A 4-YEAR SURVEY OF LOW TEMPERATURE TRANSVERSE PAVEMENT CRACKING ON THREE ONTARIO TEST ROADS

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INTRODUCTION

This paper describes the results of a transverse crack survey conducted on pavements on three Ontario Test Roads in their eighth, ninth, tenth, and eleventh years of service. This survey demonstrates that there has been a substantial increase in the number of transverse pavement cracks each year. The investigation indicates that low winter temperatures is the primary cause of transverse pavement cracking. The paper concludes with a chart for selecting asphalt cements that should enable low temperature transverse pavement cracking to be avoided during a pavement's service life.

LOCATION

Figure 1 illustrates the location of the three Ontario Test Roads. Test Road 1 is located on Highway 7 about 40 miles west and slightly north of London, Ontario. Test Road 2 is on Highway 97 immediately west of Galt, Ontario. Test Road 3 is on Highway 19 and is about 14

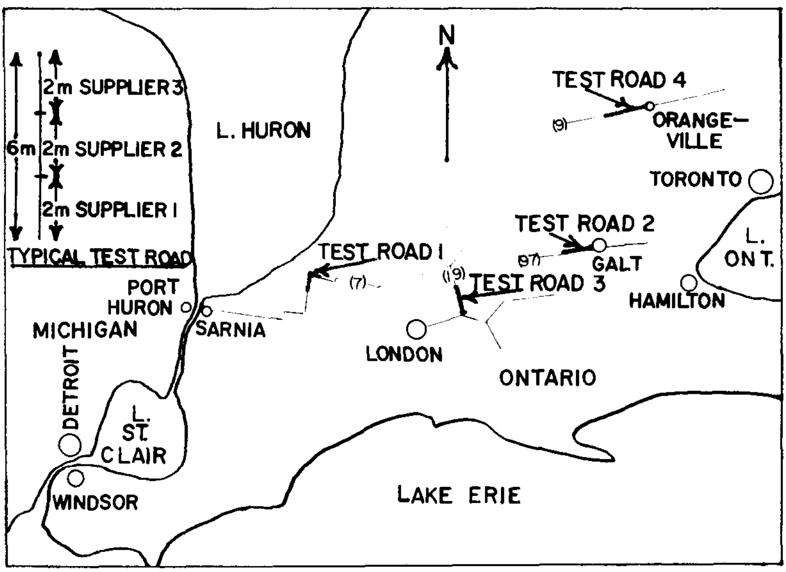

Fig. 1. Locations of Four Ontario Test Roads.

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miles east of London, Ontario. The three Test Roads are about 40 miles apart. Test Road 4, to which brief reference will be made, is located on Highway 9 immediately west of Orangeville.

CONSTRUCTION

Test Roads 1, 2, and 3 are each 6 miles in length and were constructed in 1960. As illustrated in Figure 1, each Test Road consisted o of three 2-mile sections of test pavement. One 2-mile section in each of the three Test Roads was paved with 85-100 penetration asphalt cement furnished by a single asphalt supplier. Three different 85-100 penetration asphalt cements provided by three different suppliers were included in each Test Road. The characteristics of the three 85-100 penetration asphalt cements are given in Table 1. The inspection data

Table 1. Inspection Data on Original 85/100 Penetration Asphalt Cements Used for Ontario's Three 1960 Test Roads

Supplier Number	1	2	3
Flash Point COC F.	585	525	615
Softening Point R and B, F.	115	115	119
Penetration 100 gr. 5 sec. 77 F.	83	96	87
200 gr. 60 sec. 39.2 F.	25	36	22
200 gr. 60 sec. 32 F.	22	26	19
Penetration Ratio	30.2	37.5	25.3
Ductility at 77 F., 5 cm/min	150+	150+	128
Viscosity Centistokes at 275 F.	460	365	210
Centistokes at 210 F.	3953	2763	1472
Thin Film Oven Test			
% loss by weight	0.1	0.3	0.0
Residue			
% Original Penetration at 77 F.	67.5	60.4	61.0
Ductility at 77 F., 5 cm/min	150+	110	115
Solubility in n-hexane			
% asphaltenes	19.7	24.7	18.8
Penetration Index			
(Pfeiffer and Van Doormaal)	-1.00	-0.57	-0.21
Pen-vis number	-0.19	-0.36	-1.34

were obtained by Mr. J. A. A. Lefebvre of Imperial Oil's Research Department, and the penetration index values and pen-vis numbers were calculated by the author.

The three 85-100 penetration asphalt cements selected for the asphalt pavements for the three Test Roads differed widely in temperature susceptibility. This was intentional, since it was the major objective of these three Test Roads to determine the influence of asphalt temperature susceptibility on pavement performance. The 85-100 penetration asphalt cement provided by Supplier 1 was the least temperature susceptible, while that furnished by Supplier 3 was the most temperature susceptible. The asphalt cement provided by Supplier 2 was intermediate in temperature susceptibility.

The three 2-mile pavement sections in each 6-mile Test Road were all made with the same aggregate, same mix design, same hot-mix plant, and same construction crew. However, a different contractor and different aggregate material were employed for each of the three 6-mile Test Roads. The aggregate utilized for each of the three 6-mile Test Roads was a blend of local crushed gravel and natural sand. Each asphalt pavement was laid approximately 3 in. thick, and consisted of a binder course and a surface course.

The pavement was constructed in two 12-ft. lanes on a granular base of adequate strength. The subgrade for all three Test Roads ranged from loam to clay loam. As illustrated by Figure 2, each Test Road had wide gravelled shoulders.

The present daily traffic volumes on the three Test Roads are:

Test Road 1	AADT	900	10% trucks
Test Road 2	AADT	1400	12% trucks
Test Road 3	AADT	1500	18% trucks

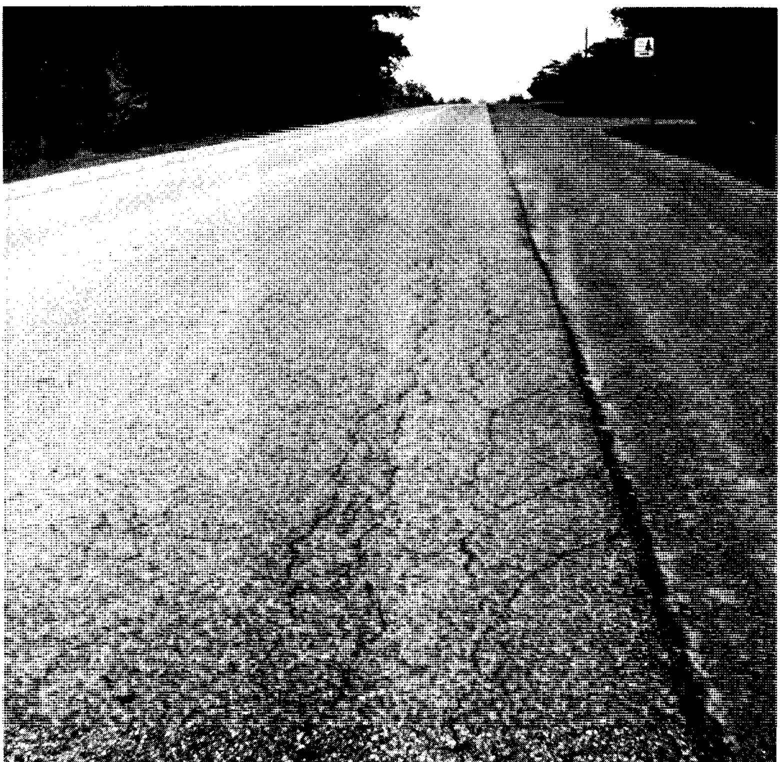

Fig. 2. Illustrating Wide Gravel Shoulders on All Three Test Roads and Pavement Edge Cracking.

FIELD MINIMUM AND OTHER TEMPERATURE DATA

As indicated by Figure 1, the London, Ontario airport, where complete weather data have been recorded since 1940, is located approximately in the centre of the three Test Roads.

From the meteorological records of the London, Ontario airport, the minimum and other temperature data for the period from 1960 to 1971 that appear in Table 2, were taken (1).

Table 2. Yearly Minimum and Other Temperature Data at London, Ontario, Airport. 1960-1971

Year	1960 1961	1961 1962	1962 1963	1963 1964	1964 1965	1965 1966	1966 1967	1967 1968	1968 1969	1969 1970	1970 1971
Month in which min. temp. occurred	Feb.	Feb.	Jan.	Dec.	Jan.	Jan.	Feb.	Feb.	Dec.	Jan.	Jan.
Mean min. temp. for this month, F.	8.3	10.1	7.0	12.4	12.8	7.7	8.8	8.4	14.4	2.5	11.0
Min. Yearly temp., F.	-15	-8	-14.0	-10	-11	-13	-12	-9	-9	-25	-14
Min. temp. day before min. temp. occurred, F.	-1	-8	-12.0	-10	-9	5	-10	-7	-7	-25	5
Min. temp. day after min. temp. occurred, F.	1	16	-3	-5	7	14	-12	16	4	23	-11
Max. temp. on date when yearly min. temp. occurred, F.	9	16	1	14	15	14	8	17	13	23	15
Max. temp. on day before min. temp. occurred, F.	9	7	11	14	6	14	4	12	17	18	19
Max. temp. on day after min. temp. occurred, F.	22	32	11	24	15	33	19	26	37	35	15
Mean temp. on date when yearly min. occurred, F.	-3	4	-7	2	2	1	-2	4	2	-1	1

TRANSVERSE CRACK SURVEY PROCEDURE

In any pavement where low temperature transverse cracking becomes a problem, four different types of transverse cracks will normally be observed, Figure 3. Type 1 cracks extend across the full width of a traffic lane. Type 2 cracks begin at the shoulder but across the traffic lane only part way. Type 3 cracks begin at the central longitudinal joint in a 2-lane pavement and also cross the traffic lane only part way. Type 4 cracks appear in the interior of a traffic lane but do not extend to either lane boundary.

During a transverse crack survey, only one traffic lane is covered at a time by an enumerator as he walks along the outside of the lane. Each of the four types of transverse cracks, as it is encountered in the traffic lane being surveyed, is marked in its appropriate column on a tally sheet carried by the enumerator. Consequently, a total of 36 miles of walking is accumulated to complete a transverse crack survey for three 6-mile Test Roads, 18 miles along each side.

To avoid any possibility of pavement overlap with two different asphalt cements, a portion of pavement about 1/8 mile in length on each

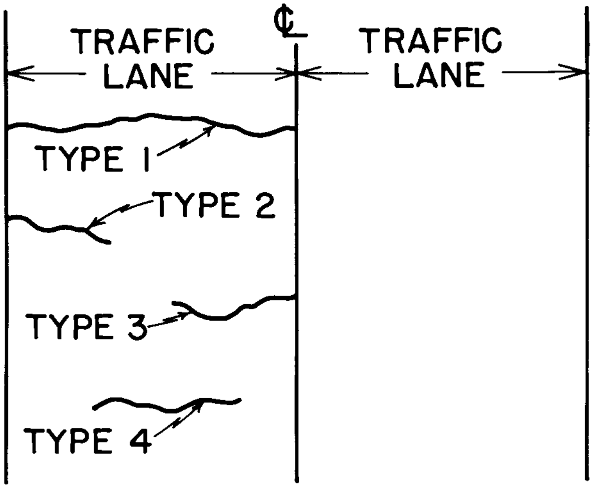

Fig. 3. Types of Transverse Pavement Cracks.

side of the nominal junction at the end of each 2-mile test section, is not included in the transverse crack survey.

Table 3 lists the number of transverse cracks per lane mile for each of the four types of transverse cracks counted during each of the four annual crack surveys. For the 1970 and 1971 crack surveys on Test Road 1, all values should probably be somewhat higher for the pavement sections in which asphalt cements provided by Suppliers 1 and 2 have been incorporated. The transverse cracking in these two pavement sections had become so serious, that from one-third to one-half of each of these test pavements has been resurfaced in a number of short sections. The amount of this resurfacing was substantially greater before the 1971 than before the 1970 crack survey. This would seem to explain why the Type 1 transverse crack count in Test Road 1 in the pavement section in which Supplier 3's asphalt cement was used, was less than 1971 than in 1970.

The transverse crack surveys on these three Test Roads in 1968 and 1969 were made by Mr. Charles Perkins. The 1970 and 1971 crack surveys were made by the author.

For Types 2, 3, and 4 transverse cracks, it is unlikely that any two individuals would record the same number of cracks in any pavement section during an annual crack survey. Even a single individual would probably report different numbers for these three types of transverse cracks, if he repeated his annual survey on any pavement test section. The reasons for this are clear from Figures 2 and 4. Figure 2 illustrates cracks extending in from the gravel shoulder that some individuals might include in their counts of Type 2 cracks. In his own surveys, the author ignored these as Type 2 cracks, since they appeared to be associated with the longitudinal cracking resulting from frost action. A similar crack pattern sometimes occurs in the vicinity of a longitudinal joint in the centre of a 2-lane road, or in the middle of a traffic lane, and might be included as Type 3 or as Type 4 cracks, respectively.

Figure 4 illustrates the multitude of transverse cracks that are sometimes associated with Type 1 cracking. This multitude of cracks might often be considered to include several Types 1, 2, 3, and 4 transverse cracks. However, in his survey, the author included the multiplicity of cracks in Figure 4 as a single Type 1 transverse crack, on the assumption that the family of cracks illustrated had been all generated from a single original Type 1 transverse crack.

Table 3. Numbers of Transverse Pavement Cracks per Lane Mile

Asphalt Supplier	Year	Type 1	Type 2	Type 3	Type 4
		Test Road 1			
Supplier 1	1968	11	19	28	13
	1969	20	23	38	13
	1970	35	49	62	69
	1971	46	40	80	66
Supplier 2	1968	19	53	124	90
	1969	57	55	170	105
	1970	89	79	181	246
	1971	176*	61	139	327
Supplier 3	1968	227	95	307	72
	1969	251	62	157	86
	1970	302	48	70	69
	1971	294*	22	64	60
*Substantial resurfacing					
		Test Road 2			
Supplier 1	1968	3	1	3	2
	1969	4	2	3	2
	1970	8	45	23	18
	1971	14	53	25	14
Supplier 2	1968	7	3	16	14
	1969	12	3	19	28
	1970	25	9	47	125
	1971	37	10	60	134
Supplier 3	1968	62	18	52	29
	1969	93	20	72	36
	1970	123	28	44	56
	1971	158	30	44	32
		Test Road 3			
Supplier 1	1968	1	0	1	0
	1969	2	1	2	1
	1970	6	18	6	9
	1971	9	34	17	15
Supplier 2	1968	2	1	2	1
	1969	5	3	13	12
	1970	9	8	20	18
	1971	21	26	51	85
Supplier 3	1968	46	12	72	4
	1969	76	50	172	56
	1970	110	24	49	17
	1971	152	44	106	40

Fig. 4. An Example of Multiple Cracking.

Figures 1 and 4 illustrate rather clear cut examples of what an enumerator may or may not choose to include in his transverse crack tally. In many other cases it is more difficult to decide whether or not a transverse crack should be included, and in which category. As the enumerator is walking along he must decide usually within a period of a few seconds, to which one if any, of the four categories any observed transverse crack belongs.

Because of the uncertainties just described, the author believes th that Types 2, 3, and 4 transverse cracks should be disregarded when trying to relate transverse crack count to other pavement or environmental variables. On the other hand, Type 1 cracks, which extend completely across a traffic lane, can usually be recognized without ambiguity, and two enumerators could be expected to agree closely with their Type 1 transverse crack counts on any pavement section. It is for this reason that in this paper, only Type 1 transverse cracks are considered to be significant.

It is clearly recognized that some transverse pavement cracking is occasionally due to cracks that develop in the subgrade and base course.

However, in four years of transverse crack surveys on these three 6-mile Ontario Test Roads, no evidence of subgrade or base course cracking was ever observed. The transverse cracking appears to be confined entirely to the asphalt pavement itself.

LABORATORY DATA

The most complete laboratory data to date on the three Test Roads were obtained by Mr. Lefebvre of Imperial Oil's Research Department in 1969, on surface course samples from each of the nine pavement test sections taken that year.

Table 4 lists the asphalt content of surface course pavement samples by extraction, the sieve analyses and specific gravities of the recovered aggregate, Marshall data on the recompacted pavement samples, air voids and percent of laboratory compacted density for the pavement in place.

The hardness of the asphalt cement recovered from the surface course in place in 1969, was also determined from samples taken from each of the three pavement sections in each Test Road. Furthermore, it was decided to investigate the hardness of the asphalt cement in the top 1/4 in. of the surface course, in the balance of the surface course, and in the entire thickness of surface course. This information on the asphalt cements recovered from each of the three pavement sections is given in Table 5 for Test Road 1, in Table 6 for Test Road 2, and in Table 7 for Test Road 3. Having these three sets of data on the hardness of the recovered asphalt in the top 1/4 in., in the remainder of the surface course, and in the total surface course, for each of the three pavement sections in each of the three Test Roads is particularly useful, because for each pavement section it provides three asphalt cement hardness values that can be checked against each other for accuracy.

DISCUSSION OF RESULTS

Asphalt Cement Temperature Susceptibility

Asphalt cements differ widely in temperature susceptibility. Pfeiffer and Van Doormaal (2) developed a penetration index (PI) method, based on the softening point and penetration at 77 F. of an asphalt cement, for expressing differences in temperature susceptibility in quantitative terms. In Table 1, the Pfeiffer and Van Doormaal penetration index (PI) values for the three asphalt cements used in the three Test Roads are listed.

In Figure 5 the number of Type 1 transverse cracks counted on each of the three Test Roads in 1969 (any of the other four years would serve equally well) have been plotted versus the Pfeiffer and Van Doormaal PI values for the three original asphalt cements. Figure 5 indicates that the number of Type 1 cracks decreases with a decrease in penetration index of the asphalt cements. This is contrary to all the

Table 4. Analysis of Surface Course Pavement Samples from the Three Pavement Sections in Each of Three Test Roads

Test Road		1			2			2	
Asphalt Supplier	1	2	3	1	2	3	1	2	3
Recovered Aggregate									
Passing Sieve 3/4 inch	100	100	100	100	100	100	100	100	100
1/2 inch	97.7	97.3	98.2	99.6	98.1	98.6	98.2	97.2	96.1
3/8 inch	78.7	80.9	81.3	86.1	85.0	83.3	79.8	80.4	79.3
No. 4	55.9	59.3	57.6	57.9	59.3	59.1	57.0	56.1	57.6
No. 8	47.6	44.8	49.2	47.5	47.0	46.3	47.6	46.1	47.9
No. 16	41.4	39.9	43.5	40.8	39.2	37.0	38.7	37.0	39.8
No. 30	32.7	31.1	36.1	31.3	28.9	27.1	25.1	24.4	27.6
No. 50	170	17.2	20.7	14.0	13.0	11.9	10.0	10.9	12.0
No. 100	73	7.1	8.7	5.8	5.8	5.3	5.7	6.0	5.4
No. 200	4.9	4.5	5.7	3.7	4.0	3.7	4.3	4.4	3.6
Specific Gravity Aggregate									
ASTM Bulk	2.652	2.653	2.652	2.681	2.680	2.682	2.627	2.627	2.627
ASTM Apparent	2.746	2.764	2.762	2.775	2.775	2.775	2.728	2.727	2.728
Virtual	2.712	2.721	2.684	2.725	2.706	2.697	2.680	2.685	2.681
Asphalt Absorption	0.84	0.94	0.46	0.60	0.36	0.23	0.75	0.82	0.77
Water Absorption, Wt. %	1.3	1.5	1.5	1.3	1.27	1.26	1.4	1.4	1.4
Characteristics									
Asphalt Content % by wt. of mix	5.63	5.91	5.60	6.45	6.15	6.0	6.17	5.63	6.02
Maximum Specific Gravity	2.474	2.470	2.464	2.452	2.449	2.448	2.428	2.452	2.435
Bulk Specific Gravity, Slabs	2.394	2.406	2.384	2.421	2.380	2.400	2.335	2.392	2.381
Bulk Specific Gravity, Recompacted	2.438	2.421	2.434	2.420	2.433	2.423	2.387	2.393	2.411
Percentage of Laboratory Density	98.2	99.4	97.9	100.0	97.8	99.1	97.8	100.0	98.8
Air Voids, Slabs, %	3.2	2.6	3.2	1.3	2.8	2.0	3.8	2.4	2.2
Air Voids, Recompacted, %	1.5	2.0	1.2	1.3	0.6	0.9	1.8	2.4	1.0
Voids, Mineral Aggregate, Recompacted %	13.2	14.1	13.3	15.6	14.8	15.1	14.9	14.0	13.7
Marshall Stability, Lb. at 140 F.	3400	3300	3150	2185	2800	2500	2475	2475	2625
Marshall Flow Index	14	11	13	13	14	11	11	11	11.5

Table 5. Analysis of Asphalt Binders Recovered from Surface Course of Test Road 1

Asphalt Supplier	1			2			3		
Description	Top 1/4 in.	Minus Top 1/4 in.	Full Thickness	Top 1/4 in.	Minus Top 1/4 in.	Full Thickness	Top 1/4 in.	Minus Top 1/4 in.	Full Thickness
Penetration									
100 g., 5 sec., 77 F.	22	30	-	23	34	30	26	31	28.5
200 g., 60 sec., 39.2 F.	10.5	13.5	-	14	21	17.5	13	15.5	14
Penetration Ratio	47.7	45.0	-	60.9	61.8	58.3	50.0	50.0	49.1
Ductility, 5 cm/min/77 F.	148	150-	-	21	71	51	10	20	15
Viscosity									
Poises at 140 F.	20,757	10,235	-	29,004	9,144	15,369	13,705	7,252	8,452
Centistokes at 275 F.	1,092	770	-	1,036	654	799	504	409	431

Table 6. Analysis of Asphalt Binders Recovered from Surface Course of Test Road 2

Asphalt Supplier	1			2			3		
Description	Top 1/4 in.	Less Top 7/16 in.	Full Thickness	Top 1/4 in.	Less Top 7/16 in.	Full Thickness	Top 1/4 in.	Less Top 7/16 in.	Full Thickness
Penetration									
100 g., 5 sec., 77 F.	30	51	44.5	37	37	34	33	40.5	35
200 g., 60 sec., 39.2 F.	16	23	20.5	14	18	16	17.5	20	18
Penetration Ratio	53.3	45.1	46.1	51.9	48.6	47.0	53.0	49.4	51.4
Ductility, 5 cm/min/77 F.	150+	150+	150+	37	99	107	23	69	51
Viscosity									
Poises at 140 F.	9,791	3,809	4,446	19,666	7,988	11,368	6,947	3,341	5,303
Centistokes at 275 F.	815	589	631	949	659	733	435	334	370

Table 7. Analysis of Asphalt Binders Recovered from Surface Course of Test Road 3

Asphalt Supplier		1			2			3	
Description	Top 1/4 in.	Minus Top 1/4 in.	Full Thickness	Top 1/4 in.	Minus Top 1/4 in.	Full Thickness	Top 1/4 in.	Minus Top 1/4 in.	Full Thickness
Penetration									
100 g., 5 sec., 77 F.	32	43	38.5	26	52	40	30	37	35
200 g., 60 sec., 39.2 F.	15	18.5	16.5	15	26	22	14	16.5	15
Penetration Ratio	46.9	43.0	42.9	57.7	50.0	55.0	46.7	44.6	42.9
Ductility, 5 cm/min/77 F.	150+	150+	150+	42	150+	141	17	46	36
Viscosity									
Poises at 140 F.	8,945	4,838	6,165	17,673	3,652	8,081	9,691	4,059	4,646
Centistokes at 275 F.	788	597	695	884	481	640	439	339	371

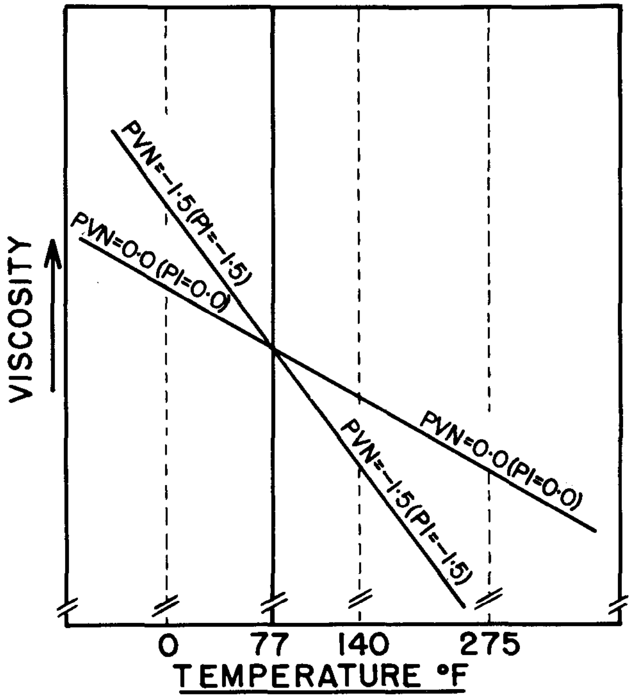

Fig. 5. Sketch Illustrating Influence of Pen-Vis Numbers (PI Values) on Relationships between Viscosity and Temperature of Asphalt Cements.

evidence accumulated to date (for example 3, 4). For this and other reasons (5), the author has concluded that Pfeiffer and Van Doormaal PI values do not always provide a realistic measure of asphalt temperature susceptibility.

Therefore, the author (6), (7) had to develop a different method for providing a quantitative measure of the variation in temperature susceptibilities of asphalt cements. This method is based on the penetration of an asphalt cement at 77 F. and on its viscosity in centistokes at 275 F. Figure 6 demonstrates that for asphalt cements of the same penetration at 77 F., differences in their viscosities at 275 F. provide a very reasonable basis for expressing differences in temperature susceptibility. Since this basis for evaluating paving asphalt temperature susceptibility is different from that employed for determining penetration index, the term "pen-vis number" is employed instead of penetration index as a quantitative measure of temperature susceptibility. The procedure for determining and for applying the pen-vis number of a paving asphalt is described in the Appendix. Because of the way in which they are derived (see Appendix), pen-vis numbers are numerically similar to, and may be numerically identical with penetration index values for many paving asphalts.

With respect to either an increasing or decreasing order of temperature susceptibility, their pen-vis numbers arrange the three asphalts of Table 1 completely opposite to their ranking by their PI values. For example, Supplier 1's asphalt cement has the lowest PI value of the three paving asphalts, whereas it has the highest pen-vis number.

It will be demonstrated later that when pen-vis numbers are employed as a measure of paving asphalt temperature susceptibility, the relationships normally expected between the temperature susceptibilities of the three asphalt cements listed in Table 1 versus the transverse cracking patterns that have developed in the three Test Roads, are obtained (3), (4).

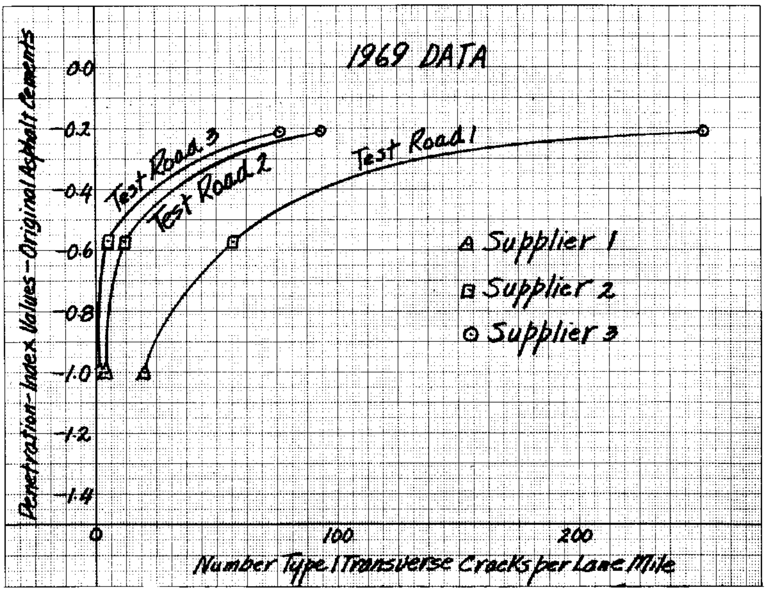

Fig. 6. Illustrating Relationship between Type 1 Transverse Cracking versus Penetration Index.

Paving Mixture Characteristics

Table 4 indicates that the paving mixtures employed for all three Test Roads are very much alike. The principal difference is at the No. 50 sieve, where Test Road 1 shows several percent more passing than for the other two Test Roads. The asphalt content for all three Test Roads lies within the range of 6.0 ± 0.5 percent. All paving mixtures are densely graded and contain approximately 3.0 percent air voids in the in-place condition. Consequently, there would not appear to be any significant difference between the paving mixtures themselves that would account for the very large differences in the numbers of transverse cracks between the three Test Roads.

Differences in Hardness of Recovered Asphalt with Thickness of Surface Course

Tables 5, 6 and 7 contain data on properties of the asphalt cement recovered from the top 1/4 in. of the surface course, from the remainder of the surface course, and from the total surface course for the three pavement sections in each of the three Test Roads.

In all cases, the asphalt recovered from the top 1/4 in. of the surface course is the hardest. On the average it is 20-30 penetration, and it is roughly 10 penetration points harder than the asphalt recovered from the remainder of the same sample, which in general is near the high end of 30-40 penetration, or even slightly above, particularly for Test Roads 2 and 3. In two cases, Supplier 1 for Test Road 2, and Supplier 2 for Test Road 3, the asphalt recovered from the remainder fraction of the surface course sample is approximately 50 penetration. The asphalt recovered from an entire portion of each surface sample is ordinarily 30-40 penetration, and as might be expected, it is intermediate in hardness between asphalt cement from the top 1/4 in. and that from the remainder of the same sample.

Change in Pen-Vis Numbers with Pavement Age

Table 8 compares the pen-vis numbers of the original asphalt cement versus the pen-vis numbers of the asphalt cements recovered in

Table 8. Comparison of Pen-Vis Numbers for Original Asphalt Cements versus Those of the Asphalt Cements Recovered in 1969 from the Surface Course Minus the Top 1/4 Inch, for Each of the Nine Pavement Sections in the Three Ontario Test Roads

Asphalt Supplier	Original Asphalt	Test Road 1	Test Road 2	Test Road 3
1	-0.19	-0.59	-0.46	-0.52
2	-0.36	-0.62	-0.58	-0.61
3	-1.34	-1.36	-1.34	-1.41

1969 from the surface course minus the top 1/4 in., for the nine pavement sections in the three Test Roads. Contrary to the usual expectation, except for the asphalt cement provided by Supplier 3, there has been a decrease in pen-vis number with time. Oxidation is usually considered to be the most important agency of asphalt hardening in service in a pavement. Oxidation ordinarily results in an increase in viscosity at 275 F. for any given penetration at 77 F., and therefore would ordinarily be expected to result in an increase in pen-vis number. However, at least for the asphalt cements employed in these three Test Roads, there has been either no increase in viscosity at 275 F. relative to penetration at 77 F. after nine years of service life, Supplier 1, that is no change in pen-vis number, or there has been a marked decrease in viscosity at 275 F. relative to penetration at 77 F., and therefore a corresponding decrease in pen-vis number, Suppliers 2 and 3. This finding would appear to indicate that the concept of oxidation as the principal agency of asphalt hardening should be re-examined.

Differences in Transverse Pavement Cracking

To provide the data listed in Table 3, transverse crack surveys were always conducted in October. However, in 1969, crack counts were made in both April and October, with practically identical results. This indicates that the annual increase in transverse cracks occurs during winter, and it implies that transverse cracking results from cold weather low temperature.

In Figures 7, 8, and 9, the number of Type 1 transverse pavement cracks per lane mile that are listed in Table 3 for Test Roads 1, 2, and 3 for the eighth, 1968, ninth, 1969, tenth, 1970, and eleventh, 1971, years of service, have been plotted versus the pen-vis numbers of the original asphalt cements, Table 1. These three figures support two principal conclusions:

(a) For all three Test Roads, the number of Type 1 transverse cracks per lane mile increases with a decrease in the pen-vis number of the original asphalt cement.

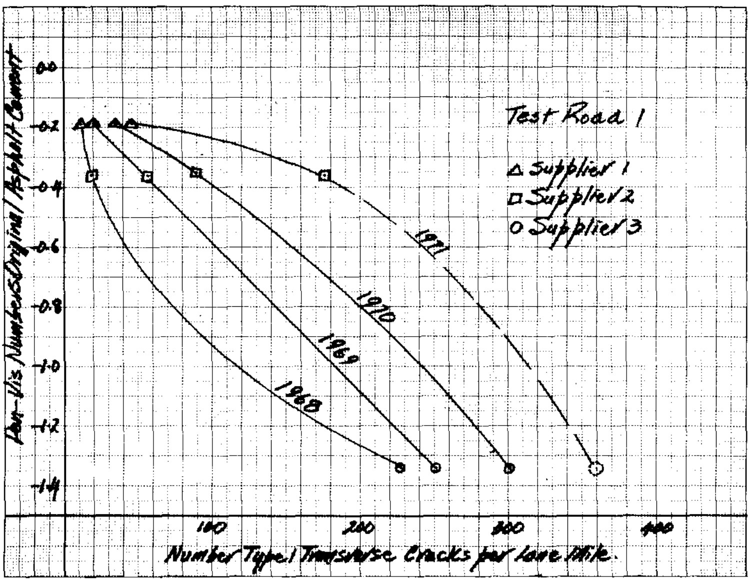

Fig. 7. Illustrating Annual Increase in Type 1 Transverse Cracks Per Lane Mile in Test Road 1.

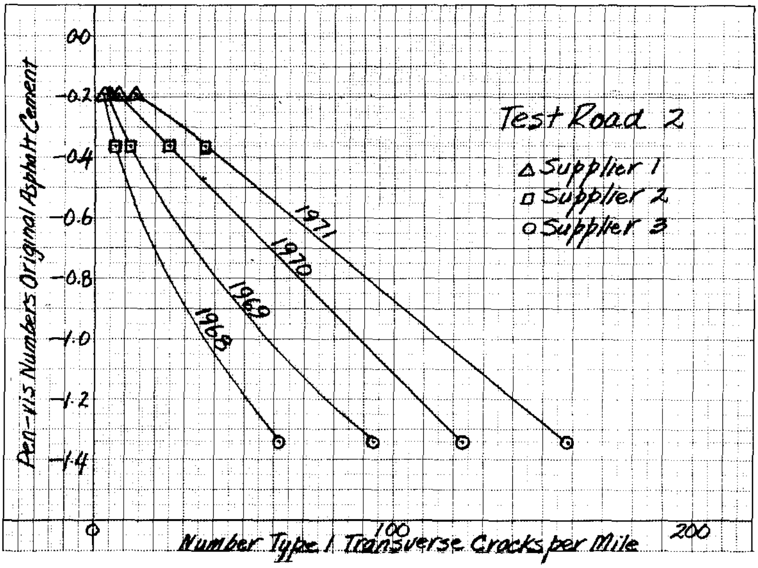

Fig. 8. Illustrating Annual Increase in Type 1 Transverse Cracks Per Lane Mile in Test Road 2.

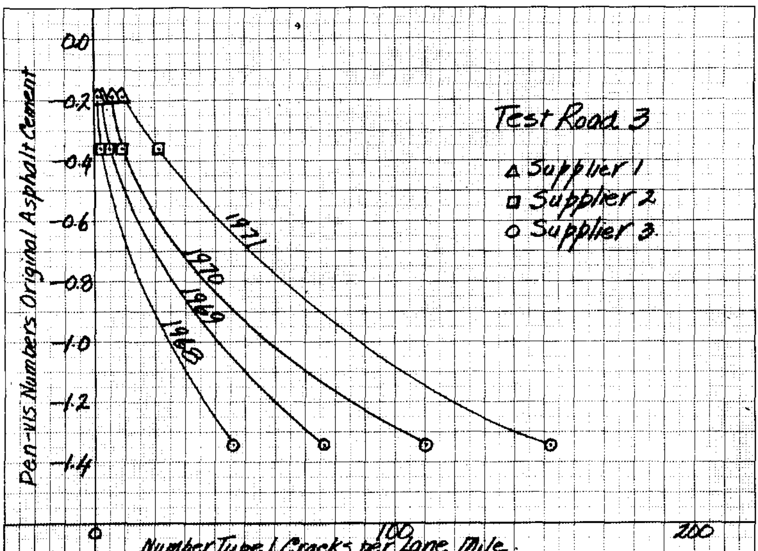

Fig. 9. Illustrating Annual Increase in Type 1 Transverse Cracks per Lane Mile in Test Road 3.

(b) For all three Test Roads, there is a substantial annual increase in the number of Type 1 transverse cracks per lane mile for each of the four years of service for which data have been collected.

In Figure 10, the numbers of Type 1 transverse cracks per lane mile for the three pavement sections in each of the three Test Roads, have been plotted versus the pen-vis numbers of the original asphalt cements for the year 1968. Figures 11, 12, and 13 present similar information for the years 1969, 1970, and 1971. These figures demonstrate very clearly that for each of the four years of service, Test

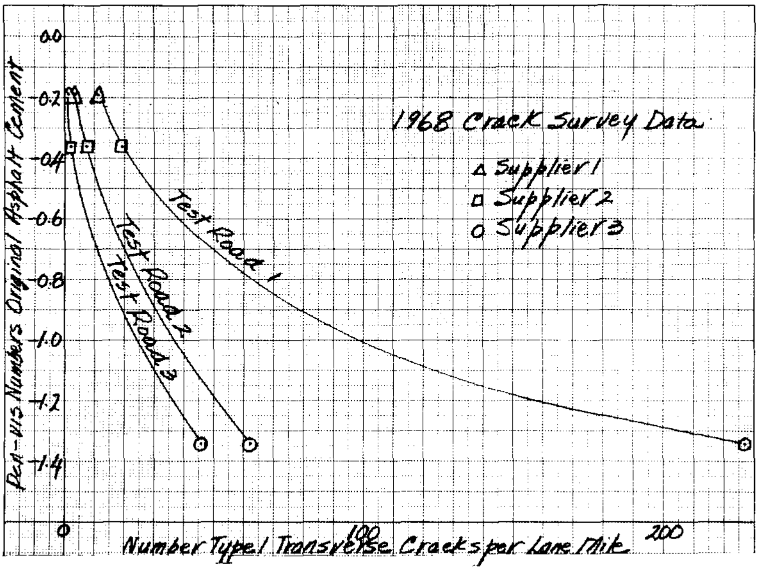

Fig. 10. Influence of Pen-Vis Number of Original Asphalt Cement on Differences in Numbers of Type 1 Transverse Cracks in Test Roads 1, 2, and 3 in 1968.

Road 1 always contains the most Type 1 transverse cracks per lane mile, followed in order by Test Road 2, and by Test Road 3 which always has the least number of Type 1 transverse cracks per lane mile.

Figures 10, 11, 12, and 13 demonstrate that in spite of the use of paving mixtures of very similar properties, and the use of the same 85-100 penetration asphalt cements, the number of Type 1 transverse cracks per mile varies substantially from Test Road to Test Road. The cause of these differences in transverse crack counts between different test locations would appear to be environmental factors that are presently unknown. Figures 10, 11, 12, and 13, illustrate the probable futility of any research program that attempts to obtain significant low temperature pavement performance information from widely separated pavement projects in which only one asphalt cement is employed per

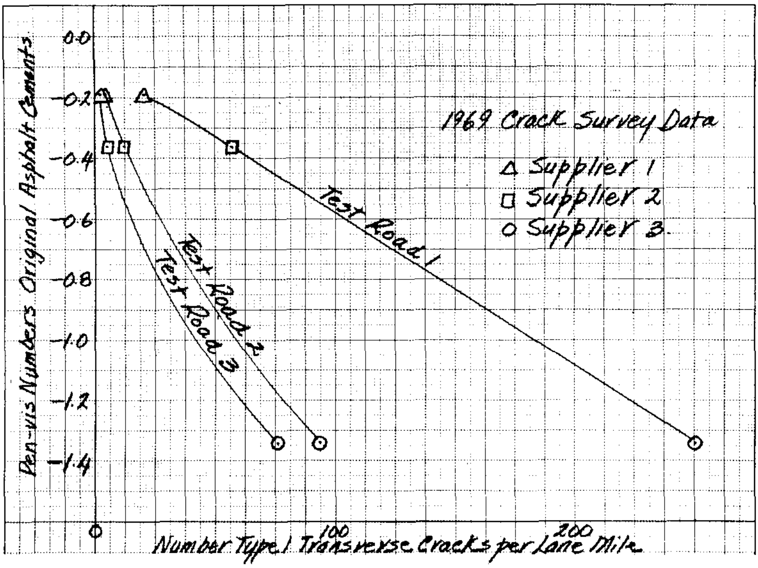

Fig. 11. Influence of Pen-Vis Number of Original Asphalt Cement on Differences in Numbers of Type 1 Transverse Cracks in Test Roads 1, 2, and 3 in 1969.

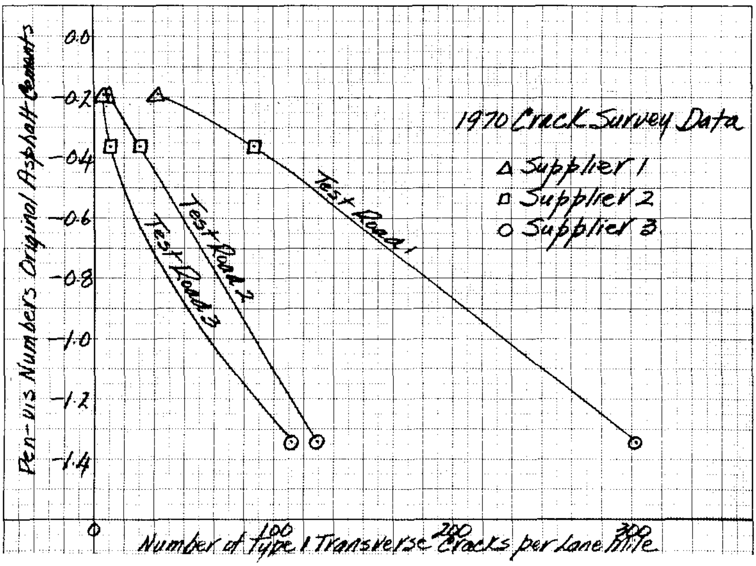

Fig. 12. Influence of Pen-Vis Number of Original Asphalt Cement on Differences in Numbers of Type 1 Transverse Cracks in Test Roads 1, 2, and 3, in 1970.

paving project. The overpowering influence of the unknown environmental factors associated with each test pavement location, would tend to mask or to obscure differences in transverse crack behaviour due to differences in the asphalt cements being compared.

The hazard in attempting to draw quantitative conclusions concerning differences in transverse cracking due to variations in the asphalt cements used in test pavements on a *single* test location, is also indicated by Figures 10, 11, 12, and 13. Because of the influence of unknown environmental factors on transverse pavement cracking, quantitative relationships with respect to the amount of transverse cracking

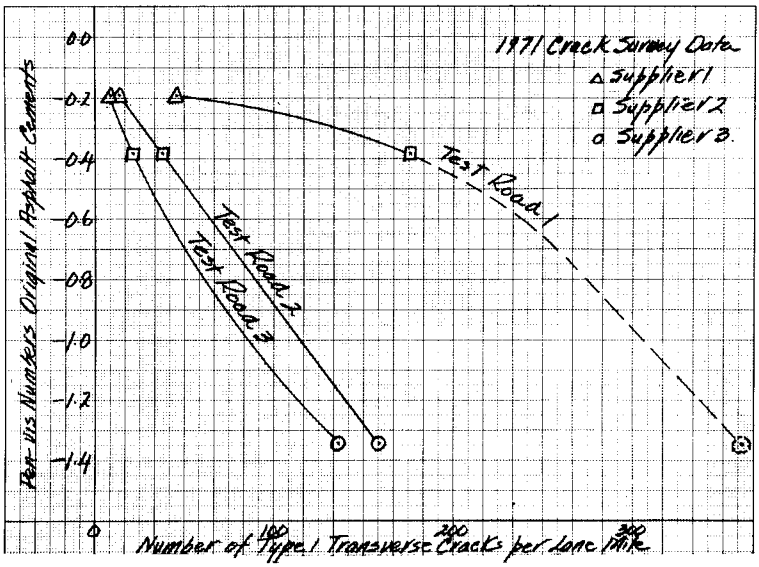

Fig. 13. Influence of Pen-Vis Number of Original Asphalt Cement on Differences in Numbers of Type 1 Transverse Cracks in Test Roads 1, 2, and 3 in 1971.

that apply to a pavement research project at a *single* test location, almost certainly would not apply to another test location some distance away.

In Figure 11, the number of Type 1 transverse cracks per lane mile for 1969 for each of the nine pavement sections in the three Test Roads, has been plotted versus the corresponding pen-vis number of the original asphalt cement. In Figure 14 the number of Type 1 transverse cracks per lane mile for 1969 has been plotted versus the corresponding 1969 pen-vis number of the asphalt cement recovered from the surface course minus the top 1/4 in., Table 8, for each of the nine pavement sections. Figure 14 is quite similar to Figure 11.

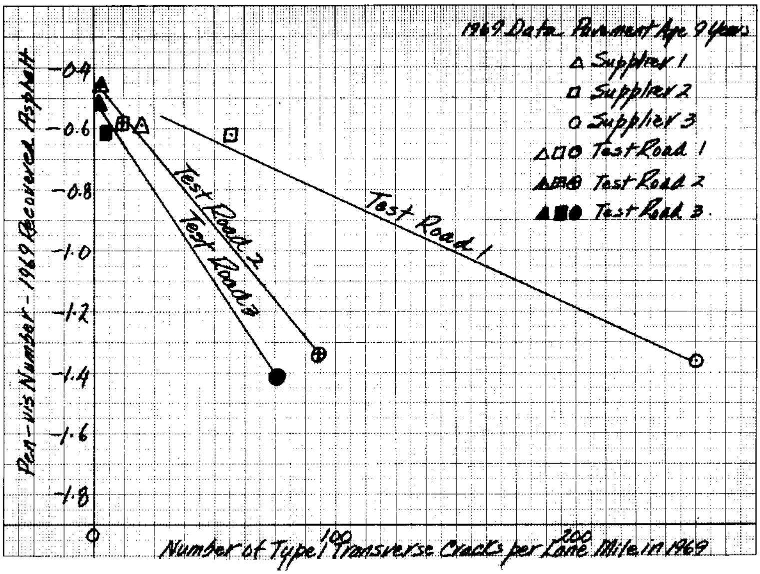

Fig. 14. Transverse Cracking in 1969 versus Pen-Vis Numbers of Asphalt Cements Recovered in 1969 from Test Roads 1, 2, and 3.

Annual Rate of Increase in Number of Low Temperature Transverse Pavement Cracks per Lane Mile

In Figures 15, 16, and 17, the number of Type 1 low temperature transverse pavement cracks per lane mile have been plotted versus year since construction, although crack survey data are available only for the eighth, ninth, tenth, and eleventh years of service life. Figure 15 illustrates the annual rate of increase in number of transverse cracks in pavements in Test Roads 1, 2, and 3, in which the asphalt cement provided by Supplier 3 was incorporated. Figures 16 and 17 illustrate similar data for the crack performance of pavements containing asphalt cements furnished by Suppliers 2 and 1, respectively.

The data in Figures 15, 16, and 17, for pavement ages of 8, 9, 10, and 11 years, indicates that the number of transverse cracks is increasing year by year. From the slopes of the curves through the points, it would appear that particularly for pavements containing asphalt cements provided by Suppliers 1 and 2, the number of cracks is developing at an increasingly faster rate with pavement age. Probably because of the greater number of cracks that have already occurred in pavements containing Supplier 1's asphalt cement, the annual rate of increase in pavement cracking appears to be more constant. By projecting the best line through the points in Figures 15, 16, and 17, representing the transverse crack counts for 1968, 1969, 1970, and

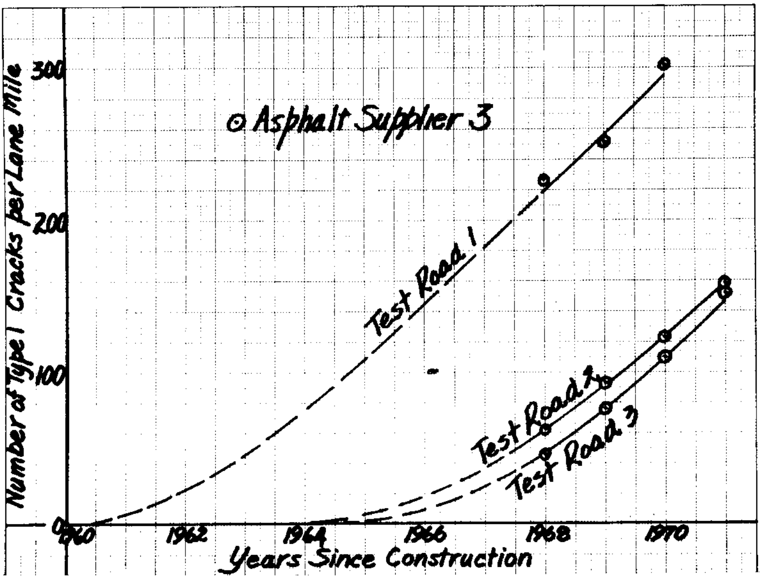

Fig. 15. Illustrating Influence of Supplier 3's Asphalt Cement on Yearly Increase in Transverse Cracking in Test Roads 1, 2, and 3.

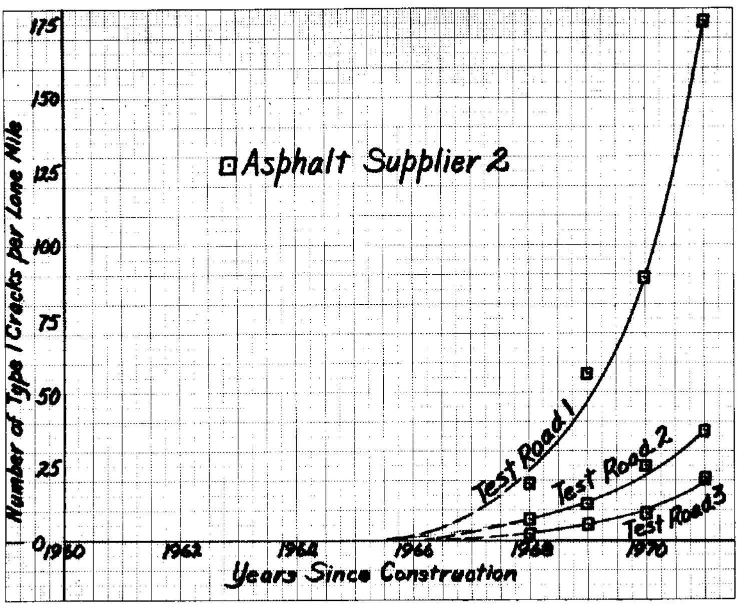

Fig. 16. Illustrating Influence of Supplier 2's Asphalt Cement on Yearly Increase in Transverse Cracking in Test Roads 1, 2, and 3.

1971, back to zero cracks, it would appear that in general, the first cracks in these pavements occurred in the period between 1965 to 1967, that is, at an age of from 5 to 7 years. This was before our crack survey began. The principal exception seems to be Test Road 1, where the pavement containing Supplier 3's asphalt cement (lowest PI) appears to have started cracking at least by its second winter.

Asphalt cements in pavements harden in service year by year. Figures 15, 16, and 17 indicate that in general, it required from 4 to 7 years of service for the 85-100 penetration asphalt cements in the pavements in these three Test Roads, to harden to the point where the

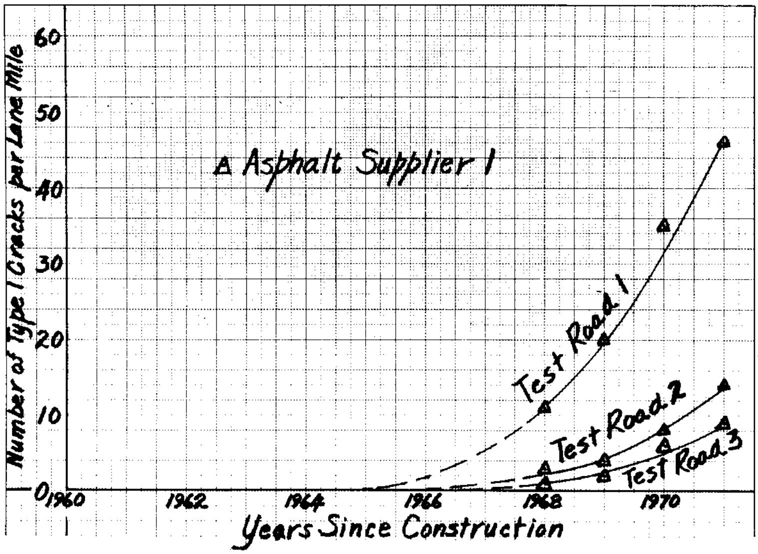

Fig. 17. Illustrating Influence of Supplier 1's Asphalt Cement on Yearly Increase in Transverse Cracking in Test Roads 1, 2, and 3.

tensile stress generated by the tendency of a pavement to contract during chilling to low temperature, exceeded the tensile strength of the pavement, and transverse pavement cracking began to occur.

This implies that by designing asphalt pavements with higher asphalt contents (in accordance with good design practice), to provide greater asphalt film thickness on the aggregate particles (8), the rate of hardening of the asphalt cement would be reduced, and a longer period of time would be required for the asphalt cement in the pavement to reach the critical hardness at which transverse pavement cracking begins to develop.

Figures 15, 16, and 17, make it clear that low temperature transverse pavement cracking is not a cataclysmic event that ends as soon as it has happened. For the conditions that pertain to these three Test

Roads, once pavement cracking begins, it increases at a constant or faster rate year by year, at least until some asymptotic number of transverse cracks is approached.

Modulus of Stiffness Values versus Transverse Cracking

Figure 18, *which is based entirely on 1969 data,* provides a plot of pavement modulus of stiffness values at -5 F. for the nine pavement sections in the three Test Roads, versus the corresponding numbers of Type 1 transverse cracks per lane mile in these pavement sections.

A low temperature of -5 F. was selected for the pavement modulus of stiffness values on the basis of the data of Table 2, in which annual minimum and other temperature data for the 11-yr. life of these pavements, as recorded at the London, Ontario, airport, are listed. The lowest temperature, -25 F., was experienced in January, 1970, long after substantial transverse cracking had occurred. Apart from this, the lowest yearly minimum air temperatures were -15, -14, and -13 F. in February, 1961, in January, 1963, and 1971, and in January, 1966, respectively. For these air temperatures, based on the temperature data reported by Young, Deme, Burgess, and Kopvillem for the Ste. Anne Test Road (9), the corresponding temperatures occurring at a pavement depth of 2 in. could be expected to be about 8 F. higher. The modulus of stiffness at a pavement depth of 2 in. has been selected to

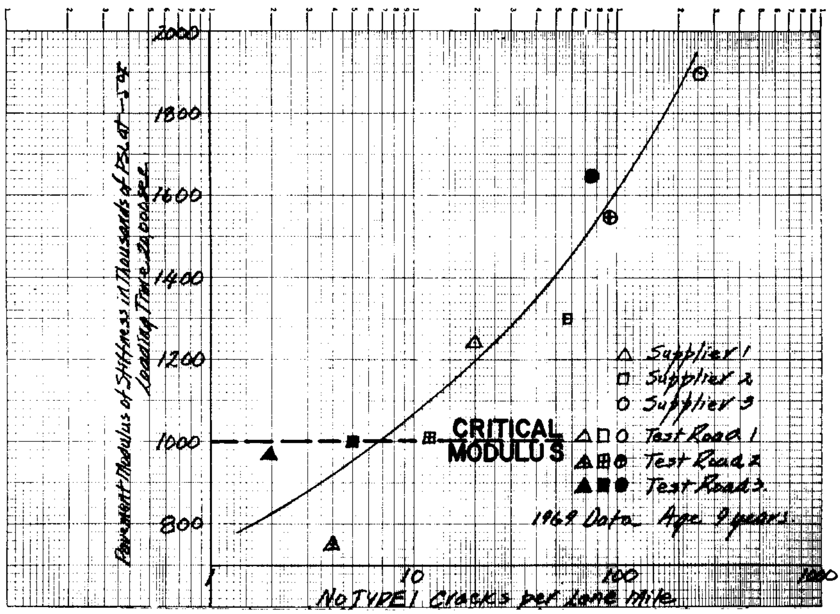

Fig. 18. Pavement Modulus of Stiffness at -5 F. versus Number of Type 1 Transverse Cracks in Test Roads 1, 2, and 3.

ensure that a substantial thickness of pavement is being subjected to the contraction stresses that can result in the development of transverse cracks. Consequently, for these three Test Roads, modulus of stiffness values have been calculated for a temperature of -5 F.

The modulus of stiffness values are also based on the 1969 penetration at 77 F., Tables 5, 6, and 7, and the 1969 pen-vis number of the asphalt cement recovered from the surface course minus the top 1/4 in., Table 8, for each of the nine pavement sections in the three Test Roads. A plot of log viscosity versus log penetration was made to smooth out the three sets of penetration at 77 F. and viscosity at 275 F. data for each pavement section. A loading time of 20,000 seconds, 5.55 hours, was selected to correspond to the slow chilling of a pavement to its lowest temperature with the onset of cold weather. The step by step procedure for determining the modulus of stiffness of a pavement is described in the Appendix.

Figure 18 indicates that the data for pavement modulus of stiffness at -5 F. in 1969, versus number of Type 1 transverse pavement cracks per lane mile in 1969, for the nine pavement test sections, tend to fall along a single line. The curvature of this line is understandable, since it is doubtful that the number of Type 1 cracks per lane mile would exceed approximately 1000 as an asymptote, that is an average of one Type 1 crack every 5 ft.

Figure 18 represents the relationship between Type 1 transverse pavement cracking and pavement modulus of stiffness values when these pavement test sections were only nine years old. It would seem not unreasonable to expect that as these test pavements become older, the number of Type 1 transverse cracks per lane mile will continue to increase as indicated by Figures 15, 16, and 17, and the asphalt cements will become harder. That is, with the passage of additional time, the plotted points might be expected to move upward and to the right, more or less parallel to the curved line in Figure 18.

Selecting Asphalt Cements to Avoid Transverse Pavement Cracking

The principal conclusion indicated by Figures 7 to 17, is that based on a pavement life of 20 years, each of the three 85-100 penetration asphalt cements is too hard a grade to employ, if low temperature transverse pavement cracking is to be avoided during a pavement's service life in this particular region. What softer grade of asphalt cement should be selected?

In 1961, the Ontario Department of Transportation and Communications constructed a 9-mile test pavement on Highway 9 west of Orangeville. This is Test Road 4 illustrated in Figure 1. The only variable in this pavement was the penetration grade of the asphalt cement being used. Several miles were paved with 150-200 penetration asphalt cement, and the balance with the same 85-100 penetration asphalt cement that Supplier 3 had furnished the previous year for Test Roads 1, 2, and 3. Both asphalt cements were made from the same crude oil and had pen-vis numbers of -1.5 and -1.4, respectively.

Fig. 19. 85-100 Penetration Pavement, Test Road 4, Located West of Orangeville, Ontario. 4-Years Old.

Figures 19, 20, and 21 are pictures of Test Road 4 after it had been in service for four years. Figure 19 illustrates the serious transverse cracking that occurred in the pavement made with 85-100 penetration asphalt, which contains more than 400 Type 1 transverse cracks per lane mile. Figure 20 illustrates that no transverse cracking of any kind developed in the pavement made with 150-200 penetration asphalt cement. Figure 21 illustrates the performance of a short section of about 1700 feet where these two pavements were laid side by side in adjacent lanes. The transverse cracks in the 85-100 penetration pavement in the right lane, cross the centre joint about 6 in. and disappear in the 150-200 penetration pavement in the left lane in which no transverse cracks of any kind occurred. For the pavement illustrated in Figure 21, the modulus of stiffness of the 85-100 penetration pavement on the right is approximately ten times the modulus of stiffness of the 150-200 penetration pavement on the left.

Figures 18, 19, and 21 indicate that 85-100 penetration asphalt is too hard a grade of asphalt cement to employ in normal paving mixtures, if transverse pavement cracking is to be avoided for the low temperature conditions that occur in the region in which these Test Roads are located. On the other hand, 150-200 penetration asphalt may be a softer grade than necessary. To obtain more pavement stability under traffic in warm weather, engineers will wish to employ the hardest grade of asphalt cement that will just avoid transverse pavement cracking during a pavement's service life. What criteria can be employed to select an asphalt cement that will satisfy these requirements?

Fig. 20. 150-200 Penetration Pavement Test Road 4, Located West of Orangeville, Ontario. 4-Years Old.

On the basis of the performance of the four Ontario Test Roads, and of the Ste. Anne Test Road (4), (9), from laboratory studies on numerous pavement samples, and from observation of the service behaviour of many thousands of miles of asphalt pavements in Canada, in the Northern U.S.A., and in Norway, the author has concluded that low temperature transverse pavement cracking is likely to occur whenever the modulus of stiffness of a pavement attains a value of 1,000,000 psi at a pavement depth of 2 in. due to any critical combination of chilling to a low pavement temperature, hardness of the asphalt cement, and other controlling factors. This modulus of stiffness value of 1,000,000 psi is based on Van der Poel's chart (10), (11) for a loading time of 20,000 seconds (5.55 hours), and applies to well designed paving mixtures with a C_v value (see Appendix) of 0.88 (14.5 percent VMA and 3 percent air voids). Somewhat different low temperature modulus of stiffness values would apply to pavements with other characteristics.

The factors that contribute to the attainment of a critical low temperature pavement modulus of stiffness of 1,000,000 psi, or equivalent, are:

(a) the penetration of the asphalt cement at 77 F. When all other factors are equal, the higher the penetration at 77 F. of the asphalt cement the less is the low temperature cracking that develops, Figures 19, 20, and 21.
(b) the pen-vis number (or penetration index) of the asphalt cement. When all other factors are equal, the higher the pen-vis number of

Fig. 21. 85-100 Penetration Pavement in Right Lane, 150-200 Penetration Pavement in Left Lane, Test Road 4, Located West of Orangeville, Ontario. 4-Years Old.

the asphalt cement the less is the transverse cracking that occurs, Figures 7 to 13.

(c) the rate of hardening of the asphalt cement in a pavement in service. When all other factors are equal, the harder the asphalt cement in a pavement the greater is the degree of transverse cracking that develops. The asphalt cement in a pavement becomes harder year by year, and the higher the average pavement service temperature, the faster is this rate of hardening.

(d) the lowest critical temperature that occurs at a pavement depth of 2 in. during the lifetime of the pavement. When all other factors are equal, the lower the critical minimum pavement temperature at a pavement depth of 2 in., the greater is the degree or amount of transverse pavement cracking. The critical low pavement temperature is the temperature that results in the highest modulus of stiffness of the pavement during its service life. A pavement depth of 2 in. is specified to ensure that a substantial thickness of the asphalt pavement structure is being subjected to the contraction stresses and strains developed at the critical low temperature, that are responsible for transverse pavement cracking.

(e) the quality and adequacy of the pavement design and construction procedures. When all other factors are equal, pavements that have been properly designed and constructed will develop less transverse cracking. The asphalt binder in a pavement hardens rapidly if through poor design and construction practice the air voids are high and the asphalt content is low.

The principal criterion to be considered when selecting the original asphalt cement for a pavement is the avoidance of a low temperature pavement modulus of stiffness of 1,000,000 psi or equivalent for the loading and other conditions specified, at any time during a pavement's service life, and particularly near the end of its service life when the asphalt binder has ordinarily hardened to its lowest penetration at 77 F. On this basis, Figures 7 to 14 and 18 demonstrate that 85-100 penetration asphalt is too hard a grade to use in the region of the three Test Roads, because at the age of only nine years Figure 18 demonstrates that the modulus of stiffness of the pavement sections containing all three 85-100 penetration asphalt cements equals or exceeds 1,000,000 psi at -5 F., the critical low pavement temperature for this area.

On the basis of presently available information on the five factors just listed, the author has prepared Table 9 and Figures 22 and 23 to guide the selection of asphalt cements for pavements that will avoid low temperature transverse cracking throughout their service lives, provided they have been properly designed and constructed. Table 9 and Figure 23 can be modified as required when more information becomes available.

For each minimum pavement temperature at a pavement depth of 2 in. listed on the left side of Table 9, the asphalt cement can be

Table 9. Influence of Minimum Pavement Temperature on the Pavement Modulus of Stiffness to Be Employed for Selecting the Grade of Asphalt Cement to Be Used

Minimum Temperature at a Depth of Two (2) Inches Below the Surface of the Pavement	Pavement Modulus of Stiffness Values to Be Employed When Selecting the Grade of Asphalt Cement to Be Used*	
	Initial Modulus of Stiffness for Pavement Containing the Asphalt Cement Selected, at which Low Temperature Transverse Pavement Cracking *Can Be Expected* During the Pavement's Service Life	Initial Modulus of Stiffness for Pavement Containing the Asphalt Cement Selected, at which Low Temperature Transverse Pavement Cracking *Should Be Eliminated* During the Pavement's Service Life
F	psi	psi
-40	1,000,000	500,000
-25	700,000	350,000
-10	400,000	200,000
+10	100,000	50,000

*Note: These critical low temperature modulus of pavement stiffness values are determined on the basis of the author's revision (5), (6) of Pfeiffer's and Van Doormaal's chart, on the author's modification (5), (6) of Heukelom's and Klomp's revision of Van der Poel's original monograph, and upon a loading time of 20,000 seconds, roughly six hours, as the rate at which a pavement is being stressed due to chilling to low temperature. They are also restricted to well designed paving mixtures with 14.5 percent VMA (5/8 inch nominal maximum particle size), that have been thoroughly compacted to 3 percent air voids. Equivalent critical modulus of stiffness values would apply to pavements with other characteristics.

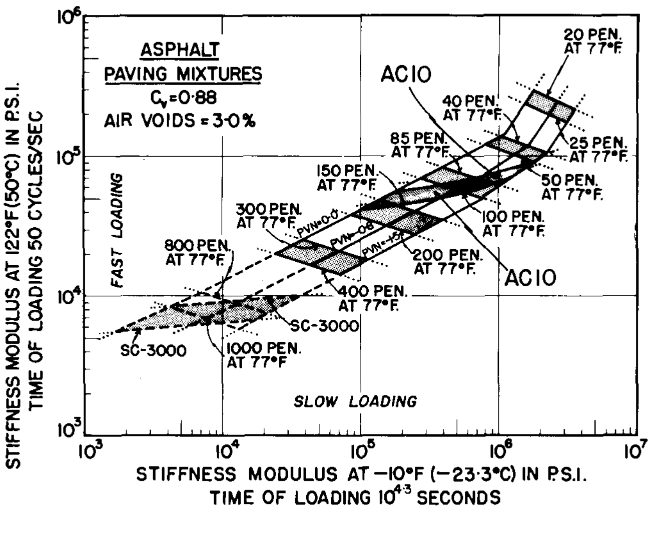

Fig. 22. Relationships between Stiffness Moduli for Asphalt Paving Mixtures for High Rate of Loading (High Speed Traffic) at High Temperature (122 F.) versus Slow Speed of Loading (Temperature Stresses) at Low Temperature (-10 F.).

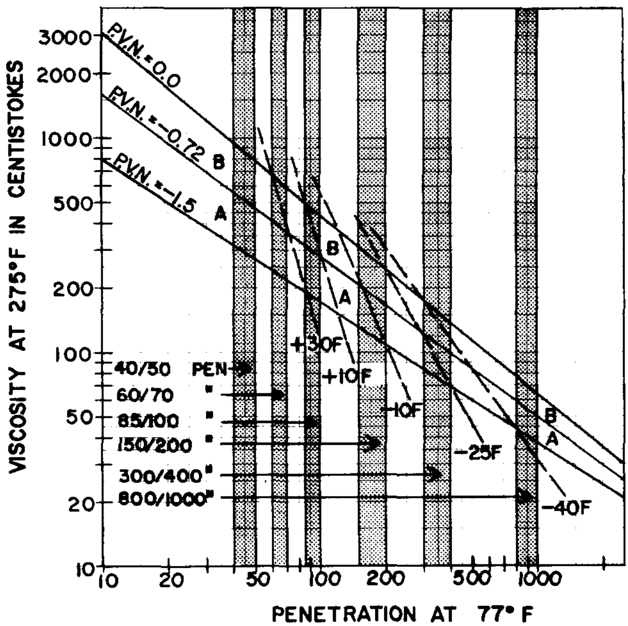

Fig. 23. Chart for Selecting Grades of Asphalt Cement to Avoid Low Temperature Transverse Pavement Cracking.

selected on the basis of the corresponding modulus of stiffness given in the right hand column of Table 9, which in turn is applied to an appropriate chart, for example, Figure 22. For instance, when the minimum pavement temperature at a pavement depth of 2 in. is -10 F. (abscissa in Figure 22), Table 9 indicates that the original asphalt cement selected should be not harder than would result in a pavement modulus of stiffness of 200,000 psi at -10 F., which Figure 22 in turn demonstrates should be not harder than 120-150 penetration for a pen-vis number of 0.0, nor harder than 200-300 penetration for a pen-vis number of -1.5. This is illustrated on Figure 23 by the diagonal line labelled -10 F.

The middle column in Table 9 indicates that if the original asphalt cement results in an initial pavement modulus of stiffness of 400,000 psi at a minimum pavement temperature of -10 F. at a pavement depth of 2 in., transverse cracking can be anticipated, since the pavement could be expected to attain a low temperature modulus of stiffness of 1,000,000 psi at -10 F. during its early service life. The abscissa of Figure 22 indicates that for a pavement modulus of stiffness of 400,000 psi at -10 F., the pavement would be made with 85 penetration asphalt with a pen-vis number of 0.0, or 150 penetration asphalt cement with a pen-vis number of -1.5. Figures 7 to 14 and 18 demonstrate that 85-100 penetration asphalt is too hard to avoid transverse pavement cracking at a temperature of -5 F. Consequently, it is much too hard a grade to eliminate transverse cracking at -10 F.

When using Figure 23 to choose a grade of asphalt cement that will essentially avoid transverse pavement cracking during a pavement's service life, the grade of asphalt cement selected *should lie to the right* of the diagonal line that represents the lowest temperature that is expected during the pavement's service life at a pavement depth of 2 in. For example, when selecting an asphalt cement for paving the Alaska Highway (which is presently only in the discussion stage), where the lowest pavement temperature at a depth of 2 in. would be at least -40 F., Figure 23 indicates that an asphalt cement of 300 penetration or softer should be selected if its pen-vis number is 0.0, while 800 penetration or softer, should be specified if its pen-vis number were -1.5. The other oblique lines with temperature labels in Figure 23 have similar significance.

If an engineer selects an asphalt cement that lies to the left of the oblique line in Figure 23 that represents the minimum pavement temperature at a depth of 2 in. anticipated during the pavement's service life, he is gambling with the probability that low temperature transverse pavement cracking will occur sometime during the service life of the pavement.

For engineers who are concerned about pavement stability under warm weather traffic when the pavements are constructed with softer asphalt cements, the successful experience of the cities of Winnipeg, Manitoba, (population 500,000+) and Edmonton, Alberta, (population 400,000+) with 150-200 penetration asphalt for a number of years for all city paving, and of the Manitoba Department of Transportation with the use of SC 3000 (SC 5 or 800-1000 penetration) for paving rural highways (12) should be reassuring. Summer temperatures in Manitoba occasionally exceed 100 F.

Pavements containing soft asphalt cements tend to densify much more rapidly under traffic. Therefore, it should be emphasized that when soft grades of asphalt cement are specified, 75-blow Marshall compaction or equivalent should be employed for paving mixture design in the laboratory, and surface course paving mixtures should be designed for from 3 to 5 percent air voids, in addition to the minimum VMA values currently specified by The Asphalt Institute.

Figure 23 emphasizes that selecting the grade of asphalt cement for a paving job *merely on the basis of its penetration at 77 F.*, as has been common engineering practice for at least the past half century, *is no longer acceptable.* Figures 7 to 13 show very clearly that to continue this practice is simply an invitation to trouble since the pen-vis number (or penetration index) of the asphalt cement must also be considered. For example, in a climate with moderate winter temperatures, Figures 7 to 13 demonstrate that some transverse pavement cracking can be expected if 85-100 penetration asphalt with a pen-vis number of 0.0 is employed, but that transverse cracking becomes very serious if 85-100 penetration asphalt with a pen-vis number of -1.5 is used. Consequently, if low temperature transverse pavement cracking is to be avoided, engineers in colder climates particularly, should select the grade of asphalt cement to be used on the basis of *both its penetration at 77 F. and its pen-vis number*, as illustrated by the oblique temperature-labelled lines in Figure 23.

For the indicated minimum temperature of -5 F. at a pavement depth of 2 in. in the region in which the three Ontario Test Roads are located, if transverse pavement cracking is to be eliminated, Figure 23 indicates that 100-120 penetration asphalt cement should be employed if its pen-vis number is 0.0, while 150-200 penetration asphalt should be stipulated if its pen-vis number is -1.5.

Finally, apart from transverse cracking, no difference in pavement performance, such as ravelling, rutting, etc., could be observed between the test sections in the three Test Roads.

Implications for Grading Asphalt Cements by Viscosity at 140 F.

Figure 24 is a chart that illustrates grading asphalt cements by viscosity at 140 F. versus grading them by penetration at 77 F. The AC10 grade for example, includes all asphalt cements from 50-60 penetration to 150-200 penetration. Even the AC5 grade includes asphalt cements from 85-100 penetration to 200-300 penetration. Grading asphalt cements by viscosity at 140 F. implies that the performance of asphalt pavements made with the asphalt cements included within any given viscosity grade will be the same. That is, for the AC10 grade for example, pavement performance will be the same whether a pavement contains 50-60 penetration (AC10) or 150-200 penetration (AC10). Figures 19, 20, and 21, indicate how utterly wrong this implication is with respect to low temperature pavement performance. The pavement containing 85-100 penetration asphalt, Figures 19 and 21, which is substantially softer than the penetration of 50-60 included in the AC10 grade, developed more than 400 transverse cracks per lane mile, while the pavement made with 150-200 penetration asphalt developed no transverse cracks, Figures 20 and 21.

Therefore, the wide range of penetration at 77 F. associated with each viscosity grade, AC5, AC10, AC20 and AC40, is a most damaging criticism of grading asphalt cements by viscosity at 140 F. in any area where pavements are subjected to low winter temperatures. This situation is made much worse by the fact that changing to a lower viscosity grade, for instance, from AC10 to AC5, would not necessarily improve low temperature pavement performance. For example, an engineer in northern Minnesota, northern Wisconsin, or North Dakota, or in Manitoba or Sasketchewan, could be experiencing serious transverse cracking with an AC10 asphalt of 150-200 penetration. However, by changing to the supposedly softer AC5 grade, he might obtain an AC5 of 120-150 penetration at 77 F. from some asphalt supplier, and would have more severe transverse pavement cracking than before.

Why do the viscosity at 140 F. graded specifications of Saskatchewan and Alberta, illustrated in Figure 24, hug the right side boundary of the chart? It is done to obtain the highest possible penetration at

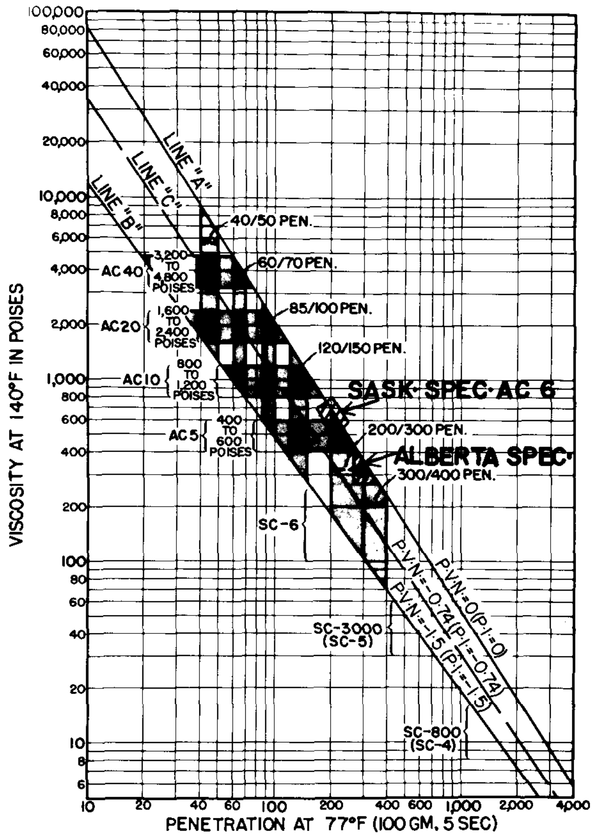

Fig. 24. Correlation between Viscosity at 140 F. and Penetration at 77 F.

77 F. for the viscosity ranges at 140 F. that are specified. This avoids the disastrous low temperature transverse pavement cracking, Figure 19, that results from the use of asphalt cements of the same viscosity range at 140 F., but with low penetrations at 77 F.

However, paving asphalt specifications like those of Saskatchewan and Alberta, which are based on viscosity grading at 140 F., place very severe restrictions on the number of crude oils from which asphalt cements can be made. If every highway department in the colder half of the United States and throughout Canada were to adopt similar highly restrictive specifications based on grading by viscosity at 140 F. to avoid low temperature transverse pavement cracking, it is doubtful that sufficient asphalt cement meeting them could be produced. Because of the limited supply and large demand, the price of these asphalt cements would drastically increase, and local shortages of supply would be common.

On the other hand, as demonstrated by Figures 7 to 17, by recognizing that *both penetration at 77 F. and pen-vis number* (or penetration index) of an asphalt cement must be specified, Figure 23 indicates that satisfactory low temperature pavement performance can be obtained when using asphalt cements from a very wide variety of crude oils, and that there is no need for the restrictive specifications for asphalt cements and the accompanying large increase in cost, that will inevitably follow any attempt to grade them by viscosity at 140 F.

SUMMARY

1. Nine pavement sections made with 85-100 penetration asphalt cements with three widely different temperature susceptibilities were constructed on the three Ontario Test Roads.
2. Laboratory data on pavement samples taken from the nine pavement sections on the three Test Roads after nine years of service, indicate that the paving mixtures are dense graded, well designed, and without significant differences.
3. The relationship between transverse cracking and Pfeiffer and Van Doormaal penetration indices of the asphalt cements is contrary to what would be expected on the basis of all information accumulated so far but the agreement is excellent if the temperature susceptibilities of the asphalt cements are expressed in terms of their pen-vis numbers instead of penetration index (PI) values.
4. The pen-vis number of a paving asphalt is determined from its penetration at 77 F. and from its viscosity in centistokes at 275 F. by a method described in the Appendix.
5. The pen-vis numbers of the asphalt cements recovered from pavement samples taken from the nine pavement test sections show either no change or a substantial decrease after nine years of service.
6. The four annual transverse crack surveys indicate that there was a substantial yearly increase in the number of transverse cracks in all pavement sections.
7. In all three Test Roads, the number of transverse cracks increased very markedly with a decrease in the pen-vis number of the asphalt cement.
8. At the minimum temperature of -5 F. at a pavement depth of 2 in., the pavement modulus of stiffness after only nine years of service is very nearly or greatly exceeds 1,000,000 psi for all of the nine pavement sections in the three Test Roads.
9. A chart is offered to enable engineers to select grades of asphalt cement that should eliminate transverse cracking during the service life of the pavement.
10. This chart indicates that if transverse pavement cracking is to be eliminated in any region with temperature conditions similar to those in the locality where the three Ontario Test Roads are located, a minimum temperature of -5 F. at a pavement depth of 2 in.,

100-120 penetration asphalt should be selected if its pen-vis number is 0.0, while 150-200 penetration asphalt cement should be employed if its pen-vis number is -1.5.

11. The hazards associated with grading paving asphalts by viscosity at 140 F. in colder climates are pointed out.
12. Apart from transverse cracking, no difference in pavement performance, such as ravelling, rutting, etc., could be observed between the test sections in the three Test Roads.

ACKNOWLEDGMENTS

Grateful acknowledgment is made to Mr. Alex Rutka, Materials and Testing Engineer, Ontario Department of Transportation and Communications, for his very generous assistance in obtaining pavement samples from each of the Test Roads, to Mr. J. A. A. Lefebvre of Imperial Oil's Research Department for the carefully obtained laboratory data included in this paper, and to Mr. Charles L. Perkins for his capable assistance with the transverse crack surveys.

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APPENDIX

DETERMINATION OF PEN-VIS NUMBERS OF ASPHALT CEMENTS

Pfeiffer and Van Doormaal developed a penetration index method for measuring the temperature susceptibility of asphalt cements based on softening point and penetration at 77 F. (1). Pfeiffer and Van Doormaal concluded that the penetration and viscosity of an asphalt at its softening point are 800 penetration and 12,000 poises, respectively. Heukelom (2) has recently refined this method by grouping asphalts into three categories, "S" or normal asphalts, "B" or blown asphalts, and "W" or waxy asphalts.

Probably because the penetration of many asphalt cements at their softening point varies widely from 800 penetration, (3), (4), (5) it was not possible to obtain a normal relationship between Pfeiffer's and Van Doormaal's penetration index for asphalt cements and low temperature transverse pavement cracking performance, for example, Figure 5. Consequently, the author had to devise another method for measuring quantitative differences between the temperature susceptibilities of asphalt cements (5), (6). This method is based on the penetration of an asphalt cement at 77 F., and its viscosity either in centistokes at 275 F., or in poises at 140 F. Because this measurement of the temperature susceptibility of an asphalt cement is based on penetration and viscosity values, it has been designated "pen-vis number" which is abbreviated to PVN.

The following is the step by step development of the pen-vis number of an asphalt cement, and of its application to the determination of the modulus of stiffness of an asphalt paving mixture.

Step 1

For many paving grades of asphalt cements, the pen-vis number and the penetration index value are numerically equal, or approximately so. This is due to the manner in which the pen-vis number is derived.

The first step in the development of the pen-vis number, as illustrated by Figure A, involved the selection of asphalt cements with a penetration index of approximately 0.0. Some years ago, Esso Research and Engineering systematically assembled detailed inspection data, providing penetration at 77 F., softening point (Ring and Ball), viscosity Saybolt Furol at 275 F., and other information, on asphalt cement grades ranging from 20 to 200 penetration, for example, 20-30, 30-40, 40-50, 60-70, etc., made from a large number of crude oils around the world.

For Figure A, from each crude oil that qualified, the series of grades of asphalt cements was selected for which the Pfeiffer and Van Doormaal penetration indices were 0.0 ± 0.2. For each of these series of asphalts, viscosities in Saybolt Furol seconds at 275 F. were plotted versus penetration at 77 F. An average line was drawn through the plotted points (viscosity SSF at 275 F. versus penetration at 77 F.) for the series of asphalt grades from each crude oil.

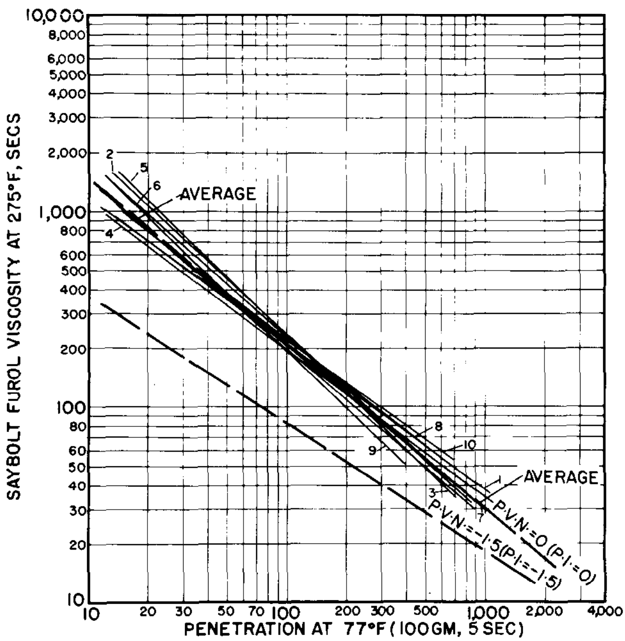

Fig. A. Relationship between Penetration at 77 F. and Viscosity at 275 F. for Pen-Vis Numbers of 0.0 and -1.5.

This resulted in the ten lines of slightly different slope in Figure A for asphalt cements from ten crude oils from the United States, Venezuela, and the Middle East, that had Pfeiffer and Van Doormaal penetration index values of 0.0 $\pm$ 0.2. A broken line was then drawn through these ten lines to represent the overall average relationship between viscosity SSF at 275 F. and penetration at 77 F. for asphalt cements with a Pfeiffer and Van Doormaal penetration index of 0.0. As illustrated by Figure A, this line also represents a pen-vis number (PVN) of 0.0.

The straight line representing the relationship between viscosity SSF at 275 F. and penetration at 77 F. for a Pfeiffer and Van Doormaal penetration index of -1.5, shown in Figure A, was similarly obtained. Out of asphalt work-ups from more than 100 different crude oils, asphalt cements from only one crude oil (a heavy Venezuelan crude oil) had a penetration index of -1.5. However, each of the different penetration grades of asphalt cement from this crude oil had a Pfeiffer and Van Doormaal penetration index of -1.5. Figure A indicates that this line also represents a pen-vis number (PVN) of -1.5.

Consequently, for the asphalt cements represented in Figure A, the values for penetration index and for pen-vis number are numerically the same.

Step 2

The second step consisted of converting the viscosity values in SSF at 275 F. for the lines representing pen-vis numbers of 0.0 and -1.5 from Figure A, to corresponding viscosity values in centistokes at 275 F. This is illustrated in

Figure B, which provides the relationships between viscosities in centistokes at 275 F. versus penetration values at 77 F. for asphalt cements with pen-vis numbers (penetration indices) of 0.0 and -1.5.

To obtain the pen-vis number for any paving asphalt between or somewhat outside the PVN boundaries of 0.0 and -1.5 in Figure B, only its viscosity in centistokes at 275 F. and its penetration at 77 F. is required. Its pen-vis number is quickly determined by interpolation or extrapolation by means of the following simple equation:

$$PVN = \frac{(L - X)}{(L - M)} (-1.5) \qquad [1]$$

where

X = log viscosity in centistokes at 275 F. for the penetration at 77 F. of the asphalt cement represented by X.

L = log viscosity in centistokes at 275 F. for a PVN of 0.0 (Figure B) for the penetration at 77 F. of the asphalt cement represented by X.

M = log viscosity in centistokes at 275 F. for a PVN of -1.5 for the penetration at 77 F. of the asphalt cement represented by X.

Suppose for example, that the penetration at 77 F. of a certain asphalt cement is 150, and its viscosity at 275 F. is 194 centistokes. What is its pen-vis number? From Figure B, the viscosity at 275 F. for an asphalt cement of 150

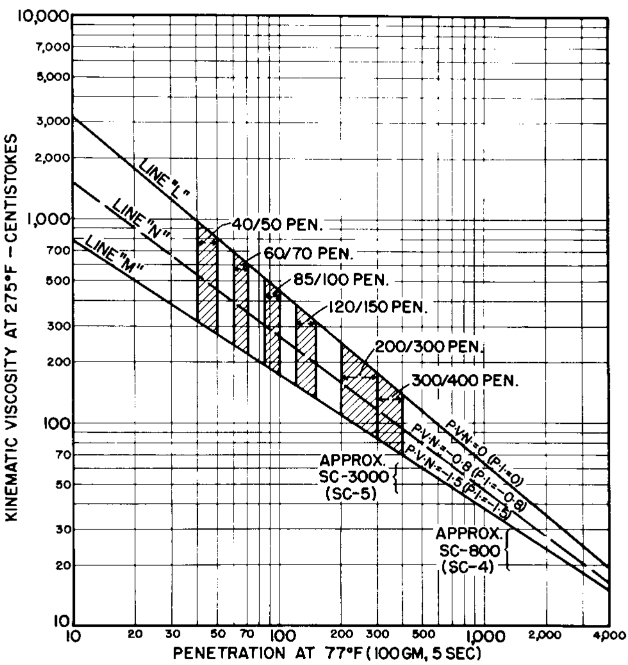

Fig. B. Correlation between Viscosity in Centistokes at 275 F. and Penetration at 77 F.

penetration at 77 F., and a pen-vis number of 0.0 is 315 centistokes (L in equation [1]). The viscosity at 275 F. for an asphalt cement of 150 penetration at 77 F., and a pen-vis number of -1.5 is 133 centistokes (M in Equation [1]). Substituting these values in Equation [1] gives:

$$PVN = \frac{\log 315 - \log 194}{\log 315 - \log 133} (-1.5) = -0.84$$

Step 3

Because of current interest in the viscosity of asphalt cements in poises at 140 F., a chart corresponding to Figure B, but in terms of viscosity in poises at 140 F. and penetration at 77 F. is desirable.

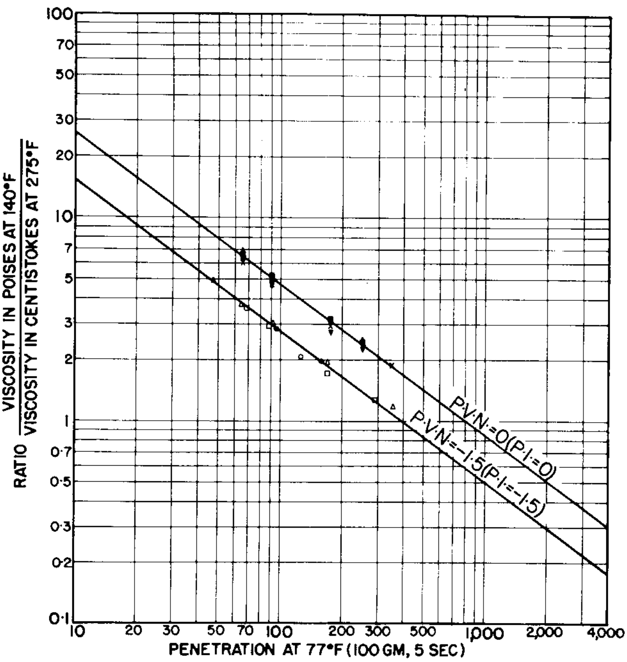

Fig. C. Relationship between Penetration at 77 F. and Ratio of Viscosity at 140 F. in Poises to Viscosity in Centistokes at 275 F. for Pen-Vis Numbers of 0.0 and -1.5.

For asphalt cements from a considerable number of crude oils, Mr. Lefebvre has obtained viscosity data in poises at 140 F. and in centistokes at 275 F. for several penetration grades of asphalt from the same crude oil. For pen-vis numbers of 0.0 and -1.5, Figure C illustrates the relationships between ratio of viscosity in poises at 140 F. over viscosity in centistokes at 275 F. versus penetration at 77 F., that has been established on the basis of Mr. Lefebvre's data.

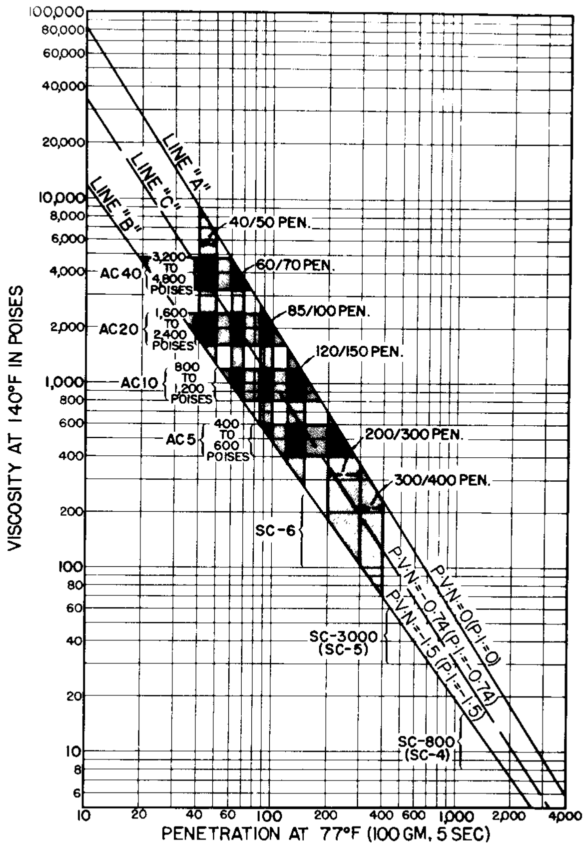

Fig. D. Correlation between Viscosity at 140 F. and Penetration at 77 F.

Step 4

Figure D illustrates viscosity in poises at 140 F. versus penetration at 77 F. for asphalt cements with pen-vis numbers of 0.0 and -1.5. Figure D was prepared from Figure B by utilizing the ratios of Figure C. For example, for a penetration of 100 at 77 F., Figure B indicates a viscosity at 275 F. of 450 centistokes for a pen-vis number of 0.0. Figure C indicates a ratio for viscosity in poises at 140 F. over viscosity in centistokes at 275 F. of 4.7 for a penetration of 100 at 77 F., and for a pen-vis number of 0.0. Consequently, for a penetration of 100 at 77 F. and for a pen-vis number of 0.0, the corresponding viscosity at 140 F. is (450)(4.7) = 2115 poises, Figure D. Other points in Figure D for line A representing a pen-vis number of 0.0 were similarly obtained. Line B, representing a pen-vis number of -1.5 in Figure D was obtained in like manner, but employing corresponding data for a pen-vis number of -1.5 from both Figures B and C for this purpose.

Step 5

The only data required to obtain the pen-vis number for any paving asphalt between or somewhat beyond the PVN boundaries of 0.0 and -1.5 in Figure D, are its viscosity in poises at 140 F., and its penetration at 77 F. Its pen-vis number can be easily obtained by interpolation or extrapolation by means of the following equation:

$$\text{PVN} = \frac{(A - Y)}{(A - B)} (-1.5) \qquad [2]$$

where

Y = log viscosity in poises at 140 F. for the penetration at 77 F. of the asphalt cement represented by Y.
A = log viscosity in poises at 140 F. for a PVN of 0.0 for the penetration at 77 F. of the asphalt cement represented by Y.
B = log viscosity in poises at 140 F. for a PVN of -1.5 for the penetration at 77 F. of the asphalt cement represented by Y.

For example, suppose the penetration at 77 F. of a certain asphalt cement is 200, and its viscosity at 140 F. is 354 poises. What is its pen-vis number? From Figure D, for a penetration of 200 at 77 F., the viscosity at 140 F. for a PVN of 0.0 is 700 poises (A in Equation [2]), and for a PVN of -1.5 it is 180 poises (B in Equation [2]). Substituting these values in Equation [2] gives:

$$\text{PVN} = \frac{(\log 700 - \log 354)}{(\log 700 - \log 180)} (-1.5) = -0.75$$

Whenever possible, it is recommended that pen-vis numbers should be obtained from Figure B based on viscosity at 275 F., rather than from Figure D which is in terms of viscosity at 140 F. Figure B is more straight forward in its derivation, and is supported directly by much more data than Figure D. However, it is recognized that either the locations, or the slopes, or both, of the boundary lines representing pen-vis numbers of 0.0 and -1.5 in Figures B and D may have to be modified as more data become available.

To calculate the modulus of stiffness at any specified rate of loading and at any given temperature for a paving mixture containing any stipulated asphalt cement, requires that the modulus of stiffness of the asphalt cement at that temperature and rate of loading must first be calculated. The entire procedure requires an additional three steps.

Step 6

On the basis of its penetration at 77 F., and its viscosity either in centistokes at 275 F. or in poises at 140 F., the pen-vis number of an asphalt cement can be obtained from either Figure B or Figure D, respectively, by means of Equation [1] or Equation [2]. From its penetration at 77 F. and its pen-vis number, the "base" temperature of the asphalt cement can be obtained from Figure E, which is a slight revision of a Pfeiffer and Van Doormaal chart that was modified by Heukelom and Klomp. The "base" temperature obtained from Figure E is essentially a "corrected" softening point for the asphalt cement.

For the particular asphalt illustrated in Figure E, for which the penetration at 77 F. is 80, and the pen-vis number is 0.0, its "base" temperature is seen to be 25 - 25 = 50 C.

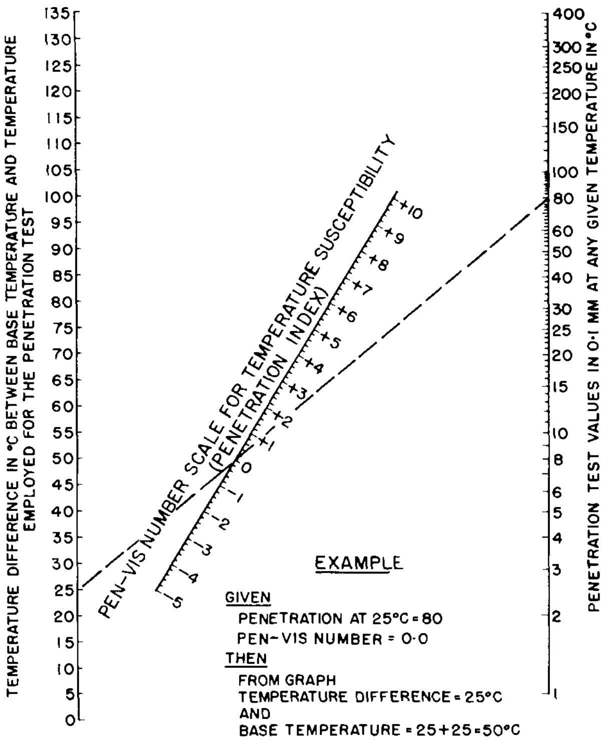

Fig. E. Suggested Modification of Heukelom's Version of Pfeiffer's and Van Doormaal's Nomograph for Relationship between Penetration, Pen-Vis Number, and Base Temperature.

Step 7

Having established the "base" temperature for the asphalt cement, the next step is to obtain the modulus of stiffness of the asphalt cement at some specified service temperature, which will be assumed to be -17.5 F. (-27.5 C.), and for a very slow loading time (slow cooling rate) of 20,000 seconds, or 5.55 hours. A loading time of 20,000 seconds is located on the bottom line of Figure F, which indicates a wide range of rates of load application. Since the "base" temperatures for this asphalt is 50 C. (Step 6), a service temperature of -27.5 C. is 50 + 27.5 = 77.5 C. below the "base" temperature of this paving asphalt. By drawing a straight line from a loading time of 20,000 seconds (bottom line of Figure F) through the point representing a temperature of 77.5 C. below the "base" temperature on the temperature scale (the middle horizontal line in Figure F), and extending this to the horizontal line at the top of the chart representing a pen-vis number of -1.0, the modulus of stiffness of the asphalt cement at -27.5 F. can be read by interpolating between the curves of modulus of stiffness values at the top of the chart, namely 1000 kg/cm^2 or 14,200 psi.

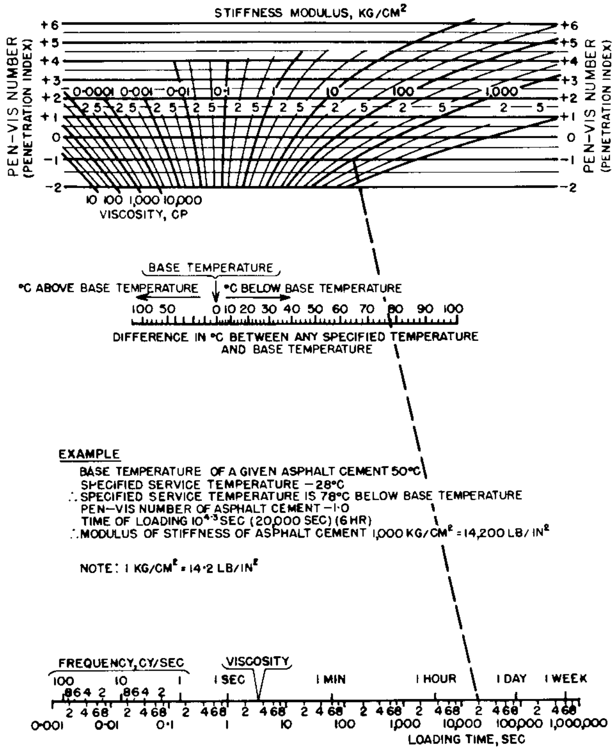

Fig. F. Suggested Modification of Heukelom's and Klomp's Version of Van der Poel's Nomograph for Determining Modulus of Stiffness of Asphalt Cements.

Step 8

The final step involves the use of Figure G, originally developed by Van der Poel (7), to go from the modulus of stiffness of the pure asphalt cement at a given temperature and rate of loading, to the modulus of stiffness of a paving mixture containing the asphalt cement for the same temperature and rate of loading.

Figure G contains C_v values for compacted paving mixtures containing 3 percent air voids, where

$$C_v = \frac{\text{volume of aggregate}}{\text{vol. agg. plus vol. bitumen}} = \frac{100 - \%\ \text{VMA}}{100 - \%\ \text{Air Voids}} \qquad [3]$$

The abscissa of Figure G gives modulus of stiffness values for the pure asphalt cement, while the ordinate axis provides modulus of stiffness values for corresponding paving mixtures.

For example, suppose the paving mixture has a VMA value of 14.5 and 3 percent air voids, which corresponds to a C_v value of 0.88, and that the modulus of stiffness of the asphalt cement is 14,200 psi for a loading time of 20,000 seconds and a service temperature of -27.5 C. (Step 7). What is the corresponding modulus of stiffness of a paving mixture containing this asphalt cement for the same temperature and rate of loading?

Enter Figure G at a value of 14,200 psi on the abscissa, proceed vertically upward to the curve representing a C_v value of 0.88 and then horizontally to the ordinate axis and read off the value, 1,850,000 psi. This is the required modulus of stiffness value for the paving mixture.

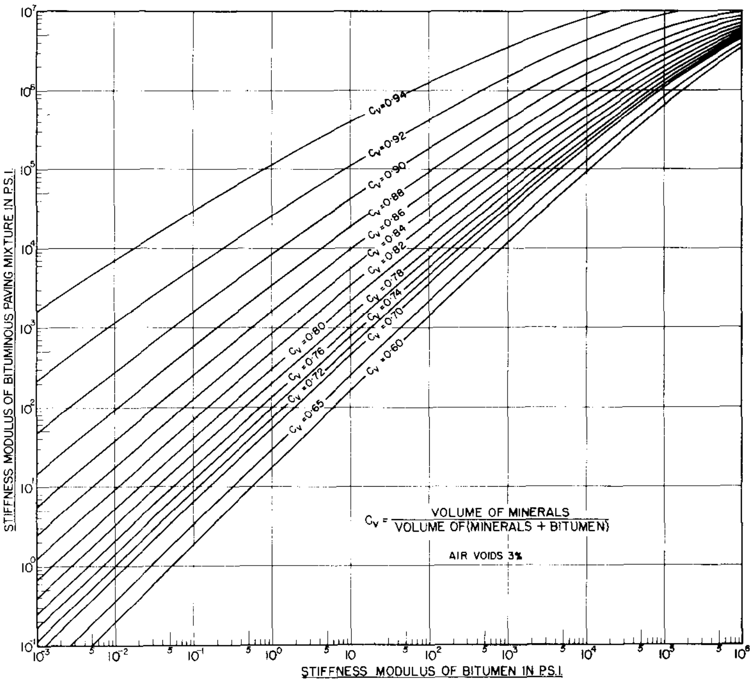

Fig. G. Relationships between Moduli of Stiffness of Asphalt Cements and Corresponding Moduli of Stiffness of Paving Mixtures Containing These Asphalt Cements. (Based on Heukelom and Klomp.)

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Discussion

MR. L. W. CORBETT (Prepared Discussion): We owe Dr. McLeod a debt of gratitude for his analysis of transverse cracking as related to the basic consistency of the asphaltic binder, especially that less cracking is realized when binder of higher penetration or lower stiffness moduli are used. Some of the illustrations used in this presentation have been used numerous times before, however, we note that the pitch has been changed to read "select the grade of asphalt cement to be used on the basis of both penetration at 77 F. and its pen-vis number." The pen-vis as defined is an indication of temperature susceptibility and is related to many other indices describing the same qualities. Whereas no one argued against the idea of using higher penetration binders in order to reduce transverse cracking, one cannot accept the anomalous use of the stiffness concept and/or the susceptibility indices as an argument against viscosity grading. Instead of keeping the door wide open for poor temperature susceptible, low shear susceptible asphaltic binders as permitted under most penetration graded specifications, it is now gratifying to note that the author admits the need for more control on these susceptibility qualities. This is exactly what viscosity grading is trying to bring out. Many authors have been saying this over recent years, to name a few: Heukelom, Dobson, LeFebvre, Halstead, Duthie and about ten others in both ASTM and HRB symposiums.

It is also unfortunate when technology becomes so verbose that conclusions are drawn in reverse of what the data tends to indicate. For example, Table 1 of this paper lists the physical properties on three binders in the 80-100 penetration range as representing a *least*, an *intermediate* and a *most* temperature susceptible asphalt in that order. This rating directionally fits your counting of transverse cracks in each of the three test roads involved. However, if you would inspect the data more carefully, you would find that asphalt 2 is less temperature susceptible than asphalt 1 based on the susceptibility parameters of 39.2 F. penetration ratio, the 32 F. penetration ratio, the 140 vis-pen at 77 F. relationship and the Pfeiffer penetration index. The same susceptibility parameters plus that indicated by the 275 F. vis-penetration at 77 F. relationship in Tables 5, 6 and 7 (which supposedly represents the binder present in the road at the time the cracks were counted) also says the same thing, namely, that your judgment of the binders is not consistent with your conclusions regarding the three test roads. Perhaps there is more to this than common test results or indices are willing to portray, thus the danger in interpreting empirically based data.

DR. N. W. McLEOD: Mr. Corbett's discussion pertains to several fairly complex matters that require more than simple comments in reply. Consequently, I would prefer to respond to his remarks in a written closure.

MR. J. E. DRISCOLL (Prepared Discussion): Dr. McLeod should be complimented on this excellent presentation of really fine information on the use of soft asphalt cement as a method to reduce transverse cracking.

We were pleased to learn that the PVN can be determined using pen. at 77 F. and viscosity at *either* 140 F. or 275 F. Based on our field experience we feel that the grading of A.C. should utilize at least two (2) temperatures.

In reviewing the many figures we observed that Test Road 1 developed many more cracks than did Test Roads 2 or 3. In an attempt to find a reason, we noted that:

(1) Test Road 1 had quite a bit *less* traffic, including trucks, than Test Roads 2 or 3 (page 426 of report)
(2) The Marshall Stability Values for Test Road 1 were noticeably higher (Table 4 of report), and
(3) The viscosity values at 140 F. for the Recovered Asphalt were out of line compared with Test Roads 2 and 3 (Tables 5, 6 and 7 of report).

Could any of the above have caused the increase in number of cracks in Test Road 1?

We would like to pass over the apparent heated discussion involving "asphalt cement grading" and express our appreciation to Dr. McLeod and our friends from Canada for encouraging us to use soft asphalt cement in asphaltic concrete in northwestern Pennsylvania.

Since the fall of 1968 we have placed approximately 50,000 tons of hot mix using an A.C. with a viscosity at 140 F. of approximately 650 poises and a pen. at 77 F. of approximately 165.

Quite a bit of the tonnage was placed under Pennsylvania DOT supervision and all of it was designed and controlled using the Pennsylvania DOT Marshall Test criteria. Most of the material was black base but several sections of surface course and overlay appear to be giving excellent performance also.

We did however deviate from accepted practice in that WE USED AN AGGREGATE DRYING AND PUGMILL MIXING TEMPERATURE OF 195 F. $\pm$ 15. The asphalt cement was held at approximately 300 F., the delivery temperature, and injected into the pugmill at that temperature.

In all cases a Ross Count of 30 seconds was sufficient and IN NO CASE WAS THERE ANY EVIDENCE OF UNCOATED AGGREGATE.

In all cases, where the subbase was adequate, we attained the proper asphaltic concrete field density. We have inspected the material many times and have found NO EVIDENCE OF STRIPPING.

The owners are happy with what appears to be a higher quality pavement, based on both appearance and tests run on the Recovered Asphalt Cement.

Typical Test Results

	Original	Recovered from Field Samples
Pen. at 77 F.	165	142-154
Vis. at 140 F. poises	650	785-741

The contractors are pleased and mentioned that the saving of approximately 10 percent was passed along to the owners.

Most hot mix in this area, using hard A.C. (AC20) is mixed at approximately 300 F., we wonder if this temperature is necessary when soft A.C. is used. We wonder if we could be actually OVER DRYING the aggregate at 300 F. and manufacturing moisture which we introduce into the hot mix system. As mentioned above we expereienced no moisture in our 195 F. mix nor did we use any antifoam addative.

NOTE: Dr. McLeod's response to Mr. Driscoll's Discussion are included in the Author's Closure.

PROFESSOR R. C. G. HAAS: Professor McLeod has presented a very good documentation of the cracking behaviour of the three test roads in Southern Ontario. We have also analyzed these roads extensively but our approach has been somewhat different.

In our work, field recovered samples were tested directly for stiffness, using the techniques referred to in the paper to this Conference by Hignell, Hajek and Haas. These directly determined stiffness values were related to observed field behaviour as described in a 1970 Department of Highways of Ontario publication (Research Report, 161, May, 1970) and in a 1970 H.R.B. publication (Research Record No. 313).

We were fairly successful in these earlier studies so we subsequently used data from both these roads together with data from a number of additional sections in Ontario and Manitoba to develop a cracking frequency prediction model (Can. Tech. Asphalt Association, Montreal, October 1971, and H.R.B., Washington, D.C., January 1972; both papers by Hajek and Haas). The model incorporates variables of stiffness, pavement age, winter design temperature, pavement thickness and subgrade soil type.

I have one additional comment on the drop in Pen-Vis number that Dr. McLeod shows for asphalts that have been in service for several years (for example, asphalt number 2 on test road number 1 has dropped by about 0.2). This would indicate that the increase in stiffness would likely not be very high with increasing age for that material. I have compared stiffness of field recovered cores (Research

Report, 161, as noted above) with stiffnesses of original simulated mixes for this material (C.T.A.A., 1971, as noted above) and have found only slight increases of stiffness with age. Thus, I would support Dr. McLeod's finding.

DR. McLEOD: If I understand Professor Haas' last comment correctly, he is suggesting that the modulus of stiffness of the original paving mixture would not be expected to increase very greatly with age. Since in general, the asphalt cement has hardened from its original 85-100 penetration to approximately 30-40 penetration at the age of 9 years, and because the pen-vis number appears to be decreasing rather than increasing with age, I would suggest that there has been a very substantial increase in pavement modulus of stiffness during 11 years of service. However, if Professor Haas is referring to the annual increase in pavement modulus of stiffness at the age of 8, 9, 10, 11 and future years, this would not be expected to be large.

MR. W. J. HALSTEAD: This paper by Dr. McLeod and the earlier one by Harold Fromm do a great deal towards clearing the air with respect to arguments, if we want to call it that, concerning viscosity grading vs. penetration grading because I believe Dr. McLeod has put his finger on the real problem that relates to cracking. That is, to properly design pavements depending on the conditions to be encountered we not only consider the grade but also the temperature susceptibility of the asphalt. This is clearly shown in the paper and the decision as to whether we should use penetration grading or viscosity grading is completely secondary to this problem. It is true that one could not use the viscosity graded AC-10 under the AASHO specification for as wide a range of conditions as you could for 100-120 penetration. But the important point we need to keep in mind is that, regardless of whether we use penetration grade or viscosity grading the data show that we must change the grade of asphalt to avoid brittleness at very low temperatures and the choice of the grade to use in any given case will depend somewhat on the viscosity temperature susceptibility of the asphalt being used. Under some conditions of extreme variations in winter and summer temperatures, very highly temperature susceptible materials will not meet the demands of service and some limitation should be placed on this characteristic. Whether or not we accept a penetration grading and set some limit on viscosity at some higher temperature or accept a viscosity grading and put some limitation on penetration or viscosity at lower temperature is really a decision that has to be made from other considerations. Whether it's ease of quality control or what have you, a number of different elements enter into the overall picture. I personally believe that it is best to use viscosity grading at 140 F., but the problem could be dealt with by using penetration grading and putting limitations on viscosity. My hope is that these papers will clear the air, and that everyone will understand the problem of cracking is not related to the decision of whether we accept penetration grading or viscosity grading for asphalt cements. The grading system doesn't make the problem any worse and it doesn't make it any better.

DR. McLEOD: In general, I am in thorough agreement with Mr. Halstead's comments. It is gratifying to have someone in Mr. Halstead's position endorsing the view that whether asphalt cements are graded by penetration or viscosity at 77 F., or by viscosity at 140 F., from now on knowledgable engineers must also take into consideration their temperature susceptibility in terms of pen-vis number, penetration index, etc., when selecting the grade of asphalt cement to employ for a paving project. However, as might be expected, I am a firm supporter of grading asphalt cements by either penetration or viscosity at 77 F.

MR. J. LEFEBVRE: I have one comment, Dr. McLeod has shown that there was a great difference in the number of cracks between Test Roads No. 1 and No. 3, but he has not tried to explain why, although he has mentioned that there could be factors such as environment. I happen to be familiar with the conditions under which these roads were built. Test Road No. 3 which has the least number of cracks, was built quite early in the paving season and consequently had the benefit of traffic during the summer. Road No. 1, that is the worst of the three, was built very late in the fall. As it was almost freezing, compaction was not as good and, of course, the pavement did not get the benefit of densification by traffic until the following summer. Furthermore, there was a serious moisture problem during construction and as a matter of fact we were asked to investigate this moisture problem. So these are factors which might explain why there was so much difference between these two roads or between the three of them because construction of No. 2 took place in mid-summer.

DR. McLEOD: I am also thoroughly familiar with the circumstances that Mr. Lefebvre has described. However, when pavement samples have been removed from these three Test Roads, there has been no substantial difference in air voids contents, indicating that there has been little or no difference in pavement compaction. As demonstrated by Table 4, the air voids in-place are very nearly 3 percent in each of the nine pavement test sections in the three Test Roads. Consequently, while one can refer to differences that occurred at the time of construction as a possible explanation for the diversity in numbers of transverse pavement cracks in the three Test Roads, I prefer to consider this as only one of the unknown environmental factors that influence transverse pavement cracking, but would be unable to hazard a guess as to whether it is a minor or major variable.

MR. T. GROENING: I had the opportunity and privilege of reading this paper some time ago and I think my remarks will follow in line with what Mr. Lefebvre said. It appeared to me, if my recollection is correct, that there was quite a difference in the traffic volume on these three roads, and it appeared to me there was a relationship between incidence of cracking of the road and traffic volume, the higher number of vehicles being associated with less cracking. If this is correct and significant, what would be the explanation for it?

DR. McLEOD: Mr. Groening is quite correct concerning the difference in traffic counts on the three Test Roads. As indicated near the beginning of the paper, the AADT counts are 900 for Test Road 1, 1400 for Test Road 2, and 1500 for Test Road 3. This is also the reverse order of transverse cracking which is greatest for Test Road 1 and least for Test Road 3. If Mr. Groening is correct, this would mean that the smaller the traffic volume the greater the amount of low temperature transverse cracking. This seems contrary to what might ordinarily be expected. Furthermore, as pointed out in reply to Mr. Lefebvre's comment, the air voids content of all pavement sections in the three Test Roads appears to be the same, indicating approximately equal degrees of compaction. In addition, from the low temperature performance of a great many other asphalt pavements in Canada, the difference in traffic count on the three Test Roads appears to be too simple an explanation for the large differences in transverse pavement cracking that have developed. Nevertheless, the weather differences during construction mentioned by Mr. Lefebvre, and the differences in traffic count referred to by Mr. Groening could be two of the several or many unknown environmental factors that have influenced the marked differences in low temperature transverse pavement cracking between the three Test Roads.

MR. V. P. PUZINAUSKAS: My question refers to Table 1 to which, I believe, Mr. Corbett referred earlier. Inspection of test data in Table I indicates direct correlation between viscosity at 275 F. or at 210 F. with either Penetration Index (PI) or with Pen-Vis number. Data indicates that as viscosity of asphalt increases also PI's and Pen-Vis number tend to gradually decrease or increase. In view of such correlation, the question may be raised why to use at all complex and indeterminate numbers such as represented by PI or Pen-Vis number? Why not use either viscosity directly or viscosity-temperature susceptibility which may be calculated on the basis of the widely accepted Walter's equation.

DR. McLEOD: The relationship between low temperature transverse pavement cracking and the Pfeiffer and Van Doormaal penetration index is the complete opposite to this relationship versus pen-vis number, as can be seen from a comparison of Figure 6 with Figure 11. All of our experience in Canada has indicated that for any given penetration at 77 F., there is a very decided increase,in low temperature transverse pavement cracking with an increase in asphalt temperature susceptibility. Fromm and Phang have also emphasized this in their paper. As indicated by Figure 6 in my paper, when temperature susceptibility is measured by the Pfeiffer and Van Doormall penetration index there is an increase in transverse pavement cracking with a *decrease* in temperature susceptibility. Consequently, for the group of asphalt cements used on these three Test Roads (and for others used elsewhere in Canada), it could only be concluded that the Pfeiffer and Van Doormaal penetration index was not providing a reliable measure of temperature susceptibility, at least for these asphalt cements. It was for this reason that I had to develop another measure of asphalt temperature susceptibility, pen-vis number, which is described in the Appendix. In every case where it has been applied, temperature susceptibility when measured by pen-vis number, correlates with the amount of transverse cracking that has occurred, with transverse cracking increasing with a decrease in pen-vis number as illustrated in Figures 7 to 14.

MR. PUZINAUSKAS: They are the reverse, but they are there. So why do you use these numbers, why not directly viscosity?

DR. McLEOD: Because it is difference in temperature susceptibility that is important, not difference in viscosity at 275 F.

MR. R. L. DUNNING: I think it's unfortunate that we must have two separate camps, both of whom are actually correct, arguing or nit picking on points and completely missing the total concept that's trying to be put across. That concept is this. In any particular area, those people who live in that area wish to grade their asphalt by a method that controls the critical factors. Actually 77 F., may be too high of a temperature to really control the critical factor that one person wished to control, while 140 F. is too low for another. What is wanted is to grade the asphalt at the temperature which the critical properties occur. In California we'd rather grade our asphalt at 140 F., yet in Canada they are much better off to grade their asphalts at 77 F. or lower. Both are right. Arguments on penetration and viscosity and arguments about fundamental units are really just a big smoke screen. We need to get back to basics. We are really trying to get a job done. You are correct and so are those who want the viscosity at 140 F.

MR. H. J. FROMM: I would like to comment briefly on what Mr. Puzinauskas just said, regarding Dr. McLeod's correlation using Pen-Vis Number rather than Visc. at 275 F. These asphalts do show a correlation with Visc. at 275 F. admittedly but this is because of a more fundamental relationship. Asphalts with the same Pen. at 77 F. have essentially the same viscosity at 77 F. but can have widely differing viscosities at 275 F. if they have different temperature susceptibilities. Thus correlating Pen.-Vis. Number which is a measure of temperature susceptibility is more correct in my estimation than correlating Visc. at 275 F.

DR. McLEOD: For the portion of this discussion concerning methods of grading asphalt cements, I would like to make it perfectly clear that I am not opposed to grading asphalt cements by viscosity. For reasons that have been outlined elsewhere, it is the temperature of

140 F. that has been proposed for viscosity grading to which I am firmly opposed. I could fully support grading asphalt cements by viscosity at 77 F. However, until some rapid viscosity test at 77 F. has been perfected and accepted, standard viscosity test procedures at 77 F. presently available are too slow for routine consistency control. In the meantime therefore, we can continue to use penetration at 77 F., which is a measure of viscosity at 77 F.

DR. McLEOD (Author's Closure): Referring to Mr. Puzinauskas' comments, if I now understand him correctly, he is asking why I did not attempt to correlate transverse pavement cracking with viscosity at 275 F. instead of inventing a new method, pen-vis number, for expressing the temperature susceptibility of an asphalt cement. In the case of the three 85-100 penetration asphalt cements referred to in Table 1, that were used in the three Test Roads, there is a rough direct correlation between viscosity at 275 F. and amount of transverse cracking. The asphalt cement with the highest viscosity at 275 F., Supplier 1, resulted in least transverse cracking, while the asphalt cement with the lowest viscosity at 275 F., Supplier 3, developed the most transverse cracks. Superficially at least therefore, there seems to be a correlation between viscosity at 275 F. and transverse pavement cracking. However, this only holds when the asphalt cements being compared all have the same penetration at 77 F. At Test Road 4, the use of 85-100 penetration asphalt and 150-200 penetration asphalt cements were compared with respect to transverse pavement cracking. Since these two asphalt cements came from the same crude oil, their viscosities at 275 F. were decidedly different, being approximately 200 centistokes for the 85-100 penetration and 120 centistokes for the 150-200 penetration asphalt. Consequently, the 150-200 penetration asphalt has a much lower viscosity at 275 F. and if Mr. Puzinauskas' suggestion were correct the pavement made with it should show the most transverse cracking. However, as illustrated by Figures 20 and 21, the pavement made with 150-200 penetration asphalt showed no transverse cracking, whereas the pavement constructed with 85-100 penetration asphalt with its much higher viscosity at 275 F. developed more than 400 Type 1 transverse cracks per lane mile. Therefore, for pavements made with asphalt cements having a wide range of penetration at 77 F., and that have been produced from a variety of crude oils, the number of transverse cracks per lane mile does *not* correlate with the viscosities of these asphalt cements at 275 F. As indicated by Figure 23, avoidance of low temperature transverse pavement cracking requires careful attention to three factors: (a) minimum anticipated pavement temperature at a pavement temperature at a pavement depth of 2 in., (b) penetration of the asphalt cement at 77 F., and (c) temperature susceptibility of the asphalt cement as measured by its pen-vis number.

Like Mr. Groening, Mr. Driscoll has referred to the difference in traffic on the three Test Roads, and I have already indicated in reply that this appears to be too simple an explanation for the differences in transverse pavement cracking that have occurred in the three Test Roads. Mr. Driscoll points out that the Marshall stabilities for pavement samples taken from Test Road I are higher than for samples taken from the other two Test Roads. This can be explained at least in part by the, generally, lower penetration at 77 F. for the asphalt cements recovered from Test Road 1. However, too much significance should not be attached to differences in Marshall stabilities on samples taken from pavements, because of the necessity to reheat the samples to form Marshall briquettes, which hardens the asphalt cement and results in abnormally high Marshall stability values. Since, in general, the asphalt cement recovered from Test Road 1 is somewhat harder than that recovered from the other two Test Roads, it would be expected that the viscosity at 140 F. of the asphalt recovered from Test Road I would be higher than that recovered from Test Roads 2 and 3. However, these are high temperature differences. Insofar as low temperature transverse pavement cracking on these three Test Roads is concerned, it is the hardness of the asphalt cements as reflected in the pavement moduli of stiffness at the minimum pavement temperature of -5 F. at a pavement depth of 2 in. that appears to correlate well with transverse pavement cracking, as illustrated by Figure 18.

We are glad that Mr. Driscoll is able to report the successful use of a softer grade of asphalt cement, 150-200 penetration, in northwestern Pennsylvania. This parallels Canadian experience with this grade of asphalt cement in parts of Canada with warmer winters, where its use avoids low temperature transverse pavement cracking. In being able to employ a low mixing temperature of 195 F. to avoid trouble with moisture in the capillary pores of individual aggregate particles, we believe Mr. Driscoll has been fortunate with the aggregates he has been using. Within my own experience, where a low mixing temperature was tried in Canada, the moisture trapped in this capillary pore space resulted in bad stripping of the asphalt cement from the aggregate in the pavement in one year of time. This occurred even in a section where an anti-stripping agent was incorporated. However, we warmly compliment Mr. Driscoll on his success in his own area, where low mixing temperatures seem to work. This is the ultimate test.

In his comments, Mr. Corbett seems to feel that the use of softer asphalt cements to avoid or reduce low temperature transverse pavement cracking has been generally accepted. I doubt this. Not long ago, a prominent engineer in the asphalt industry was claiming that the asphalt cement was not responsible for low temperature transverse pavement cracking, since it originated in the subgrade. In reply to this, I have emphasized that in walking the 18 miles of test pavements in the three Test Roads during transverse crack surveys, not even one crack in the base course or subgrade has ever been observed. In their paper for this meeting, Fromm and Phang also point out that most transverse pavement cracking is confined to the asphalt pavement. To avoid any responsibility of asphalt cement for paving faults, another large segment of the asphalt industry argues that low temperature transverse pavement cracking is due to other factors than the asphalt cement. These, of course, have been referred to in my own paper as environmental factors. However, these environmental factors, whatever they are, contribute only to differences in transverse cracking between similar pavements in different locations. They are not the primary cause of low temperature transverse pavement cracking, which is due to the use of too hard a grade of asphalt cement for its temperature susceptibility. The paper has emphasized that regardless of what these environmental factors are, the simplest and least costly remedy for low temperature transverse cracking is the use of softer grades of asphalt cement when they come from any given crude oil source, Figure 23. A committee of the Highway Research Board thought so little of this remedy that they did not publish a paper on this subject that I presented at the Highway Research Board meeting in 1968. Consequently, I question that the use of softer grades of asphalt cement to eliminate low temperature transverse pavement cracking has been as generally accepted as Mr. Corbett's comments seem to imply. However, if more high calibre research teams like Busby and Rader publish research results like those in their paper for this meeting, that support the use of softer asphalt cements to avoid low temperature transverse cracking, the idea may eventually become respectable.

With respect to the frequent use of Figures 19, 20, and 21, to which Mr. Corbett has referred, it should be pointed out that highway departments do not build test roads like Test Road 4 every day. They are almost as scarce as duplicates of the AASHO Road Test. Consequently, I know of no other project that conveys so forcefully the effectiveness of softer asphalt cements to completely eliminate low temperature transverse pavement cracking. To the message conveyed so clearly by Figures 19, 20, and 21, concerning the merits of soft asphalt cements to avoid transverse pavement cracking, I would like to add Figures H and I, which illustrate the influence of temperature on transverse cracking. Figure H is a picture of a pavement in Manitoba where temperatures well below -40 F. are not uncommon in winter.

The 150-200 penetration asphalt cement in the pavement illustrated in Figure H, is from the same crude oil as the 150-200 penetration asphalt in the pavement illustrated in Figures 20 and 21. A comparison of Figure 20 with Figure H demonstrates the very marked effect that lower pavement service temperature has on transverse pavement cracking. There are no transverse cracks in Figure 20 where the minimum pavement temperature is from -5 F. to -10 F., but transverse cracking is very severe in Figure H where the minimum pavement temperature at a pavement depth of 2 in. can be below -40 F., even though the same asphalt cement from the same crude oil was used in both locations. To eliminate low temperature transverse pavement cracking in Manitoba, the highway department has changed from 150-200 penetration asphalt cement to SC 3000 (SC 5 or 800-1000 penetration at 77 F.), with the successful results illustrated in Figure I where no transverse cracking can be seen. Consequently, Figures 19 and 20 illustrate conditions of severe and no transverse cracking respectively, at a minimum pavement temperature of from -5 F. to -10 F., due merely to the grade of asphalt cement employed, while Figures H and I provide a parallel comparison at minimum pavement temperatures of -40 F. or lower. Therefore, Figures 19, 20, and 21, Figures H and I, and Figures 7 to 14, illustrate the influence of the three easily assessable factors that are primarily responsible for low temperature transverse pavement cracking, (a) low pavement temperature, (b) penetration of the asphalt cement at 77 F., and (c) temperature susceptibility of the asphalt cement as measured by its pen-vis number. These three factors are all included in Figure 23, which provides a guide to the selection of asphalt cements that will avoid low temperature transverse pavement cracking.

Mr. Corbett states that the "pitch" has been changed to read "select the grade of asphalt cement to be used on the basis of both penetration at 77 F. and pen-vis number." If Mr. Corbett cares to read my

Fig. H. Pavement Made with 150-200 Penetration Asphalt Cement. Located Near Portage LA Prairie, Manitoba. Age 7 Years.

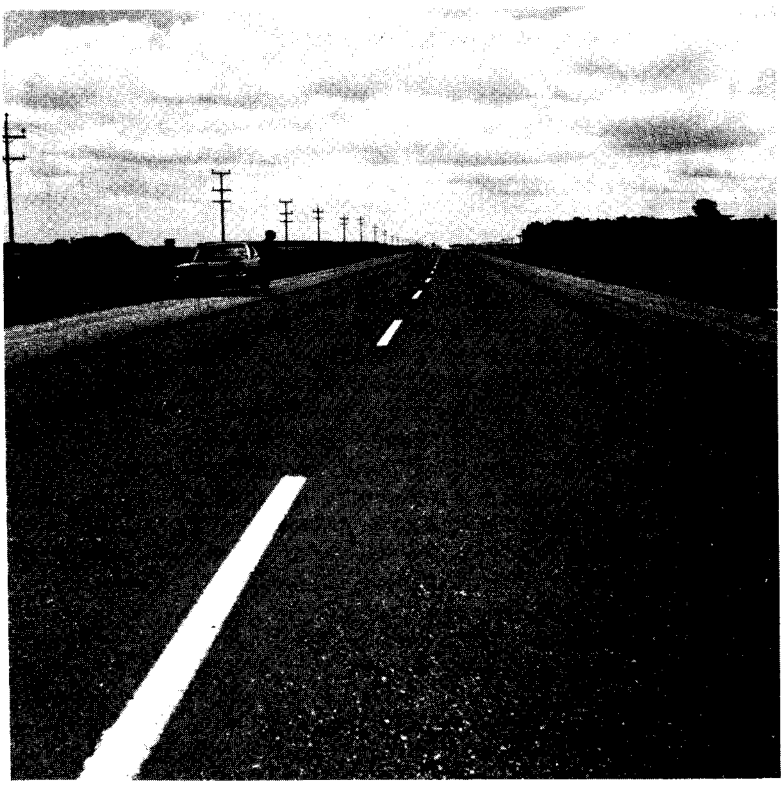

Fig. I. Pavement Made with SC 3000 (SC 5, 800-1000 Penetration at 77 F.). Located Near Morden, Manitoba. Age 3 Years.

earliest papers on this subject, he will find that the "pitch" has not been changed. From my earliest study of the low temperature transverse pavement cracking problem in Canada, it has been apparent that *both* the penetration of an asphalt cement at 77 F. *and* its temperature susceptibility contribute in a major way to the amount of low temperature transverse cracking observed. This concept of dual responsibility of grade of asphalt cement and its temperature susceptibility for low temperature transverse pavement cracking is also clearly developed in the discussion by Hills and Brien in the 1966 AAPT Proceedings, in the 1969 CTAA paper by Young, Deme, Burgess and Kopvillem, in the 1971 AAPT paper by Burgess, Kopvillem and Young, and in the 1971 CTAA paper by Busby and Rader. Consequently, this "pitch" is not new. It has been recognized by several investigators from the beginning of the study of this problem. While the different factors that are chiefly responsible for a problem may be diagnosed early, it takes time to fit the various pieces together in order to offer a remedy. Figure 23 is an attempt to provide some guidance in this respect. Figure 23 emphasizes that selecting the grade of asphalt cement to avoid low temperature transverse cracking depends on three factors: (a) the minimum pavement temperature at a pavement depth of 2 in., (b) the penetration at 77 F. of the asphalt cement, and (c) the temperature susceptibility of the asphalt cement as given by its pen-vis number or by its penetration index.

I wonder if Mr. Corbett has his tongue in his cheek when he implies that grading asphalt cements by viscosity at 140 F. necessarily eliminates what he refers to as "poor temperature susceptible, low shear susceptible asphaltic binders." One has only to glance at Figure 24 or Figure D to realize that the same asphalt cements are obtained whether they are graded by viscosity at 140 F. or by penetration at 77 F. Asphalt cements with the same wide range of temperature susceptibility from PI = -1.5 to PI = 0.0 are available by either method of grading. It is only when certain restrictions, such as minimum requirements for penetration at 77 F. are combined with viscosity grading at 140 F., that some asphalt cements can be discriminated against and eliminated. As Mr. Halstead pointed out in his discussion, one can very easily write a restrictive specification either in terms of penetration grading at 77 F. by introducing a high temperature viscosity requirement, or in terms of viscosity grading at 140 F. by including a minimum penetration requirement at 77 F.

A specification for asphalt cement can be formulated from one or the other of two principal points of view:

(1) it can be written in terms of the properties of asphalt cement as a material, which may or may not be related to the job the asphalt cement is expected to do in the field, or
(2) it can be written to satisfy the engineering requirements of an asphalt cement that are needed to facilitate pavement construction and to improve pavement performance.

In this connection, a question I would like to address to Mr. Corbett and other laboratory investigators who continue to contrive means for making asphalt cement specifications more and more restrictive, is how many asphalt pavements have you actually seen that were made with "poor temperature susceptible, low shear susceptible asphalt binders," and how were they performing? I would like to point out again, that there is one part of Canada in which asphalt cements of high temperature susceptibility approaching a pen-vis number of -1.5, have been used almost exclusively for the past 40 years, and that no part of Canada has any better asphalt pavements. Also, some time ago, the chief engineer of one of our larger Canadian highway departments stated that once they were in place, pavements made with low pen-vis number (low PI) asphalt cements appeared to perform as well as those made with asphalt cements of high pen-vis number (high PI). His principal criticism of the use of asphalt cements with low pen-vis numbers (low PI), was the delayed rolling that often occurred during their construction in hot weather. Furthermore, when walking approximately

36 miles for each transverse crack survey on the three Ontario Test Roads, apart from transverse cracking, there was no noticeable difference in service performance between pavements made with the asphalt cement of low temperature susceptibility (high pen-vis number) provided by Supplier 1, and those containing the asphalt cement of high temperature susceptibility (low pen-vis number) furnished by Supplier 3. Figures 19, 20, 21, and 23 indicates that the difference in transverse pavement cracking could have been avoided by the selection of a softer grade of asphalt cement in the case of Supplier 3.

Consequently, are you sure that you are not so much concerned with investigating the properties of asphalt as a material, that you have overlooked the practical need to correlate your results with the job the asphalt cement must do in a pavement in the field? Are you certain that in any well designed pavement, where the asphalt cement has been selected by the principles illustrated by Figures 23 and P in this paper and its discussion, that pavement service performance is noticeably influenced by the limited values for temperature susceptibility and shear susceptibility that you are proposing for more and more restrictive specifications? Furthermore, even if you are right, which I presently question, why is the assumption made that every asphalt pavement is being designed for the traffic of the New Jersey Turnpike? Why, particularly in this time of asphalt shortages, must these highly restrictive specifications be applied to asphalt cements even for use on secondary roads and streets with their usually limited service lives?

Mr. Corbett states that on the basis of the Pfeiffer and Van Doormaal penetration indices given in Table 1, Supplier 2's asphalt cement is less susceptible than that of Supplier 1. Why does Mr. Corbett not carry his comments further, and point out that on the basis of Pfeiffer and Van Doormaal penetration index values, Supplier 3's asphalt cement is less temperature susceptible than those of either of the other two Suppliers? No one familiar with these three asphalt cements, which have been widely used in Canada, would accept this for a moment. The reason is that the Pfeiffer and Van Doormaal penetration index is not a reliable indicator of temperature susceptibility for all asphalt cements. In a CTAA paper in 1968, I listed 10 asphalt cements, for several of which anomalous Pfeiffer and Van Doormaal penetration index values were obtained. This happens because the Pfeiffer and Van Doormaal penetration index depends upon softening point and penetration at 77 F., and on the questionable assumption that the penetration value at the softening point is always 800. In the table referred to, data obtained by Mr. Lefebvre are listed which indicate that for these 10 asphalt cements the penetration at the softening point ranged from 590 to 4500. Furthermore, with a number of asphalt cements, particularly those containing some wax, the softening point measured by the ring and ball test is a false softening point and is substantially higher than normal. It is for this reason that the Pfeiffer and Van Doormaal penetration index is not always a reliable indicator of temperature susceptibility. With respect to temperature susceptibility therefore, in Table 1, the

Pfeiffer and Van Doormaal penetration indices line up the asphalt cements in an order that is completely opposite to what reality indicates.

Mr. Corbett also refers to the ratio of penetration at either 39.2 F. or at 32 F. to the penetration at 77 F. as a measure of temperature susceptibility. A number of investigators have pointed out that these ratios are not reliable indicators of temperature susceptibility because of complications introduced by the different loadings and by the different lengths of loading time employed. Furthermore, these ratios are influenced by unknown and variable stresses that are changing at variable rates during the test.

The unreliability of the pen. ratio (pen. at 39.2 F. over pen. at 77 F.) as a measure of temperature susceptibility is indicated by the pen. ratios of the recovered asphalt cements in Tables 5, 6 and 7. The pen. ratios in each table indicate that Supplier 3's asphalt cement is less temperature susceptible than that of Supplier 1 for asphalt cements recovered from each of the three Test Roads. Supplier 1's asphalt cement has been acknowledged to be one of the least temperature susceptible asphalt cements used in Canada, while for the past 20 years, Supplier 3's asphalt cement has been recognized as one of the most highly temperature susceptible asphalt cements in use in this country. Consequently, it would be absurd to suggest that Supplier 3's asphalt cement is less temperature susceptible than that of Supplier 1 merely because it has a higher pen. ratio. A much more valid comparison of temperature susceptibility between the asphalt cements of Supplier 1 and Supplier 3 is given by the pen-vis numbers of Table 8, which demonstrate that Supplier 3's recovered asphalt cement is very much more temperature susceptible (pen-vis number -1.34 to -1.41) than that of Supplier 1 (pen-vis number -0.46 to -0.59). Mr. Corbett, of course, did not have this background information when his comments were made.

My calculations based on pen-vis numbers do not support Mr. Corbett's claim that the relationship between viscosity at 140 F. and penetration at 77 F. in Table 1 indicate that Supplier 2's asphalt cement is less temperature susceptible than Supplier 1's. To obtain viscosity values at 140 F., it is necessary to extrapolate from the figures for viscosity at 210 F. and at 275 F. given in Table 1, which naturally introduces some uncertainty. However, when this is done, the pen-vis numbers based on viscosity at 140 F. and penetration at 77 F. are for Supplier 1, -0.9, for Supplier 2, -1.0, and for Supplier 3, -2.0. The data contained in Table 8 for asphalt cements recovered from pavement samples from the three Test Roads, also refute Mr. Corbett's claim that Supplier 2's asphalt cement is less temperature susceptible than that of Supplier 1. In every case, the pen-vis numbers based on viscosity at 275 F. and penetration at 77 F. given in Table 8 for asphalt cements recovered from the nine pavement sections in the three Test Roads, indicate that Supplier 1's asphalt cement is the least temperature susceptible, followed in order of increasing temperature susceptibility by the asphalt cements of Supplier 2 and of Supplier 3.

The three 83-100 penetration asphalt cements selected for these three Test Roads were widely used in Ontario in 1960. It was generally recognized that in terms of temperature susceptibility, the asphalt cement provided by Supplier 3 was the most temperature susceptible, Supplier 2's asphalt cement was intermediate in temperature susceptibility, while Supplier 1's asphalt cement was the least temperature susceptible. This was also in the order of their viscosities at 275 F. with Supplier 1's asphalt cement having the highest viscosity at 275 F., while that of Supplier 3 was the lowest.

Referring to Figure 5, for two asphalt cements of the same viscosity at 77 F., it is clear that the viscosity of the asphalt cement labelled PVN = 0.0 has changed much less upon heating to 275 F. than that of the asphalt cement labelled PVN = -1.5. Consequently, the temperature susceptibility of an asphalt cement can be measured in terms of its penetration or viscosity at 77 F. and its viscosity at 275 F. This is the basis for the pen-vis number as a measure of temperature susceptibility, which is described in the Appendix. In this connection, it is of interest that Fromm and Phang for their paper for this meeting used the ratio of viscosity at 60 F. versus viscosity at 275 F. as their measure of asphalt cement temperature susceptibility.

When temperature susceptibility is measured in terms of pen-vis number, there is a clear and regular relationship between the pen-vis numbers of the three asphalt cements and the number of low temperature transverse pavement cracks that occur on each of the three Test Roads in which these asphalt cements were incorporated, Figures 7 to 17.

Therefore, one can employ the inconsistent and questionable measures of temperature susceptibility suggested by Mr. Corbett which obscure any relationship between temperature susceptibility (for the same penetration or viscosity at 77 F.) and transverse pavement cracking, or one can use a more reliable measure of temperature susceptibility, namely pen-vis number based on penetration at 77 F. and viscosity at 275 F., and have the useful correlations indicated by Figures 7 to 17.

I would like to add a few comments on Dr. Dunning's suggestion that there should be regional specifications for asphalt cements. It is surprising that such a large segment of the asphalt industry should favour this proposal. There would undoubtedly be a general agreement concerning communication, in general, between the various regions of a large country, that regional languages would be a handicap and a barrier. Regional specifications for asphalt cements, like regional languages make it difficult and in extreme cases impossible for engineers in different regions to compare their pavement experiences with each other on any common basis. Therefore, regional specifications for asphalt cement should not be considered as long as a national specification is possible. In my estimation, grading asphalt cements by viscosity at 140 F. makes regional specifications inevitable. On the other hand, grading asphalt cements by penetration or viscosity at 77 F. with a viscosity requirement at 275 F. to reduce the present wide range of viscosity at 275 F., makes a national and even an international specification for asphalt cements possible.

Any proposal for a new or modified specification for asphalt cement should have two very practical objective in mind:

(1) it should facilitate high temperature construction operations, and 275 F. is a representative temperature for the high temperature construction operations of mixing, spreading, and breakdown rolling, and
(2) it should improve pavement performance at both low and high service temperatures, and 77 F. is a representative average pavement service temperature.

Figure 23 provides guidance for selecting asphalt cements that will avoid low temperature transverse pavement cracking. Is there a similar guide for the selection of asphalt cements for high volume high speed traffic in hot climates? It will be demonstrated that there is.

Figure J demonstrates that if two asphalt cements with different temperature susceptibilities have the same viscosity at some given

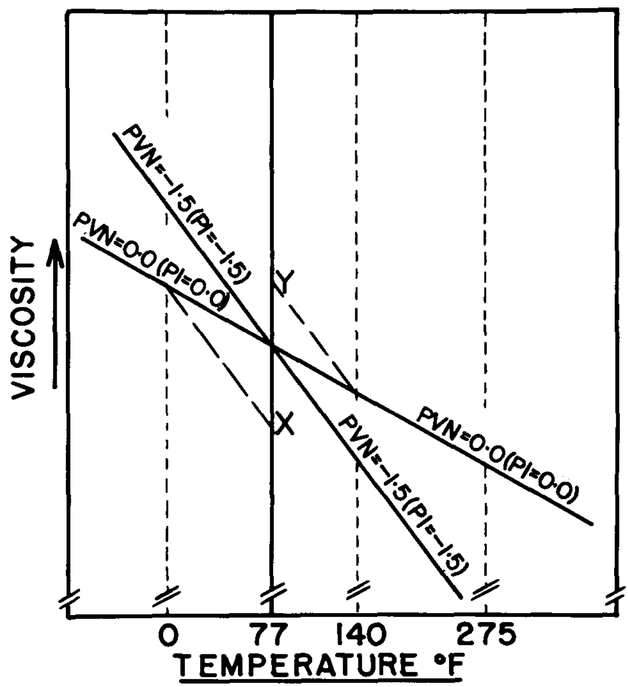

Fig. J. Illustrating the Influence of Temperature Susceptibility on the Grade of Asphalt to Be Selected to Obtain Equal Viscosities at Each of Different Service Temperatures.

temperature for example 77 F. they will have quite different viscosities at any other higher or lower temperature. Furthermore, for the same viscosity at some temperature below 77 F., for example 0 F., an asphalt cement with a pen-vis number of -1.5 must be substantially softer at 77 F., point X, than an asphalt cement with a pen-vis number of 0.0. Conversely, for the same viscosity at 140 F., an asphalt cement with a pen-vis number of -1.5 must be substantially harder at 77 F., point Y, than an asphalt cement with a pen-vis number of 0.0. Therefore, Figure J indicates that if we want the same pavement performance at some low temperature, for example 0 F., we have to select a substantially softer asphalt cement at 77 F. (higher penetration or lower viscosity at 77 F.) if its pen-vis number is -1.5, than if its pen-vis number is 0.0. Vice versa, if we want the same pavement performance at some high temperature, for example 140 F., we must select a substantially harder asphalt cement at 77 F. (lower penetration or higher viscosity at 77 F.), if its pen-vis number is -1.5, than if its pen-vis number is 0.0. Consequently, selecting asphalt cements that will provide similar pavement performance regardless of their differences in temperature susceptibility should be recognized as a major problem in asphalt pavement design. Much of the poor performance of asphalt pavements at the present time is due to our failure to select the asphalt cement in terms of *both* its penetration or viscosity at 77 F. *and* its temperature susceptibility.

Figure 23, which is based on grading asphalt cements by penetration or viscosity at 77 F., together with a viscosity requirement at 275 F., enables an engineer in a colder climate to select a grade of asphalt cement that will avoid low temperature transverse pavement cracking, without writing restrictive specifications for asphalt cements. When using Figure 23 to select a grade of asphalt cement that will essentially avoid transverse pavement cracking throughout a pavement's service life, the grade of asphalt chosen should *lie to the right* of the diagonal line that represents the minimum temperature at a pavement depth of 2 in. that is anticipated during the service life of the pavement.

On the other hand, Figure K demonstrates that when asphalt cements are graded by viscosity at 140 F., many asphalt cements in the AC5, 10, and 20 grades are rejected because they lie to the *left* of some diagonal line representing the minimum expected temperature at a pavement depth of 2 in. For example, only the fringe of asphalt cements on the extreme right of the AC5 grade in Figure K lie to the right of the diagonal line representing a minimum pavement temperature of -25 F. Consequently, with respect to low temperature pavement performance, as illustrated by Figures K and 24, grading asphalt cements by viscosity at 140 F. is so restrictive that only asphalt cements from a limited number of crude oils can comply.

It will be shown that charts analogous to Figure 23 can be developed to guide the selection of asphalt cements for pavements carrying fast traffic in hot climates.

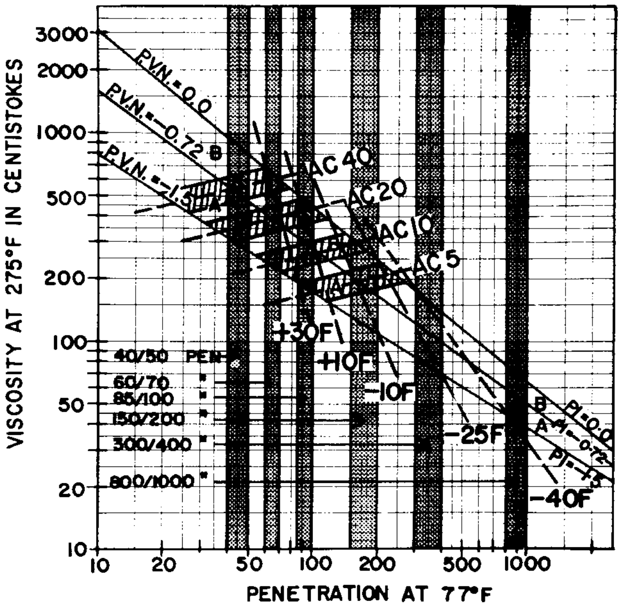

Fig. K. Illustrating that Grading Asphalt Cements by Viscosity at 140 F. Favours Asphalt Cements with High Penetrations at 77 F. and High Pen-Vis Numbers (Penetration Indices) for Use When Avoiding Low Temperature Transverse Pavement Cracking.

Figure L is a graph based on Van der Poel's charts, in which pavement moduli of stiffness for fast loading (50 cycles per second, corresponding to fast moving traffic) at 122 F. as ordinate, have been plotted against pavement moduli of stiffness for slow loading (due to chilling to low temperature) at -10 F. as abscissa.

Pavement temperature studies by Kallas at Washington, D.C., indicate that in that area, there is only about 1 percent of the year in total when the pavement temperature at a pavement depth of 2 in. exceeds 122 F. Arena reports very similar results at Baton Rouge, Louisiana. Consequently, over even the warmest areas in most of North America, the highest practical pavement temperature at a pavement depth of 2 in. is 122 F. A pavement depth of 2 in. is selected as critical for fast moving traffic in tropical climates because the thinner a pavement is, the more stable it is. Therefore, even if 1/4 in. or 1/2 in. at the top of a pavement attains a temperature of 140 F., this layer will be stable under traffic because of its thinness.

In many tropical areas around the world, 80-100 penetration asphalt cement is employed for pavements for highways and city streets. Therefore, in these hot climates 80-100 penetration asphalt cements appears to provide adequate pavement stability.

An examination of Figure L shows that a pavement containing 100 penetration asphalt cement with a pen-vis number (penetration index) of 0.0 develops a modulus of stiffness of 70,000 psi under fast loading (50 cycles per second corresponding to fast moving traffic) at 122 F. Figure L also demonstrates that 70 penetration asphalt cement with a pen-vis number of -1.5 likewise develops a modulus of stiffness of 70,000 psi under fast loading (50 cycles per second) at 122 F. Consequently, pavements containing either 100 penetration asphalt cement with a pen-vis number (penetration index) of 0.0, or 70 penetration asphalt cement with a pen-vis number of -1.5, develop the same modulus of stiffness, 70,000 psi, under fast loading (50 cycles per second corresponding to fast traffic) at a pavement temperature of 122 F.

This value for modulus of stiffness, 70,000 psi, at 122 F. forms the basis for Figure M, which is offered as a guide for the selection of asphalt cements for asphalt concrete surface courses for fast moving traffic in tropical climates. Any asphalt cement that lies to the _left_ of the heavy line labelled X should provide properly designed asphalt concrete surface courses with moduli of stiffness values in excess of 70,000 psi at a pavement temperature of 122 F., and should therefore be adequate for high speed traffic in hot climates. Asphalt cements that lie to the right of line X in Figure M could be selected for well-designed asphalt concrete surface courses for medium and light traffic. The shorter lighter lines in Figure M indicate combinations of

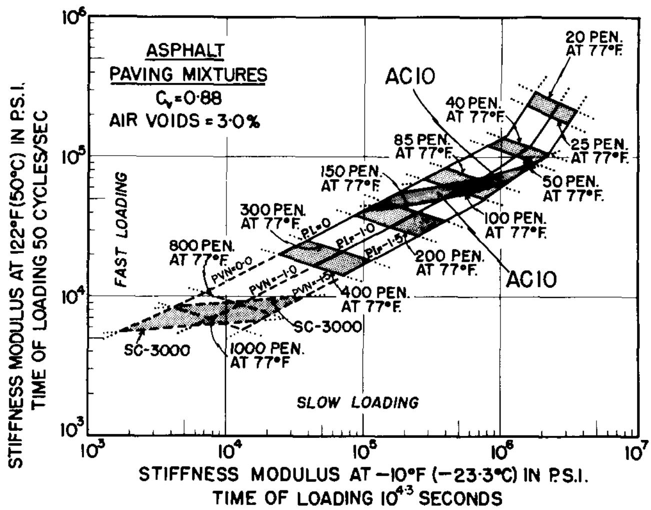

Fig. L. Relationship between Stiffness Moduli for Asphalt Paving Mixtures for High Rate of Loading (High Speed Traffic) at High Temperature (122 F.) versus Slow Speed of Loading (Temperature Stresses) at Low Temperature (-10 F.).

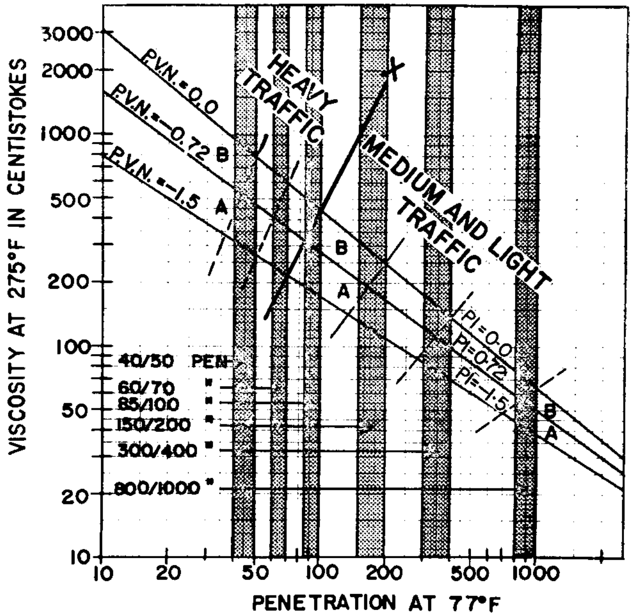

Fig. M. A Chart for Selecting Asphalt Cements for Asphalt Concrete Surface Courses in Hot Climates. Based on Temperatures of 122 F. at Pavement Depth of 2 Inches and Fast Traffic.

penetration at 77 F. and pen-vis number for asphalt cements that would provide asphalt concrete surface courses with equal modulus of stiffness values at 122 F. These values for modulus of stiffness can be easily read from Figure L.

Figure M provides guidance to the selection of asphalt concrete surface course paving mixtures exposed to high sun temperatures in tropical areas, and that are carrying fast traffic. However, what about asphalt concrete surface course paving mixtures in tunnels, thoroughly shaded areas, and in similar locations that do not reach these high temperatures even in the tropics, or base course layers in deep strength or full depth asphalt pavements that do not approach the tropical surface course temperatures, but all of which are subject to fast moving vehicles? Answers to this question are provided by Figure N, which is also based on Van der Poel's charts. The ordinate axis of Figure N provides pavement modulus of stiffness values under fast loading (50 cycles per second corresponding to fast moving traffic) for pavement temperatures of 100 F., 77 F., and 50 F. The abscissa is still pavement moduli of stiffness for slow loading (chilling to low temperature) at -10 F.

The ordinate axis of Figure N shows that at each of these temperatures, a pavement containing an asphalt cement of 100 penetration for example, has a higher modulus of stiffness if its pen-vis number is -1.5 than when its pen-vis number is 0.0. This difference becomes greater and greater as the temperature decreases from 100 F. to 77 F. and to 50 F.

It should be noted in Figure N that the band of modulus of stiffness values at a temperature of 100 F. becomes only a line at 77 F. Also, moduli of stiffness values for pavements made with asphalt cements with a pen-vis number of 0.0 provide the top boundary of the band at 100 F., but become the bottom of the band at 50 F. The changeover

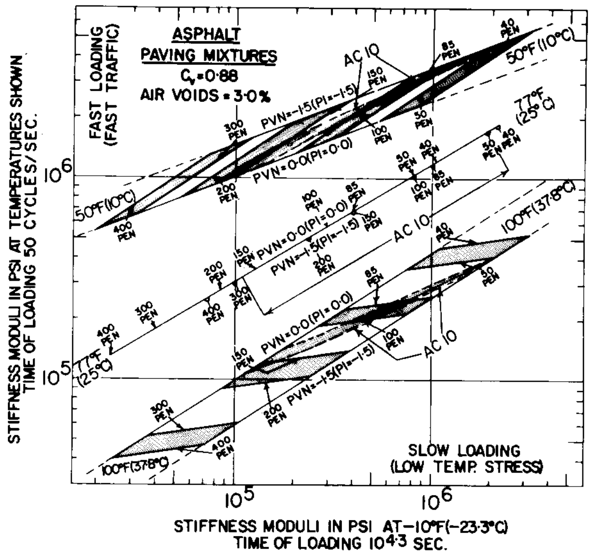

Fig. N. Relationships between Pavement Moduli of Stiffness for Fast Loading (Fast Traffic, 50 Cycles per Second) at the Temperatures Indicated versus Pavement Moduli of Stiffness for Slow Loading (Low Temperature Stresses at -10 F.).

occurs at 77 F. Furthermore, even at a temperature of 77 F., the ordinate axis indicates that a pavement containing 100 penetration asphalt for example, has a much higher modulus of stiffness if its pen-vis number is -1.5, 1,000,000 psi, than when its pen-vis number is 0.0, 575,000 psi.

Figure O indicates asphalt cements with combinations of penetration at 77 F. and pen-vis number that provide paving mixtures with the same modulus of stiffness under fast loading, as 100 penetration asphalt with a pen-vis number of 0.0. For example, under fast loading, a paving mixture containing 180 penetration asphalt cement with a pen-vis number of -1.5 develops the same modulus of stiffness, 575,000 psi, as a paving mixture containing 100 penetration asphalt cement with a pen-vis number of 0.0 when both pavements are at a temperature of 77 F. Also, for fast loading at a pavement service temperature of 50 F., a pavement containing 400 penetration asphalt with a pen-vis number of -1.5 develops the same modulus of stiffness, 1,300,000 psi as a pavement containing 100-penetration asphalt cement with a pen-vis number of 0.0. Figure O is based on Figures L and N. For conditions of fast loading, Figure O demonstrates that at all temperatures below about 110 F., which Kallas' temperature study indicates applies to pavement layers below a depth of 6 in., asphalt cements with certain combinations of pen-vis numbers less than 0.0 and penetrations at 77 F. higher than 100, provide pavements with the same modulus of stiffness values as 100 penetration asphalt cement with a pen-vis value of 0.0. Furthermore, under conditions of fast loading, for each temperature labelled line in Figure O, pavements containing asphalt cements with any combination of penetration at 77 F. and pen-vis number that lies to the *left* of this line, will have a higher modulus of stiffness than a pavement containing 100-penetration asphalt cement with a pen-vis number of 0.0 at the same temperature.

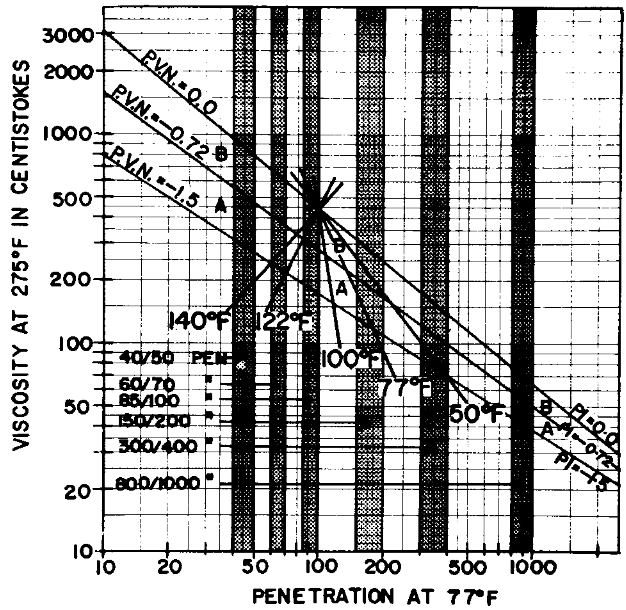

Fig. O. Illustrating Combinations of Penetrations at 77 F. and Pen-Vis Numbers (Penetration Indices) for Asphalt Cements for Each of a Range of Pavement Temperatures, that Provide the Same Pavement Moduli of Stiffness Values for Fast Loading (Fast Traffic, 50 Cycles per Second) as 100 Penetration Asphalt Cement with a Pen-Vis Number of 0.0 at Each of the Same Temperatures.

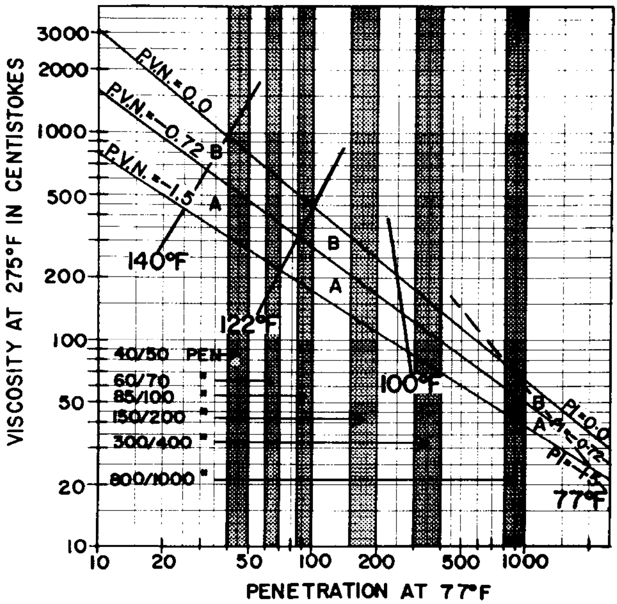

Fig. P. Illustrating Combinations of Penetration at 77 F. and Pen-Vis Numbers (Penetration Indices) for Asphalt Cements, All of Which Provide a Pavement Modulus of Stiffness of 70,000 psi for Fast Loading (Fast Traffic, 50 Cycles per Second) at the Pavement Temperatures Indicated.

The temperature-labelled lines in Figure P illustrate combinations of penetration at 77 F. and pen-vis number, all of which at the temperature indicated, provide a pavement modulus of stiffness of 70,000 psi under fast loading. It should be of more than usual interest that at a pavement temperature of 77 F., a pavement containing asphalt cement of about 2,000 penetration with a pen-vis number of -1.5, or at a pavement temperature of 100 F., a pavement containing asphalt cement of about 280 penetration with a pen-vis number of -1.5, provide the same modulus of stiffness, 70,000 psi, as a pavement containing 40 penetration asphalt cement with a pen-vis number of 0.0 at a pavement temperature of 140 F.

Figures L and N demonstrate that at all pavement service temperatures, 122 F., 100 F., 77 F., and 50 F., the hard end (low penetration at 77 F.) of the AC10 viscosity grade provides pavements with much higher modulus of stiffness values under fast loading conditions than the soft end (high penetration at 77 F.) of the AC10 grade. The extreme differences in moduli of stiffness are shown in the tabulation on page 492.

The practical significance of these differences in modulus of stiffness is demonstrated further in Figure Q, which results when the proposed viscosity grades at 140 F., AC5, AC10, AC20, and AC40 are

Pavement Service Temperature	Pavement Modulus of Stiffness at Hard End of AC10 Grade psi	Pavement Modulus of Stiffness at Soft End of AC10 Grade psi	Ratio of Moduli Values
(140 F.)*	(30,000)	(18,000)	(1.7)
122 F.	90,000	45,000	2
100 F.	400,000	110,000	3.6
77 F.	1,800,000	300,000	6
50 F.	4,500,000	1,000,000	4.5

* From a chart similar to Figures L and N.

plotted on Figure P. Each temperature labelled diagonal line in Figure Q indicates combinations of penetration at 77 F. and pen-vis number for asphalt cements that will provide a pavement with a modulus of stiffness of 70,000 psi at the temperature shown. Figure Q demonstrates that to provide a pavement with a modulus of stiffness of 70,000 psi at 140 F., an AC80 viscosity grade (presently non-existent) would be required if its pen-vis number were 0.0, whereas an AC40 grade is adequate if the pen-vis number of the asphalt cement is -1.5. Similarly, to provide a pavement modulus of stiffness of 70,000 psi at 122 F.,

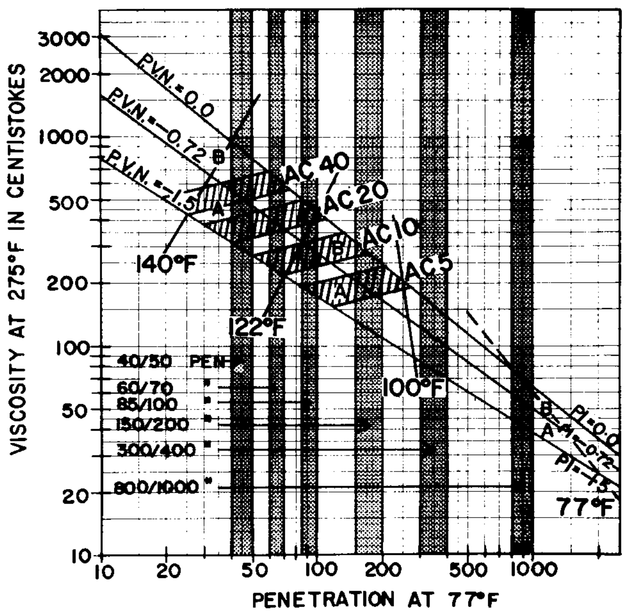

Fig. Q. Illustrating That Grading Asphalt Cements by Viscosity at 140 F. Favours the Use of Asphalt Cements with Low Penetrations at 77 F. and Low Pen-Vis Numbers (Penetration Indices), Because of the Very Much Higher Strengths (Higher Moduli of Stiffness) These Provide for Pavements Under Fast Traffic in Hot Climates.

either an AC20 asphalt cement with a pen-vis number of 0.0 or an AC10 asphalt cement with a pen-vis number of -1.5 would be required. The farther to the *left* of any one of the temperature-labelled diagonal lines in Figure Q that one proceeds, the higher the pavement modulus of stiffness *at that temperature* becomes. For example, if for a pavement service temperature of 122 F. under fast traffic, an engineer were selecting an AC20 grade, why should he choose an asphalt cement at the extreme right of the AC20 grade in Figure Q, which would provide a pavement modulus of stiffness of 70,000 psi, when by selecting an asphalt cement at the extreme left of the AC20 grade, he could have a very much stronger pavement with a modulus of stiffness of 150,000 psi at the same service temperature for the same traffic? Therefore, insofar as fast moving traffic in a hot climate is concerned, Figure Q indicates that by selecting an asphalt cement from the hard end (low penetration at 77 F.) of each viscosity grade at 140 F., for example, AC10, a very much higher pavement modulus of stiffness (very much higher pavement stability) is obtained, than when an asphalt cement from the soft end (high penetration at 77 F.) of the same viscosity grade at 140 F., is chosen. This becomes particularly important when designing asphalt concrete base courses because of the lower service temperatures to which they are exposed.

Consequently, if asphalt cements are graded by viscosity at 140 F., engineers in colder climates tend to select asphalt cements at the soft end (high penetration at 77 F.) of each viscosity grade, Figure 24, to avoid low temperature transverse pavement cracking. On the other hand, for fast traffic in hot climates, informed engineers will tend to select asphalt cements at or near the hard end (low penetration at 77 F.) of each viscosity grade, particularly for base courses, because of the much higher pavement stability this selection will provide. As a result grading by viscosity at 140 F. tends to eliminate asphalt cements with low pen-vis numbers (high temperature susceptibility) in colder climates, Figure 24, and it will tend to reduce or eliminate the use of asphalt cements with high pen-vis numbers (low temperature susceptibility) in hot climates, Figure Q. Therefore, because of these conflicting requirements, a proliferation of regional specifications each with its own severe restrictions, becomes inevitable, when asphalt cements are graded by viscosity at 140 F.

On the other hand, as illustrated by Figure 23 and Figure P, when they are graded by either penetration or viscosity at 77 F. plus a viscosity requirement at 275 F., asphalt cements with the entire range of pen-vis numbers (temperature susceptibility) can be selected for use in either cold climates or hot climates. Consequently, grading asphalt cements by penetration or viscosity at 77 F. plus a viscosity requirement at 275 F. forms a simple and very logical basis for a national and even for an international specification for asphalt cements.