gr^2}{4(l_2^2-l_1^2)}\times D_{Hg}\times 100$$

$$C=\frac{gr^2}{4(l_2^2-l_1^2)}\left[1-\frac{2(l_2^2+l_2l_1+l_1^2)}{3(l_2+l_1)}\right]\times 100$$

ν = Kinematic viscosity in stokes,
ν_a = Kinematic viscosity in centistokes,
Δt = Time of rise between l_1 and l_2 (sec.),
r = Radius of capillary bore (0.0571 cm.),
g = Acceleration due to gravity (980 cm. per sec.^{2}),
l_1 = Length of capillary filled with liquid at start of time interval (cm.),
l_2 = Length of capillary filled with liquid at end of time interval (cm.),
h = Vacuum in centimeters of water,
H = Vacuum in centimeters of mercury.
ρ = Density of sample at test temperature (gm. per cm.^{3}),
D_{Hg} = Density of mercury at 25° C. (13.534 gm. per cm.^{3}).

l_1	l_2	K	C	l_1	l_2	K	C
2	3	216.20	−24.5	3	5	67.57	−15.4
2	4	90.09	−14.0	4	5	120.10	−31.2
2	5	51.48	−10.3	3	8	19.66	−7.1
2	6	33.78	−9.1	3	10	11.88	−5.4
3	6	40.04	−10.8	3	11	9.65	−4.8
4	6	54.05	−16.2	4	11	10.30	−5.4
5	6	98.28	−32.8	4	12	8.45	−4.8
3	4	154.50	−28.8				

In this study the largest interval used was $l_1=4$ centimeters, $l_2=12$ centimeters. In table 2 are shown comparisons of the values of $\nu_a/\Delta t$ obtained with the exact equation and the approximate equation 4. The exact calculations were made by equation 1 except where notation is made that equation 2 was used. For the purposes of comparison, these calculations have been carried to a greater number of significant figures than would ordinarily be employed in computing viscosities from the test results. Calculations are shown for the intervals $l_1=4$ centimeters, $l_2=12$ centimeters, the largest interval used, and $l_1=3$ centimeters, $l_2=6$ centimeters, one of the intervals more frequently used in this study. The values of H/ρ included vary from 1.00 to 7.31 and it is seen that for all values of H/ρ of 3 or more the maximum error is less than 0.5 percent, the error decreasing rapidly with increasing values of H/ρ. Although for values of H/ρ even as low as 2.20 the maximum error is only approximately 1 percent, for all values of H/ρ less than 3 it will generally be desirable to compute viscosities by equation 1, or to use a graph constructed with calculations made by this equation.

In this investigation, data on the specific gravity or density of the materials were available, and thus the kinematic viscosity has been reported. However, the absolute viscosity is desirable in many cases and for viscous asphaltic materials can be calculated within the accuracy of the method without the use of the density.

TABLE 2.—*Comparison of values of* $\frac{\nu_a}{\Delta t}$ *obtained with exact and approximate equations*

$\frac{H}{\rho}$	l_1=4 cm., l_2=12 cm.			l_1=3 cm., l_2=6 cm.		
	Values of $\frac{\nu_a}{\Delta t}$		$\frac{\nu_a}{\Delta t}$ (eq. 4) / $\frac{\nu_a}{\Delta t}$ (exact)	Values of $\frac{\nu_a}{\Delta t}$		$\frac{\nu_a}{\Delta t}$ (eq. 4) / $\frac{\nu_a}{\Delta t}$ (exact)
	Exact	Equation 4		Exact	Equation 4	
1.00	3.14	3.66	1.16561	28.98	29.19	1.00725
1.20	5.00	5.35	1.07000	37.03	37.20	1.00459
1.40	6.78	7.04	1.03835	45.07	45.21	1.00311
1.80	10.24	10.42	1.01758	61.13	61.22	1.00147
2.20	13.67	13.80	1.00950	77.16	77.24	1.00104
2.60	17.08	17.18	1.00585	93.18	93.25	1.00075
3.00	[1] 20.47	20.56	1.00440	[1] 109.22	109.27	1.00046
3.62	[1] 25.72	25.80	1.00311	[1] 134.07	134.11	1.00030
5.10	[1] 38.23	38.29	1.00157	[1] 193.26	193.28	1.00010
7.31	[1] 56.96	57.02	1.00105	[1] 282.02	282.04	1.00007

[1] Values computed by equation 2 with 6 terms in the series.

It has been shown (equation 5) that the equation for kinematic viscosity is:

$$\frac{\nu_a}{\Delta t}=K\left(\frac{H}{\rho}\right)+C$$

$$\nu_a=\frac{\mu}{\rho};\ \mu=\text{absolute viscosity in centipoises.}$$

thus

$$\frac{\mu}{\Delta t}=\rho\left[K\left(\frac{\mathrm{H}}{\rho}\right)+C\right]$$

$$\frac{\mu}{\Delta t}=KH+\rho C.$$

For high vacuums the constant C is small compared to KH and the difference between C and ρC would not affect the results appreciably since for bituminous materials the density is usually very close to 1 gram per cubic centimeter.

In making the tests on asphalts it was found much more satisfactory to vary the values for l_1 and l_2 with the general consistency of the material rather than use only the intervals 4 to 12 centimeters for materials of low viscosity and 2 to 4 centimeters for those of high viscosity, as suggested in the original report.[1]

The values for the height intervals most frequently used in this investigation were 3 to 6 centimeters for the higher temperatures, and 2 to 4 centimeters for the lower temperatures in testing the semisolid asphalts. For the test runs on the liquid materials the intervals 4 to 12 centimeters or 3 to 11 centimeters were generally used.

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[1] New Viscosimeter for Bitumens Has Extended Range. Engineering News-Record, vol. 115, Nov. 21, 1935.

The capillary tubes were calibrated by calculating the volume, and thus the diameter, from the weight of mercury necessary to fill the tube over a definite recorded length. These calibrations were made both at the beginning and end of the tests. The results are shown in table 3.

The standard diameter is 0.1142 centimeters. An equation for the correction factors for the differences from this standard was derived; it is:

$$\left(\frac{\nu}{\Delta t}\right)_1=\left(\frac{\nu}{\Delta t}\right)_0\left(1+\frac{\Delta d}{r_0}\right)$$

where

$\left(\frac{\nu}{\Delta t}\right)_1$=correct value,

$\left(\frac{\nu}{\Delta t}\right)_0$=value computed for standard diameter.

r_0=standard radius, and

Δd=difference between actual and standard diameters.

This is an approximate equation that gives results differing from those given by the exact equation by negligible amounts.

TABLE 3.—*Initial and final diameters of capillary tubes*

Tube No.	Initial diameter	Final diameter
	Cm.	*Cm.*
1	0.1149	0.1150
2	.1144	.1141
3		.1149

Using this equation, factors for each tube were found to be those given in table 4.

Since the maximum difference between the correct and computed value is approximately 1 percent, the precision of the determinations did not warrant making the correction.

APPARATUS MODIFIED TO GIVE MORE ACCURATE RESULTS

For this work the sample container supplied with the instrument was discarded and a test tube of 8-inch length and 1-inch inside diameter was used. This permitted use of a larger amount of material, and the clear vertical wall of the tube enabled better vision. In addition, sufficient test tubes were available so that the samples could be stored and repeated determinations at various temperatures could be made.

TABLE 4.—*Conversion factors for diameters of capillary tubes*

Tube No.	Conversion factor	
	Initial	Final
1	1.012	1.014
2	1.0035	.9982
3		1.012

It was found that the centering and depth of immersion of the tube were important factors in obtaining accurate results. In order to insure accuracy, a special holder which fits tightly in the top of the tube was made. It holds the capillary in place with a finger spring just tight enough to allow it to slide easily but not slip. In addition to this holder, a pasteboard disk cut to fit loosely in the test tube and tightly on the capillary, was placed on the tube approximately 3 centimeters above the surface of the sample. The use of these appliances made it possible to locate the capillary exactly in the center of the tube and to determine the depth of immersion accurately without difficulty. Figure 1 shows a photograph of the modified testing unit and the unit furnished with the instrument.

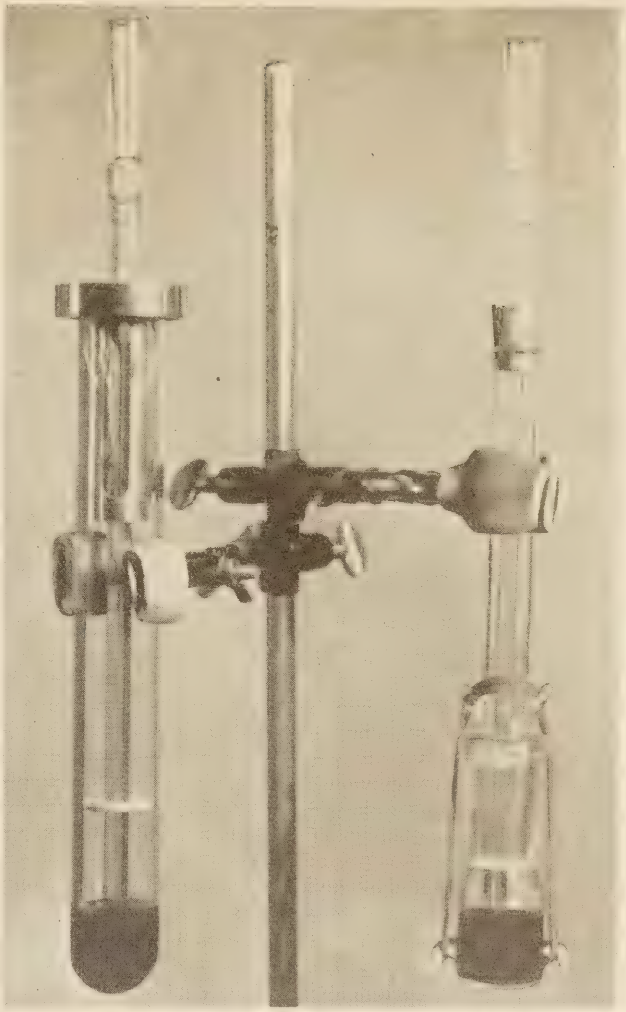

FIGURE 1.—MODIFIED TESTING UNIT (LEFT), AND UNIT SUPPLIED WITH INSTRUMENT (RIGHT).

Accurate temperature control was obtained by the use of a standard thermometer placed in a test tube containing asphalt of the same type as the material under test. This gave a measure of the asphalt temperature at the center of the tube rather than the bath temperature.

A large enough portion of the sample to be tested to fill about 1 inch of the tube was heated and poured, then allowed to cool to room temperature for 1 hour. It was then placed in the bath maintained at the test temperature and allowed to stand for at least 1 hour before testing. The capillary tube was put in position at least 20 minutes before the first determination.

The reservoir was evacuated to the desired amount, the capillary connected to the system, and the stopcock opened. The time of rise through the distance

l_1 to l_2 was recorded with a stop watch. The mercury manometer for the determination of vacuum was read at the beginning and at the end of the test. Under ordinary circumstances the vacuum will remain constant throughout the test since the decrease in volume of the air space resulting from the rise of the asphalt is infinitesimal compared to the total volume of the reservoir.

The temperature, length of time, initial and final height, vacuum, and density of the material at test temperature were recorded. These data were then used to calculate the viscosity.

The capillary tubes were cleaned by heating in a bath of nitrobenzene maintained at approximately 100° C. by a boiling water bath. Air pressure was used to blow the asphalt out of each tube after it had softened sufficiently from the action of the heat and solvent. The tube was then washed clean in the same bath by alternate soaking and flushing, and the excess nitrobenzene removed with a current of air. The tube was allowed to cool slightly and then washed with ethyl ether and dried with air. Using this method, the tubes could be cleaned thoroughly in 3 to 5 minutes.

Check determinations were made on the same samples after the capillary tube had been cleaned and replaced. In order to insure complete equilibrium the capillary was allowed to stand in the sample at least 20 minutes before each test.

Samples that had remained undisturbed in the test tubes overnight or longer were preheated in an oil bath to 140–150° C. They were then allowed to cool to room temperature and the described procedure was followed. This preheating was found necessary in order to eliminate any effect of age hardening, except when the test temperature was 20 or more degrees above the softening point of the materials being tested. For these temperatures, tests showed no difference between results obtained on samples preheated and those placed directly in the bath.

The following four variables must be recorded for each determination: Temperature of test, vacuum (H), initial and final values of l_1 and l_2, and the time of rise (Δt). However, three of these are independent and are made constant for each determination; that is, the temperature, the values of l_1 and l_2, and the vacuum. The time of rise is the only dependent variable and there is no difficulty in recording the necessary data.

The viscosity can be calculated very easily by the use of the approximate formulas as derived. The time required is no more than that necessary when the chart supplied with the instrument is used, and direct calculations eliminate the necessity for interpolating values of the density. It also makes possible the use of more convenient values for l_1 and l_2.

FLOW GENERALLY UNIFORM THROUGHOUT LENGTH OF TUBE

Seventy-eight asphalts, which are representative of nearly every source and method of manufacture used in the United States, were studied in this investigation. Thirty-nine of these materials were of the 50–60 penetration grade and 39 were of the 85–100 penetration grade. Physical and chemical tests, both routine and special, have been made on all these asphalts, and are included in a report by Lewis and Welborn.[4]

Table 5 gives all available data on the source and method of refining these materials. Table 6 shows penetrations, softening points, and the kinematic viscosities at two temperatures of these asphalts.

TABLE 5.—*Source and method of refining asphalt cements*

Identification No.	Producer identification	Source of base petroleum	Method of refining
1	1	California, Coalinga field	Vacuum distillation.
2	2	California, San Joaquin Valley field.	Reduction and steam distillation.
3	3	do	Do.
4	4	do	Steam distillation in continuous-tube still.
5	5	California, Elk Hills field	Vacuum distillation.
6	6–A	Colombia	Vacuum distillation with pipe still.
7	7–A	Mexico, Ebano field	Straight steam distillation.
8	8	Mexico	
9	9	Mexico, Panuco field	Steam distillation in Trumble (pipe) still.
10	10	do	
11	11	do	Vacuum distillation in pipe still.
12	6–B	Mexico	Do.
13	12	Venezuela	Fire and steam distillation.
14	13–A	Venezuela, Mene Grande field.	Continuous distillation under subatmospheric pressure with steam.
15	13–B	do	Distilled in batch stills at atmospheric pressure with steam.
16	7–B	Venezuela	Straight steam distillation.
17	6–C	do	Vacuum distillation in pipe still.
18	14	do	Steam distillation.
19	15	Arkansas, Smackover field	Vacuum distillation at a low temperature.
20	16–A	do	Vacuum distillation, 89 melting point flux.
21	16–B	do	Vacuum distillation, 101 melting point flux.
22	17	Arkansas, Nevada County	Pipe still distillation unit and vacuum bubble tower.
23	18	Oklahoma, Cement and Walters field.	
24	19–A	Oklahoma	Vacuum distillation in pipe still, partially oxidized.
25	19–B	do	Do.
26	19–C	do	Do.
27	20–A	do[1]	
28	20–B	do	
29	21	Oklahoma, Healdton and Graham.	
30	22	Kentucky and Illinois	Fire and steam distillation, possibly blown.
31	23	Mexican - duo - sol - residuum from Oklahoma crude.	Steam distillation and air conversion in batch shell stills.
32	24–A	Kansas	Straight run, steam refined, vacuum process.
33	24–B	do	Produced from Winkler-Koch Shell still.
34	25–A	Wyoming	Fire and steam distillation.
35	25–B	Unknown	Do.
36	25–C	do	Do.
37	26–A	Mexico and domestic Gulf Coast.	
38	26–B	do	
39	27	Texas, Westbrook field	
40	28	Kentucky	Dubbs cracking process.

[1] Source assumed, considering the producer and from the interpretation of test results.

True viscous liquids have laminar or straight-line flow in a capillary tube. In deriving the formula for this instrument it is assumed that the materials under test are such viscous liquids. The theoretical formula is also derived from a consideration of the viscous resistance between parallel layers of the substance being tested, when these layers are moving at various speeds from zero at the outer wall of the tube to a maximum at the axis. This condition is fulfilled in most capillary viscosimeters by wetting the tube with the material under test before the determination is made. However, with opaque substances such as bituminous materials this is not practical, and the determination is made by timing the rise in a clean tube.

In order to ascertain the effect of these deviations from the theoretical conditions on the flow of the asphalts in the tube, tests were made in which the times of rise for various increments of height were recorded.

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[4] The Physical and Chemical Properties of Petroleum Asphalts of the 50–60 and 85–100 Penetration Grades. Annual meeting of Association of Asphalt Paving Technologists, Chicago, Ill., Jan. 1940. PUBLIC ROADS, March 1940, vol. 21, No. 1.

TABLE 6.—*Consistency of the asphalts studied*

Identification No.	50–60 penetration grade: Softening point	50–60 penetration grade: Penetration 100 gm. 5 sec., 25° C.	50–60 penetration grade: Kinematic viscosity At 65° C.	50–60 penetration grade: Kinematic viscosity At 85° C.	85–100 penetration grade: Softening point	85–100 penetration grade: Penetration 100 gm. 5 sec., 25° C.	85–100 penetration grade: Kinematic viscosity At 55° C.	85–100 penetration grade: Kinematic viscosity At 75° C.
	°*C.*		*Centistokes* ×*10*⁻⁴	*Centistokes* ×*10*⁻⁴	°*C.*		*Centistokes* ×*10*⁻⁴	*Centistokes* ×*10*⁻⁴
1	48.1	57	10.0	1.29	44.9	85	25.2	1.62
2	48.0	61	16.5	2.07	44.1	96	27.0	1.93
3	47.9	61	10.5	1.18	44.2	95	23.3	1.92
4	48.0	60	14.7	1.20	44.2	92	22.5	1.75
5	48.8	58	10.7	1.49	45.0	91	34.7	2.66
6	52.2	52	25.1	2.28	47.0	92	43.8	3.84
7	55.3	58	39.9	3.58	49.0	96	65.9	5.92
8	54.7	56	68.8	5.05	49.7	96	60.4	4.41
9	55.4	53	53.9	5.61	49.2	96	75.6	6.24
10	54.8	56	53.1	5.76	49.5	95	80.1	6.31
11	55.7	54	55.1	6.16	48.5	97	68.9	6.20
12	55.8	55	50.1	5.77	48.4	97	67.7	5.68
13	55.3	51	100.6	7.25	47.4	94	52.7	4.10
14	52.2	52	24.7	2.43	46.2	95	36.0	3.07
15	52.0	52	46.6	3.31	46.2	92	41.2	3.17
16	55.8	48	78.5	6.10	47.0	94	75.1	5.06
17	53.2	48	37.5	4.20	47.8	92	70.7	5.28
18	54.1	51	32.8	4.05	50.4	85	74.1	5.96
19	51.8	57	22.3	2.69	46.4	90	41.4	3.70
20	58.4	58	76.9	5.45	49.3	90	71.3	5.26
21	54.6	57	31.4	3.17	46.1	97	42.6	3.79
22	58.4	57	76.2	6.33	47.3	96	62.6	4.58
23	48.8	60	7.3	.76	44.4	91	26.3	1.77
24	55.1	54	63.3	4.73	47.7	94		
25	52.8	58	30.4	3.02	48.0	94	34.6	2.99
26	54.0	53	45.4	2.89	48.6	84	54.5	3.99
27	55.2	49	39.2	3.79	46.6	93	59.1	4.32
28	52.0	58	24.6	2.53	46.3	92	32.5	2.66
29					45.2	92	25.1	1.88
30	55.1	48	53.3	4.02	46.9	90	59.8	4.20
31	56.2	59	62.2	5.11	49.3	93	79.6	5.98
32	53.1	49	29.9	3.15	49.5	85	45.1	3.73
33	52.8	46	16.8	1.02	48.4	83	46.6	2.50
34	53.4	58	46.3	3.69	46.9	94	57.0	4.07
35	50.8	57	20.0	1.74	46.9	96	38.4	3.03
36	51.9	55	28.9	2.56	49.6	92	84.2	4.66
37	55.8	52	54.9	4.76	48.0	96	59.0	4.29
38	55.4	55	79.0	5.24	49.5	95	111.2	6.02
39	53.8	47	40.5	3.11	46.8	86	47.7	3.44
40	50.5	50	23.8	1.46	45.0	87	34.3	2.45

These tests were made on the 85–100 penetration asphalts at 55° C. only. Asphalts 2 to 18, inclusive, with the exception of asphalt 14, were tested at the following intervals of height (in centimeters): 2 to 3, 2 to 4, 2 to 5, 2 to 6, 3 to 6, 4 to 6, and 5 to 6. Asphalts 19 to 40, inclusive, with the exception of asphalts 24 and 26, were tested at the following intervals (in centimeters): 2 to 3, 3 to 4, 4 to 5, and 5 to 6.

In general, at least two rounds of tests were made with each of these height intervals. The average, the maximum and minimum calculated value, the height intervals at which the maximum and minimum occurred and the maximum and average deviations from the mean for each round are shown in table 7.

All asphalts showed some deviation in the results, and there was considerable difference in the behavior of the various samples. The maximum deviation from the mean varied from zero for one round on sample 33 to as high as 8.4 percent for one round on sample 27. While a few of the asphalts showed very erratic results, as will be discussed later, in general there was no definite trend either in the height interval at which the maximum or minimum occurred or in the effect of the source or type of manufacture on results.

In general the maximum viscosities were obtained more frequently for the larger values of l_2 and the minimum viscosities for the lower values of l_2. However, this trend is not definite enough to draw any positive conclusions. There was no point in the tube which gave consistently high or low values. The average maximum deviation from the mean for group A was 1.2 percent, and for group B was 1.3 percent. The mean deviation averaged 0.5 percent for group A and 0.7 percent for group B.

TABLE 7.—*Effect of various values of l_1 and l_2 on the computed values for viscosity of the asphalts of the 85–100 penetration grade at 55° C.*

A. CALCULATIONS FOR INTERVALS OF 2 TO 3 CM., 2 TO 4 CM., 2 TO 5 CM., 2 TO 6 CM., 3 TO 6 CM., 4 TO 6 CM., AND 5 TO 6 CM.

Identification No.	Kinematic viscosity: Maximum	Kinematic viscosity: Minimum	Kinematic viscosity: Average	Interval: For maximum value	Interval: For minimum value	Deviation from mean: Maximum	Deviation from mean: Average
	Centistokes ×*10*⁻⁴	*Centistokes* ×*10*⁻⁴	*Centistokes* ×*10*⁻⁴	*Cm.*	*Cm.*	*Percent*	*Percent*
2	27.2	26.7	27.0	2–4	2–5	1.1	0.6
	27.2	26.8	27.0	4–6	2–4	.7	.4
3	23.6	23.0	23.2	5–6	2–5	1.7	.9
	23.6	23.1	23.3	5–6	2–5	1.3	.6
4	22.8	22.2	22.5	2–3	2–5	1.3	.8
	22.8	22.4	22.6	2–4	5–6	.9	.5
5	33.8	33.1	33.4	5–6	2–5	1.2	.6
	35.3	34.8	35.0	5–6	2–5	.9	.4
	36.3	35.4	35.8	5–6	3–6	1.4	.7
6	44.8	43.3	44.1	5–6	2–3	1.8	1.0
	44.4	43.2	43.7	2–3	2–5	1.6	.7
	43.9	43.2	43.6	4–5	3–4	.9	.6
7	68.4	65.8	66.7	5–6	2–4	2.5	.9
	65.7	64.0	65.1	5–6	2–3	1.7	.7
8	60.8	60.0	60.3	2–3	2–5	.8	.4
	61.5	59.6	60.6	5–6	2–4	1.7	.7
9	75.2	74.5	75.0	4–6	2–3	.7	.2
	76.4	76.1	76.2	3–6	2–4	.3	.1
10	80.5	78.8	79.8	4–6	2–3	1.3	.7
	81.0	80.0	80.4	4–6	2–4	.8	.7
11	69.4	69.2	69.3	2–3	2–4	.1	.1
	68.9	68.2	68.5	5–6	2–3	.6	.3
12	66.9	66.4	66.6	5–6	2–5	.5	.3
	69.0	68.3	68.8	3–6	2–3	.7	.3
13	53.1	51.9	52.6	5–6	2–4	1.0	.7
	53.1	51.9	52.7	4–6	2–4	1.5	.6
15	41.8	40.8	41.2	2–3	4–6	1.5	.8
16	75.4	74.7	75.1	2–5	5–6	.5	.2
	75.8	74.0	75.1	2–4	2–3	1.5	.5
17	71.3	70.3	70.7	5–6	2–5	.8	.4
	71.1	70.3	70.6	5–6	3–6	.7	.3
18	74.7	72.9	73.6	5–6	4–5	1.5	.6
	76.3	72.6	74.6	5–6	2–3	2.7	1.2
Average						1.2	0.5

B. CALCULATIONS FOR INTERVALS OE 2 TO 3 CM., 3 TO 4 CM., 4 TO 5 CM., AND 5 TO 6 CM.

Identification No.	Kinematic viscosity: Maximum	Kinematic viscosity: Minimum	Kinematic viscosity: Average	Interval: For maximum value	Interval: For minimum value	Deviation from mean: Maximum	Deviation from mean: Average
19	42.0	40.3	41.2	3–4	2–3	2.2	0.6
	41.8	41.1	41.5	4–5	5–6	1.0	.6
	41.9	41.3	41.6	2–3	5–6	.7	.5
20	72.8	70.4	71.5	2–3	4–5	1.8	1.0
	71.5	70.7	71.2	4–5	3–4	.7	.4
21	43.0	42.5	42.7	3–4	4–5	.7	.5
	43.3	41.7	42.5	4–5	5–6	1.9	1.2
22	63.3	62.0	62.6	2–3	5–6	1.1	.8
	64.1	62.7	63.4	2–3	5–6	1.1	.5
	62.3	61.3	61.7	5–6	2–3	1.0	.5
23	26.6	26.2	26.5	3–4	5–6	1.1	.6
	26.4	26.6	26.2	3–4	4–5	.8	.4
25	34.7	34.1	34.5	5–6	2–3	1.2	.5
	34.3	33.7	34.0	4–5	2–3	[illegible]	.5
	35.8	35.1	35.5	2–3	4–5	1.1	.8
28	33.7	32.6	33.2	2–3	4–5	1.8	.8
	32.8	32.3	32.6	4–5	3–4	.9	.6
	32.0	31.3	31.6	5–6	3–4	1.3	.7
29	25.0	24.9	24.9	3–6	2–5	.4	.4
	25.5	25.3	25.3	5–6	2–3	.8	.2
30	60.3	58.9	59.7	2–3	3–4	1.3	.5
	61.7	58.5	60.0	2–3	3–4	2.8	2.0
	60.0	59.3	59.7	2–3	5–6	.7	.7
32	45.6	44.6	45.0	5–6	2–3	1.3	.5
	45.6	44.8	45.1	5–6	2–3	1.1	.4
33	44.4	44.4	44.4	3–4	5–6	0	0
	46.7	45.8	46.1	5–6	3–4	1.3	.6
	49.9	48.7	49.1	2–3	5–6	1.6	.7
34	57.1	55.4	56.1	5–6	2–3	1.8	.9
	55.2	53.2	54.0	4–5	2–3	2.2	.6
35	37.7	37.1	37.4	5–6	2–3	.8	.5
	38.8	38.0	38.5	4–5	2–3	1.3	.8
	39.9	38.8	39.3	5–6	2–3	1.5	1.1
36	84.9	81.9	83.2	5–6	3–4	2.0	1.2
	85.6	84.8	85.2	4–5	3–4	.5	.4
37	59.3	57.9	58.5	5–6	2–3	1.4	.7
	60.5	58.7	59.4	4–5	3–4	1.9	1.0
40	34.6	34.1	34.4	2–3	5–6	.9	.5
	34.5	33.5	34.1	3–4	4–5	1.8	.8
Average						1.3	.7

TABLE 7.—*Effect of various values of l_1 and l_2 on the computed values for viscosity of the asphalts of the 85–100 penetration grade at 55° C.*—Continued

C. SAMPLES SHOWING ERRATIC RESULTS

Identification No.	Kinematic viscosity			Interval		Deviation from mean	
	Maximum	Minimum	Average	For maximum value	For minimum value	Maximum	Average
	Centistokes $\times 10^{-4}$	*Centistokes* $\times 10^{-}$	*Centistokes* $\times 10^{-4}$	*Cm.*	*Cm.*	*Percent*	*Percent*
27	65.6	60.6	62.5	2–3	5–6	5.0	2.4
	61.9	57.1	59.4	2–3	5–6	4.2	2.9
	72.3	62.7	66.7	2–3	5–6	8.4	4.8
31	80.8	75.0	78.1	5–6	2–3	4.0	2.4
	82.6	80.0	81.1	5–6	2–3	1.8	1.1
	80.7	77.5	79.6	5–6	2–3	2.6	1.5
38	113.8	108.3	111.0	5–6	2–3	2.5	2.2
	115.6	107.3	111.4	5–6	2–3	3.8	2.4
39	47.8	47.2	47.5	2–3	5–6	.6	.2
	49.2	45.6	47.9	3–4	4–5	4.8	1.2

Samples 27, 31, 38, and 39 gave results showing much greater deviations from the mean than did the other materials. These samples are also peculiar as judged by the trend which the results showed. In all rounds sample 27 showed a progressive decrease in the calculated viscosity as the value of l_2 increased. For example, results on one round were: 65.6×10^{4} centistokes for 2 to 3 centimeters; 62.4×10^{4} for 3 to 4 centimeters; 61.5×10^{4} for 4 to 5 centimeters; and 60.6×10^{4} for 5 to 6 centimeters. For samples 31 and 38, the opposite condition was true—the calculated viscosity increased as the value of l_2 increased. For sample 31, one round showed 75.0×10^{4} centistokes for 2 to 3 centimeters, 77.6×10^{4} for 3 to 4 centimeters, 79.2×10^{4} for 4 to 5 centimeters, and 80.8×10^{4} for 5 to 6 centimeters. Sample 39 gave consistent results for one round, the maximum deviation from the mean being below the average; but for the other round there was a maximum deviation of 4.8 percent even though the average results of the two rounds checked very closely.

It is interesting to note that the materials known to be blends of different base asphalts had greater deviations from the mean than most of the other materials. Samples 31 and 38 were blends and showed marked peculiarities as already discussed. Samples 30 and 37, also blends, showed differences from the ordinary, but to a lesser degree. No definite information as to the source of the base petroleum or the method of manufacture was available for sample 27, but there is a possibility that it, too, was a blend.

These results indicate that the inside diameter of the tube is uniform since, if this were not true, there would be separate points at which the maximum and minimum values would be obtained. The accuracy of the formulas is also indicated by this lack of any systematic variation in results. In addition to this, the fact that the same asphalt shows maximum deviations varying appreciably between separate rounds on the same sample indicate that for this grade of asphalt the conditions of the test, the procedure, and the exactness of recording the data, cannot be expected to give an accuracy better than about 1 percent for calculations made with various height intervals.

All of the asphalts of the 50–60 grade were tested at 65° and 85° C., and all those of the 85–100 grade were tested at 55° and 75° C. These results are reported in table 6. Other tests were made on a selected group of the asphalts over a range of temperature from 45° to 90° C., as shown in table 8.

TABLE 8. *Kinematic viscosity of selected asphalts at various temperatures*

50-60 PENETRATION GRADE

Identification No.	Kinematic viscosity at—								
	45° C.	55° C.	60° C.	65° C.	70° C.	75° C.	80° C.	85° C.	90° C.
	Centistokes $\times 10^{-4}$	*Centistokes* $\times 10^{-4}$	*Centistokes* $\times 10^{-4}$	*Centistokes* $\times 10^{-4}$	*Centistokes* $\times 10^{-4}$	*Centistokes* $\times 10^{-4}$	*Centistokes* $\times 10^{-4}$	*Centistokes* $\times 10^{-4}$	*Centistokes* $\times 10^{-4}$
3	------	------	21.6	10.5	------	3.41	2.53	1.18	------
7	------	167	78.7	39.9	19.5	------	5.94	3.58	------
13	------	------	------	100.6	59.1	28.23	12.20	7.25	------
14	------	120	51.6	24.7	12.9	------	4.01	2.43	------
15	------	------	------	46.6	22.8	11.70	5.64	3.31	------
23	------	------	16.0	7.3	------	2.14	------	.76	------
24	------	330	------	63.3	------	17.01	8.84	4.73	2.82
25	------	147	------	30.4	------	9.47	5.24	3.02	1.82
26	------	248	------	45.4	20.2	9.95	5.38	2.89	1.77
30	------	------	------	53.3	26.4	13.61	------	4.02	------
31	------	270	104.4	62.2	26.5	------	8.12	5.11	------
32	------	148	------	29.9	16.5	9.80	4.83	3.15	------
33	------	------	------	16.8	7.0	3.40	------	1.02	.65
40	------	------	48.4	23.8	11.5	4.52	2.88	1.46	------

85-100 PENETRATION GRADE

Identification No.	45° C.	55° C.	60° C.	65° C.	70° C.	75° C.	80° C.	85° C.	90° C.
3	134	23.3	------	6.2	------	1.92	------	0.64	------
7	387	65.9	------	19.5	------	5.92	------	2.31	------
13	364	52.7	------	14.6	------	4.10	------	1.54	------
14	237	36.0	------	9.4	------	3.07	------	1.12	------
15	278	41.2	------	10.8	------	3.17	------	1.15	------
23	233	26.3	------	7.2	------	1.77	------	.69	------
25	205	34.6	------	10.2	------	2.99	------	1.21	------
30	345	59.8	------	15.2	------	4.20	------	1.62	------
31	513	79.6	------	22.2	------	5.98	------	2.23	------
32	315	45.1	------	12.8	------	3.73	------	1.43	------
33	593	46.6	------	9.6	------	2.50	------	.82	------
40	291	34.3	------	8.6	------	2.45	------	.81	------

GREATER PRECISION OBTAINED FOR LIQUID PRODUCTS THAN FOR SEMISOLID ASPHALTS

These reported results are the average of two or three tests; two when there was close agreement, and three or more when the difference in results of the first two tests was rather large. Since it was of primary interest to gain a definite knowledge of the ability to get check results with this type of material, an analysis of the maximum percentage deviation from the mean is shown in table 9. The total number of samples tested at each temperature and the number of samples which had maximum deviation from the mean between various percentage limits are shown. The average maximum deviation for all tests, and for values below 6.1 percent, are also included.

The average maximum deviation from the mean for all tests on the asphalts of 50–60 penetration, excluding those values of 6.1 percent or greater, was 2.3 percent; and for the asphalts of 85–100 penetration was 1.4 percent. The asphalts of the 85–100 grade were tested after the changes in the apparatus had been made, as previously described. Therefore, it is believed that the average maximum deviation of 1.4 percent more nearly represents the accuracy of the test than the higher figure obtained with the 50–60 grade.

It will be noted that 72.8 percent of the tests on the 85–100 grade checked within 2 percent and 85.1 percent had maximum deviations of less than 3 percent. In general, with most asphalts of these grades the operator should be able to obtain checks within ±2 percent deviation from the mean, by running 3 or 4 trials. However, some asphalts exhibit peculiarities and the results of repeated trials will not check closely despite every precaution of the operator.

TABLE 9.—*Precision of test results obtained with asphalts of the 50–60 and 85–100 penetration grades*

50–60 PENETRATION GRADE

Test temperature, °C.	Number of samples tested	Number of samples with maximum deviation from the mean between—						Average maximum deviation	
		0–1.0 per-cent	1.1–2.0 percent	2.1–3.0 percent	3.1–4.0 percent	4.1–6.0 percent	6.1+ percent	For all values	For values less than 6.1
								Percent	*Percent*
55	4	3	0	1	0	0	0	0.9	0.9
60	12	0	1	4	4	1	2	3.5	3.0
65	39	14	8	8	4	5	0	2.1	2.1
70	10	4	2	1	0	1	2	2.6	1.5
75	11	2	3	2	1	0	3	3.5	1.8
80	11	5	1	2	2	1	0	1.9	1.9
85	39	13	10	7	2	3	4	2.2	1.7
90	4	2	1	0	0	1	0	1.8	1.8
Total	130	43	26	25	13	12	11		
Percentage		33.1	20.0	19.2	10.0	9.2	8.5		
Average								2.4	2.3

85–100 PENETRATION GRADE

Test temperature, °C.	Number of samples tested	0–1.0 per-cent	1.1–2.0 percent	2.1–3.0 percent	3.1–4.0 percent	4.1–6.0 percent	6.1+ percent	For all values	For values less than 6.1
45	12	3	2	3	2	2	0	2.5	2.5
55	39	24	8	4	1	1	1	1.4	1.1
65	12	5	2	0	1	2	2	2.7	1.6
75	39	19	13	4	2	1	0	1.2	1.2
85	12	5	2	3	1	1	0	1.7	1.7
Total	114	56	27	14	7	7	3		
Percentage		49.1	23.7	12.3	6.15	6.15	2.6		
Average								1.6	1.4

The most striking example of this erratic behavior was sample 33 of the 85–100 penetration grade. This material was a cracked product which showed a positive spot in xylene when tested according to the Oliensis method. The test results on this sample are given in table 10.

Sample 27 of the 85–100 penetration grade, which showed the greatest deviation in the same round (table 7), also gave the greatest difficulty in obtaining check results at 55° C. Six tests were made, the results varying as follows: 52.6×10^4; 58.8×10^4; 54.8×10^4; 62.5×10^4; 59.4×10^4; 66.7×10^4. The average was 59.1×10^4. The maximum deviation from the mean is 12.6 percent. The results at 75° C. for this sample did not show this same irregularity but checked within 0.6 percent deviation from the mean.

TABLE 10.—*Results of tests on sample 33*

Test temperature	Kinematic viscosity determination—					Maximum deviation from mean
	No. 1	No. 2	No. 3	No. 4	Average	
° *C.*	*Centistokes* $\times10^{-4}$	*Centistokes* $\times10^{-4}$	*Centistokes* $\times10^{-4}$	*Centistokes* $\times10^{-4}$	*Centistokes* $\times10^{-4}$	*Percent*
5	587.9	563.6	623.9	[1] 464.6	593.4	5.1
5	44.39	46.13	49.14		46.6	5.6
5	[1] 12.28	10.44	8.85	9.89	9.6	8.3
5	[1] 3.000	2.506	2.494		2.50	.3
5	.80	.84			.82	2.5

[1] Test not included in average.

For testing the asphalts of the 85–100 penetration grade, the greatest average maximum deviation for all values varying less than 6.1 percent was 2.5 percent and this value was obtained for tests made at 45° C., the lowest temperature used for this grade of material. At the lowest test temperature used for the 50–60 penetration asphalts, which was 55° C., only seven asphalts were tested and on three of these only one test was made. The four that were checked had an average maximum deviation from the mean of only 0.9 percent. However, the average maximum deviations from the mean for the 50–60 grade asphalts tested at 60° C. and 65° C., excluding all values of 6.1 percent or greater, were higher than those values obtained at the higher temperatures. These results indicate that the instrument is less accurate for the determination of high viscosities of the magnitude obtained near temperatures of the softening points of the asphalts.

A number of liquid asphaltic materials of the rapid-, medium-, and slow-curing types, as well as two asphalts of approximately 200 penetration, also were tested for kinematic viscosity with this instrument. All of these materials were tested at 35° C., the temperature used in the work reported by Rhodes, Volkmann, and Barker.[1] Eleven samples were tested also at 25° C. and 50° C. The results of these tests are shown in table 11.

The viscosities of these materials at the test temperature of 35° C. ranged from 513 centistokes for the RC material to 138×10^4 centistokes for one of the 200 penetration asphalts. As in the case of the work done on the harder asphalts, two or more determinations were made on the same sample, and the mean of these results is the value reported for the viscosity. The maximum percentage deviation for the tests on each sample is also shown in table 11. It will be noted that more consistent results were obtained with these less viscous materials than with the semisolid asphalts. The greatest maximum deviation from the mean was only 2.6 percent and, out of 49 tests, only 7 had maximum deviations from the mean of 2 percent or more. Thirty-five samples checked within 1 percent or less. Test values widely different from the mean, as reported for some of the asphalts, were not obtained with these materials. In most cases three tests were made for each sample, and all the results were used to compute the average. The tests made on these materials indicate that the instrument has a relatively wide range, and that the consistency of a large number of asphaltic materials can be determined adequately at a temperature of 35° C.

VISCOSITY-TEMPERATURE DATA PLOTTED TO GIVE A STRAIGHT LINE

The data shown in table 6 on the kinematic viscosities of all the asphalts of each grade serve to emphasize the known fact that asphalts having essentially the same consistency at 25° C. may have widely different consistencies at higher temperatures. For example, the viscosity of the 50–60 penetration asphalts at 65° C. ranged from a minimum of 7.3×10^4 centistokes for sample 23 to a maximum of 100.6×10^4 centistokes for sample 13. These asphalts had penetrations at 25° C. of 60 and 51, respectively. The same relative difference is shown for the tests made at 85° C. While the maximum difference is not as great with the 85–100 grade, the viscosities ranged from 22.5×10^4 to 111.2×10^4 centistokes at 55° C., and from 1.62×10^4 to 6.31×10^4 centistokes at 75° C.

Since these differences are known to exist, knowledge

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[1] New Viscosimeter for Bitumens Has Extended Range. Engineering News-Record, vol. 115, Nov. 21, 1935.

TABLE 11.—*Viscosity determinations for various types of asphaltic materials*

Type	Grade designation[a]	Routine consistency determination				Tests at 25° C.		Tests at 35° C.		Tests at 50° C.	
		Furol viscosity		Engler specific viscosity at 100° C.	Penetration 100 gm., 5 sec. at 25° C.	Kinematic viscosity	Maximum deviation from mean	Kinematic viscosity	Maximum deviation from mean	Kinematic viscosity	Maximum deviation from mean
		At 50° C.	At 60° C.								
		Seconds	*Seconds*			*Centistokes*	*Percent*	*Centistokes*	*Percent*	*Centistokes*	*Percent*
RC	1	108						513	1.0		
RC	2	320				794×10	1.1	262×10	2.3	584	0.6
RC	3		292					480×10	.4		
RC	3		325					532×10	.5		
RC	3		310					460×10	.7		
RC	3		299					505×10	.9		
RC	3		307					454×10	.2		
RC	3		286					453×10	.6		
RC	3		313					485×10	.3		
RC	3		325					497×10	.2		
RC	3		380					629×10	.2		
RC	3		383					519×10	.1		
RC	3		377					592×10	.5		
RC	3		340					588×10	.5		
RC	3		364					608×10	1.0		
RC	4		631			133×10^3	1.1	277×10^2	.4	430×10	2.0
MC	2	213				588×10	.8	186×10	2.0	487	.4
MC	2	234				101×10^2	.7	222×10	.4	554	2.2
SC	2		178					442×10	.1		
SC	2		196					475×10	1.7		
SC	2		170			168×10^2	.4	416×10	1.2	858	1.0
SC	(b)		225			300×10^2	1.3	657×10	.3	126×10	.8
SC	(b)		247			785×10	2.6	355×10	.8	106×10	1.1
SC	(b)		231			964×10	.4	378×10	.8	103×10	.4
SC	3		366			810×10^2	.7	153×10^2	1.0	241×10	.4
SC	4			21.7				698×10^2	.4		
SC	4			16.2				366×10^2	.3		
AP	(c)				202	178×10^5	(d)	108×10^4	1.0	761×10^2	2.2
AP	(c)				212	183×10^5	(d)	138×10^4	.2	884×10^2	2.6

[a] Asphalt Institute Construction Series Number 51, Jan. 1, 1940, except as noted in footnote *c*.
[b] Falls between grades 2 and 3.
[c] Penetration grade, 200–250.
[d] Only one test made.

of the change of consistency with temperature is very desirable. This problem has recently received the attention of many investigators. In order to determine the suitability of the instrument for obtaining these data, tests were made over a range of temperature for a selected group of asphalts. Fourteen of the 50–60 grade asphalts and 12 of the 85–100 grade were tested at temperatures varying from slightly below the softening points of the materials to 90° C. Table 8 shows the results of these tests, which range from approximately 6,000 to 6,000,000 centistokes.

While it is possible to obtain higher viscosities than here reported, the time of rise becomes so long that it is not practical to run tests for viscosities higher than 6,000,000 centistokes. For this value the time of rise from 2 to 3 centimeters is approximately 12 minutes at the maximum vacuum obtainable. In addition, the time of rise to the starting point is several minutes.

In tests run for other investigations, results as high as 31,000,000 centistokes were obtained. However, the time required for one test was approximately 3 hours. Inability to obtain check tests and the time required in making each determination renders the instrument unsuitable to use for such high viscosities.

It is also possible to obtain viscosities much lower than the 6,000 centistokes reported for these asphalts at 90° C., but the high temperature necessary for these grades of asphalt makes it difficult with the same procedure and bath normally used. With additional heating coils and suitable liquids for the thermostat, it would be possible to extend the range to higher temperatures than here used, but for the purpose of this investigation this was not considered necessary.

Graphical presentation of results is very desirable for viscosity-temperature data, and many relations have been proposed so that the curve when plotted becomes a straight line. Several investigators[5] working independently have shown that for a liquid of definite chemical composition the viscosity should change with temperature according to the formula:

$$\mu=Ae^{B/T}$$

where

μ=absolute viscosity,
T=absolute temperature,
e=constant (base of Napierian logarithms), and
A, B=constants.

When this formula is expressed in logarithmic form it becomes:

$$\log \mu=\log A+\left(\frac{B}{T}\right)\log e$$

Thus a straight line should be obtained when log μ is plotted against the reciprocal of the absolute temperature.

The data shown in table 8 were plotted in this manner except that the kinematic instead of absolute viscosity was used. However, the density of the asphalts is so close to 1 gram per cubic centimeter at these test temperatures that there is no essential difference between the curves plotted with either value.

Figures 2 and 3 show these curves for each grade of asphalt. As will be noted, the curvature of the line increases as the temperature approaches the softening point of the asphalt. As will be shown later, there is a possibility that the viscosities obtained with the instrument at or near temperatures of the softening point are higher than the true viscosities because of the limitations of the instrument. Consequently, the curvature

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[5] Elasticity, Plasticity and Structure of Matter, by Houwink. Cambridge University Press (1937), p. 38. See also. E. N. da C. Andrade, Nature, vol. 125 (1930) p. 580. S. E. Sheppard, J. Rheology, vol. 1 (1930), p. 349.

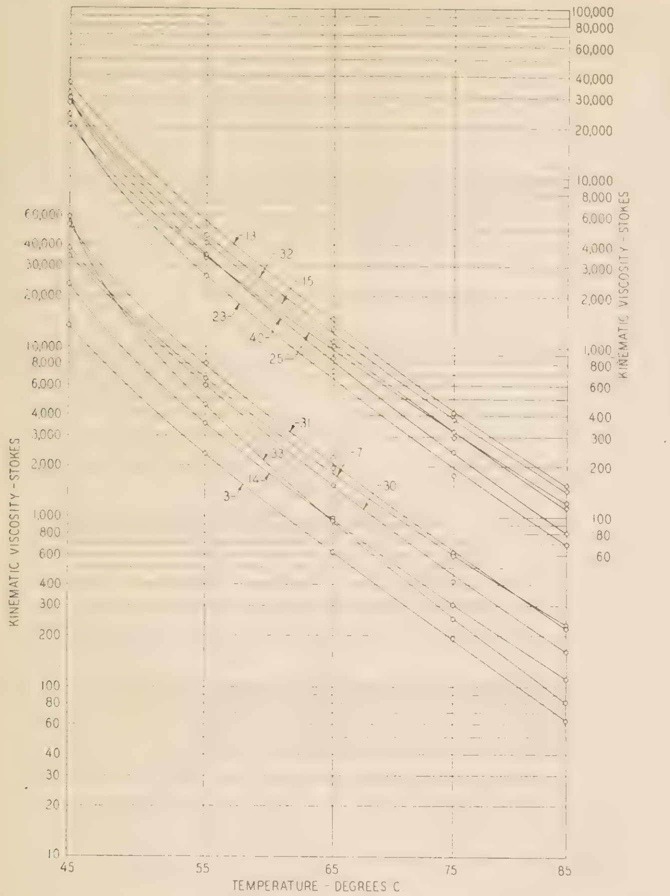

FIGURE 2.—RELATION BETWEEN LOG VISCOSITY AND RECIPROCAL OF ABSOLUTE TEMPERATURE FOR THE 85–100 PENETRATION ASPHALTS.

shown in the graph may be somewhat exaggerated. The shape of each curve is essentially the same, although some show slightly greater curvature than others.

Although asphalts are not liquids of a definite chemical composition, and in some cases exhibit plastic properties, these curves are of interest since they take into consideration the physical characteristics of the asphalts and no empirical constants have been introduced. It is believed that in a study of the deviations from a true liquid, or the changes in susceptibility over a wide range of temperature, these curves would be very valuable. However, from a practical standpoint they have no direct application and they cannot be used to calculate a susceptibility factor which would hold over an appreciable range of temperature.

As discussed by Rhodes, Volkmann, and Barker,[3] an empirical relationship between viscosity and temperature has been established. It is:

$$\log\left(\frac{\log(\nu_{a1}+0.8)}{\log(\nu_{a2}+0.8)}\right)=m\times\log.\frac{T_2}{T_1}$$

where ν_{a1} and ν_{a2} are the kinematic viscosities in centistokes at the absolute temperatures T_1 and T_2, respectively. Ubbelohde, Ullrich, and Walther[6] found this relationship to be the most accurate expression for the viscosity-temperature data for coal tars, and the same formula is used by the American Society for Testing Materials as the basis for the construction of the tentative standard viscosity-temperature charts for liquid petroleum products.[7]

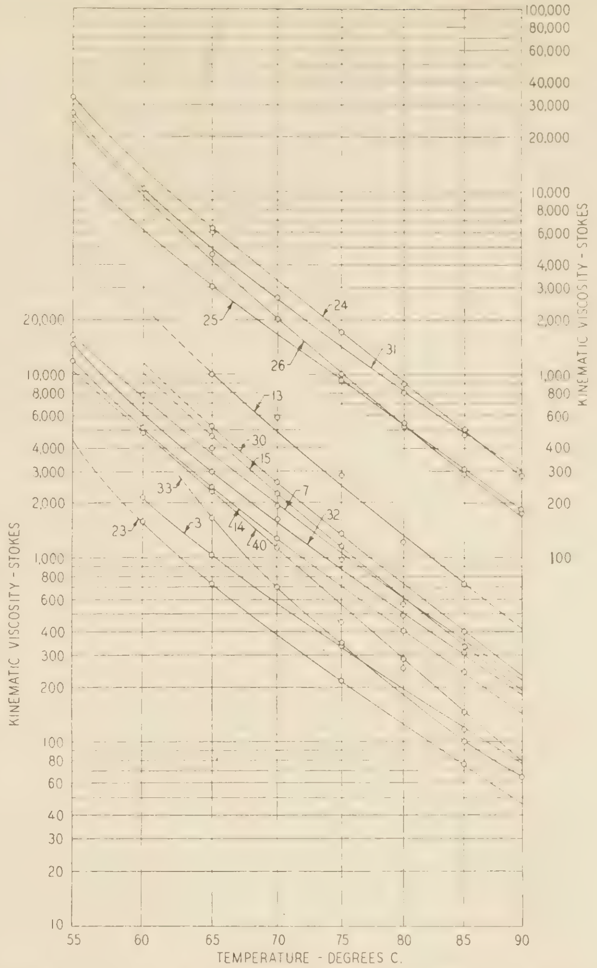

FIGURE 3.—RELATION BETWEEN LOG VISCOSITY AND RECIPROCAL OF ABSOLUTE TEMPERATURE FOR THE 50–60 PENETRATION ASPHALTS.

SLOPE OF VISCOSITY-TEMPERATURE CURVE DIFFERS FROM V. T. S. COEFFICIENT BY A CONSTANT FACTOR

For high viscosities the figure 0.8 added to the kinematic viscosity has no significance, and thus, if the double logarithm of the kinematic viscosity in centistokes is plotted against the logarithm of the absolute temperature, a straight line should be obtained.

The data in table 8 were plotted in this way and several typical curves are shown in figures 4 and 5. With the exception of some of the viscosities determined at or very close to the temperature of the softening point of the materials under test, all the values fall close to the straight line. If the viscosities at temperatures close to those of the softening point deviate from the straight line they always fall above it. No attempt was made to determine the cause of this deviation since no other instrument to measure absolute viscosities of this magnitude was available. This deviation may be caused by a change in the susceptibility of the asphalts at temperatures near the softening point, or because of

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[3] Consistency Measurements in the Coal Tar Industry, by Rhodes, Volkmann, and Barker. Symposium on Consistency, A. S. T. M., June 1937.

[6] Beitrag zur Kennzeichnung von Teeren und Bitumen auf Grund der Abhängigkeit iher Viskosität von der Temperatur, Oel und Koble, Veneinigt mit Endoel und Teer, vol. 11, No 36, Sept. 22, 1935, pp. 684–690.

[7] Tentative viscosity-temperature chart for liquid petroleum products. A. S. T. M. D341-39T.

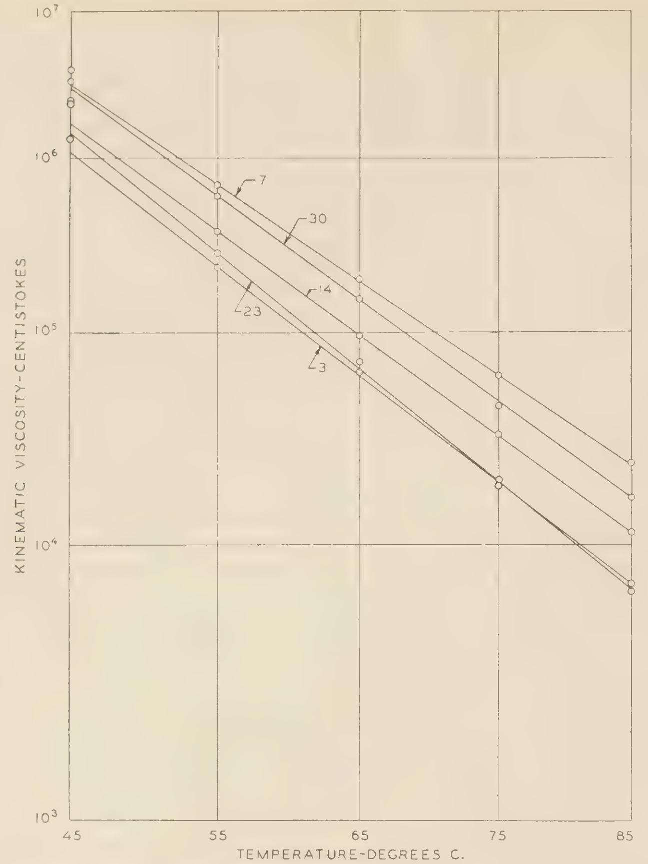

Figure 4.—Relation Between Log Log Viscosity and Log Absolute Temperature for Selected 85–100 Grade Asphalts.

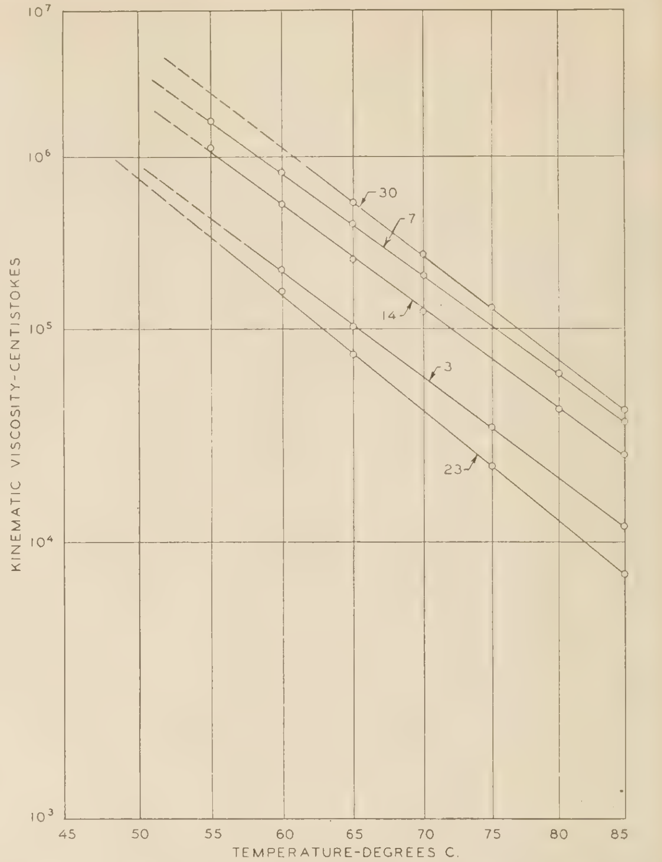

Figure 5.—Relation Between Log Log Viscosity and Log Absolute Temperature for Selected 50–60 Grade Asphalts.

the inability of the instrument to give accurate results at these high viscosities. However, no definite conclusions can be drawn.

The slope m of the viscosity-temperature curve can readily be calculated from the viscosity at two temperatures or from the graph when plotted. The equation for the slope may be expressed as follows:

$$m=\frac{\log \log \nu_{a1}-\log \log \nu_{a2}}{\log T_1-\log T_2}$$

where ν_{a1} and ν_{a2} are the kinematic viscosities in centistokes at the absolute temperatures T_1 and T_2 respectively.

The value of the slope m was calculated for all the asphalts using the viscosities at 65° C. and 85° C. for the 50–60 penetration grade and the viscosities at 55° C. and 75° C. for the 85–100 penetration grade. These data are shown in table 12. While the sign of these slopes is always negative, this sign only indicates the direction of the slope and is not shown in the table.

These slopes differ by a constant factor from the "viscosity-temperature-susceptibility" (V. T. S.) coefficient which has been proposed by H. G. Nevitt and L. C. Krchma [8] as a temperature susceptibility index, and which these authors claim gives more useful information than the various susceptibility factors based on empirical consistency measurements. The V. T. S. coefficient for these asphalts can be calculated by multiplying the slopes as given in table 12 by the factor 0.221. The V. T. S. coefficient also can be determined directly from the A. S. T. M. viscosity-temperature chart when the data are plotted, since it is equal to the tangent of the measured angle that the plotted line makes with the temperature axis.

Table 12.—*Calculated slope [1] of the log. log. kinematic viscosity–log. absolute temperature curves*

Identification No.	Slope	
	50–60 penetration grade	85–100 penetration grade
1	3.40	4.21
2	3.30	4.00
3	3.64	3.81
4	4.11	3.92
5	3.24	3.80
6	3.72	3.51
7	3.60	3.35
8	3.75	3.70
9	3.27	3.44
10	3.21	3.50
11	3.15	3.34
12	3.13	3.45
13	3.67	3.64
14	3.59	3.61
15	3.93	3.74
16	3.62	3.76
17	3.25	3.62
18	3.13	3.92
19	3.27	3.49
20	3.78	3.63
21	3.45	3.49
22	3.52	3.69
23	3.92	4.12
24	3.75	----------
25	3.51	3.25
26	4.17	3.73
27	3.48	3.70
28	3.52	3.71
29	----------	3.95
30	3.79	3.76
31	3.60	3.57
32	3.42	3.59
33	4.61	4.29
34	3.75	3.75
35	3.88	3.72
36	3.72	4.03
37	3.55	3.71
38	3.87	3.97
39	3.85	3.79
40	4.44	3.92

[1] Calculated from kinematic viscosity data given in table 6.

The viscosity values obtained on the 50–60 and 85–100 penetration grade asphalts at the temperatures used in this report could not readily be correlated with

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[8] The Effect of Temperature on the Consistency of Asphalts—the Viscosity Temperature Susceptibility Coefficient as an Index. Industrial and Engineering Chemistry, Analytical Edition, vol. 9, No. 3, pp. 119–122 (1937).

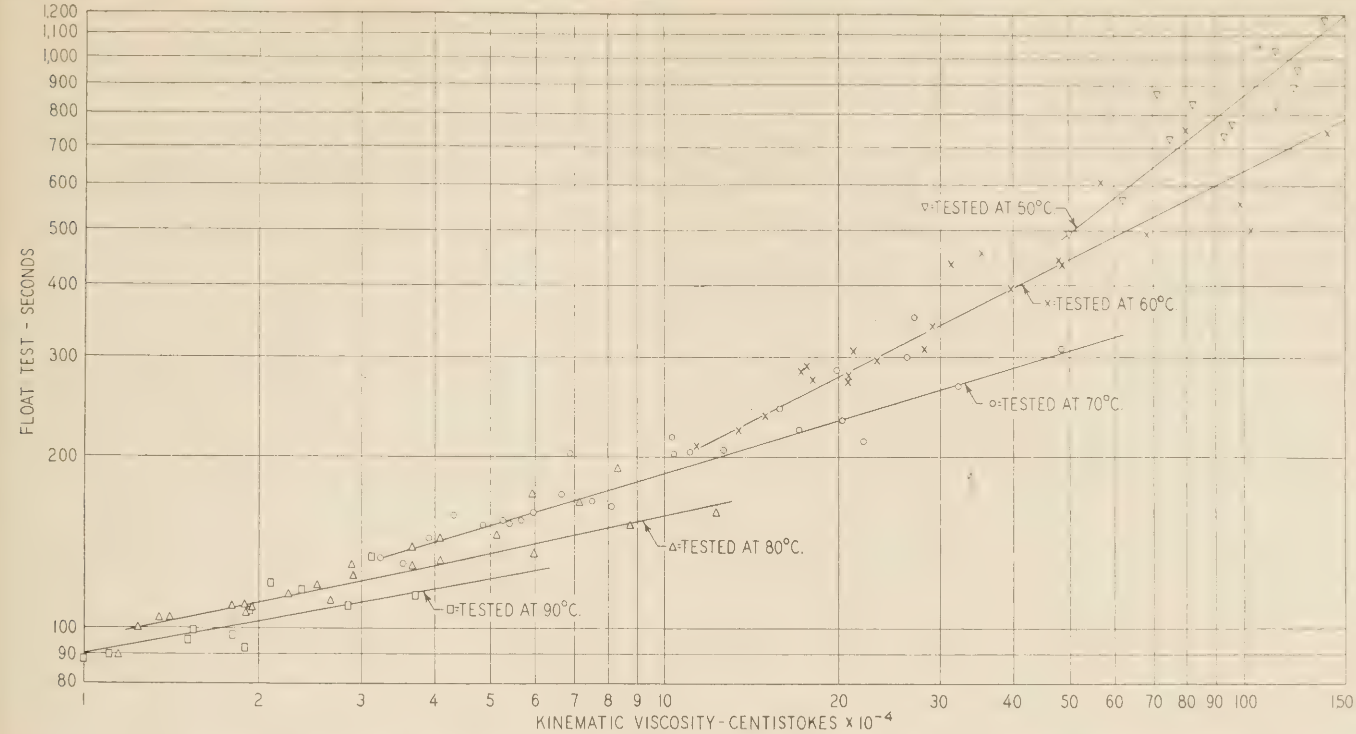

FIGURE 6.—RELATION BETWEEN KINEMATIC VISCOSITY AND FLOAT TEST AT VARIOUS TEMPERATURES.

TABLE 13.—*Float test and interpolated viscosity at various temperatures*

50–60 PENETRATION GRADE

Identification number	Tests at 50° C.		Tests at 60° C.		Tests at 70° C.		Tests at 80° C.		Tests at 90° C.	
	Float test	Kinematic viscosity	Float test	Kinematic viscosity	Float test	Kinematic viscosity	Float test	Kinematic viscosity	Float test	Kinematic viscosity
	Seconds	*Centistokes ×10⁻⁴*	*Seconds*	*Centistokes ×10⁻⁴*	*Seconds*	*Centistokes ×10⁻⁴*	*Seconds*	*Centistokes ×10⁻⁴*	*Seconds*	*Centistokes ×10⁻⁴*
3			308	21.6	160	6.0	108	2.53	79	0.73
7			751	78.7	285	19.5	173	5.94	120	2.11
13			858	241.0	310	59.1	160	12.20	114	3.72
14			443	51.6	206	12.9	131	4.01	96	1.51
15			504	102.7	214	22.8	135	5.64	93	1.89
23			237	16.0	144	3.9	100	1.24	66	.46
24			748	139.5	267	32.2	152	8.84	109	2.82
25			493	68.3	224	17.2	132	5.24	97	1.82
26			558	99.5	232	20.2	144	5.38	98	1.77
30			821	113.8	300	26.4	167	7.13	117	2.37
31			1,067	104.4	352	26.5	193	8.12	134	3.07
32			606	56.9	244	16.5	146	4.83	108	1.93
33			438	31.3	204	7.0	123	2.92	83	.65
40			438	48.4	204	11.5	129	2.88	88	.94
85–100 PENETRATION GRADE										
	492	50	210	11.4	133	3.22	90	1.11		
	1,187	137	457	35.2	217	10.30	139	3.68		
13	893	122	310	28.2	168	7.50	118	2.52		
14	729	75	273	18.2	155	5.26	109	1.80		
15	734	93	271	20.9	155	5.66	109	1.89		
23	567	62	223	13.5	130	3.55	89	1.14		
25	874	71	290	17.7	153	5.90	106	1.89		
30	966	124	340	29.1	164	8.11	112	2.67		
31	1,276	167	394	39.6	205	11.10	128	3.68		
32	770	96	296	23.4	172	6.68	115	2.26		
33	1,038	113	279	20.9	152	4.88	104	1.41		
40	839	82	283	17.2	158	4.32	104	1.35		

the empirical tests that are usually employed for measuring the consistency of asphalts. However, in the investigation of these materials, float test determinations were made at 50°, 60°, 70°, 80°, and 90° C. The values obtained at 80° C. were used in the report of Lewis and Welborn [4] for the calculation of the float-test index. The kinematic viscosity determinations made on the selected 50–60 and 85–100 penetration grade asphalts, shown in table 7, were in most cases made at 65°, 75°, and 85° C., but the values at the temperature used for the float-test determinations were interpolated from the curves. These values for the float-test and the kinematic viscosity at the same temperature are shown in table 13. The data in this table have been plotted in figure 6 to logarithmic scales.

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[4] The Physical and Chemical Properties of Petroleum Asphalts of the 50–60 and 85–100 Penetration Grades. Annual Meeting of Association of Asphalt Paving Technologists, Chicago, Ill., Jan. 1940. PUBLIC ROADS, March 1940, vol. 21, No. 1.

In this figure the best straight line has been drawn through the points for each temperature. Some of the points deviate widely from this line, but this is to be expected since the materials tested differed widely in source and inherent characteristics such as specific heat and surface tension. However, in general a good relationship is indicated.

The curve for each test temperature has a different slope. This slope increases for decreasing temperature, the increase becoming progressively greater for each decrement of temperature. It will be noted also that the tests run at the higher temperatures, especially 70° and 80° C., show less deviation from the straight line than those run at 50° and 60° C.

While this general relationship between the float test and kinematic viscosity was found, no definite conversion factor can be determined that would be applicable to all types of asphalt cements. Rhodes, Volkmann, and Barker [3] report this same condition for the float test determination on road tars, even though their work was done on coal tar residues which were perhaps from the same or similar sources and similar types of manufacture.

SUMMARY

The determination of the viscosity of all grades of bituminous materials over a wide range of temperature in absolute units is desirable since it gives a definite basis for comparison of the consistency of all types by a common measure. However, it is recognized that one instrument will not give results over the complete range but measurements by two or three instruments are necessary. These tests have shown that a capillary type instrument, such as the one used in this investigation, will give results from a minimum of approximately 100 centistokes to a maximum of approximately 6,000,000 centistokes. Thus it would be valuable as a unit in any combination of instruments necessary to cover the entire range of consistency of bituminous road materials.

The limitations of the instrument permit viscosities of asphalts of the 50–60 and 85–100 penetration grades to be made only over a temperature range of approximately 45° to 90° C. This range does not permit a study of the consistency of these asphalts at most of the temperatures that are of interest to users of these types of asphaltic materials. In actual service the asphalts are at temperatures from below 0° C. to about 60° C., and they are heated to approximately 135° to 180° C. for use in hot mixed pavements or for application in the construction of penetration macadam. It is not possible to measure the viscosity of these asphalts at atmospheric temperatures with this instrument, although the use of a larger capillary might permit the determinations to be made at lower temperatures than used in this study.

By the use of additional heating coils and a clear oil bath which would not flash at the higher temperature, it might also be possible to extend the range of the instrument to include viscosity measurements at the mixing or application temperatures; but, even with these modifications, the instrument is not readily adapted to cover the consistency measurements of the semisolid asphalts of the grades studied at those temperatures for which such measurements would be of practical significance.

For the liquid asphaltic materials, the instrument can be satisfactorily employed to measure the consistency of all grades at 35° C., the temperature suggested for evaluating the relative consistency of the various grades of road tars. The adoption of a standard method for the determination of the absolute viscosity of all grades of both the liquid asphaltic road materials and road tars at a test temperature, such as 35° C., close to that of normal atmospheric temperature should prove of great value in that it would give a definite knowledge of the consistency of these materials at the time of application and before any appreciable loss of volatile material occurred.

The results obtained with this instrument may be expected to check within ±2 percent or better for these penetration grades of asphalt at the test temperatures used, and this accuracy compares favorably with that usually obtained in ordinary testing of bituminous materials. The instrument gives much closer checks with liquid asphalts of lower viscosities at atmospheric temperatures.

No satisfactory factor for converting the values for float test at various temperatures to kinematic viscosity can be determined that would be applicable to all asphalts.

The data obtained with the instrument can be plotted in a straight line by plotting the double logarithm of the viscosity in centistokes against the logarithm of the absolute temperature, and the slope of this line gives a factor for the viscosity-temperature susceptibility over the range of temperature at which test results can be obtained.

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[3] Consistency Measurements in the Coal Tar Industry, by Rhodes, Volkmann, and Barker. Symposium on Consistency, A. S. T. M., June 1937.

(Continued from p. 126)

IMPORTANCE OF DETERMINING FLEXURAL STRENGTH OF PAVEMENT CONCRETE EMPHASIZED

Figure 5 shows the strength data given in figure 4 plotted against the water-cement ratio instead of the cement factor. Here again the quality of the coarse aggregate is reflected in the results obtained. Note, for instance, that a water-cement ratio of 0.60 was required to develop a modulus of rupture of 550 pounds per square inch with combination 1–10, whereas this strength was obtained with a water-cement ratio of 0.95 in combination 1–1.

Attention is directed to the fact that the curves for combinations 1–1 and 1–10 are straight lines. However, this was not the case for all combinations of materials investigated, many combinations giving curves which had the characteristic shape of the typical water-cement ratio—compressive strength curve. In fact the average curve shown is of this general shape.

The data shown in figures 2 and 3 might have been plotted with the principal relation between water-cement ratio and strength as in figure 5, with additional curves to give the other desired information. The arrangement of data is of course a matter to be decided by circumstances.

Complete compressive strength data are not available for this series of tests because of the fact that companion compressive strength specimens were not made. However, limited data were obtained for the three leanest mixes (4.4, 5.2, and 6.0 sacks of cement per cubic yard) as the result of tests on modified cubes remaining from the flexure tests. These data showed that for combination 1–1 the compressive strengths were 9 percent

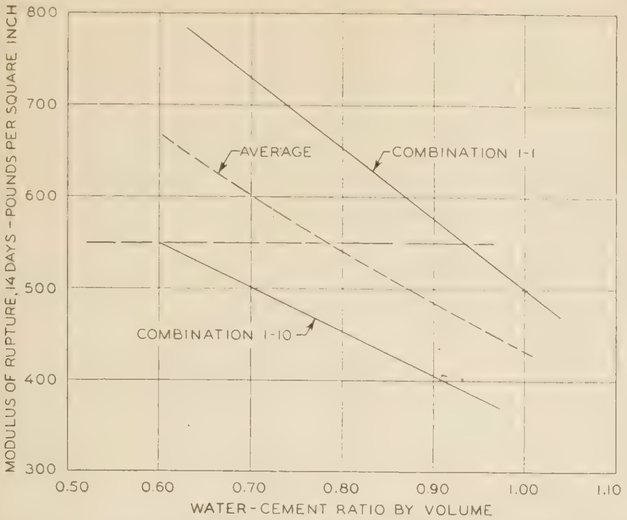

Figure 5.—Relation Between Water-Cement Ratio and Flexural Strength of Concrete. (Average Curve and Maximum Range.)

greater than those for combination 1–10 as compared with the corresponding average flexural strength differential of 32 percent.

Of the group in which sand No. 2 was combined with eight different coarse aggregates, combination 2–13 gave just about as high compressive strength as any combination in the group. However, it was found that, at a cement factor of 6 sacks per cubic yard, the flexural strength of combination 2–13 was the lowest of all, other combinations in the group giving strengths up to 17 percent higher than combination 2–13 (table 4). Many other examples could be given to show that two concretes having the same compressive strength do not necessarily have the same flexural strength, emphasizing the importance of determining the flexural strength characteristics of the constituent materials used in pavement concrete.

It is believed that the data presented are sufficient to indicate that, when pavement concrete is to be made of a variety of combinations of aggregates and a reasonably uniform minimum flexural strength is desired, investigations of the materials should be made along the lines indicated in this report in order to predetermine the flexural strengths to be expected. Compressive strength tests on concrete made with the materials to be used are inadequate, as the ratio of flexural to compressive strength varies over wide limits for different combinations of materials.

INDEX TO PUBLIC ROADS, VOLUME 20, NOW AVAILABLE

The index to PUBLIC ROADS, volume 20, is now available. A chronological list of articles and a list of authors are included with the index. The index will be sent free to subscribers to PUBLIC ROADS requesting it. Requests should be addressed to the Public Roads Administration, Federal Works Agency, Washington, D. C.

Indexes to volumes 6 to 8 and 10 to 19, inclusive, are also available and will be sent to PUBLIC ROADS subscribers upon request. Indexes to volumes 1 to 5, inclusive, have never been prepared. The supply of the index to volume 9 is exhausted.

REORGANIZATION WITHIN DEPARTMENT OF COMMERCE

Effective August 14, 1940, the name of the Automotive-Aeronautics Trade Division of the Bureau of Foreign and Domestic Commerce, Department of Commerce, has been changed to Motive Products Division. The Railway Equipment Section, formerly a part of the Transportation Division, has been transferred to the Motive Products Division.

STATUS OF FEDERAL-AID HIGHWAY PROJECTS

AS OF AUGUST 31, 1940

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$ 1,464,149	$ 729,767	36.2	$ 4,322,451	$ 2,146,773	164.6	$ 2,089,250	$ 1,040,470	73.6	$ 2,317,772
Arizona	266,375	185,485	12.3	1,196,267	785,707	49.2	351,629	170,320	15.6	1,453,417
Arkansas	1,391,182	617,532	19.4	2,557,404	1,287,053	127.1	468,865	228,867	15.3	904,398
California	1,725,188	924,507	31.1	8,428,219	4,354,359	129.6	2,144,067	1,170,270	49.1	2,314,705
Colorado	688,141	387,836	32.5	2,573,204	1,430,728	130.2	290,719	163,849	93.9	2,375,856
Connecticut	15,000	7,500		2,671,413	1,304,214	21.9	283,541	133,343	4.6	1,060,462
Delaware	52,661	26,330	.9	1,563,392	780,967	16.5	561,996	254,289	15.1	1,048,125
Florida	152,500	76,250	1.1	3,811,683	1,895,563	115.8	786,995	393,498	17.1	2,340,569
Georgia	511,766	255,883	37.1	6,226,919	3,113,460	294.9	4,801,481	2,401,241	174.2	4,888,279
Idaho	411,947	251,915	33.4	1,405,055	825,348	134.8	67,429	41,590	6.7	1,799,201
Illinois	1,071,400	535,700	25.9	9,496,598	4,747,404	197.9	1,710,876	855,438	59.4	3,128,998
Indiana	1,582,010	791,005	40.4	6,663,821	3,325,504	126.0	3,898,700	1,754,500	57.3	951,740
Iowa	1,056,836	443,290	19.9	5,651,428	2,595,462	195.9	2,736,462	1,284,760	93.9	463,961
Kansas	592,276	296,138	38.2	7,159,735	3,594,469	429.9	2,542,552	1,256,328	261.1	3,576,242
Kentucky	810,339	403,613	12.5	4,279,129	2,139,564	95.4	557,235	278,618	69.5	2,991,045
Louisiana	102,203	45,577	.6	11,772,001	2,934,899	36.7	2,520,534	1,248,671	60.0	2,933,530
Maine	322,100	161,050	6.3	1,394,798	697,398	37.6	346,410	173,205	5.9	602,959
Maryland	86,000	43,000	.9	3,846,031	1,914,697	48.1	461,503	228,651	5.3	1,269,091
Massachusetts	537,234	268,191	4.4	3,711,347	1,846,600	30.9	198,728	99,364	.7	2,803,104
Michigan	733,782	366,891	16.9	9,645,810	4,734,804	301.7	3,421,728	1,711,864	90.0	499,128
Minnesota	1,254,476	581,860	79.3	7,550,186	3,764,754	519.0	1,519,753	757,636	95.1	3,184,096
Mississippi	630,400	238,750	30.5	5,923,606	2,642,859	299.0	3,168,760	1,477,830	148.7	1,490,118
Missouri	1,471,813	735,907	69.3	7,015,236	3,324,022	209.1	2,740,970	1,075,023	76.2	4,382,374
Montana	1,772,545	1,005,189	117.3	3,053,507	1,725,537	192.7	711,489	370,833	39.3	3,748,414
Nebraska	1,746,156	873,078	210.4	5,414,542	2,619,255	637.4	1,485,928	742,964	156.7	2,572,484
Nevada	903,337	777,776	49.1	1,667,109	1,446,157	73.9	5,600	4,881		759,186
New Hampshire	363,297	178,779	7.9	1,200,627	591,075	31.6	293,186	141,043	6.0	890,424
New Jersey	1,089,800	544,670	8.9	4,416,148	2,208,074	32.9	152,290	76,145		2,157,070
New Mexico	295,323	182,885	35.6	2,045,879	1,253,915	106.7	569,311	343,181	58.3	1,321,376
New York	1,605,890	798,782	31.2	15,520,362	7,659,680	236.0	3,245,077	1,394,209	34.9	1,769,545
North Carolina	2,018,935	1,008,510	99.8	4,263,331	2,132,197	202.9	1,311,810	655,330	51.3	1,967,891
North Dakota	368,910	197,727	27.4	3,215,338	1,793,666	267.8	3,222,544	1,654,102	274.9	3,247,421
Ohio	885,723	442,862	10.1	11,194,444	5,569,577	111.9	5,015,400	2,507,700	39.1	4,928,659
Oklahoma	709,792	376,887	39.0	3,576,597	1,891,289	117.2	1,431,085	705,629	52.4	4,108,137
Oregon	1,069,898	643,910	95.4	3,054,835	1,819,275	68.2	390,370	235,540	7.3	1,292,674
Pennsylvania	1,111,060	553,190	16.5	10,489,569	5,194,605	114.9	5,368,512	2,659,329	36.6	2,547,885
Rhode Island	203,702	101,635	1.8	1,195,476	596,635	11.9	350,158	174,780	3.8	1,001,817
South Carolina	22,600	11,300	.1	2,704,264	1,304,440	169.6	886,092	427,655	108.4	2,315,306
South Dakota	822,094	472,894	139.8	4,189,890	2,450,540	571.3	1,604,660	990,090	238.2	2,734,371
Tennessee	334,614	167,307	3.5	3,836,352	1,918,176	113.5	1,497,110	748,555	61.6	3,733,138
Texas	2,395,957	1,179,390	193.4	7,486,535	3,711,272	337.2	3,441,092	1,649,645	186.3	6,860,611
Utah	360,045	263,205	32.1	1,182,595	838,293	59.7	465,060	196,660	19.7	924,958
Vermont	134,700	67,350	4.5	1,578,498	787,599	47.2	251,669	125,835	5.1	298,845
Virginia	679,622	293,164	25.2	3,034,347	1,472,840	68.3	1,125,073	560,904	30.2	1,749,171
Washington	848,456	444,394	9.8	3,616,683	1,913,535	82.0	534,391	282,500	9.8	990,478
West Virginia	352,800	175,220	12.6	3,093,970	1,540,696	93.9	1,238,740	618,520	27.2	1,679,556
Wisconsin	1,745,764	857,310	91.1	4,699,141	2,315,800	137.6	489,165	236,430	30.0	3,568,886
Wyoming	995,142	627,108	110.8	852,951	551,358	93.8	593,680	369,207	63.4	892,837
District of Columbia	38,300	19,150	.4	499,942	249,971	4.1	119,500	59,750	1.0	382,475
Hawaii	29,184	11,010		237,910	122,602	2.8	662,741	329,516	11.6	1,496,753
Puerto Rico	20,338	9,980	.2	1,380,599	682,575	25.6	228,404	113,550	.6	764,665
TOTALS	39,853,762	20,658,639	1,923.0	227,567,174	112,547,242	7,724.4	74,360,320	36,574,108	3,042.0	109,484,203

U. S. GOVERNMENT PRINTING OFFICE: 1940

STATUS OF FEDERAL-AID SECONDARY OR FEEDER ROAD PROJECTS

AS OF AUGUST 31, 1940

STATE	COMPLETED DURING CURRENT FISCAL YEAR			UNDER CONSTRUCTION			APPROVED FOR CONSTRUCTION			BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	Estimated Total Cost	Federal Aid	Miles	
Alabama	$ 152,844	$ 76,213	1.4	$ 975,579	$ 486,070	56.3	$ 112,400	$ 56,200	0.3	$ 483,029
Arizona	53,782	17,866	4.7	261,016	188,429	12.8	25,963	18,745	1.0	234,685
Arkansas	331,054	154,443	7.7	271,725	135,651	23.9	114,125	74,526	10.6	70,879
California	341,885	185,938	10.5	624,380	338,814	31.2	137,102	73,776	.5	819,162
Colorado				152,679	63,187	1.2	46,749	26,348	.7	200,688
Connecticut	52,818	25,299	.8	314,408	152,710	3.8	104,991	50,041	1.8	165,763
Delaware	54,721	27,361	7.6	73,439	29,007	5.1	40,371	19,751	2.8	268,125
Florida				351,383	174,893	.4	606,994	278,024	19.8	173,686
Georgia	25,161	12,581	4.6	569,038	269,519	53.5	543,346	271,673	46.2	1,058,954
Idaho				101,331	62,475	15.2	70,844	37,885	7.6	203,486
Illinois	327,500	163,750	20.1	1,833,485	899,568	67.4	324,400	162,200	14.7	304,077
Indiana	227,670	113,835	16.8	314,102	155,812	17.9	91,936	45,900	4.4	916,997
Iowa	763,200	362,275	141.3	1,145,674	546,216	223.2	840,411	396,280	241.1	235,697
Kansas	202,136	101,068	1.9	741,979	373,898	52.5	287,357	143,678	46.9	1,212,201
Kentucky	453,306	127,985	25.9	553,896	202,045	43.3	294,932	80,800	15.0	332,278
Louisiana	41,637	20,818	3.7	256,292	128,091	22.0				458,796
Maine	72,650	35,536	4.5	189,474	91,428	10.8	71,200	33,500	3.2	7,907
Maryland				177,996	88,998	8.2				427,378
Massachusetts	110,536	54,886	2.7	523,730	259,616	10.7				497,383
Michigan	72,760	36,380	12.2	1,524,117	765,448	114.2	155,760	77,880	15.3	578,361
Minnesota	125,732	59,354	6.6	693,263	345,915	104.3	333,167	166,583	68.8	1,026,170
Mississippi	146,300	73,150	10.6	526,814	257,907	12.0	593,020	284,975	39.2	421,072
Missouri	177,806	88,903	24.8	515,128	254,153	49.7	362,668	114,512	46.2	703,803
Montana	429,411	242,892	61.4	249,798	140,960	19.2	29,357	16,566	2.3	655,794
Nebraska	241,075	120,379	43.8	671,543	340,348	82.7	97,331	43,569	23.4	287,707
Nevada	84,598	73,231	15.5	168,076	140,559	27.1	30,543	23,629	3.9	89,390
New Hampshire	48,387	23,241	2.2	37,254	16,906	.1	71,651	35,488	1.2	162,156
New Jersey	254,560	127,280	10.5	329,030	164,435	9.1	61,333	30,660	2.4	499,449
New Mexico	101,564	63,386	13.1	396,987	244,848	14.7	247,335	84,392	11.9	101,030
New York	688,360	344,180	24.8	2,213,924	1,056,282	59.9	350,540	136,870	14.4	171,955
North Carolina	232,540	116,270	21.1	867,213	434,573	76.6				327,757
North Dakota	39,433	21,136	.3	145,151	79,399	1.2	27,520	14,750	2.4	1,014,688
Ohio	244,707	122,288	10.4	2,329,350	1,171,450	82.6	807,841	402,550	17.9	791,442
Oklahoma	450,988	239,251	31.8	216,365	114,370	16.1	267,180	116,876	12.4	929,254
Oregon	189,797	96,650	29.8	304,017	137,910	31.5	135,049	79,280	15.0	241,854
Pennsylvania	449,502	218,646	19.4	1,682,197	840,190	45.8	195,984	97,992	4.7	235,836
Rhode Island	2,716	1,329		227,397	113,672	3.7				95,049
South Carolina	41,500	18,100	3.8	616,040	235,716	57.2	184,830	74,850	56.4	225,295
South Dakota				3,624	3,624					1,280,913
Tennessee	91,090	45,545	7.5	62,560	31,280	3.4	186,188	93,094	7.2	909,350
Texas	738,992	363,625	106.2	690,048	330,210	80.0	334,950	160,725	37.3	982,372
Utah				195,647	120,000	16.1	81,845	58,600	15.6	118,707
Vermont	139,900	48,305	5.4	366,408	103,750	14.0				22,500
Virginia	168,540	80,212	9.0	454,710	207,319	24.7	123,866	51,685	1.6	284,724
Washington	94,191	49,488	2.8	528,552	280,039	28.1	156,374	80,000	17.3	184,084
West Virginia	123,800	61,375	7.5	186,819	93,409	9.2	79,808	39,904	4.4	446,189
Wisconsin	180,211	89,800	2.2	525,609	262,710	16.2	221,661	110,800	11.5	653,577
Wyoming	261,777	165,255	29.8	183,125	103,159	13.0	58,269	37,245	4.0	113,561
District of Columbia				43,684	21,342	.6	92,200	37,500	.8	28,150
Hawaii	164,258	82,085	6.4	114,489	57,793	2.2				158,778
Puerto Rico				302,225	147,640	14.0	55,188	27,140	2.1	80,408
TOTALS	9,195,395	4,551,590	773.1	26,802,770	13,263,743	1,688.6	9,054,579	4,267,442	856.2	21,892,546

STATUS OF FEDERAL-AID GRADE CROSSING PROJECTS

AS OF AUGUST 31, 1940

STATE	COMPLETED DURING CURRENT FISCAL YEAR					UNDER CONSTRUCTION					APPROVED FOR CONSTRUCTION					BALANCE OF FUNDS AVAILABLE FOR PROGRAMMED PROJECTS
			NUMBER					NUMBER					NUMBER			
	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	Estimated Total Cost	Federal Aid	Grade Crossings Eliminated by Separation or Relocation	Grade Crossing Structures Reconstructed	Grade Crossings Protected by Signals or Otherwise	
Alabama						$ 722,004	$ 701,927	6		1	$ 16,800	$ 16,800			5	$ 943,965
Arizona	$ 354,097	$ 319,636	4			9,473	9,473				6,006	6,006			2	276,646
Arkansas	10,230	10,230			4	1,154,833	1,150,686	8	1		232,393	232,180	5		12	411,345
California	181,075	181,075	2		3	886,146	707,665	3	1		18,276	18,276			9	1,696,719
Colorado						277,100	277,100	1			9,522	9,522			1	918,723
Connecticut	153,792	148,343		1		631,483	625,932	7								451,839
Delaware	39,821	39,821			8	106,826	106,826	1		3	50,450	50,450	4		6	467,605
Florida	114,447	109,949	1		1	88,900	88,900	1			168,970	168,445	2		16	1,287,491
Georgia	81,253	81,253	2		7	733,165	733,165	9	4	1	657,241	657,241	4	4	9	1,791,106
Idaho	104,842	104,237	1			102,897	100,072	4			85,358	85,358			33	424,756
Illinois	109,232	107,621	1		4	2,858,728	2,597,922	11	2	42	260,966	213,247	1		73	1,859,346
Indiana	77,455	77,455		1	17	1,019,801	1,019,801	7	1	44	112,783	112,783			35	1,006,040
Iowa	88,665	83,100			23	313,303	239,822	4		27	249,577	235,392	2		47	1,210,949
Kansas	7,242	7,241			3	878,803	878,325	12		3	270,788	270,788	3	2	16	1,095,945
Kentucky	157,925	157,925	4		9	1,007,185	1,007,185	9			44,325	44,325	2		3	571,318
Louisiana						440,618	387,123	3			627,884	570,154	11			801,459
Maine	73,922	73,922		1	4	97,898	97,898	1	1		132,585	132,585	1		2	251,016
Maryland	4,600	4,600			1	636,709	604,916	3	2	1	27,800	27,800			8	770,425
Massachusetts	15,710	15,710				336,591	326,168	1								2,025,042
Michigan	193,014	193,014	1	1	7	1,909,627	1,909,627	8	4	5	158,572	158,572			24	908,161
Minnesota	507,767	499,910	4	1		1,458,599	1,458,599	12	3	9	220,385	220,385		2	9	1,055,027
Mississippi						506,594	506,594	6	1		91,300	91,300	3		1	828,349
Missouri	150,832	150,832		2		1,033,074	1,033,074	6	2		1,725,711	1,231,145	4	2	1	1,090,903
Montana	281,054	281,054	5		2	154,873	85,232				99,948	96,682	1		2	354,768
Nebraska	188,369	188,369		1	3	561,934	561,934	6	1	5	194,103	194,103	4		2	563,847
Nevada						115,732	115,732	2		5	42,138	42,138			20	115,071
New Hampshire	100,989	100,953	3			80,259	80,259	1			3,324	3,324			1	390,249
New Jersey						772,219	772,219	5			69,720	69,720		1	1	1,214,345
New Mexico	20,902	20,902			6	230,045	230,045	2			102,612	97,850	2			548,809
New York	307,110	306,000	2	1		3,766,739	3,699,173	10	17		461,795	457,195		3	8	2,712,937
North Carolina	104,415	104,415	1	1	5	980,368	980,368	13	2	8	111,740	111,440		2	17	858,246
North Dakota	314,410	314,410	4		3	210,780	210,780	3		11	143,020	119,223	1		9	741,485
Ohio	276,468	254,706	3		1	2,518,025	2,468,835	11	3	10	473,067	448,075	2		5	2,614,346
Oklahoma	132,719	131,692	2		7	632,962	632,962	9	1	9	284,817	279,431	2		49	1,881,590
Oregon						462,848	315,518	4								363,725
Pennsylvania	34,709	34,709		1		1,936,810	1,927,334	17	1		977,336	977,131	7			3,949,718
Rhode Island	3,831	3,750				191,039	191,039		1							95,913
South Carolina	79,742	79,742	2	1	1	389,449	389,449	3	2	9	145,000	144,597			24	974,116
South Dakota						228,022	227,162	5	1	4	227,400	211,450	5			1,102,307
Tennessee	160,052	160,052	1	1		92,736	92,736	1	1		124,741	124,741		1		1,749,947
Texas	291,059	290,200	4		3	2,006,677	1,992,363	16	1	4	75,150	75,150	1		4	2,030,627
Utah	7,420	7,420			2	42,751	42,751			11	54,011	54,011			20	297,988
Vermont	2,969	2,969			1	209,428	209,428		2	1	34,546	34,546			7	223,562
Virginia	17,400	17,400	1		3	280,068	278,402	3	2		272,447	272,447	1	2	8	940,287
Washington	138,380	138,380	1	1	2	220,472	218,972	3	1	1	78,830	78,830	1		6	513,498
West Virginia						229,982	229,982	2			5,400	5,400			2	1,144,537
Wisconsin	337,377	333,340	4	1	7	936,427	896,342	5	3	3	13,998	13,998			4	1,371,022
Wyoming						540,923	540,923	5								192,955
District of Columbia						11,061	11,061				48,000	48,000	1			150,010
Hawaii						194,036	194,029	2			9,494	9,494			2	290,147
Puerto Rico						584,007	579,336	11								414,857
TOTALS	5,225,296	5,136,337	53	15	137	35,791,029	34,743,166	262	61	217	9,220,329	8,521,730	70	19	503	49,945,084