PVN as a Measure of Paving Asphalt Temperature Susceptibility, and its Relationship to Paving Asphalt Specifications, Paving Mixture Design and Pavement Performance

by

Norman W. McLeod
Vice President and Asphalt Consultant
McAsphalt Engineering Services
Toronto, Ontario, Canada

Acknowledgements

Grateful acknowledgement is made to Mr. John J. Carrick, President, McAsphalt Industries Limited, for the time and facilities required for the preparation of this paper, and to Mrs. Heidi Hughes for the superb job she has done on typing this paper.

ABSTRACT

Characterization of the temperature susceptibility of an asphalt cement is critical for the design of a pavement that is resistant to low temperature cracking, rutting and instability in summer traffic. Temperature susceptibility of asphalt cements (or residues of asphalt emulsions) plays a role in the performance of surface treatments as well.

This paper describes the development of the PVN (pen-vis number) concept of the temperature susceptibility of paving asphalts. PVN is based on an asphalt cement's penetration at 25°C and its viscosity (in centistokes) at 135°C.

Paving asphalts can be divided into three groups:

- Group A, low temperature susceptibility, PVN = -0.5 minimum
- Group B, medium temperature susceptibility, PVN = -0.5 to -1.0
- Group C, high temperature susceptibility, PVN = -1.0 maximum

The original PVN value of a paving asphalt does not appear to change either with time or temperature (of manufacture or in-service). Hence, PVN acts as a "fingerprint" of the asphalt cement. This feature makes PVN useful for developing a more rational method for pavement design, pavement recycling and for monitoring construction of virgin and recycled pavements.

Incorporation of PVN as a measure of temperature susceptibility in paving asphalt specifications is recommended.

RÉSUMÉ

L'établissement de la sensibilité thermique d'un ciment asphaltique est très important pour la conception d'une chaussée résistant au fissure et à l'orniérage transversaux à basse température dus à son instabilité sous la circulation estivale. La sensibilité thermique des ciments asphaltiques (ou des résidus de béton émulsionné) joue également un rôle dans le rendement des traitements de revêtement.

Cet exposé présent l'élaboration du concept du PVN (nombre de pénétration-viscosité) pour le calcul de la sensibilité thermique des bitumes de pavage. Le PVN se fonde sur la pénétration du ciment asphaltique à 25 C et sur sa viscosité en centistokes à 135 C. On peut classer les bitumes de pavage en trois groupes:

Groupe A, faible sensibilité thermique, PVN = -0,5 (minimum)
Groupe B, sensibilité thermique moyenne, PVN = -0,5 à -1,0
Groupe C, forte sensibilité thermique, PVN = -1,0 (maximum).

La valeur originelle du PVN d'un bitume de pavage ne semble pas varier avec le temps ou selon la température (en cours de fabrication et en service). Par conséquent, le PVN joue le rôle d'"empreinte digitale" du ciment asphaltique. Cette caractéristique rend le PVN utile pour l'élaboration d'une méthode plus rationnelle de recyclage des chaussées et pour le contrôle de la construction des chaussées vierges et recyclées.

Il est donc recommandé d'inclure le PVN comme mesure de la sensibilité thermique dans les spécifications des bitumes de pavage.

I. INTRODUCTION

As a measure of paving asphalt temperature susceptibility, PVN is an abbreviation for pen-vis number, which in turn is a shortened version of "penetration at 25°C (77°F) - viscosity at 135°C (275°F) number". PVN is evaluated from the penetration at 25°C and corresponding viscosity at 135°C of "wax-free" paving asphalts from asphalt-based "wax-free" crude oils, insofar as any asphalt is entirely free from wax.

In 1947, light waxy crudes that provided asphalts of high temperature susceptibility were discovered in Western Canada in large volume. Shortly afterward, the Canadian Federal Government decreed that all petroleum products marketed west of the Ontario-Quebec border had to be made from these crude oils. Up to that time most of the asphalt used in Ontario came from Venezualan crude oils that were refined in Montreal, Quebec. They had low temperature susceptibility and a high viscosity at 135°C. Paving mixtures made with these asphalts were so stable that the rollers could be operated right up to the spreader.

Paving asphalts from Western Canadian light waxy crude oils, on the other hand, were of high temperature susceptibility with very low viscosity at 135°C. Rolling had to be delayed to allow the paving mixture to cool and develop sufficient stability to support the weight of the roller. As one Materials Engineer said facetiously, "The roller man operated the spreader in the morning and in the afternoon he operated the roller to compact what he had spread in the morning."

Contractor complaints over delayed rolling were so serious that in 1960 Ontario constructed three six-mile test pavements over 40 miles apart on existing highways in Southwestern Ontario, Figure 5. In each 6-mile test pavement there were three 2-mile test sections, each paved with 85/100 penetration asphalt of a different temperature susceptibility. That is, 2 miles were paved with asphalt of low temperature susceptibility (Group A), 2 miles with approximately medium temperature susceptibility (Group B) and 2 miles with high temperature susceptibility (Group C). The same three asphalts were replicated in the three test pavements. The terms Group A, Group B and Group C are demonstrated in Figure 14.

Two or three years later, without waiting for results from its test pavements, Ontario adopted a specification for 85/100 penetration paving asphalt requiring a minimum viscosity of 140 seconds Saybolt Furol at 135°C, later changed to 280 centistokes at 135°C. For the 150/200 penetration grade, the minimum viscosity at 135°C was 200 centistokes. They rejected all asphalts of high temperature susceptibility and about half of those of medium susceptibility.

Ontario's use of asphalts of three different temperature susceptibilities in its three test pavements and its adoption of minimum viscosities at 135°C for its new specification for paving asphalts led the writer (1,2,3,4 and 5) to wonder if temperature susceptibility for paving asphalts could be based on penetration at 25°C and viscosity in centistokes at 135°C.

Since the pen-vis number (PVN) concept for expressing paving asphalt temperature susceptibility was originated by the author about twenty years ago, it has evolved from bits and pieces of information, some of them my own, but some from the publication of others. Only within the past few months has the author been able to fit all the isolated bits of information together into a well-organized whole, which is the subject of this paper.

The major asphalt paving problems today are centred largely upon:

1) Requirement for a more useful paving asphalt specification.
2) Low temperature transverse pavement cracking in winter.
3) Need for adequate pavement stability for summer traffic.
4) Pavement rutting.
5) A more rational method for pavement recycling.
6) More effective monitoring of virgin and recycled pavement construction.
7) Need for surface treatments with superior service performance.

The paper shows that when everything else is equal, a major part of the solution for each of these seven items involves providing asphalts with higher viscosity at 135°C for any given penetration at 25°C. That is, the paving asphalt must often have a lower temperature susceptibility. This is one of the basic purposes of pen-vis number (PVN). In terms of their PVN values, all paving asphalts can be separated into one of three groups; Group A, low temperature susceptibility (PVN = -0.5 minimum), Group B, medium temperature susceptibiltiy (PVN from -0.5 to -1.0) and Group C, high temperature susceptibility (PVN = -1.0), as shown in Figure 14.

Figure 1 illustrates that two-thirds of the U.S.A. north of the Mason-Dixon Line has a frost penetration in winter ranging from 18 inches in the south to 72 inches in northern Minnesota. Still greater depths of frost penetration occur in Canada and Alaska. Because of the repeated contraction and expansion stresses caused by changing temperatures in winter, severe low temperature transverse cracking occurs, resulting in expensive maintenance for crack-filling, etc., and in the unseen costs of shortened pavement service lives.

Unstable pavements under summer traffic are subject to rutting and other forms of pavement distortion because of the lack of adequate pavement stability.

Pavement recycling is increasing, but current methods of design seem to be ill-considered and inadequate. They appear to be geared for short range success at the expense of pavement deterioration that led to recycling in the first place. A more rational method with much improved long range service life is proposed.

A better method for monitoring virgin and recycled pavement construction is proposed.

More serviceable surface treatments can also be constructed.

II <u>PAVING ASPHALT TEMPERATURE SUSCEPTIBILITY AND PVN</u>

The temperature susceptibility of a paving asphalt is the change in consistency (viscosity or penetration of the asphalt) for a given change in its temperature. As shown in Figure 2, taken from ASTM D2493, a straight line graph results when the log log viscosity of an asphalt is plotted versus the log of its absolute temperature. The slope of this line provides the temperature susceptibility of the asphalt.

The line in Figure 2 reperesents only one paving asphalt. Corbett and Schweyer (6) estimated that paving asphalts are manufactured from more than 600 crude oils or crude oil blends. Consequently, the log log viscosity versus log absolute temperature for each of these many paving asphalts would result in numerous straight lines of different position and different slope on Figure 2.

Figure 3 is taken from a small portion of Figure 2, and illustrates the temperature susceptibility of three asphalts, all of which have the same consistency at 25°C. Because it has the steepest slope, Asphalt 3 is said to have a high temperature susceptibility since its consistency changes the most for a given change in temperature. Asphalt 1 is said to have low temperature susceptibility. Because the slope of Asphalt 2 is in between the slopes of the other two asphalts, Asphalt 2 is said to have intermediate or medium temperature susceptibility.

Figure 4 illustrates the five principal methods that have been proposed as measures of paving asphalt temperature susceptibility. The first, penetration ratio, is based upon penetrations at 4°C and 25°C (39°F and 77°F). It has had local application but does not appear to have been adopted on a national scale.

The second, viscosity temperature susceptibility (VTS), has been promoted by the Asphalt Institute as a criterion for paving asphalt temperature susceptibility. VTS is based on the difference in log log viscosity at each of two temperatures, usually 135°C and 60°C, divided by the difference in the logs of the same two absolute temperatures. This equation reduces temperature susceptibility to a very small number. For example, the log log 1000 is only 0.4771 and for 500 is only 0.4312, with the difference between them being only 0.0459. With such small numbers, the supporters of VTS, who refuse to admit that temperature susceptibility is an important property of paving asphalts, can argue that paving asphalt temperature susceptibility either does not exist or that it is not significant, or that it is merely the result of experimental error. This is illustrated by the following data for two asphalts that were obtained by The Asphalt Institute, with PVN values added for comparison:

Penetration at 25°C	119	103
Viscosity at 60°C (poise)	808	2222
Viscosity at 135°C (Cst)	223	540
VTS	3.67	3.34
PVN	-0.94	+0.28

Difference in VTS = 3.67 - 3.34 = 0.33
Difference in PVN = +0.28 - (-0.94) = 1.22

In his AAPT paper of 1970, Lefebvre (4) provided Figure 6, which shows the ratio between viscosity in poises at 60°C and viscosity in centistokes at 135°C. Figure 6 indicates that this ratio varies with both penetration at 25°C and with PVN (although it was not called PVN at that time) and that its value ranges from about one to eight.

As a basis for paving asphalt specifications, the asphalt suppliers encouraged both ASTM and AASHTO to change the method for grading paving asphalts from penetration at 25°C to viscosity in poises at 60°C, with the resulting five grades - AC 2.5, AC 5, AC 10, AC 20 and AC 40, to which a sixth grade AC 30 was added later (Figure 7). Figure 8 shows how these five viscosity grades at 60°C appear when they are plotted on a chart in terms of PVN values. Both Figures 6 and 8 demonstrate that the relationship between viscosity in poises at 60°C and viscosity in centistokes at 135°C is not simple.

Pfeiffer and Van Doormaal of the Royal Dutch Shell Laboratories at Amsterdam, Holland, in a paper published in 1936 (7), adopted a very different approach for the measurement of paving asphalt temperature susceptibility, which they named penetration index, or PI. As an axis for reference they based their zero point PI on a Mexican asphalt of 200 penetration at 25°C that was derived from a "wax-free" asphalt-based crude oil. To measure the temperature susceptibilies of various paving asphalts, they prepared a nomograph, Figure 9, for which the penetration at 25° C and the ring and ball softening point of a paving asphalt were required, as indicated by Equation 3 on Figure 4. To use this nomograph, a straight line was drawn from the point representing the penetration test value on the ordinate on the right, which lists values for the penetration test at whatever temperature in °C it was measured, usually 25°C, to a corresponding point on the ordinate on the left, which marks the difference in temperature in °C between the ring and ball softening point and the temperature at which the penetration test was made. The value indicated by the point where this line intersects the oblique line representing the penetration index, indicates the PI of the paving asphalt.

As shown by Equation 3 in Figure 4, values for a paving asphalt's penetration at 25°C and for its ring and ball softening point temperature are required for Pfeiffer and Van Doormaal's temperature susceptibility measurement in terms of PI. However, because of small quantities of wax retained in paving asphalts made from Western Canada's light waxy crudes, the softening point temperatures were much too high. They exceeded the softening point temperatures of paving asphalts otherwise the same but free from wax. This made Pfeiffer and Van Doormaal's equation useless for expressing the temperature susceptibility of paving asphalts from these waxy crude oils.

Heukelom (8) attempted to overcome the effect of wax in these paving asphalts by making penetration tests at 4°C, 10°C and 25° C, and extending the least squares line through these values to obtain the temperature corresponding to a penetration of 800, since for many asphalts this corresponded approximately to the ring and ball softening point temperature. Heukelom substituted this temperature for the ring and ball softening point temperature in Pfeiffer and Van Doormaal's equation to obtain a corrected value for PI, or the PI could alternatively be taken from Shell's Bitumen Test Data Chart (8). However, Heukelom appears to have over-corrected for wax content. Consequently, for asphalts from these light waxy crude oils, Pfeiffer and Van Doormaal's method gives PI values that are too high, while Heukelom's method seems to provide PI values that are too low.

Since Pfeiffer and Van Doormaal had coined the phrase "penetration index" or PI for temperature susceptibility in their paper published in 1936 (7), my first references to temperature susceptibility, PVN, was referred to as a "modified PI". By 1972, the need for a different term was realized and since then it has been referred to as "pen-vis number" or PVN (9).

When introducing a new concept, one prefers, if possible, to build on what has gone on before. In 1936, Pfeiffer and Van Doormaal (7) provided axes of reference for their measure of paving asphalt temperature susceptibility or PI. I tried their zero PI as the zero for PVN and found that it appeared to fit (Figures 10, 11 and 12). It also happened that a PVN of -1.5 for paving asphalts from appropriate "wax-free" asphalt-based crude oils matched Pfeiffer and Van Doormaal's PI of -1.5 for the same asphalts.

In the Appendix of my 1972 AAPT paper (9), I show a rough plot of viscosity SSF at 135°C versus penetration at 25°C for 10 asphalts with a Pfeiffer and Van Doormaal PI of 0.0 in Figure 10, which also shows a similar plot for PI of -1.5. The lines representing PI = 0.0 and PI = -1.5 in Figure 10 were drawn as best lines through the data. The data illustrated in Figure 10 came from an internal report by Esso Research and Engineering, showing values for the penetration at 25°C, softening point by ring and ball, viscosity SSF at 135°C and other data for residues obtained by steam or vacuum distillation. All the asphalts came from "wax-free" asphalt-based crude oils. These asphalts, ranging in penetration at 25°C from about 200 to 35, have the same PVN values, either PVN = 0.0 or PVN = -1.5.

Later, the author made a more thorough investigation of penetration at 25°C, viscosity at 135°C and other inspection data published by the U.S. Bureau of Public Roads on 310 samples of paving asphalts from USA and Canada in Public Roads Magazine in 1959 and 1960 (10, 11). Most of these asphalt samples were manufactured either by steam or vacuum distillation. On the basis of their ring and ball softening points and their penetrations at 25°C, Pfeiffer and Van Doormaal PI values were calculated for each of these 310 asphalts. Of those produced by steam or vacuum distillation, there were 82 paving asphalts with PI values of 0.0 ± 0.2 and eight asphalts with PI of -1.5 ± 0.2. In Figure 11, the ring and ball softening points for these 90 asphalts have been plotted against their corresponding penetrations at 25°C and least squares lines labelled PI = 0.0 and PI = -1.5 have been drawn through the data. The agreement for PI values of 0.0 and -1.5 is very good.

The viscosity in centistokes at 135°C as ordinate versus the corresponding penetration at 25 C as abscissa for each of the 82 asphalts in Figure 11 with PI = 0 ± 0.2 have been plotted in Figure 12 and the least squares line through these data is labelled PVN = PI = 0.0. The same was done for the eight paving asphalts with PI = -1.5 ± 0.2 and the least squares line through those points labelled PVN = PI = -1.5 in Figure 12. Consequently, for at least the 90 asphalts manufactured by steam or vacuum distillation, values for PVN = 0.0 and -1.5 are numerically equal or very nearly so to their corresponding values for PI = 0.0 and -1.5 respectively. Misleadingly high PI values resulting from false ring and ball softening points due to the presence of wax can be avoided by using the corresponding PVN values which are based on "wax-free" asphalts. It should be emphasized that all the data illustrated in Figures 10, 11 and 12 are for paving asphalts obtained from crude oils that were "wax-free".

Figure 13 generalizes the data in Figure 12, with PVN values ranging from +0.5 to -2.0, covering practically all paving asphalts being marketed in North America.

It is a simple matter to go from the general PVN chart of Figure 13 to the paving asphalt specification chart of Figure 14, where paving asphalts are separated into Groups A, B and C in terms of their temperature susceptibilities. Group A paving asphalts of low temperature susceptibility and Group C asphalts of high temperature susceptibility are at the opposite extremes of the paving asphalt temperature susceptibility scale. They result in great differences in low temperature transverse pavement cracking as shown in Figure 22. There were 15 times as many Type 1 low temperature transverse pavement cracks per lane mile in the pavement containing Group C asphalt as there were in the test pavement made with Group A asphalt. Figure 14 should be part of every paving specification, two versions of which are given in Appendix B.

It should be noted that no extra testing is required to obtain the PVN value of any paving asphalt. Simply determine the penetration at 25 C of the asphalt and its viscosity in centistokes at 135 C. These values are normally determined as a part of the routine inspection on any asphalt sample. Plot these values as the coordinates of a point on Figure 13. From the nearest oblique line representing PVN values, the PVN of the paving asphalt can be read by interpolation. This value of PVN is probably accurate enough for most purposes. If a truly accurate value of PVN is required, it can be obtained from Appendix A, which lists the equations required for this purpose and provides a sample calculation.

The data on 310 asphalts published in Public Roads magazine (10,11) by the US Bureau of Public Roads have been plotted on the pattern of Figure 14 to give Figure 15, which shows that the temperature susceptibilities of these asphalt samples ranged from a PVN of +0.5, representing low temperature susceptibility, to a PVN of -1.5, representing high temperature susceptibility.

In Figure 16, the data of Figure 15 have been plotted in terms of PVN versus Pfeiffer and Van Doormaal's PI.

For Figure 17, the data in Figure 16 have been plotted as the average of the PVN values versus the average of the PI values for Groups A, B and C. To utilize all of the data, the values for PVN = 0.0 ± 0.25 were taken to represent asphalt with a PVN of 0.0, the values of PVN = -0.5 ± 0.25 were taken to represent asphalts with a PVN of -0.5. Similarly for asphalts with PVN = -1.0 ± 0.25 and -1.5 ± 0.25. In each case, the corresponding value for Pfeiffer and Van Doormaal's PI was also calculated. It will be noted that the averages for asphalt of low temperature susceptibility with a PVN of 0.0 and also with a PI of 0.0 practically coincide. This could be expected because asphalts with PVN or PI of 0.0 are "wax-free" from asphalt-based "wax-free" asphalts. Because of the effect of wax on asphalt softening point, the average values for PI for asphalts with higher and higher wax contents diverge further and further from their corresponding PVN values. That is, with increasing wax content, the PI values become higher and higher than the corresponding PVN values that represent "wax-free" asphalts. This is why Pfeiffer and Van Doormaal's PI values for these waxy asphalts are always misleading. They are misleading by the amount of the difference shown in Figure 17 between the corresponding average PI and PVN values. Because they represent the "wax-free" condition, the PVN values are the correct values to use when assessing pavement performance.

Figure 18 is a plot of data published by The Asphalt Institute in 1979 (12) in terms of penetration at 25 C and viscosity at 135 C for 68 samples of paving asphalt being marketed in the USA and Canada. It will be noted that in comparison with Figure 15, there has been a downward shift in the data toward higher temperature susceptibility, because of the OPEC oil crisis in 1973. The data of Figure 18 have been plotted on Figure 19 as PVN versus corresponding PI values as determined by Heukelom.

For Figure 19, the data of Figure 18 has been given in terms of PVN versus Heukelom's corresponding PI values. Unfortunately, the Asphalt Institute study did not include softening point values. Hence a direct comparison between Pfeiffer and Van Doormaal's and Heukelom's PI values cannot be made.

In Figure 20, the average PVN values for each of the groups of data in Figure 19 have been plotted against the corresponding average PI (Heukelom) value. Heukelom was supposed to be correcting Pfeiffer and Van Doormaal's values for wax contents in these paving asphalts. However, Figure 20 demonstrates that Heukelom over-corrected for wax content. For example, for PVN 0.0 for "wax-free" asphalt of low temperature susceptibility, PVN and Pfeiffer and Van Doormaal's values are in close agreement, both being nearly zero. For this "wax-free" condition, with PVN = 0, Heukelom's PI should also have been close to zero and should have agreed with Pfeiffer and Van Doormaal's PI = 0. Instead, Heukelom's PI value is -1.0. Similar very wide divergences occur for PVN values of -0.5, -1.0 and -1.5. Consequently, for asphalts from waxy crude oils, modulus of stiffness values calculated from Van der Poel's nomographs (13, 14), corresponding to Heukelom's PI values, will be much too low, just as the modulus of stiffness values corresponding to Pfeiffer and Van Doormaal's PI values of -1.0 and -1.5 are much too high.

Since the PVN values for the data of both the Bureau of Public Roads and The Asphalt Institute practically coincide for the entire PVN range of 0.0 to -1.5, these are most likely the correct temperature susceptibility values to use with Van der Poel's nomographs for paving mixture design.

III <u>THIN-FILM OVEN TEST RESIDUE</u>

The Thin Film Oven Test residue of a paving asphalt has the same PVN value as the original asphalt. This is supported by data obtained by Meidinger and Kasianchuk of the British Columbia Department of Highways (15), by Anderson, Dukatz and Peterson (16), by Anderson, Dukatz and Rosenberg (17), by Kandhal and Koehler (18), by our own laboratory, McLeod (19) and by the data in Table 7.

IV <u>LOW TEMPERATURE TRANSVERSE PAVEMENT CRACKING AND PVN</u>

By 1968, low temperature transverse pavement cracking was becoming a serious problem on Canadian highways. At that point, the writer realized that the three 6-mile test sections built in Southwestern Ontario eight years earlier would provide an excellent outdoor laboratory for studying the problem. For each of the next thirteen years my associate Charles Perkins (for the first two years) and I (for the final eleven years) tallied each of the low temperature transverse cracks that had developed. The cracks that completely crossed the full width of a traffic lane, called Type 1, turned out to be the most significant in relation to the properties of the asphalts in the pavements.

The results of this crack survey are illustrated in Figure 22, where the number of Type 1 low temperature transverse pavement cracks per lane mile on the abscissa are plotted against the PVN values (-0.23, -0.41 and -1.35) of the three 85/100 penetration asphalts as ordinate, on an annual basis. Particularly in these pavements' early lives (from 10 to 15 years), it can be seen that pavements made with asphalt of low temperature susceptibility (-0.23) had the lowest number of Type 1 transverse cracks per lane mile, and that the numbers of these cracks increased as the temperature susceptibility of the asphalts increased. It is also apparent that 85/100 penetration asphalt was too hard a grade of asphalt to use if one wished to eliminate or at least greatly reduce low temperature transverse pavement cracking.

Table 1 provides inspection data obtained by Lefebvre of

Imperial Oil's Research Department for the three 85/100 penetration asphalts of different temperature susceptibilities that were used in the three Ontario test pavements. It is obvious from Table 1 that the values for PVN and for Pfeiffer and Van Doormaal's PI point in completely opposite directions. For example, Supplier 1's asphalt had a PI of 1.00, but a PVN of -0.23. However, Figure 22 shows that the values for PVN point in the right direction insofar as thermal cracking is concerned. The PI values in Table 1 are in error because of the influence of wax in the asphalt, particularly in the asphalt furnished by Supplier 3, which provides values for both softening point and PI that are much too high.

In 1961, on an existing highway, Ontario built Test Road 4 (Figure 5), consisting of two pavement sections, each several miles long. In this project the asphalt was of high temperature susceptibility in both cases, PVN = -1.5. For one pavement section 150/200 penetration was used and for the other, 85/100 penetration grade asphalt. Figures 23, 24 and 25 show the appearance of these two test pavements after 4 years of service, after which they were overlaid. The pavement made with 85/100 penetration asphalt had developed more than 400 Type 1 low temperature transverse pavement cracks per lane mile (Figure 23) while there was not a single crack in the pavement with 150/200 penetration asphalt (Figure 24). Since critics may say that the subgrade or some other factor must have been different in these two test pavements, Figure 25 is presented. Here, 1700 feet of pavement on the right side were constructed with 85/100 penetration asphalt, while the pavement on the left side was made with 150/200 penetration asphalt. In the pavement on the right side there are more than 400 Type 1 low temperature transverse cracks per lane mile, but no cracks in the pavement on the left (20).

Based on this study of low temperature pavement cracking on the four Ontario test pavements (20), on the Ste. Anne Test Road (21), on laboratory studies of numerous pavement samples, on observations of many thousands of miles of pavement in service in Canada, the northern USA and Norway, as well as on theoretical considerations, the writer has concluded that the two most important properties of paving asphalt associated with low temperature transverse pavement cracking are

- its penetration at 25°C and
- its temperature susceptibility as given by its PVN value.

These two paving asphalt properties influence low temperature transverse pavement cracking as follows:

1) If temperature susceptibility is held constant, low temperature transverse pavement cracking increases as the penetration at 25°C of the paving asphalt decreases (i.e. as the asphalt becomes harder) as shown in Figures 23, 24 and 25.

2) If the penetration at 25°C is held constant, low temperature transverse cracking increases with increase in temperature susceptibility (Figure 22).

3) Low temperature transverse pavement cracking increases with pavement age because the asphalt in the cement hardens with time, its penetration at 25°C becoming lower and lower.

These principles are further supported by an example of very rapid failure of a pavement by low temperature transverse pavement cracking in one case and by the success of a pavement in another.

About 1966 or 1967 Ontario let a contract for paving a road into the Red Lake Mining Centre in Northwestern Ontario, where the minimum winter temperature can be -51°C (-60°F).

The asphalt to be used for this pavement was 85/100 penetration with a high temperature susceptibility (PVN = -1.5). Since the pavement construction was not completed in the first year, it was expected to be finished the following spring. However, during the intervening winter the low temperature transverse pavement cracking that had occurred in the new pavement was so severe that the paving contract was cancelled.

The other pavement was the James Bay Access Road in the Province of Quebec. This was for a planned 16 billion dollar hydro electric project, which was 400 miles north of the end of rail service. It was decided to build a paved highway to service this project. The minimum temperature in winter was -51°C and the maximum temperature in summer was 32°C (90°F). The consultants for this road construction were Desjardins, Sauriol and Associates of Montreal. They asked the writer to act as consultant for the pavement. The pavement was to last for 10 years, which was the length of time Quebec Hydro believed was needed to complete construction of the generating facilities. All the bridges on this road were designed to carry a load of 500 tons, the weight of large sections of hydro generating equipment, which the pavement also had to support. One of my principle assignments was the selection of the asphalt binder to be used. It had to provide a pavement that would satisfy two basic requirements:

- to minimize the amount of low temperature transverse pavement cracking in winter and
- to provide adequate stability for warm weather traffic.

After considerable study (reported in the 1978 AAPT Proceedings) I recommended a paving asphalt of 300/400 penetration with a low temperature susceptibility, minimum PVN of -0.2, even though Quebec Highways had used only 85/100 penetration asphalt up to that time. After some hesitation, this recommendation was adopted. Figure 26 illustrates the nature of the problems in selecting the grade of paving asphalt for the project and how they were resolved.

To pave this 400 mile road, five contracts of approximately 40 miles each were let and finished in 1975 and then again in 1976. I have not seen this project since 1977, but from conversations with those who have, it is still providing acceptable service 13 and 14 years later. Quebec Hydro is about to begin construction on another large dam project for the development of more hydro-electric energy in the same area, which will require an extension of this paved highway. I have been informed that they plan to pave this extension with 300/400 penetration asphalt - I trust of low temperature susceptibility.

The first project failed immediately because, as illustrated by Figures 3 and 26, the penetration at 25°C of the paving asphalt, 85/100, was much too low for that environment, and its temperature susceptibility, PVN = -1.5, was much too high. The second project is still giving good service because the paving asphalt was sufficiently soft and its temperature susceptibility, PVN = -0.2, was low enough that the pavement had good resistance to low temperature cracking in winter and had adequate stability for summer traffic.

Both of these projects indicate that for greater resistance to low temperature transverse cracking, softer paving asphalts are required that include both a higher penetration at 25°C and low temperature susceptibility. As shown by Figures 3 and 26, the low temperature susceptibility ensures higher pavement stability under warm summer temperatures and a softer asphalt at minimum winter temperatures.

Quantitative data from a limited number of other projects are available to support these three principles as well:

1. The three 6-mile Ontario test pavements were built in 1960 with asphalt penetration held constant at 85/100 and with temperature susceptibilities ranging from low to medium to high (PVN = -0.23, -0.41 and -1.35). Figure 22 shows that for the average minimum winter temperature prevailing at these projects, -20°C (-4°F), pavement cracking increased markedly with an increase in temperature susceptibility. After 10 years, Test Road # 2 had 15 times as many Type 1 low temperature transverse pavement cracks per lane mile in the pavement containing asphalt of highest temperature susceptibility, Group C, PVN = -1.35 as in the pavement made with the asphalt of lowest temperature susceptibility, Group A, PVN = -0.23.

2. Ontario Test Road 4, constructed in 1961, had asphalts with a constant, high temperature susceptibility (PVN = -1.35) but of two different penetrations - 85/100 in one test section and 150/200 in the other. The minimum winter temperature at this test road was -23.3°C (-10°F). After four years of service, when it was overlaid, the test pavement containing 85/100 penetration asphalt had more than 400 Type 1 thermal cracks per lane mile, while the test pavement made with the 150/200 penetration asphalt had no low temperature transverse cracks of any type.

3. Table 3 lists data reported by Kandahl and Koehler (18) for six asphalt test pavements in Pennsylvania. The minimum winter temperature at the site of the PenDot test pavements was -29°C (-20°F). The six paving asphalts used represented the entire spectrum of temperature susceptibility. One asphalt, T-6, was of low temperature susceptibility, Group A; three asphalts, T-2, T-3 and T-4 were of medium temperature susceptibility, Group B; while T-1 and T-5 were of high temperature susceptibility, Group C. All being AC 20 asphalts, their penetrations at 25°C varied from 42 to 80. Nevertheless, the combination of lowest penetration at 25°C and highest temperature susceptibility resulted in pavements with the highest number of low temperature thermal cracks after seven years of service.

Table 3 lists PVN and Heukelom PI data on the original asphalts and on asphalts recovered from the pavements just after construction, after 20 months and after seven years in service. The PVN values for each asphalt are approximately constant regardless of time in pavement service, while Heukelom's PI data have no recognizable pattern.

4. Table 4 indicates that similar conclusions can be drawn from Iowa data reported by Marks and Huisman (23). The minimum winter temperature at the Iowa test site was also -29°C. A test pavement containing paving asphalt with high temperature susceptibility (PVN = -1.2, Group C) and a penetration of 75 had low temperature thermal crack spacing of only 35 feet after 3.5 years in service (when the pavements were overlaid). The other test pavement containing asphalt of medium temperature susceptibility (PVN = -0.6, Group B) and a penetration at 25°C of 100 had a thermal crack spacing of 170 feet. After 3.5 years of service, the

PVN for the asphalt recovered from the pavement with original PVN of -1.2 had a PVN of -1.4. Recovery of the binder from the second pavement after the same number of years of service gave an asphalt (whose original PVN was -0.6) with PVN = -0.61. Furthermore, Marks and Huisman report that PVN values for asphalts recovered from other pavements on a routine basis have remained relatively constant over a period of years.

5. Data from the Ste. Anne Test Road where minimum winter temperature was -40°C (-40°F), reported by Deme and Young (21) and shown in Table 2, indicate that recovered paving asphalt PVN values remain essentially unchanged after pavement service periods up to 20 years. For example, 150/200 penetration asphalt of medium temperature susceptibility, PVN = -0.59, Group B, had a PVN of -0.73, Group B, when recovered from the test pavement after 20 years. After five years of service this pavement had 41 thermal cracks per kilometer.

Another test pavement at the Ste. Anne Test Road containing 150/200 penetration asphalt of high temperature susceptibility, with an original PVN of -1.61, Group CC, had a PVN of -1.71, Group CC, when recovered from the pavement after three years, and a PVN of -1.80, Group CC, when recovered after 20 years.

A third test pavement, made with 300/400 penetration asphalt of high temperature susceptibility, had an original PVN of -1.52, Group CC, a PVN of -1.78, Group CC, when recovered after three years and a PVN of -1.76, Group CC, when recovered after 20 years of service.

6. For the data in Table 5 (19), one of our asphalt sales engineers went to nine hot-mix plants located in different parts of Ontario and obtained a sample of the asphalt going into the hot-mix plant and a sample of the hot-mix being discharged. In our laboratory PVN values were determined for the samples going into the mixer, on the thin-film oven test residues from these samples and on asphalts recovered from the paving mixtures being discharged. Parallel tests were made to determine Heukelom's PI values for each of these three conditions. Table 5 shows that for all nine paving asphalt samples, the PVN values for the original asphalts, for their thin film oven test residues and for asphalt recovered from the paving mixture samples remain essentially unchanged. Heukelom's PI values, on the other hand, are scattered with no discernible pattern.

All asphalts in Table 5 had to meet Ontario's specification for which the requirements for minimum penetration at 25°C and minimum viscosity at 135°C correspond to a minimum PVN of about -0.8. It will be noted that every one of the nine paving asphalts meets this minimum PVN requirement.

7. The data in Tables 7 and 8 pertain to an overseas project. The minimum average monthly temperature at this site is 10°C (50°F). We are interested at the moment only in Stage 1, the first three lanes of an eventual 6-lane pavement, which was eight years old when sampled. The paving asphalt was 80/100 penetration at 25°C, provided by Supplier 1, with a PVN of -0.31, Group A. The PVN values of the asphalt samples recovered from the pavement after eight years of service are also seen to be Group A, PVN = 0.0 to -0.5.

8. Professor Haas from the University of Waterloo and Associates (24) has recently completed a very thorough investigation of pavement samples from 26 airports across Canada (Figure 27), some of them more than 30 years old. The PVN values for the bitumens recovered from these pavement samples were found to be very near to what the PVN values for the original bitumens must have been.

In older pavements there is always the question of whether the asphalt in the pavements had developed some internal structure with time that would be lost when the asphalt was recovered for PVN testing. However, Professor Haas made direct tensile strength tests on three undisturbed briquettes that were cut from the pavement samples from each airport. These direct tensile tests were made at temperatures of 0°C, -17°C and -34°C. When I quizzed Professor Haas directly on this point, he re-examined his data and stated that his tensile strength tests showed no evidence of the development of any internal structure within the paving asphalts themselves in these pavement samples. Consequently, the PVN values represented the condition of the asphalt in the pavements in-place.

9. In his 1974 AAPT paper Fabb (25), after a very thorough laboratory study, reported that during cooling to low temperatures, cracking was initiated in any asphalt paving mixture when the asphalt binder in a mix was chilled to a critical modulus of stiffness on which changes in paving mixture design had little or no influence.

A number of important conclusions can be drawn from the data in Tables 2,3,4,5,7,8, and Figure 27:

a) The PVN of an asphalt remains constant regardless of its time in pavement service.

b) Regardless of wide differences in temperatures to which it has been subjected, the asphalt retains its original PVN. The PVN remains constant whether subjected to a temperature of 163°C (325°F) for five hours in the Thin Film Oven Test, after minimum temperatures of 10°C or -40°C in pavement service. The decreases in penetration at 25°C and the corresponding increases in viscosity at 135°C take place in such a way that the PVN value remains constant and unchanged with either time or temperature in service.

c) Professor Haas' conclusions concerning the reversing of the direction of the PVN values of aged asphalt recovered from pavements to their same original PVN values supports the double headed arrow in Figure 29. This means that an original asphalt in the Group A category, low temperature susceptibility, remains Group A throughout its service life. Similiarly for asphalts in the Group B, medium temperature susceptibibilty, and Group C, high temperature susceptibility, categories. It also means that the direction of hardening with time for an original paving asphalt, and the direction through which hardening of an aged asphalt has occurred are on the same path but in opposite directions.

Critics have suggested that PVN cannot be associated with the cause or cure of thermal cracking because neither penetration at 25°C nor viscosity at 135°C of a paving asphalt, on which PVN is based, can be correlated with low temperature transverse pavement cracking. In reply, the writer would like to point out that he has used a completely different criterion for low temperature performance, namely the number of low temperature transverse pavement cracks per lane mile or per lane kilometer, or crack spacing in feet or meters, that have developed when a pavement is chilled to a minimum winter temperature. When all other factors are equal, this criterion shows that Group A asphalts, with PVN values higher than -0.5, develop the smallest number of temperature transverse cracks per lane kilometer of pavement, while Group C asphalts, with PVN values lower than -1.0, develop the greatest number of low temperature transverse cracks per lane kilometer of pavement (Tables 2,3,4,7,8 and Figures 22 and 27). Therefore penetration at 25°C and viscosity at 135°C, or corrresponding PVN values, are very accurate indicators of low temperature pavement performance.

The PVN values of paving asphalts appear to vary only with the crude oil or crude oil blend from which they are manufactured by steam or vacuum distillation (Figure 10). PVN is an asphalt fingerprint that remains constant throughout an asphalt pavement's service life.

V <u>USEFULNESS OF PVN FOR NORMAL PAVING ASPHALTS</u>

The PVN charts of Figures 13, 14 and 29 are based on PVN values for "wax-free" asphalt from "wax-free" asphalt-based crudes. Why then can the PVN values for normal paving asphalts meeting an ordinary paving asphalt specification be taken with sufficient accuracy from these PVN charts ?

The constancy of the PVN values for the original paving asphalt and for the corresponding paving asphalts recovered from pavements in service up to 20 or 30 years indicate that this procedure is very close to being correct. This is particularly true when the differences in pavement service temperatures are considered. The principal difference in PVN values, if any, would probably be due to small amounts of wax retained in normal paving asphalt. Table 6 is offered as evidence that any wax remaining in a normal paving asphalt is so small that its effect on the asphalt's PVN value is probably insignificant.

Refinery slack wax with a ring and ball softening point of 64.4° C (148°F) and a viscosity of 3.39 centistokes at 135°C was blended at ratios of 0.0, 0.5, 1.0, 2.0, 5.0 and 10.0 percent into 85/100 penetration paving asphalts of Group A, Group B and Group C temperature susceptibility. Data for percent slack wax, penetration at 25°C, viscosity in centistokes at 135°C, PVN value, ductility in cm at 25°C, 5 cm/min and ring and ball softening point are listed in Table 6.

At a temperature of 135°C the slack wax is a very fluid material. Consequently, with increasing wax content, the penetration at 25°C of the blend is increased and the viscosity of the blend at 135°C is decreased. For the addition of very small amounts of wax, these changes in penetration and viscosity compensate each other in such a way that the PVN values of the blends are not noticeably affected. For example, for an increase from 0.0 to 2.0 percent in slack wax, the PVN changed from -0.24 to -0.55 for the Group A asphalt, from -0.73 to -0.87 for the Group B asphalt and from -1.59 to -1.73 for the Group C asphalt. Therefore, the PVN values for the normal paving asphalts and for the corresponding asphalts in Figures 13, 14 and 29 do not appear to differ significantly. Consequently, the PVN charts of Figure 13, 14 and 29, which are based on "wax-free" crude oils, can be used with confidence to obtain the PVN values of normal paving asphalts satisfying a minimum ductility requirement of 100 cm, 5 cm/min, at 25°C. Nevertheless, Table 6 indicates that the accuracy of this comparison could be improved if the wax content of ordinary specification paving asphalts could be further reduced.

VI PAVING ASPHALT SELECTION

Neither ASTM nor AASHTO has a temperature susceptibility requirement in its specification for paving grades of asphalt. Although Table 1 in these specifications permits the use of paving asphalts of higher temperature susceptibility than Table 2, nowhere in these specifications is any mention made of temperature susceptibility. From investigations of pavement failures in the USA that the writer has read, no mention of the temperature susceptibility of the paving asphalt is ever made.

In many cases, insofar as a completely informative report is concerned, ignoring the temperature susceptibilities of the paving asphalt that was used is like sending a boxer into the ring with one hand tied behind his back. All the information required for a thorough explanation of the pavement failure is not being employed.

I am quite aware that aggregates, voids properties, stability, flow index, pavement design and construction practice all have an influence on pavement performance. However, assuming that all variables except for the asphalt cement have been adequately providked for, this paper points out the very important influence on pavement performance that is provided by the asphalt's penetration at 25°C and its temperature susceptibility as measured by its PVN.

In the USA, since no mention of temperature susceptibility is made in either ASTM or AASHTO specifications, paving asphalts of low, medium and high temperature susceptibility are selected indiscriminately for pavement design, regardless of the traffic category - heavy, medium or light - the pavement is to carry. U.S. Highway Departments pay a heavy proce for this misunderstanding in the form of millions of dollars for filling cracks that should never have been there in the first place, and other millions of dollars in the form of shortened pavement service lives. They will continue to do so until they recognize the need for specifying the temperature susceptibility of paving asphalts as outlined in Figure 29 or in Appendix B(2). They must especially recognize that, in general, only Group A asphalts should be permitted for heavy traffic, Group B asphalts for medium traffic and Group C paving asphalts for light traffic.

In Canada, cold winter temperatures have forced us to recognize the need for softer asphalts in terms of <u>both penetration at 25 C and temperature susceptibility</u> to avoid or reduce low temperature transverse pavement cracking. Consequently, most provincial paving asphalt specifications completely reject Group C (high temperature susceptibility) paving asphalts. However, we still do not write paving asphalt specifications for each particular paving site as we should, and we still allow Group B (medium temperature susceptibility) asphalts to be used in pavements with heavy traffic where, if pavement rutting is to be avoided, only Group A asphalts (low temperature susceptibility) should be permitted.

There is a place in our highway construction programs for all three groups of paving asphalts - Group A, B and C. Roads to carry light traffic seldom have a uniformly adequate foundation. Therefore, provided they are selected with care for the minimum penetration at 25°C and minimum viscosity at 135°C required for the minimum winter temperature at the job site, Group C asphalts should provide pavements with satisfactory service. For medium traffic, the road foundation is usually better designed and constructed, and the selection of a Group B asphalt at the correct minimum penetration at 25°C and minimum viscosity at 135°C for the minimum winter temperature associated with the pavement site should provide a pavement with good service. For heavy traffic the road foundation should be uniform and firm and the selection of a Group A asphalt of a minimum penetration at 25°C and minimum viscosity at 135°C appropriate for the expected minimum winter temperature should be mandatory to provide the stability required for summer traffic and to avoid pavement rutting.

In colder climates asphalt pavements must be designed with three principle criteria in mind:

- avoiding or greatly reducing low temperature transverse pavement cracking in winter
- providing adequate stability for summer traffic and
- eliminating pavement rutting.

In warmer climates only the second and third of the above three criteria are important. As this is too big a topic to be handled in this paper, some general guidelines will be presented. A detailed treatment is given in references (26) and (27).

1. Paving Asphalt Selection for Colder Climates

Figures 30 and 31 indicate how paving asphalts should be selected to avoid low temperature pavement cracking in winter and to provide adequate pavement stability and eliminate rutting under summer traffic.

Figure 30 is based on test road data (20, 21), on theoretical considerations (22) and on the field performance of thousands of miles of paved highways in Canada, the U.S.A. and Norway and represents the writer's best estimate of the combinations of penetration at 25°C and viscosity at 135°C for the original asphalts to be selected to eliminate or at least greatly reduce low temperature transverse pavement cracking at the minimum winter temperature at a pavement site throughout a pavement's service life. For example, if the minimum pavement temperature anticipated at a pavement site is -23°C (-10°F), only combinations of penetrations at 25°C and viscosities at 135°C that lie on or to the right of the oblique line in Figure 30 labelled -10°F should be selected if the pavement is to avoid low temperature transverse cracking at that temperature throughout its service life. Grades of paving asphalt that lie to the left of this line are too hard and would result in thermal cracking at the anticipated minimum temperature of -23.3°C. This is also true of the other oblique lines in Figure 30 representing other anticipated minimum winter temperatures.

On the other hand, it should be noted that with all other factors being equal, to obtain the highest pavement stability, the combinations of penetrations at 25°C and viscosity at 135°C that lie on each pertinent oblique temperature-labelled line in Figure 30 should also be selected, because these will provide the lowest penetrations at 25°C and therefore the highest pavement stabilities that can be obtained without causing low temperature transverse pavement cracking.

Pavement performance in cold climates would be much improved, all other variables being equal, if paving asphalts were selected for heavy, medium and light traffic as indicated in Figure 31. To avoid low temperature transverse cracking for the service life of the pavement, Figure 31 makes it quite clear that Group A paving asphalts provide pavements that withstand lower winter temperatures without low temperature transverse pavement cracking. Their lower penetrations at 25°C also provide pavements with higher stability for summer traffic. Therefore, only Group A asphalts (low temperature susceptibility) should be selected for heavy traffic.

To avoid low temperature transverse pavement cracking, Figure 31 shows that group B asphalts must be of higher penetration at 25°C to withstand low temperature transverse pavement cracking at any given minimum winter pavement temperature. These higher penetrations at 25°C provide pavements of lower stability for summer traffic. Consequently, considerations of thermal cracking at winter and lower stabilities at summer temperatures assign these Group B (medium temperature susceptibility) to pavements for the medium traffic category.

Figure 31 also indicates that Group C asphalts (high temperature susceptibility) must be of still higher penetration at 25°C to withstand thermal cracking at any given winter temperature. When other factors are equal, these still higher penetrations at 25°C provide pavements with still lower stability for summer traffic. Therefore, when their lesser ability to withstand thermal cracking in winter and to provide adequate stability for summer traffic are considered, it is clear that these Group C asphalts should be limited to pavements for the light category of traffic. In addition, roads for light traffic are often lacking in foundation support that further justifies the limitation to pavements made with Group C asphalts.

However, if only Group A asphalts are available in any region, they are more than satisfactory for pavements for either the medium or light traffic category, and the same is true for Group B asphalts for pavements of light traffic.

2. Paving Asphalt Selection for Climates without Frost

Figure 32 illustrates the proper selection of paving asphalts in climates where there is no frost. At present, the paving asphalt for any paving project in these climates is generally specified as a single grade, for example 85/100 penetration, without the slightest regard for the asphalt's temperature susceptibility. One solution to this problem, Van der Poel's nomographs (13, 14), requires that as the temperature susceptibility of the asphalt increases, its penetration at 25°C must be decreased in order to provide a constant pavement stability (modulus of stiffness) as follows :

- 85/100 penetration asphalt, if its PVN is 0.0
- 70/85 penetration asphalt, if its PVN is -0.5
- 60/75 penetration asphalt, if its PVN is -1.0 and
- 50/65 penetration asphalt, if its PVN is -1.5.

Although both the paving asphalt of 85/100 penetration and 50/65 penetration provide the same pavement stability at a temperature of 60°C (140°F), the 50/65 penetration asphalt could be expected to be much harder (lower penetration at 25°C) in pavement service after, say, ten years than the originally softer 85/100 penetration asphalt. This greater hardening of the 50/65 and 60/75 penetration grades of asphalt with higher temperature susceptibility could be avoided by incorporating a small percentage of an appropriate polymer (Figure 33) into them to increase their penetrations at 25°C to give an asphalt with 85/100 penetration in Group A or even Group AA category.

VII PAVEMENT RUTTING

Paving asphalts have two basic properties, elastic and viscous, depending on temperature and time of loading. Under fast traffic, even on a warm day, the asphalt binder in a pavement can perform very largely as an elastic material. However, in parking areas where pavements are subject to stationary tire loadings for long periods of time, the viscous property of the asphalt becomes important and because of its viscous flow under load, the pavement can begin to rut. Therefore, apart from the important role played by the aggregate, pavement rutting is associated with the viscous property of paving asphalts. The viscous resistance of an asphalt binder can be increased by increasing its viscosity. Therefore, with all other mix variables the same, because of their higher viscosity at 135°C for the same penetration at 25°C, asphalts of low temperature susceptibility, Group A, can be expected to provide a pavement with higher viscous resistance than asphalts of medium temperature susceptibility, Group B. Similiarly, Group B asphalts can be expected to provide a pavement with more viscous resistance than asphalts of high temperature susceptibility, Group C.

Since, as shown in Figure 33, a paving asphalt's viscosity at 135°C can be substantially increased by incorporating a small percentage of an appropriate polymer, providing the asphalt with a higher PVN, this treatment should provide a pavement with still greater resistance to rutting.

VIII THE ROLE OF POLYMERS

Oxidation, which consists of blowing air through a soft asphalt maintained at a temperature of about 260°C (500°F), is commonly used to increase the softening point for any given penetration at 25°C for roofing and industrial asphalt products and to increase the viscosity at 135°C of paving asphalts. Oxidation is an extra stage in the manufacture of asphalt and increases the cost of asphalt production. When a specified ductility requirement of 100 cm at 25°C, 5 cm/min must be satisfied, oxidation is of very limited usefulness for increasing the viscosity at 135°C of a paving asphalt. At most, it may be able to increase the viscosity at 135°C from a Group C to a Group B, or from Group B to Group A (Figure 14). By adding an appropriate polymer, however, the viscosity at 135°C of a Group C paving asphalt can be easily increased to that of a Group A or higher. Consequently, all paving asphalts could be manufactured by steam or vacuum distillation, and when necessary to satisfy a paving asphalt specification, their viscosities at 135°C or their PVN values could be increased to any required degree by incorporating a small percentage of a suitable polymer.

Figure 33 illustrates the role of polymers in this respect. The lowest small circle in Figure 33 indicates the temperature susceptibility, PVN = about -0.8, that is normally been available for paving asphalts marketed in Ontario in recent years. The incorporation of one percent of a certain polymer lowered its temperature susceptibility to a PVN of about -0.2, while two percent of the same polymer lowered its temperature susceptibility to a PVN of + 0.4. A PVN value of + 0.4 is well above the range of temperature susceptibility of normal paving asphalt from any crude oil produced in Canada at present, and this is also true for nearly all normal paving asphalts produced or marketed in the U.S.A.

The Elastic Recovery Test indicates that paving asphalts treated with certain polymers (elastomers) are much more elastic than the untreated asphalt. This test is made on specimens formed in ductility molds used for a normal ductility test. One mold is filled with normal asphalt as a control and another mold with a polymer-modified asphalt. The ductility bath is maintained at a temperature of 10°C (50°F). The procedure for a normal ductility test is used when preparing the specimens. When brought to the test temperature of 10°C, the molds are placed on the pins of the ductility machine and pulled at a rate of 5 cm/min to a length of exactly 20 cm. They are maintained at this length for 5 minutes after which the ductility threads are cut in the middle into two equal segments of 10 cm each and allowed to stand undisturbed for one hour. The threads are then brought together until the cut ends just touch and their total length is again measured. The ductility thread of the normal asphalt is now, because of elastic recovery, from 90 to 95 percent of its original 20 cm length. The length of the thread of the polymer modified asphalt is from 20 to 40 percent of its original length of 20 cm, depending on the polymer (elastomer) employed. The polymer modified asphalt ordinarily has a very much higher elastic recovery than normal asphalts.

This is only a laboratory test. The influence of polymers on pavement properties such as low temperature transverse pavement cracking and pavement rutting must still be determined by the performance of test pavements in the field. However, the potential benefits of using certain polymer-modified asphalts, as implied by the results of the Elastic Recovery Test, would appear to be as follows:

1) As illustrated by the arrow in Figure 34, polymer addition could result in a shift to the left, to a noticeably lower temperature at which low temperature pavement cracking would begin.

2) This in turn would result in a shift of one or two grades towards lower penetration at 25°C, providing a higher pavement stability for summer traffic, Figure 34(a).

3) The increased pavement stability at summer temperatures should provide greater resistance to the rutting of pavements.

4) The increased elasticity of certain polymer-modified asphalts should also result in greater pavement resistance to rutting.

In any region where only Group A asphalts are available, they are more than satisfactory for pavements of the high, medium or light categories. If only Group B asphalts are available, they are equally suitable for pavements with medium or light traffic. However, by the addition of small percentages of an appropriate polymer, the temperature susceptibility of a Group B asphalt can be improved to that of a Group A asphalt when required, and the temperature susceptibility of a Group C asphalt can be improved to that either of Group B or Group A, whenever a specification calls for a Group B or Group A paving asphalt.

For anyone interested in the broad scope and the present status of polymer-modified asphalts, the low-key, comprehensive and concise paper by Gayle King and associates (28) is recommended.

IX PAVEMENT RECYCLING

1. Pavement Recycling in Cold Climates

Avoidance of low temperature transverse pavement cracking is as important after pavement recycling as it should have been for the original pavement. Suitable guidelines to achieve this do not appear to be in use at the present time. However, recognition of paving asphalt temperature susceptibility seems to offer a promising approach to this problem for pavement recycling in cold climates (Figure 35).

The background for Figure 35 is Figure 30, which illustrates the selection of bitumens for original paving mixtures to avoid low temperature transverse pavement cracking throughout the service life of a pavement. For Figure 35, it is assumed that the minimum winter pavement temperature at Location 1 in some given area is -28.9°C (-20°F). Location 1 is the site of the proposed recycling project because the existing pavement shows serious low temperature transverse pavement cracking and other evidence of severe pavement distress.

Ordinarily, everyone will have forgotten what the characteristics of the original binder were when the badly cracked pavement at Location 1 was constructed many years ago, which upon extraction is found to have a penetration of 20 and a viscosity of 820 centistokes (PVN = -0.9). This indicates that the asphalt binder in this pavement is of medium temperature susceptibility, Group B category (PVN = -0.5 to -1.0).

It is assumed that the recycled pavement is to carry much more traffic, and that it is to be designed for the heavy traffic category. For the middle of the heavy traffic band (PVN = -0.25) and for a minimum winter pavement temperature of -28.9°C, Figure 35 indicates that this would require a bitumen of 180 penetration and viscosity of 250 centistokes at 135°C (Group A traffic category, Point 2). This would be provided by Treatment A, consisting of a single (or a combination of) softening agent(s) that would change the penetration at 25°C to 180 and the viscosity at 135°C to 250 centistokes (PVN = -0.25) in the recycled paving mixture. A large assortment of softening agents, including soft asphalts and commercial modifiers, is available to the designer for this purpose. After this treatment, according to the fingerprint effect, the asphalt binder in the recycled pavement would slowly harden in service as indicated by Line 3 in Figure 35.

The engineer responsible for the recycled pavement project might decide that Treatment A (giving a binder with 180 penetration and 250 centistokes viscosity) would not produce the required minimum stability at summer temperatures for the anticipated heavier traffic. She might, therefore, favour Treatment B, for example, to provide a bitumen with a penetration at 25°C of 120 and a viscosity at 135°C of 575 centistokes (PVN = + 0.5), Point 4. This would also avoid low temperature transverse cracking at -28.9°C throughout the pavement's service life if it were properly designed and constructed. It would be difficult to locate a normal conbination of softening agents that could change the asphalt penetration of 20 in the old pavement to a penetration of 120 in the recycled pavement while at the same time increasing the bitumen's PVN from -0.9 to + 0.5. Therefore this might require the addition of a suitable polymer.

Following Treatment B, and in accordance with the fingerprint effect, the bitumen in the recycled pavement would gradually harden along Line 5 within the heavy traffic band of Figure 35.

A similar method would be required for pavement recycling for other minimum winter pavement temperatures illustrated in Figure 35.

2. Pavement Recycling in Climates without Frost

Figure 36 shows a similar approach to the design of recycled paving mixtures for a region that is free from frost. By determining the penetration at 25°C and viscosity at 135°C of the bitumen recovered from the old pavement and plotting these as a point on Figure 36, the temperature susceptibility group to which the bitumen in the old pavement belongs can be quickly established.

Suppose the recovered bitumen has a penetration of 20 at 25°C and that it lies in Group B (PVN = -0.5 to -1.0), which is suitable for medium traffic, Point 1. Because of increased traffic on this old pavement, the engineer has decided to design the recycled pavement for the heavy traffic category for which a Group A bitumen is required - a penetration of 120 and a minimum viscosity of 340 centistokes, for example. By adding an appropriate softening agent or group of softening agents (Treatment A) the old asphalt can be softened to a Group A asphalt of 120 penetration as shown by Point 2 on Figure 36. After reconstruction the bitumen in the recycled pavement will remain in Group A and will harden in service along Line 3 if it conforms to the fingerprint principle.

However, the engineer may decide that he requires a harder asphalt with a penetration of 85 with a still lower temperature susceptibility (higher PVN) for the recycled paving mixture to carry the anticipated traffic loading. In this case, by incorporating the softening materials indicated by Treatment B, the 20 pen asphalt recovered from the old pavement may be softened to a penetration of 85 with a PVN of +0.3 in the recycled mixture, Point 4 on Figure 36. However, because a PVN of +0.3 is higher than normal paving bitumens or other softening agents can provide, a small percentage of a suitable polymer may have to be incorporated. This may also be necessary for Treatment A. After Treatment B, the bitumen in the recycled paving mixture can be expected to harden in service along Line 5 (fingerprint effect).

Because of the additon of the required softening materials, the bitumen content of a 100 percent recycled paving mixture would probably be too high for adequate stability and resistance to rutting. Incorporation of new aggregate would most likely be necessary. In this case, the proportion of old pavement in the recycled paving mixture would have to be reduced. This, however, would have the advantage of providing an opportunity for correcting any deficiency in the gradation of the old pavement.

For cold mix pavement recycling, Treatments A or B (Figure 35, 36) can be applied in the form of an emulsion. Figure 37 indicates that about six months time is required for an asphalt emulsion to thoroughly cure and to develop the pavement stability that its base asphalt would develop if it were used in a hot paving mixture (29). The stabilities of the fully cured asphalt emulsion mixes are shown to compare favourably with corresponding hot mixes (29). Because of the fluxing action between the old bitumen and the softening agent that has been applied, the time to cure in cold recycling will probably be longer than is indicated by Figures 37 and 38. This may also be true for hot-mixing recycling.

X MONITORING THE CONSTRUCTION OF VIRGIN AND RECYCLED PAVEMENTS

Tables 2, 3, 4, 7 and 8 and Figure 29 all indicate that PVN provides user agencies with an entirely new and extremely powerful method for monitoring the construction of virgin or recycled pavements. The PVN of asphalt recovered after pavement construction should be the same, or very nearly the same (within experimental error) as the PVN of the original asphalt that was selected for the pavement design, since PVN of a paving asphalt does not change either with time or temperature in pavement service. At present, the only method available to user agencies to monitor the asphalt recovered from a pavement after construction has been to compare its penetration at 25°C with that of the original asphalt used for the pavement's design. To obtain the recovered asphalt's PVN value, only the measurement of its viscosity at 135°C is required in addition to the measurement of its penetration at 25°C. Determining the PVN of the recovered asphalt provides completely different information from the measurement of its penetration alone.

The use of PVN to monitor the construction of a recycled pavement is of particular value to user agencies because, unknown to the user, more RAP (recovered asphalt pavement) may be added to the recycled mix than the design calls for. Thus when the asphalt recovered from the RAP has a lower PVN than what was determined from a designed amount of RAP, new asphalt plus commercial softeners, an increase in the amount of RAP can be quickly detected. This could not so easily be detected by the penetration at 25°C alone. In any case, the two tests can be used to reinforce each other.

All of this is illustrated in Tables 7 and 8 which provide data on an overseas 6-lane highway project that was built in two stages. Three lanes were constructed as Stage 1 and the other three lanes were added over the period between 1981 and 1983. The data in Table 8 pertains to Stage 1 and to a section of Stage 2, both of which were built by the same contractor. For Stage 1, 80/100 penetration asphalt, Group A, was used and the pavement is still in very good condition. For the portion of Stage 2 built by the same contractor, the asphalt was changed to 60/70 penetration. The contractor found a second source of asphalt, Supplier 2, at lower cost. It had a penetration of 40/80, was also a Group A asphalt, but its ductility at 25 C was well below the specified 100 cm, as shown by the inspection data given in Table 7.

By blending 60% of Supplier 1's 80/100 pen asphalt with 40% of Supplier 2's 40/80 pen asphalt, the ductility requirement could be met and this blend still belonged to Group A. Table 7 lists inspection data for 3:1, 1:1, 40:60 and 1:3 blends of Supplier 2's and Supplier 1's asphalts. These blends were all Group A asphalts and it was decided to use the 40:60 blend of 40/80 and 80/100 penetration asphalts. For samples submitted to us, however, the penetration at 25°C was 83 instead of 60/70. Based on penetration data on asphalt recovered from Stage 2 pavement samples (Table 8), the actual asphalt being blended appears to have varied all the way from 100% of the 40/80 penetration asphalt from Supplier 2 to 100% of the 80/100 pen asphalt from Supplier 1. Data are also included for two samples of Supplier 1's 60/70 penetration asphalt which had PVN values of -0.96 and -0.88, Group B, bordering on Group C. The pavement placed on this portion of Stage 2 by this contractor rutted very badly and had to be replaced.

For Stage 2 the original 60/70 pen asphalt was also supposedly Group A with a PVN of -0.14 (Table 7). The recovered asphalt from pavement samples should also have been Group A with a PVN between 0.0 and -0.5. However, for the base course at Locations 8, 16 and 17, the recovered asphalt had PVN values of -0.81, -0.63 and -0.64 respectively (Group B) and for the surface course at sample Locations 8, 16, 18 and 21, the recovered asphalt had PVN values of -0.95, -0.63, -0.62 and -0.68 rspectively, also Group B. The results at Location B could have been obtained if the original 60/70 penetration asphalt from Supplier 1 had been used, since samples of it had PVN values of -0.96 and -0.88.

The data for Stage 2 in Table 8 illustrate what is also happening to recycled pavement construction in North America at the present time. RAP obtained from several often widely different locations with quite different PVN values for their recovered asphalts is being deposited at random in the same stockpiles. For hot-mix recycling at least two asphalts are usually employed - the hard asphalt recovered from the old pavement and the new softer asphalt, with or without modifiers. The recommended blend of these old and new asphalts will have a certain PVN value and a certain penetration at 25°C. Since the PVN of the asphalt recovered from the RAP will in most cases be less than the PVN of the asphalt blend used for the design of the recycled mix, to maintain a constant PVN value before and after construction means that very close control of PVN of the asphalt recovered from the RAP going into the recycled mix will be required. Furthermore, no longer will contractors be able to change the percentages of RAP at will in the recycled mix, since this will change the PVN of the asphalt recovered after recycled pavement construction. Hence, PVN values provide a very powerful tool for user agencies to employ for the control of recycled pavement construction.

For pavement recycling, if a pavement was originally designed for light traffic and a Group C asphalt was used, then when recycled, because of increasing traffic, the pavement should be designed for medium traffic at least, and a Group B asphalt should be used. If the pavement was initially designed for medium traffic and a Group B asphalt was specified, when recycled it should usually be designed for heavy traffic and Group A asphalt would be required. The need for this is illustrated in Figure 3 which shows that with everything else being equal, as the temperature susceptibility of an asphalt is decreased, thermal cracking begins at a lower and lower temperature, pavement stability under summer traffic is increased and resistance to pavement rutting is greatly improved. When it is necessary to achieve a lower temperature susceptibility, an appropriate polymer can be used.

Axle loads have increased, the use of radial tires has greatly elevated tire pressures on pavements, petroleum refiners are running crude oils for their distillates and the asphalts produced do not always have the properties required. No longer will a paving asphalt manufacturer be able to sell any asphalt just as it comes from the bottom of a vacuum tower and market it indiscriminately for heavy, medium and light traffic. The user agencies, whenever they elect to do so, are now in a position to employ Group C asphalts (high temperature susceptibility) in pavements for light traffic, Group B asphalts (medium temperature susceptibility) in pavements for medium traffic and to demand and obtain Group A or Group AA asphalts (low temperature susceptibility) for heavy traffic. The introduction of polymer-modified paving asphalts has changed control of the marketing of paving asphalts from the manufacturer to the user. For the first time, the user can specify and obtain paving asphalts with the engineering properties required for any project. If the asphalt from the bottom of the vacuum tower does not have the temperature susceptibility required, it can easily be obtained by the incorporation of a small percentage of a suitable polymer. From the user's point of view, this is chiefly a matter of the cost to benefits ratio, namely comparing the greater cost of polymer-modified asphalt with the savings resulting from reduced thermal cracking, higher pavement stability for summer traffic, reduction in pavement rutting, and better performance of recycled pavements.

The attitude toward the manufacture and marketing of paving asphalts must change just as it did for lubricants. No salesman for lubricants today would think of trying to sell a raw lubricating oil just as it comes from a vacuum tower. It must be further refined and appropriate additives incorporated to provide the properties required for various uses as lubricants. It is just beginning, but something similar is starting to happen for the production of improved paving asphalts, particularly to improve their temperature susceptibility properties, or PVN values, which have been ignored for too long.

XI PVN AND SURFACE TREATMENTS (CHIP SEALS)

Asphalt emulsions are generally favoured for surface treatments in North America at the present time. In the USA, with regard to chip seals, both ASTM and AASHTO require a minimum penetration at 25°C of 100 for the emulsion residue. In Canada, a minimum penetration of 100 at 25°C is also usually specified for the distillation residue of an asphalt emulsion. In neither country is a corresponding minimum PVN value specified for an emulsion distillation residue. This means that both in the USA and Canada, the distillation residue from an asphalt emulsion could belong to Group A (low temperature susceptibility, PVN = 0 to -0.5), to Group B (medium temperature susceptibility, PVN = -0.5 to -1.0) or to Group C (high temperature susceptibility, PVN = -1.0 to -1.5).

At all temperatures above 25°C, surface treatments containing emulsions whose distillation residue belongs to Group C can be expected to have the least stability and the greatest tendency to flush or bleed. The residues would also be the hardest at all temperatures below 25°C and surface treatments made with these emulsions would be candidates for most thermal cracks. At the other extreme, if the emulsion residues belong to Group A, at all temperatures above 25°C surface treatments made with these emulsions would have the highest stability, the least tendency to flush or bleed and the least tendency for thermal cracking. The performance of an emulsion residue that belongs to Group B would be superior to that of Group C but inferior to that of Group A. The most serviceable surface treatments should be those whose emulsion distillation residues belong to Group A or AA. There is a need for a meaningful minimum viscosity at 135°C or a significant minimum PVN in ASTM, AASHTO and Canadian specifications for emulsion distillation residues for chip seals, as well as a minimum penetration at 25°C.

XII ITEMS FOR FURTHER INVESTIGATION

The data presented in this paper supports the conclusions presented but are limited in number and further investigation is required to either support or refute these findings. Some of the items requiring more study follow.

1. While PVN for the considerable number of asphalts referred to in the paper support the concept of PVN being an asphalt

fingerprint that does not change with either time or temperature, more data are required for a larger number of asphalts produced by steam or vacuum distillation from a much wider range of crude oils to either support or modify this conclusion.

2. The PVN value for any paving asphalt is presently based on penetration at 25°C and viscosity in centistokes at 135°C. This is due to the abundance of these data that are available on paving asphalts. However, other combinations of penetration and viscosity might provide still more accurate values of PVN, particularly at the extremes of paving asphalt consistency. Combinations of penetrations at 10°C (50°F), 15.6°C (60°F), 25°C (77°F) and 37.8°C (100°F) with corresponding viscosities at 121.1°C (250°F), 135°C (275°F) and 148°C (300°F) should be investigated. For example, combinations of penetration at 37.8°C with viscosity in centistokes at 148.7°C might be more useful for calculating PVN values for quite hard asphalts recovered from some aged asphalts for recycling, while combinations of penetration at 10 C with corresponding viscosity at 121.1°C might provide a more accurate measure of PVN for the softer asphalts now used for recycling.

3. Table 6 indicates that more than two percent of added refinery crude wax incorporated into a normal paving asphalt can make the PVN of the normal asphalt deviate away significantly from the PVN given by Figures 13, 14 and 29 for a corresponding "wax-free" asphalt. In North America we depend on a minimum ductility of 100 cm, 5 cm/min, at 25°C to provide paving asphalts that are relatively free from wax, although this criterion provides no data on the actual wax content of the asphalt. However, hard asphalts of about 30 penetration at 25°C are often too brittle at this temperature and the ductility briquettes fracture when the ductility molds are extended by a very small amount, often less than one cm. Consequently, the ductility test cannot be used as a significant indicator for wax removal for these hard asphalts, which may be recovered from RAP. Also, for paving asphalts that are quite soft, e.g. 300/400 penetration at 25° C, meaningful ductility values cannot be measured at 25°C although significant ductility values may be given if a test temperature of 15.6°C is employed. In Europe, a maximum wax content, determined by a standard wax content test, is sometimes specified for paving asphalts. This presumably gives the total percentage of wax in a paving asphalt sample.

   PVN appears to be such a useful concept for paving asphalts that an investigation of the ductility test at different temperatures and different rates of pull and of the actual wax content by a suitable standard method would appear to be necessary to obtain the critical wax content at which the PVN of a normal paving asphalt begins to diverge significantly from the corresponding PVN value obtained for "wax-free" paving asphalts.

4. Figure 30 illustrates a finding that is intended to facilitate the selection of paving asphalts for sites with various minimum winter temperatures that will avoid low temperature transverse pavement cracking for the service life of a pavement, which is assumed to be 20 years. More data are needed to fine-tune Figure 30 and to revise it if necessary.

5. Further data are needed to confirm or revise Figure 31 which attempts to show that an asphalt selected to avoid low temperature transverse pavement cracking at any minimum

winter temperature will provide a pavement with adequate stability to carry summer traffic. Will the pavement have adequate stability for light, medium or heavy traffic ? If only light traffic is carried, can the pavement stability be further increased by the incorporation of a small percentage of a suitable polymer to provide a polymer-modified asphalt ?

6. Reference is made in the paper to the "Elastic Recovery Test", which shows that by incorporating a suitable polymer into a normal asphalt, the elastic recovery of the polymer-asphalt can be from 60 to 80 percent of its original length of 20 cm, depending on type and quantity of polymer, versus an elastic recovery of only 5 to 10 percent for a normal asphalt. At present, this is only a laboratory test, but it implies a marked reduction in the minimum winter temperature at which low temperature transverse cracking begins. It also implies a much greater resisitance to pavement rutting than can be provided by normal paving asphalts. This should be investigated.

7. The use of polymer-modified asphalts for pavement recycling requires investigation.

8. The PVN of the asphalt blend used for the design of a recycled paving mixture and the PVN of the asphalt recovered from the recycled pavement after construction have been shown to be nearly the same. At present, RAP from several completely different sources is being added to the same stockpile. An investigation is required to determine the best way to handle RAP so that PVN values of the asphalt recovered from random samples taken from the RAP stockpile are approximately constant.

9. The advantages of Group A asphalts for surface treatment operations should also be a subject for enquiry because of the benefits it appears to offer over the use of the Group B and Group C asphalts now commonly used in asphalt emulsions for surface treatments. This includes examining the use of appropriate polymers for improving the temperature susceptibilities of Group C and Group B asphalts to that of Group A or Group AA for the asphalt base for these emulsions.

XIII WARNING ! DANGER !

New asphalt pavements or overlays that have been designed to avoid pavement cracking throughout their service lives should never be placed on a badly cracked asphalt or portland cement pavement because the cracks in the underlying surface will very quickly reflect through the new pavement.

In their 1988 AAPT paper, Haas and Phang (30) have indicated that if through poor design (usually poor binder selection) low temperature transverse pavement cracking is going to develop in the new pavement, this cracking is normally initiated at the surface of the new pavement by contraction stresses due to low winter temperatures, because its immediate surface s subjected to the lowest temperature. With the successive thermal contraction and expansion stresses due to the cycle of higher and lower temperatures, these cracks gradually propagate downward through the full depth of the new pavement. However, when a new pavement is placed on a cracked asphalt or portland cement pavement, thermal cracks start at the bottom of the new pavement where it meets the old pavement, and propagate upward through the new pavement. To obtain the most crack-free performance from a new pavement it should be built on a properly designed and thoroughly compacted base course or equivalent.

XIV SUMMARY AND CONCLUSIONS

Much of the data presented should be interpreted as being spoken by the pavements in service in response to all of the varied environmental conditions to which they are exposed, and not as being given by some sanitary laboratory test or group of laboratory tests that try to tell the pavements how they should be responding to these conditions but quite obviously are not doing so. In other words, find out first what a pavement in service can tell you about a problem, then use this as a basis for laboratory investigation, and not vice versa.

1. The temperature susceptibility of a paving asphalt is the change in consistency (penetration or viscosity) that the asphalt undergoes for a given change in temperature.

2. PVN as a measure of temperature susceptibility of a paving asphalt is based on the penetration at 25°C and the viscosity in centistokes at 135°C of the asphalt.

3. The use of paving asphalts of lower temperature susceptibility (higher PVN values) through improved asphalt specifications could
   - increase pavement stability under summer traffic
   - avoid or greatly reduce low temperature pavement cracking in winter
   - greatly reduce or eliminate pavement rutting
   - provide a more rational method for pavement recycling
   - provide a tool for more effectively monitoring the construction of virgin and recycled pavements and
   - provide surface treatments with improved performance.

4. Tables of data "spoken by" the pavements themselves show that PVN values of the original asphalts and of corresponding asphalts recovered from pavements up to 20-30 years of age remain constant regardless of time of service. The same data also show that the PVN values of the original asphalts, of the corresponding residues from the Thin Film Oven Test at 163°C (325°F) and of corresponding asphalts recovered from pavements in service up to 20-30 years also remain constant regardless of temperature in service. These factors indicate that PVN is the best measure of paving asphalt temperature susceptibility that has been developed to date.

5. Current mainstream paving asphalts can be divided into three groups of temperature susceptibility,
   - low temperature susceptibility, Group A, PVN = -0.5 minimum
   - medium temperature susceptibility, Group B, PVN = -0.5 to -1.0
   - high temperature susceptibility, Group C, PVN = -1.0 maximum

6. A chart with double-headed arrows indicates either the direction of hardening of an asphalt that will occur or has already taken place in a pavement in service. The chart shows that Groups A, B and C asphalts remain essentially as Groups A, B and C asphalts, respectively, throughout their pavement service lives.

7. Charts are provided in terms of PVN values that will enable paving asphalts to be selected that will avoid low temperature transverse pavement cracking throughout the service life of the pavement, in regions with a wide range of minimum winter temperatures while at the same time providing adequate stability for summer traffic.

8. To avoid low temperature transverse pavement cracking, harder Group A asphalts (lower penetration at 25°C) should be used for lowest minimum winter temperatures; somewhat softer (higher penetration at 25°C) Group B asphalts will give protection against thermal cracks for somewhat higher minimum winter temperatures and still softer (higher penetration at 25°C) Group C asphalts must be used to provide protection against thermal cracking at still higher minimum winter temperatures.

9. For the same protection against low temperature transverse pavement cracking, Group A asphalts should be used for heavy traffic, Group B asphalts can be used for medium traffic and Group C can be used for light traffic. As the temperature susceptibility of paving asphalt increases, softer and softer paving asphalts (in terms of penetration at 25°C and viscosity at 135°C) must be used if low temperature transverse pavement cracking is to be avoided.

10. For climates without frost, to have a constant pavement stability as the temperature susceptibility of the paving asphalt increases, the asphalt penetration at 25 C must become lower and lower (asphalt becomes harder and harder).

11. Paving asphalts exhibit two different properties, elastic and viscous, depending on pavement temperature and time of loading. Under very rapid loading they can perform as purely elastic materials but under sustained loading, their viscous property becomes important, viscous flow can take place and pavement rutting can begin. When all other factors are equal, the higher the viscosity at 135°C, that is, the higher the PVN of the paving asphalt, the greater will be the pavement's resistance to rutting.

12. For regions subject to frost penetration, methods for designing either completely new or recycled pavements which avoid low temperature transverse pavement cracking at the minimum winter temperature at any pavement site throughout a pavement's service life while providing adequate stability for summer traffic are described.

13. A method that points out the advantages of using Group A asphalts for pavements in regions without frost is also described.

14. For new or recycled pavements, recognition that the PVN value of asphalts recovered from the pavement following construction should be the same as the PVN of the original asphalt used for design of the paving mixture provides user agencies with a powerful and highly useful tool for monitoring the construction of these pavements.

15. The performance of surface treatments could be greatly improved by using asphalts of lower temperature susceptibility, that is with higher PVN values. Therefore ASTM, AASHTO and Canadian specifications should require a meaningful minimum viscosity at 135°C, or a significant minimum PVN value, in addition to a minimum penetration at 25°C for the distillation residues of asphalt emulsions used.

16. While the data provided in the paper unanimously support the conclusions presented, the need for more data to either confirm or modify these findings is recognized. A brief list of useful further investigations for this purpose is included.

17. The benefits of using paving asphalts of low temperature susceptibiity or higher PVN have been emphasized. It is also pointed out that the incorporation of a small percentage of an appropriate polymer can improve the temperature susceptibility of a Group C asphalt to that of a Group B or Group A, or of a Group B asphalt to that of a Group A asphalt.

18. Two appendices are included with the paper.
Appendix A provides equations for the accurate calculation of the PVN value for any asphalt manufactured by steam or vacuum distillation, and gives an example of its application.
Appendix B-1 provides a general use specification for penetration-graded asphalts with temperature susceptibility requirements.
Appendix B-2 provides a working specification similar to B-1, but includes additional information that avoids the need for a separate manual to indicate its proper application.

The introduction of temperature susceptibility requirements, as measured by PVN, into asphalt paving technology, would open a whole new world of understanding of the service behaviour of asphalt pavements and how they should be designed for longer lives and superior pavement performance. It is quite remarkable that most of the highly useful benefits implied by this paper could be made available by the use of two simple, long-standing laboratory tests, penetration at 25°C and viscosity at 135°C, on which values for PVN are based.

XV REFERENCES

1. McLeod, Norman W., "Transverse Pavement Cracking Related to Hardness of the Asphalt Cement", Proceedings, Canadian Technical Asphalt Association, 13 5 (1968).

2. McLeod, Norman W., Discussion of paper by Shook and Kallas, Proceedings, Association of Asphalt Paving Technologists 38 166 (1969).

3. McLeod, Norman W., Discussion of paper by F.D. Young, I. Deme, R.A. Burgess and O. Kopvillem, Proceedings, Canadian Technical Asphalt Association, 14 110 (1969).

4. Lefebvre, J.A.A., "A Modified Penetration Index for Canadian Asphalts", Proceedings, Association of Asphalt Paving Technologists, 39 443 (1970).

5. McLeod, Norman W., Discussion of paper by J.A.A. Lefebvre, Proceedings, Association of Asphalt Paving Technologists 39 474 (1970).

6. Corbett, L.W. and Schweyer, H.E., "Composition and Rheology Considerations in Age Hardening of Bitumen" Proceedings, Association of Asphalt Paving Technologists 50 571 (1981).

7. Pfeiffer, V.Ph. and Van Doormaal, P.M., "The Rheological Properties of Asphaltic Bitumen", Journal of the Institute of Petroleum Technologists 22 414 (1936).

8. Heukelom, W., "An Improved Method of Characterizing Asphaltic Bitumen with the Aid of their Mechanical Properties" Proceedings, Association of Asphalt Paving Technologists 42 67 (1973).

9. McLeod, N.W., "A 4-Year Survey of Low Temperature Transverse Pavement Cracking on Three Ontario Test Roads", Proceedings, Association of Asphalt Paving Technologists 41 424 (1972).

10. Welborn, J.Y. and Halstead, W.J., "Properties of Highway Asphalts, Part I, 85/100 Penetration Grade", Public Roads 30 (9) 198 (1959) and Proceedings, Association of Asphalt Paving Technologists 28 242 (1959).

11. Welborn, J.Y., Halstead, W.J. and Boone, J.G., "Properties of Highway Asphalts, Part II, Various Grades", Public Roads 31 (4) 74 (1960) and Proceedings, Association of Asphalt Paving Technologists 29 276 (1960).

12. Puzinauskas, V.P., "Properties of Asphalt Cements", Proceedings, Association of Asphalt Paving Technologists 48 646 (1979).

13. Van der Poel, C., "A General System Describing the Visco-Elastic Properties of Bitumens and its Relation to Routine Test Data", Journal of Applied Chemistry 4 221 (1954).

14. Van der Poel, C., "Time and Temperature Effects on the Deformation of Asphalt Bitumens and Bitumen-Mineral Mixtures", Society of Plastics Engineers Journal 11 (7) 47 (1955).

15. Meidinger, J.F. and Kasianchuk, D.A., "Asphalt Specifications for British Columbia Highways", Proceedings, Canadian Technical Asphalt Association 19 25 (1974).

16. Anderson, D.A., Dukatz, E.L. and Petersen, J.C., "The Effect of Antistrip Additives on the Properties of Asphalt Cements", Proceedings, Association of Asphalt Paving Technologists 51 298 (1982).

17. Dukatz, E.L. Jr., Anderson, D.A. and Rosenberger, J.L., "Relationship Between Asphalt Flow Properties and Asphalt Composition", Proceedings, Association of Asphalt Paving Technologists 53 160 (1984).

18. Kandhal, P.S. and Koehler, W.C., "Effect of Rheological Properties of Asphalts on Pavement Cracking", American Society for Testing and Materials, STP 941, p. 99 (1985).

19. McLeod, Norman W., Discussion, Proceedings, Sixth International Conference on the Structural Design of Asphalt Pavements 2 378 (1987).

20. McLeod, Norman W., "Test Data from Three Ontario Test Roads after 15 Years of Service", Proceedings, Canadian Technical Asphalt Association 23 534 (1978).

21. Deme, I.J. and Young, F.D., "Ste. Anne Test Road Revisited Twenty Years Later", Proceedings, Canadian Technical Asphalt Association 32 254 (1987).

22. McLeod, Norman W., "The Case for Grading Asphalt Cements by Pentration at 77 F (25 C)", Proceedings, Canadian Technical Asphalt Association 20 251 (1975).

23. Marks, Vernon J and Huisman, Charles L., "Reducing the Adverse Effects of Transverse Cracking", Proceedings, Association of Asphalt Paving Technologists 54 651 (1985).

24. Haas, R., Meyer, F., Assaf, G. and Lee, H., "A Comprehensive Study of Cold Climate Airport Pavement Cracking", Proceedings, Association of Asphalt Paving Technologists 56 198 (1987).

25. Fabb, A.J., "The Influence of Mix Composition, Binder Properties and Cooling Rate on Asphalt Cracking at Low Temperatures", Proceedings, Association of Asphalt Paving Technologists 43 285 (1974).

26. McLeod, Norman W., "Using the Freezing Index for the Optimum Selection of Paving Asphalts with Different Temperature Susceptibilities for any Pavement Site", Proceedings, Canadian Technical Asphalt Association 30 282 (1985).

27. McLeod, Norman W., "Using Paving Asphalt Rheology to Improve or Impair Asphalt Pavement Design and Performance", American Society for Testing and Materials, STP 941, p 51 (1985).

28. King, Gayle N., King, Helen W., Harders, Otto and Chaverot, Pierre, "Low Temperature Benefits of Polymer Modified Asphalts", Proceedings, Canadian Technical Asphalt Association 33 198 (1988).

29. The Asphalt Institute, "Research and Development of the Asphalt Institute's Thickness Design Manual, (MS-1)", Ninth Edition, Research Report No. 82.2, p 22 (1982).

30. Haas, R.C.G. and Phang, W.A., "Relationships Between Mix Characteristics and Low Temperature Transverse Pavement Cracking", Proceedings, Association of Asphalt Paving Technologists 57 290 (1988).

TABLE I

INSPECTION DATA ON ORIGINAL PAVING ASPHALTS
FOR THE THREE ONTARIO TEST ROADS

SUPPLIER NO	1	2	3
Flash Point F	585	525	615
Soft. Pt. R and B F	115	115	119
Penetration			
100 g, 5 s, 77 F	83	96	87
200 g, 60 s, 39.2 F	25	36	22
200 g, 60 s, 32 F	22	26	19
Penetration Ratio 39.2/77 X 100	30.1	37.5	25.3
Ductility at 77 F, 5 cm/min, cm	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 Pen at 77 F	67.5	60.4	61.0
Ductility at 77 F, 5 cm/min, cm	150+	110	115
Solubility in n-hexane			
% asphaltenes	19.7	24.7	18.8
Penetration Index, PI			
Pfeiffer and Van Doormaal	-1.0	-0.57	-0.21
Pen-Vis Number, PVN	-0.23	-0.41	-1.35

TABLE 2

STE. ANNE TEST ROAD

MINIMUM WINTER TEMPERATURE -40 C (-40 F)

PERIOD OF SERVICE	PVN VALUES		
	150/200 PEN HIGH VISCOSITY AT 275 F	150/200 PEN LOW VISCOSITY AT 275 F	300/400 PEN LOW VISCOSITY AT 275 F
ORIGINAL 1967	-0.59	-1.61	-1.52
RECOVERED 1970	-0.75	-1.71	-1.78
RECOVERED 1987	-0.73	-1.80	-1.76
GROUP PVN	B -0.5 to -1.0	CC -1.5 to -2.0	CC -1.5 to -2.0

TABLE 3

TEMPERATURE SUSCEPTIBILITIES OF ORIGINAL AND AGED ASPHALTS

PENDOT STUDY

ASPHALT TYPE	PI (PEN/PEN)				PVN (PEN-VIS NUMBER)			
	ORIGINAL	JUST AFTER CONSTRUCTION	20 MONTHS	7 YEARS	ORIGINAL	JUST AFTER CONSTRUCTION	20 MONTHS	7 YEARS
T-1	-2.77	-2.24	+0.34	+1.82	-1.04	-1.13	-1.07	-1.12
T-2	-0.71	-0.80	+1.22	+1.52	-0.70	-0.68	-0.54	-0.60
T-3	-1.51	-0.99	-0.12	-0.58	-0.61	-0.72	-0.65	-0.56
T-4	-1.05	-0.65	+0.93	+0.39	-0.86	-1.03	-0.76	-0.79
T-5	-2.23	-2.03	-0.32	-0.87	-1.03	-1.16	-1.07	-1.12
T-6	-1.29	-0.64	+0.60	-0.46	-0.45	-0.47	-0.40	-0.39

MINIMUM WINTER TEMPERATURE -29 C (-20 F)

TABLE 4

IOWA THERMAL CRACK STUDY

DESIGN

ASPHALT SURFACE COURSE 1.5 INCHES
ASPHALT BASE COURSE 1.5 INCHES
ASPHALT TREATED BASE 8.0 INCHES

ASPHALT SOURCE	PVN VALUES			THERMAL CRACK SPACING IN FEET AFTER 3.5 YEARS
	ORIGINAL	RECOVERED AFTER 3.5 YEARS	GROUP PVN RANGE	
SUGAR CREEK	-1.2	-1.04	C -1.0 to -1.5	35
WOOD RIVER	-0.60	-0.61	B -0.5 to -1.0	170
STANDARD AC 10 + 1.0% (ATB)				528

MINIMUM WINTER TEMPERATURE -29 C (-20 F)

TABLE 5

TEMPERATURE SUSCEPTIBILITIES OF ORIGINAL AND AGED ASPHALTS

McASPHALT STUDY

ORIGINAL ASPHALT		PI PEN/PEN (HEUKELOM)			PVN		
NO	PEN	ORIGINAL	THIN FILM RESIDUE	PUGMILL DISCHARGE	ORIGINAL	THIN FILM RESIDUE	PUGMILL DISCHARGE
1	85/100	-2·86	-2·33	-1·81	-0·61	-0·67	-0·56
2	85/100	-1·63	-2·06	-2·00	-0·67	-0·69	-0·69
3	85/100	-2·73	-1·64	-2·18	-0·70	-0·68	-0·67
4	150/200	-1·73	-1·16	-0·65	-0·59	-0·67	-0·64
5	85/100	-1·98	-2·38	-0·81	-0·67	-0·69	-0·56
6	85/100	-1·23	-1·06	-0·84	-0·77	-0·64	-0·49
7	85/100	-0·94	-0·21	-0·80	-0·47	-0·41	-0·36
8	85/100	-1·11	-2·88	-1·93	-0·55	-0·56	-0·47
9	85/100	-1·24	-1·49	-1·92	-0·53	-0·52	-0·34

TABLE 6

Influence of Wax on PVN

% Wax	Penetration at 25 C (77 F)	Viscosity cs 135 C (275 F)	PVN	Ductility cm 25 C (77 F)	Soft Point F (C)
Group A Asphalt - Lloydminster					
100	-	3.39	-	-	148.0
0.0	93	417	-0.24	135+	111.0
0.5	98	386	-0.32	135+	107.0
1.0	100	368	-0.35	135+	108.0
2.0	107	307	-0.55	135+	109.0
5.0	115	227	-0.95	135+	109.5
10.0	119	148	-1.59	42	115.0
Group B Asphalt - Mixed Blend					
100	-	3.39	-	-	148.0
0.0	87	318	-0.73	145+	116.5
0.5	90	304	-0.79	145+	117.5
1.0	90	312	-0.72	145+	116.0
2.0	93	275	-0.87	145+	116.5
5.0	100	225	-1.11	96	120.0
10.0	101	145	-1.77	27	123.0
Group C Asphalt - Redwater					
100	-	3.39	-	-	148.0
0.0	94	171	-1.59	130+	115.0
0.5	97	167	-1.59	130+	117.5
1.0	100	162	-1.61	130+	118.5
2.0	112	140	-1.73	130+	116.0
5.0	116	112	-2.06	101	116.5
10.0	126	116	-2.09	28	125.0

TABLE 7
INSPECTION DATA

Asphalt Blend	SUPPLIER 2	BLEND 3:1	BLEND 1:1	BLEND 40:60	BLEND 1:3	SUPPLIER 1	SUPPLIER 1 SAMPLES 1	SUPPLIER 1 SAMPLES 2
Pen @ 77 F	59	72	81	83	89	88	57	63
Soft Point (R&B) F	124.5	121.5	118	115	115	114	118	119
Kin Vis @ 275 F	684	574	505	488	421	412	362	359
295 F	410	327	303	305	257	237	209	210
315 F	286	234	200	192	183	150	139	121
S.G. @ 77 F	.9828	.9978	1.0076	1.0106	1.0191	1.0325		1.0274
Ductility @ 77 F cm	32.5	51.5	110+	110+	110+	110+	110+	110+
PVN	-.02	-0.06	-0.12	-.14	-0.28	-.31	-.96	-.88
PI	-.46	-0.37	-.58	-.99	-.79	-1.00	-1.47	-1.09
Thin Film Oven Test % Loss	.011	.027	.018	.0126	.0122	.035	.0356	.0484
Pen @ 77 F	46	50	60	60	59	57	37	42
% Ret Pen	78.0	69.4	74.1	72.3	66.3	64.8	64.9	66.7
Kin Vis @ 275 F	988	819	656	640	580	532	479	455
Soft Point F	127.5	126	122.5	121.5	120	117	125	124
Ductility @ 77 F	15	30	110+	110+	110+	110+	110+	110+
PVN	+0.19	0.03	-0.08	-.11	-0.27	-.43	-.98	-.93
PI	-0.66	-.66	-0.70	-.84	-1.10	-1.62	-1.44	-1.31

TABLE 8

PENETRATION AT 25°C AND CORRESPONDING PVN VALUES FOR BITUMEN RECOVERED FROM PAVEMENT SAMPLES

Location	Contract	BITUMEN PROPERTIES			
		Penetration at 25°C		PVN Values	
		Surface	Base	Surface	Base
1	STAGE 1	20	24	-0.18	-0.03
2	STAGE 1	23	22.5	+0.08	-0.17
3	STAGE 1	26	21	-0.40	-0.43
4	STAGE 1	25	23	+0.19	-0.27
5	STAGE 1	19	23	-0.08	-0.29
6	STAGE 2	31	51	+0.37	-0.48
7	STAGE 2	49	21	-0.59	-0.25
8	STAGE 2	38	58.5	-0.95	-0.81
9	STAGE 2	40	27	-0.26	-0.23
10	STAGE 2	41	32	-0.22	-0.07
16	STAGE 2	67	63	-0.63	-0.63
17	STAGE 2	42	65	-0.33	-0.64
18	STAGE 2	31	28	-0.62	-0.28
19	STAGE 2	65	77	-0.20	-0.48
20	STAGE 2	44	31	-0.28	-0.21
21	STAGE 2	25	23	-0.68	-0.33
22	STAGE 2	26	27	-0.16	-0.37
23	STAGE 2	29	26	-0.03	-0.25

MINIMUM WINTER TEMPERATURE +10 C (+50 F)

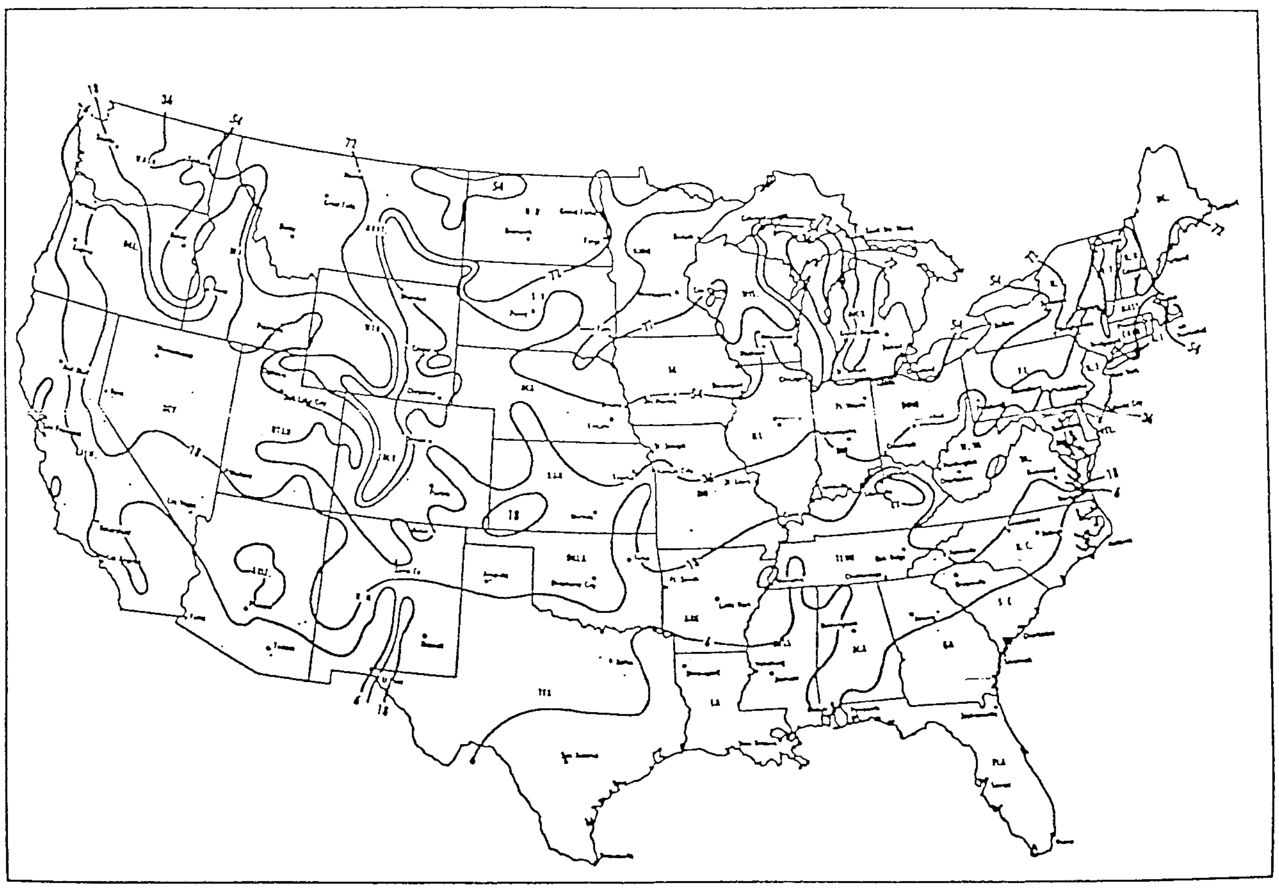


FIGURE 1 MAXIMUM DEPTH OF FROST PENETRATION, INCHES

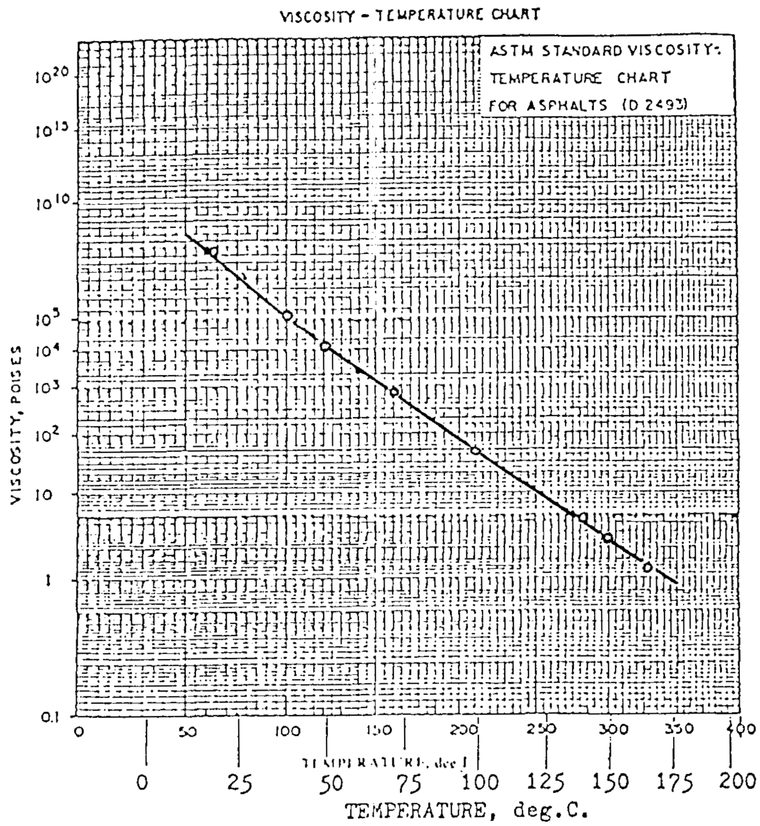


FIG. 2 Facsimile of Viscosity-Temperature Chart on which a Typical Experimental Curve has been plotted

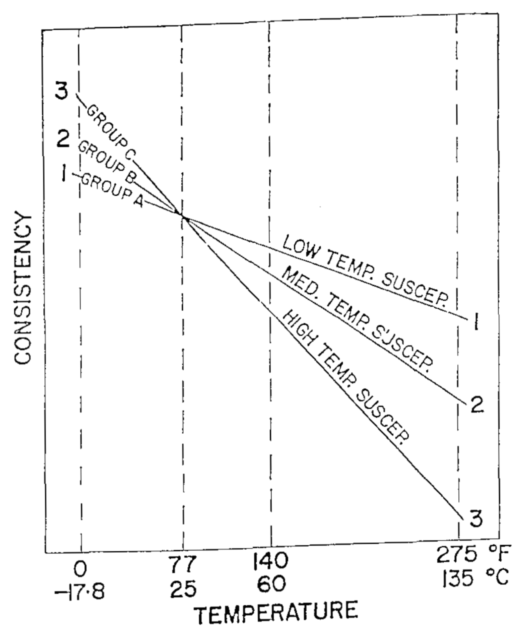


FIG. 3 Sketch illustrating different temperature susceptibilities of paving asphalts

TEMPERATURE SUSCEPTIBILITIES

1. PENETRATION RATIO

$$= \frac{\text{PEN AT } 25\,°C \ \ 100g \ \ 5s}{\text{PEN AT } 4\,°C \ \ 200g \ \ 60s}$$

2. VISCOSITY TEMPERATURE SUSCEPTIBILITY (VTS)

$$VTS = \frac{\text{LOG LOG VISCOSITY at } T_2 - \text{LOG LOG VISCOSITY at } T_1}{\text{LOG } T_1 - \text{LOG } T_2}$$

3. PENETRATION INDEX (PI)

PFEIFFER AND VAN DOORMAAL

$$B = \frac{\text{LOG}(800) - \text{LOG (PEN at } 25\,°C)}{T(R\&B)\,°C - 25\,°C}$$

$$PI = \frac{20 - 500B}{50B - 1}$$

4. PENETRATION INDEX (PI)

HEUKELOM

PEN AT 4, 10, 25 °C EXTRAPOLATED TO PEN=800

(100g 5s)

PI BY PIVOT ON SHELL BTD CHART

5. PEN – VIS NUMBER (PVN)

PEN AT 25 °C (77 °F)

VISCOSITY AT 135°C (275° F)

FIG. 4 Indicating five methods for expressing paving asphalt temperature susceptibility

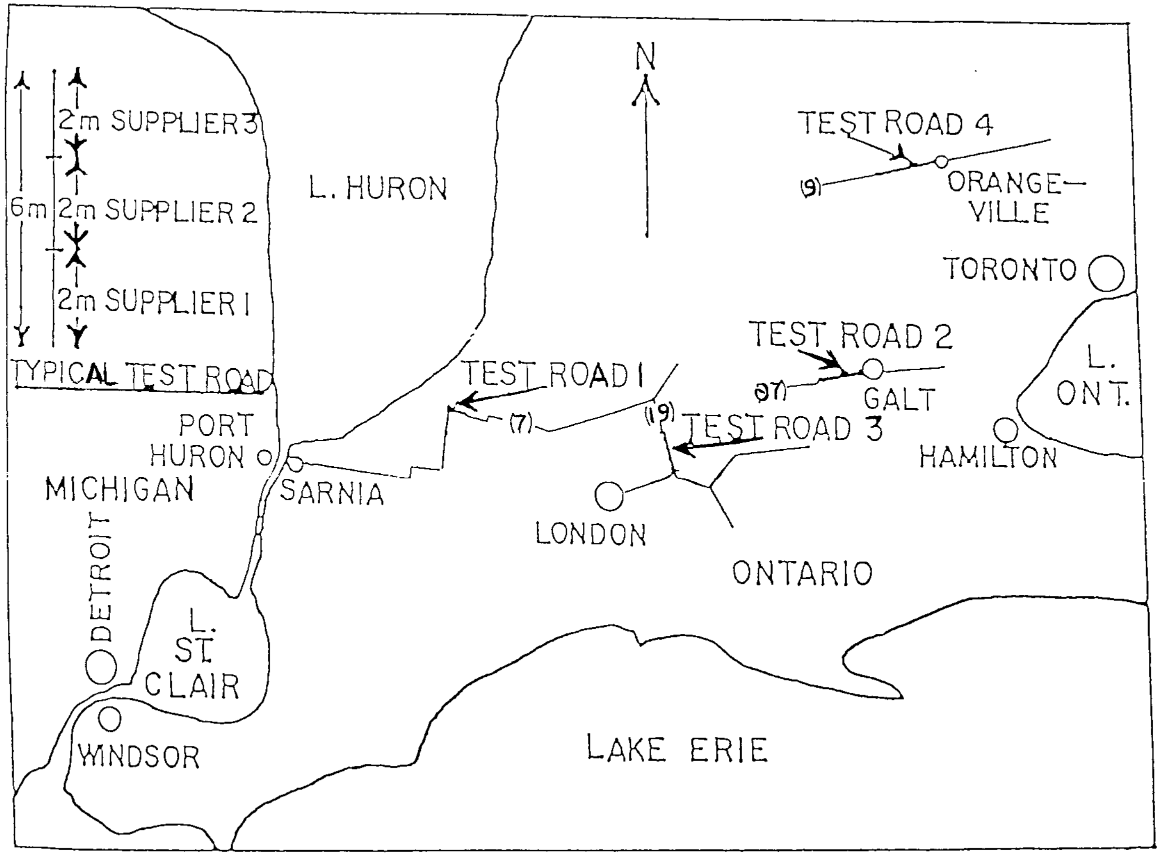


FIGURE 5 LOCATIONS OF FOUR ONTARIO TEST ROADS

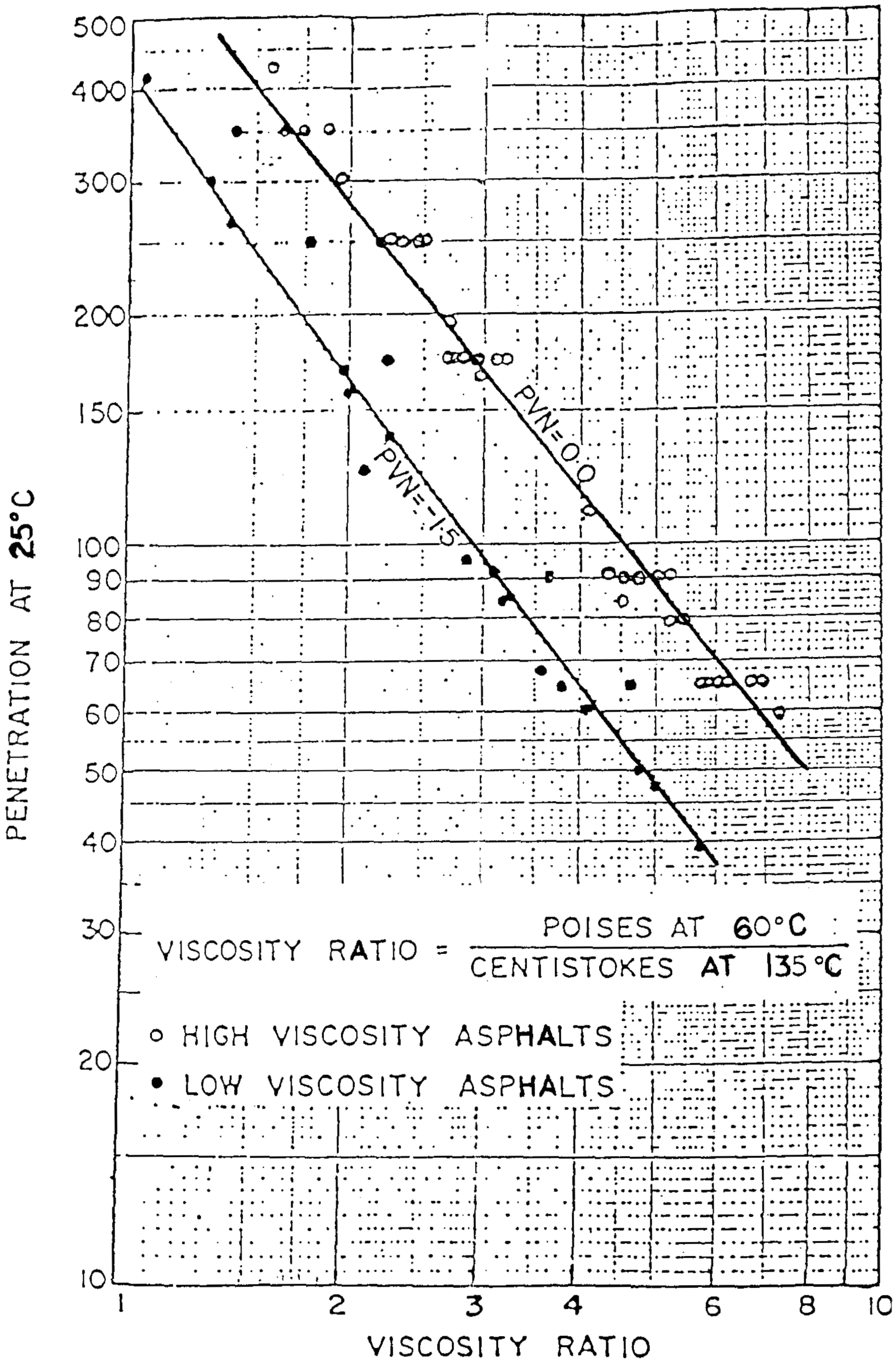


FIG. 6 Relationship between Viscosity Ratio and Penetration at 25 C

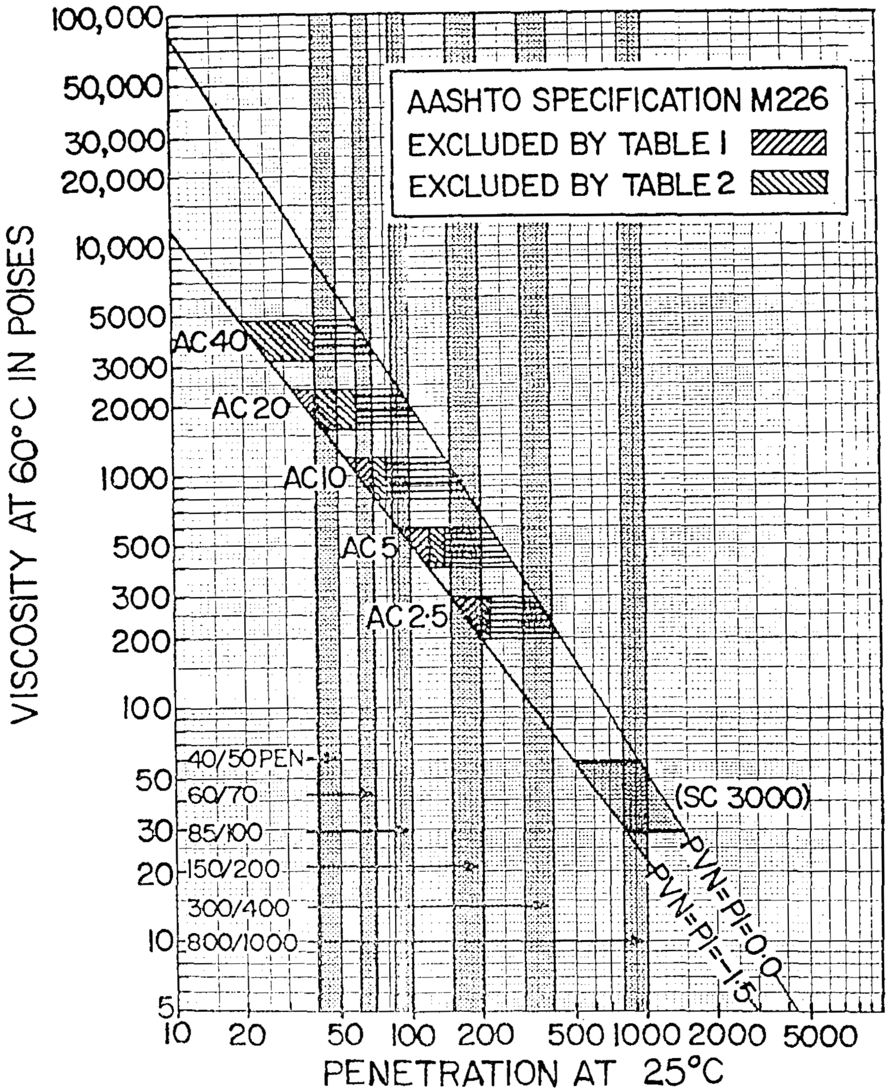


FIG. 7 Relationships between viscosity at 60 C, penetration at 25 C and temperature susceptibility

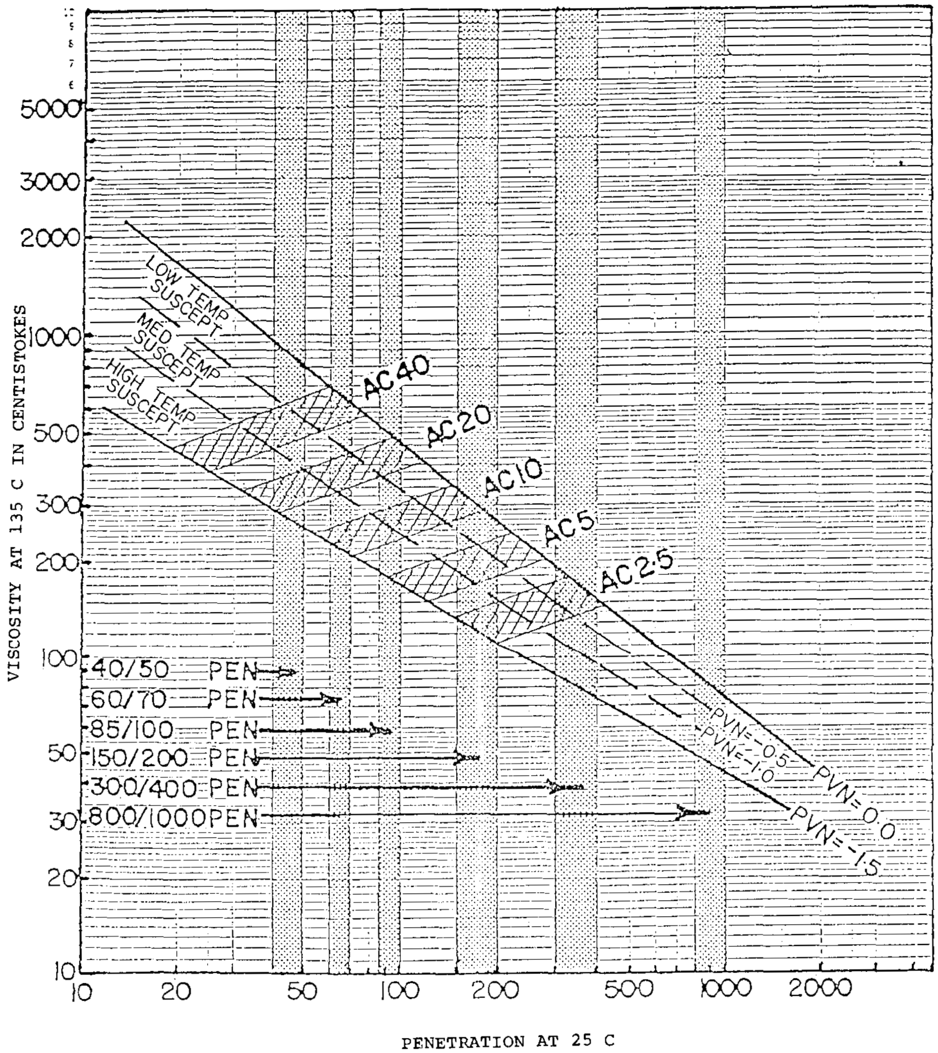


FIG. 8 Viscosity grades at 60 C plotted on a PVN chart

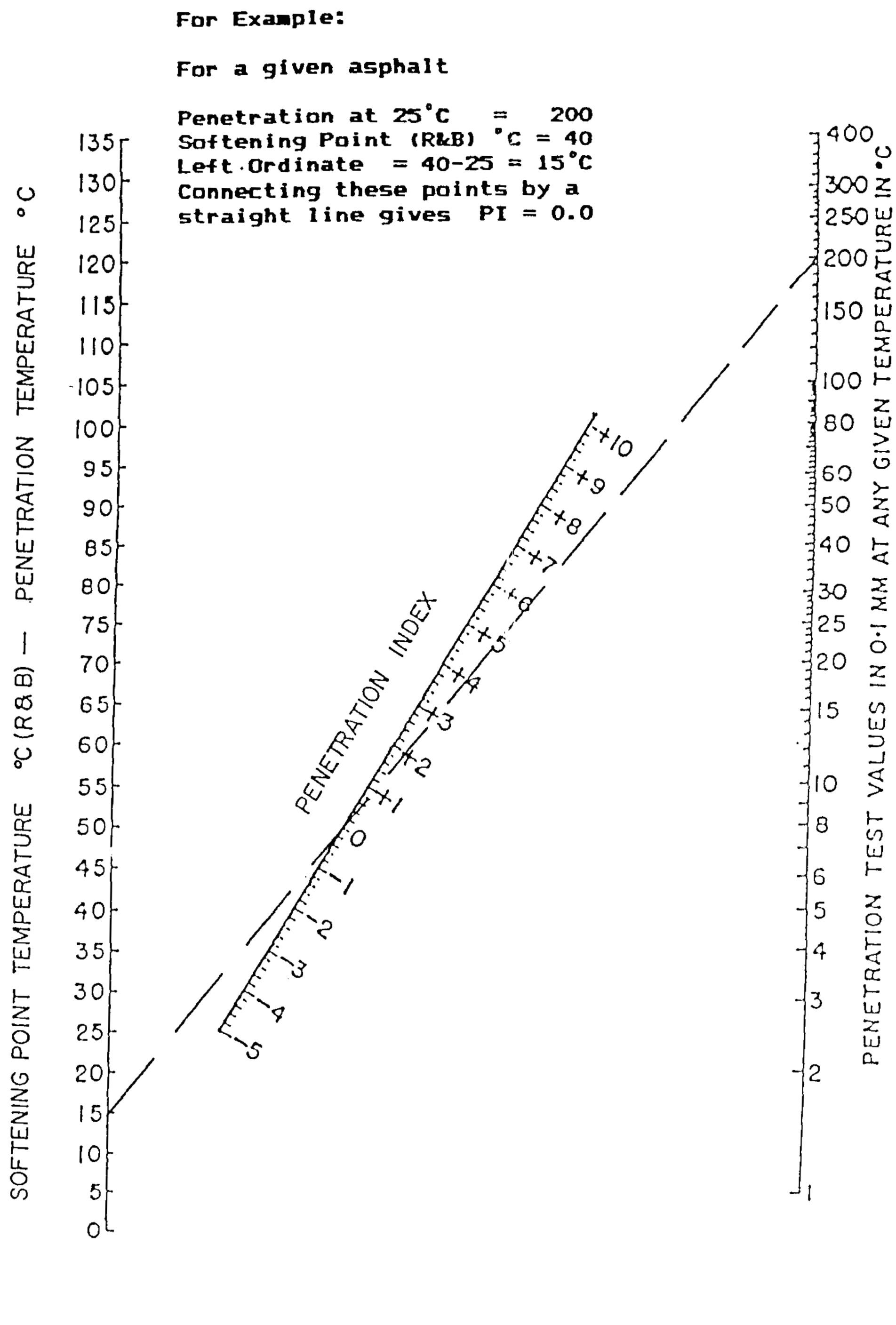


FIG. 9 Pfeiffer's and Van Doormaal's nomograph for paving asphalt temperature susceptibility

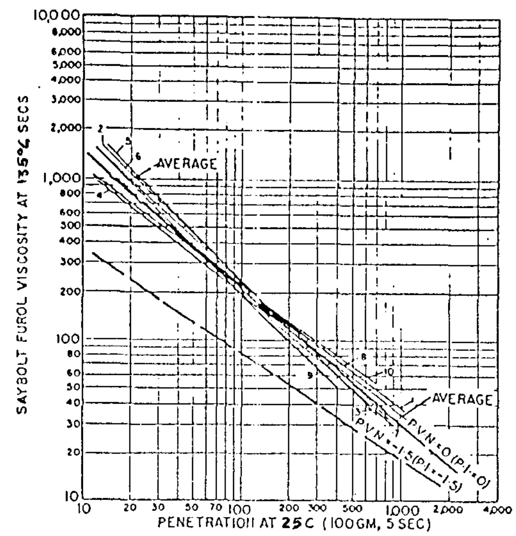


FIG. 10 Relationship between penetration at 25 C and Viscosity at 135 C for Pen-Vis Numbers of 0.0 and -1.5.

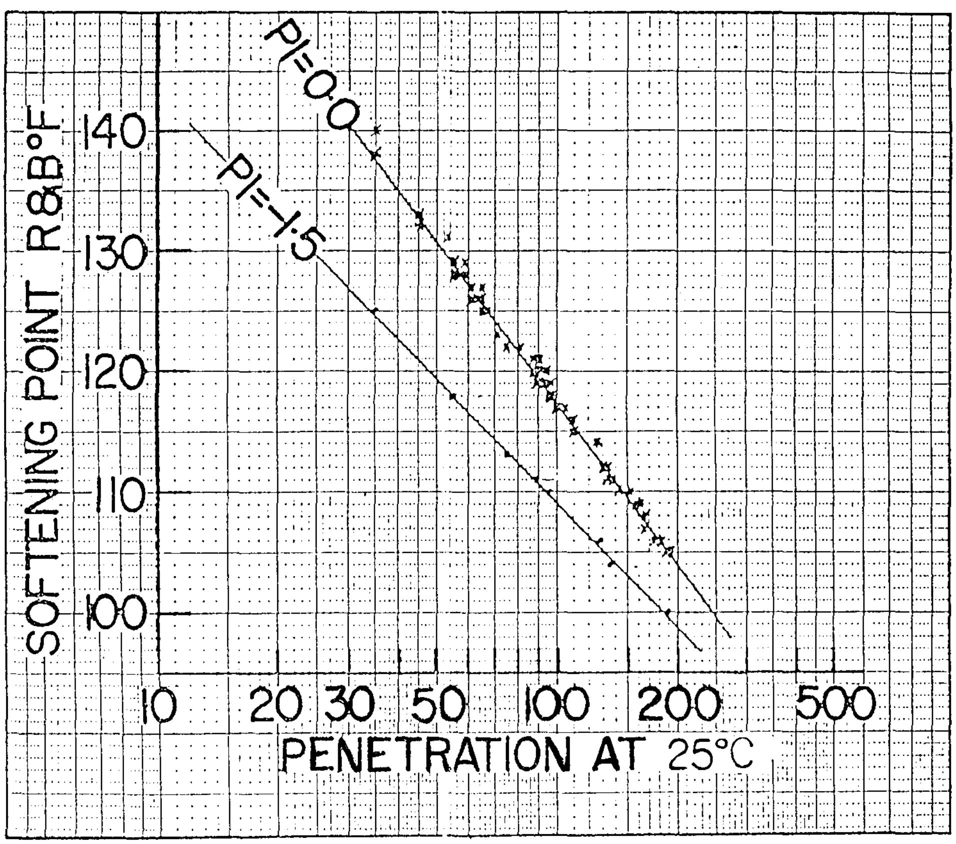


FIG. 11 Illustrating relationships between penetration at 25 C, softening point F (Ring & Ball) and penetration index (PI) values of 0.0 and -1.5 for paving asphalts manufactured by steam or vacuum reduction

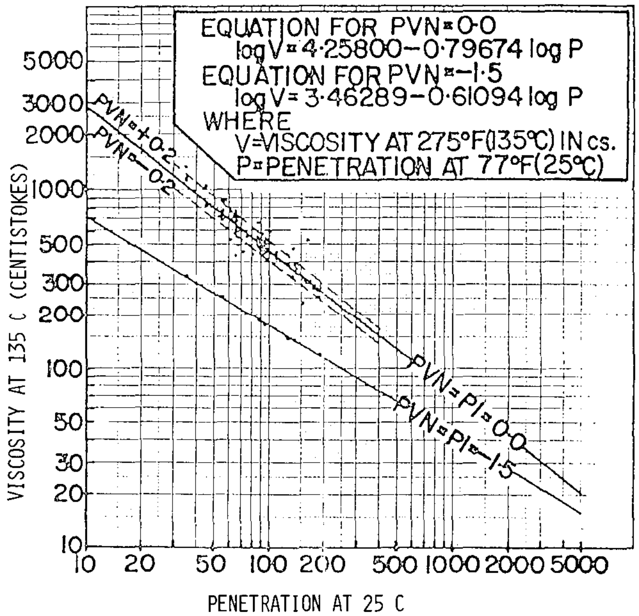


FIG. 12 Illustrating development of pen-vis numbers from relationships betwee viscosity at 135 C in centistokes, penetration at 25 C and penetration indices

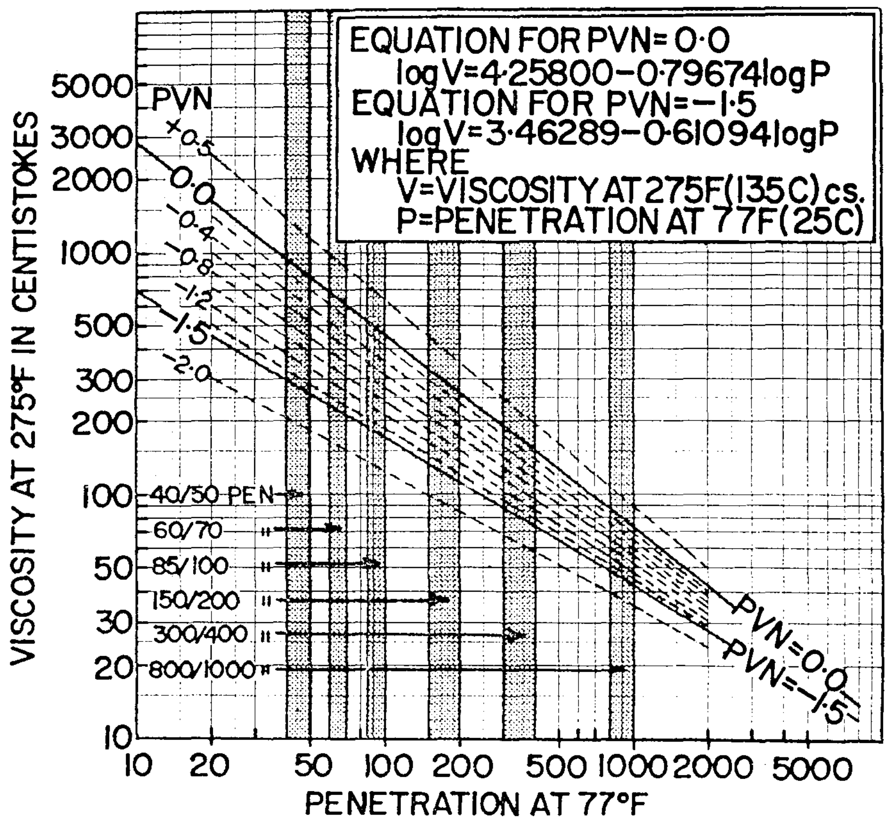


FIG. 13 A chart for the determination of approximate values for pen-vis numbers for asphalt cements

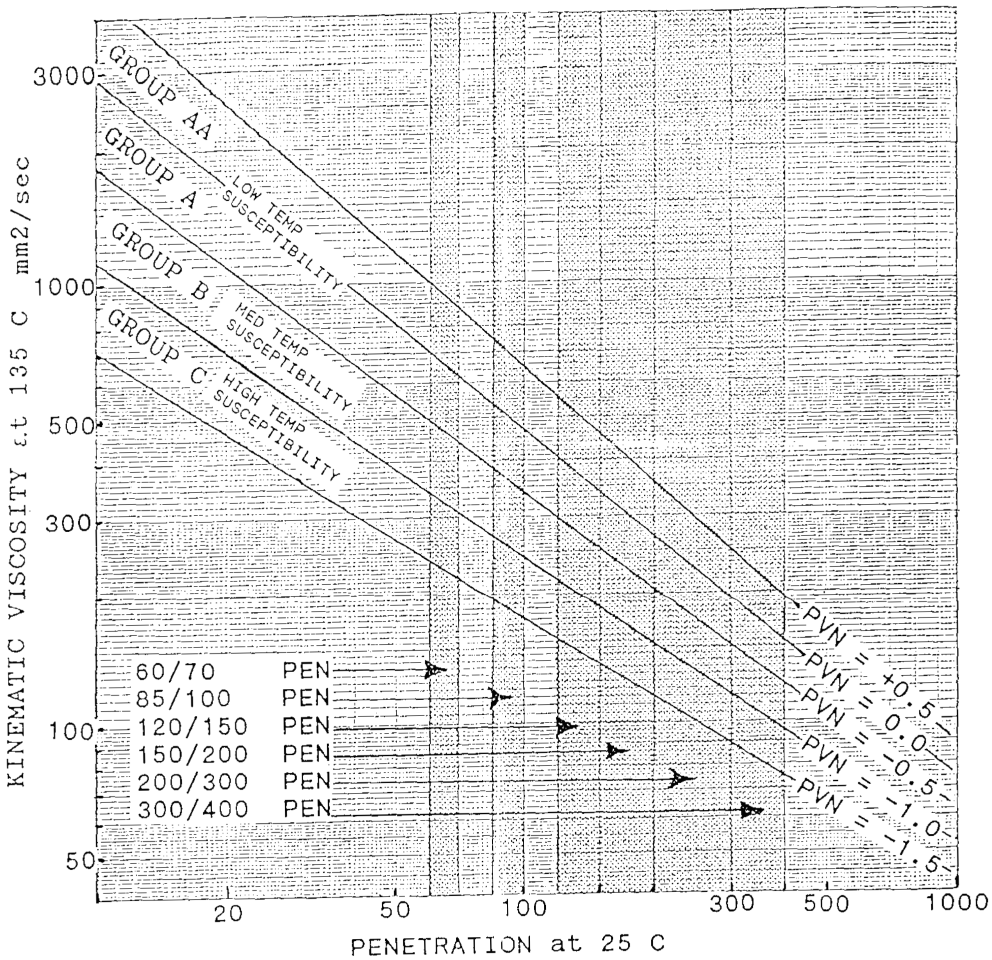


FIG. 14 Illustrating a specification based on penetrations at 25 C, viscosities at 135 C and temperature susceptibilities of paving asphalts

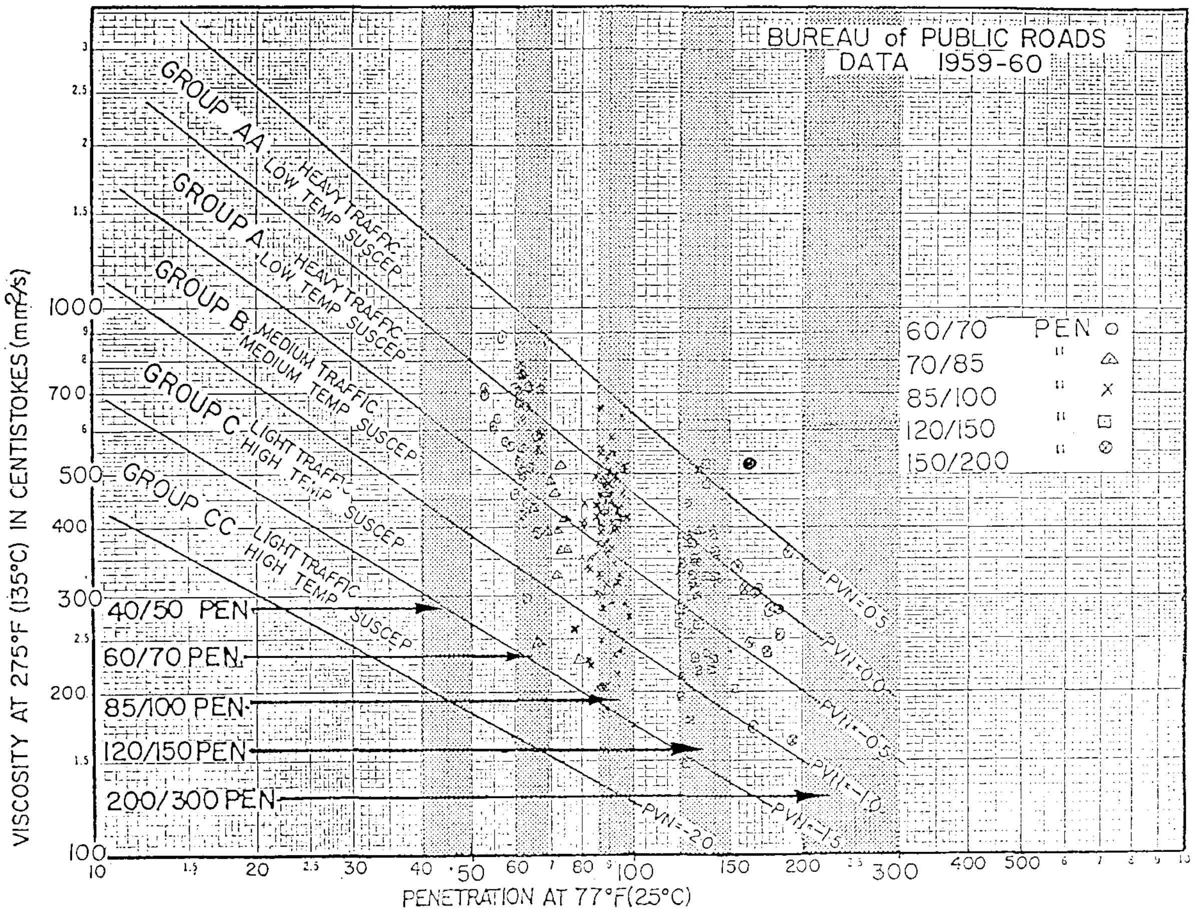


FIG. 15 PAVING ASPHALT TEMPERATURE SUSCEPTIBILITY GROUPS A, B AND C FROM US BUREAU OF PUBLIC ROADS PAVING ASPHALT SAMPLE SURVEY PUBLISHED IN 1959 AND 1960.

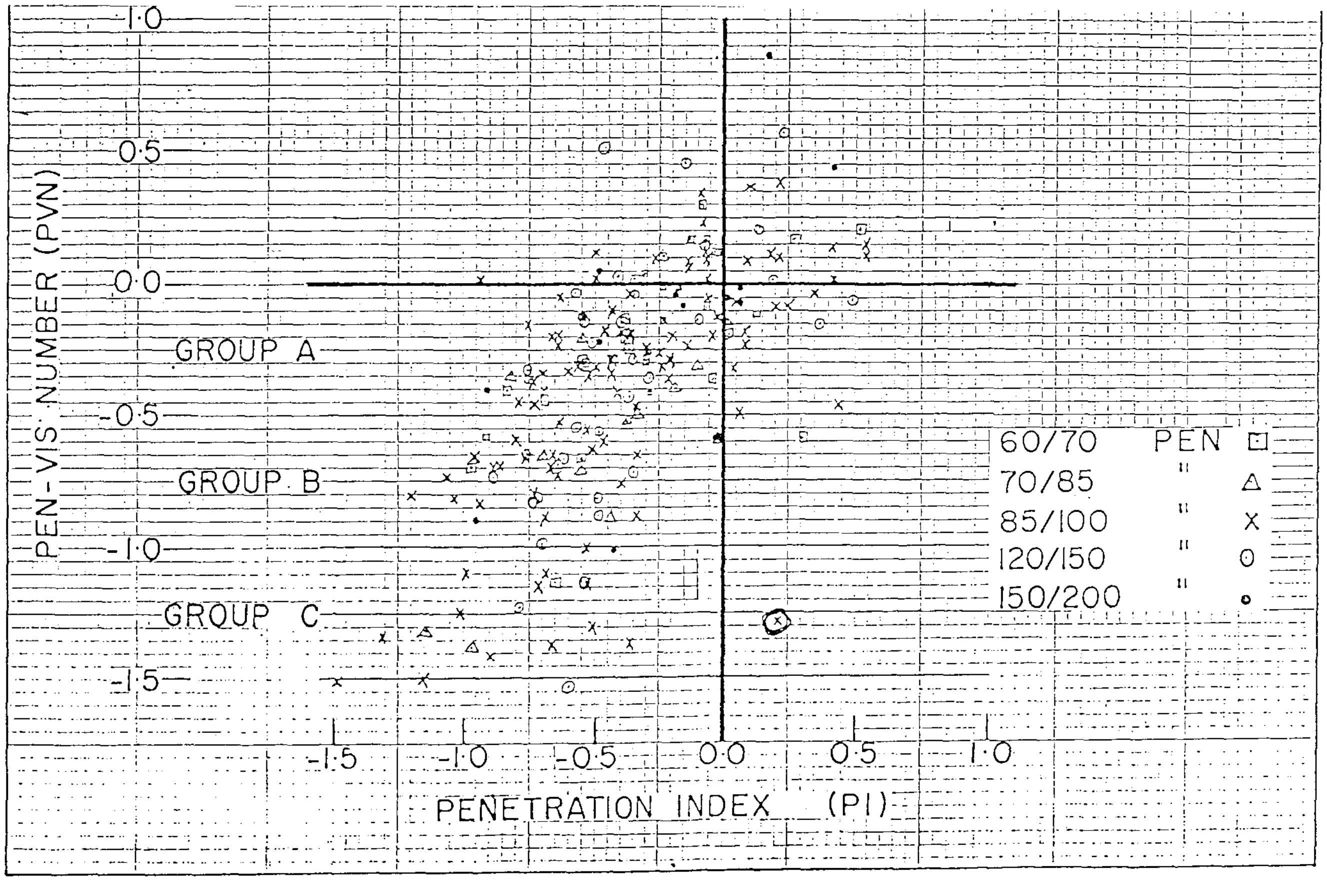


FIG. 16 PLOT OF PVN VALUES VERSUS PFEIFFER'S AND VAN DOORMAL'S PI VALUES FOR THE BUREAU OF PUBLIC ROADS DATA FOR TEMPERATURE SUSCEPTIBILITY GROUPS A, B AND C

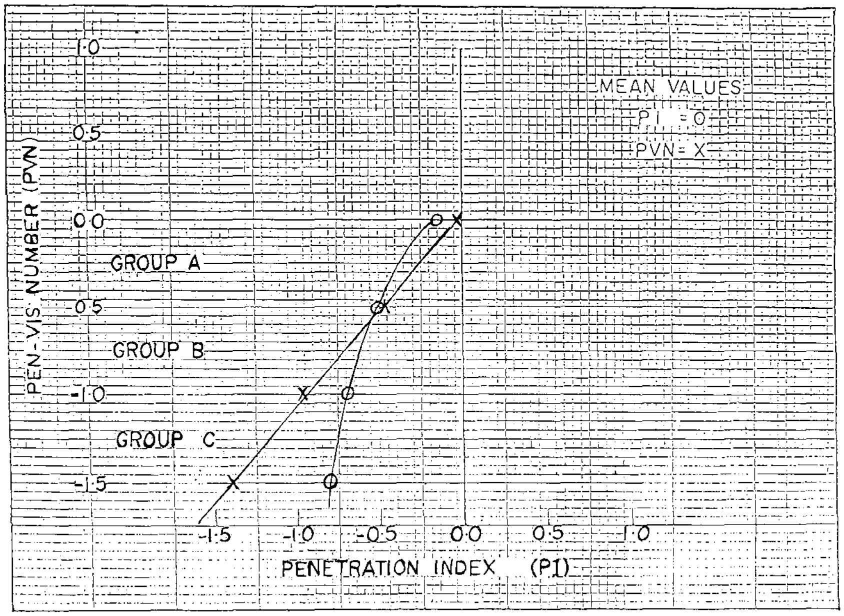


FIG. 17 ABOUT 200 SAMPLES OF PAVING ASPHALTS OBTAINED BY THE U.S. BUREAU OF PUBLIC ROADS DIVIDED INTO TEMPERATURE SUSCEPTIBILITY GROUPS A, B AND C, AND THE MEAN VALUES FOR PVN VERSUS PI DETERMINED FOR EACH GROUP

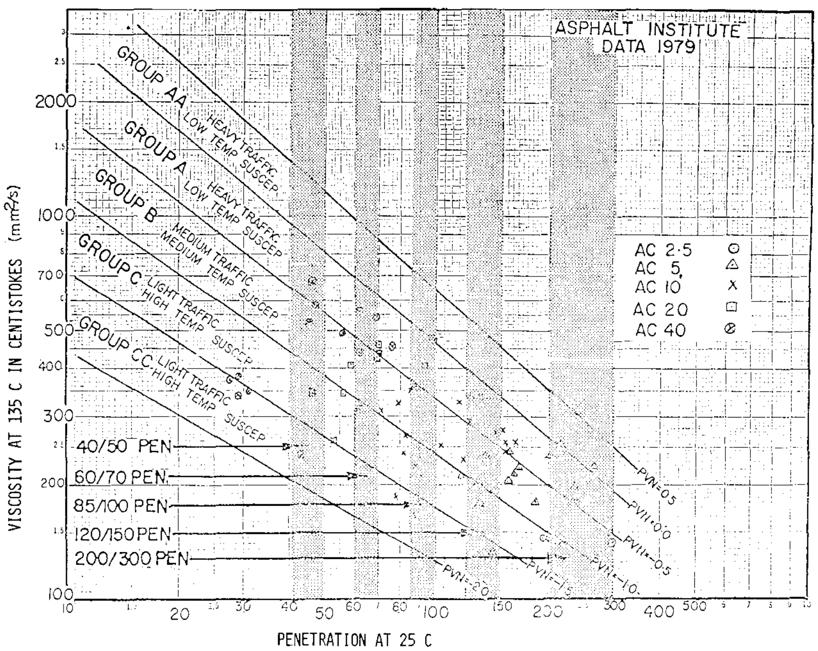


FIG. 18 PAVING ASPHALT TEMPERATURE SUSCEPTIBILITY GROUPS A, B AND C, FROM THE ASPHALT INSTITUTE'S 1979 SURVEY

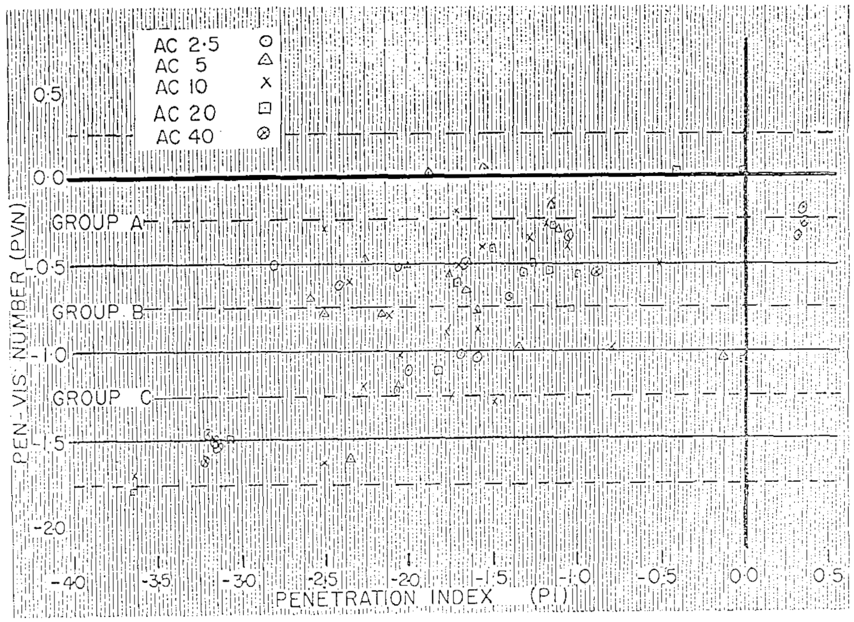


FIG. 19 PLOT OF PVN VERSUS HEUKELOM'S PI VALUES FOR THE ASPHALT INSTITUTE'S DATA

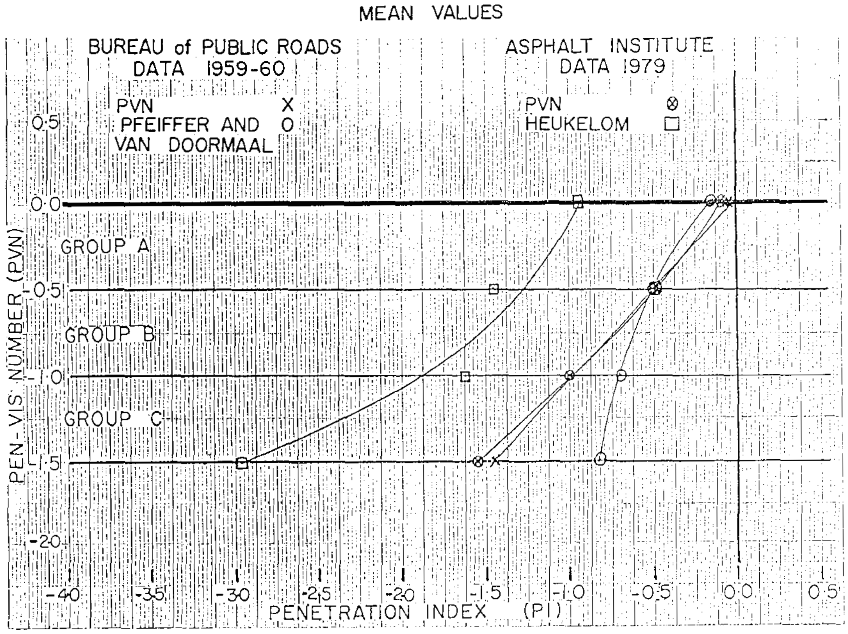


FIG. 20 PLOT OF AVERAGE VALUES OF TEMPERATURE SUSCEPTIBILITY IN TERMS OF PVN VERSUS HEUKELOM'S PI VALUES FOR GROUP A, B AND C FOR THE ASPHALT INSTITUTE'S DATA AND COMPARED WITH SIMILAR VALUES IN FIGURE 17.

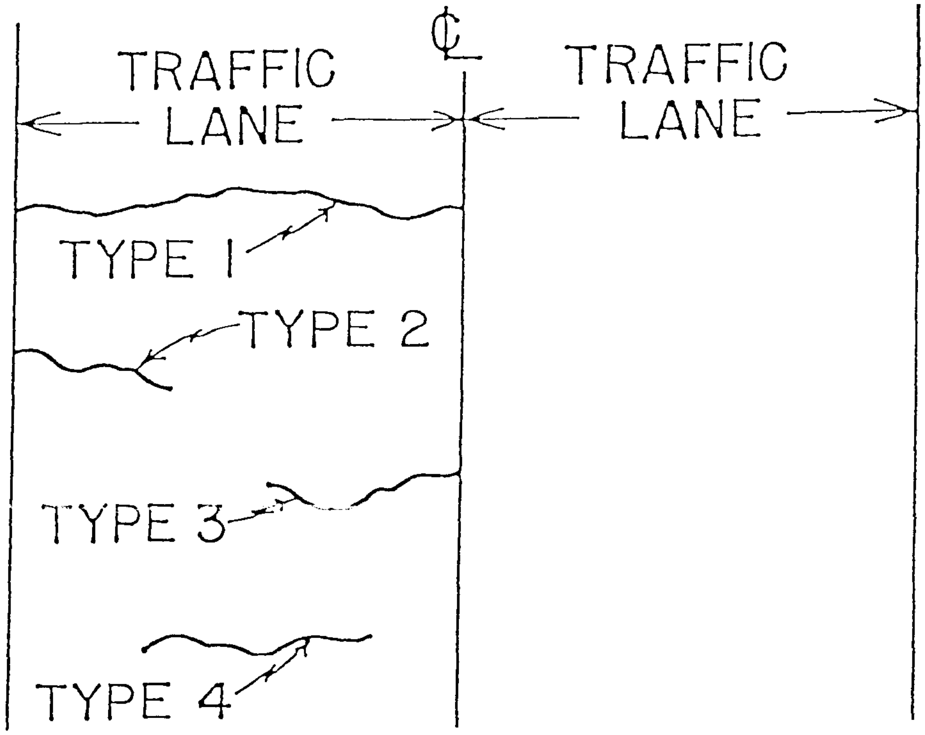


FIG. 21 TYPES OF TRANSVERSE PAVEMENT CRACKS

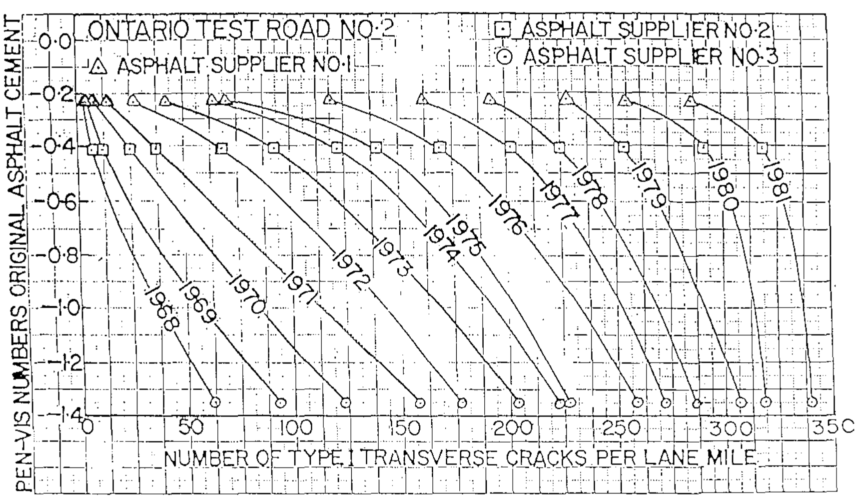


FIG. 22 INFLUENCE OF PAVING ASPHALT TEMPERATURE SUSCEPTIBILITY ON ANNUAL COUNT OF TYPE 1 LOW TEMPERATURE TRANSVERSE PAVEMENT CRACKS PER LANE MILE.

FIG. 23 Pavement with 85/100 penetration asphalt. West of Orangeville. Four years old.

FIG. 24 Pavement with 150/200 penetration asphalt. West of Orangeville. Four years old.

FIG. 25 85/100 penetration asphalt in right lane. 150/200 pen in left lane. Four years old. (Note: Blemish is in the photographic film, not in the pavement)

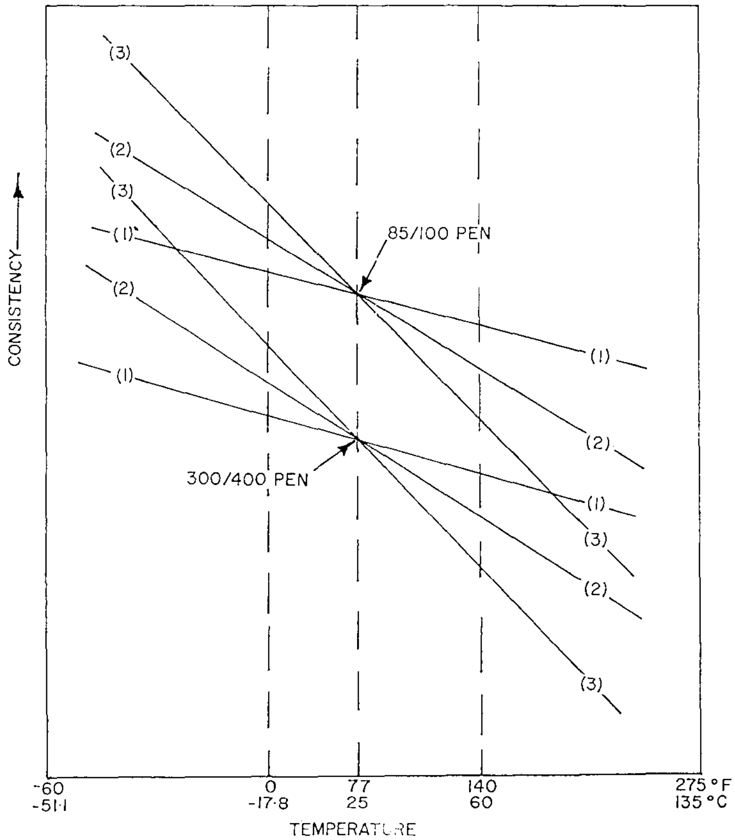


Figure 26 ILLUSTRATING INFLUENCE OF TEMPERATURE SUSCEPTIBILITY ON CONSISTENCY OF TWO ASPHALTS

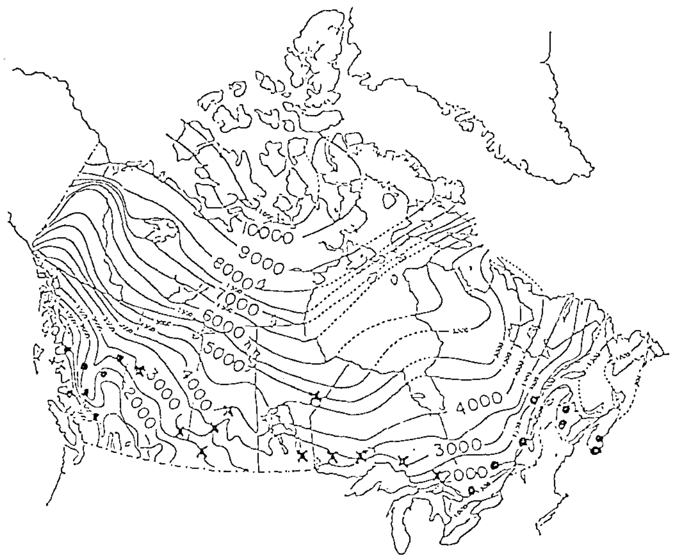


FIG. 27 Approximate locations of the 26 airports (where x's indicate interior airports and o's indicate coastally associated airports). Freezing index contours are in °F days (with credit to Ralph Haas).

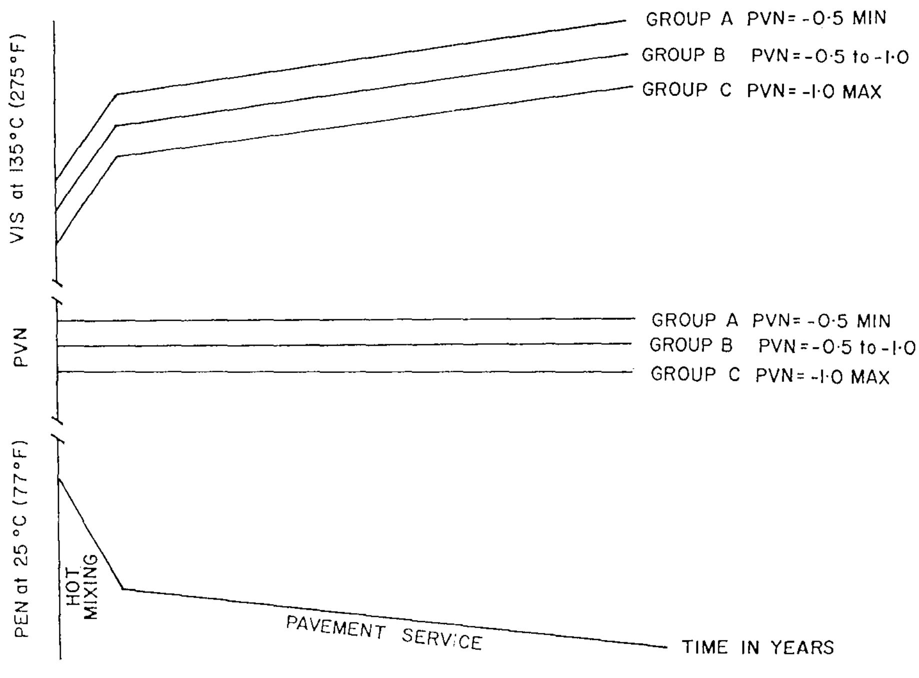


Figure 28 ILLUSTRATING THAT PVN REMAINS CONSTANT AND UNCHANGED WITH TIME AND TEMPERATURE IN SERVICE

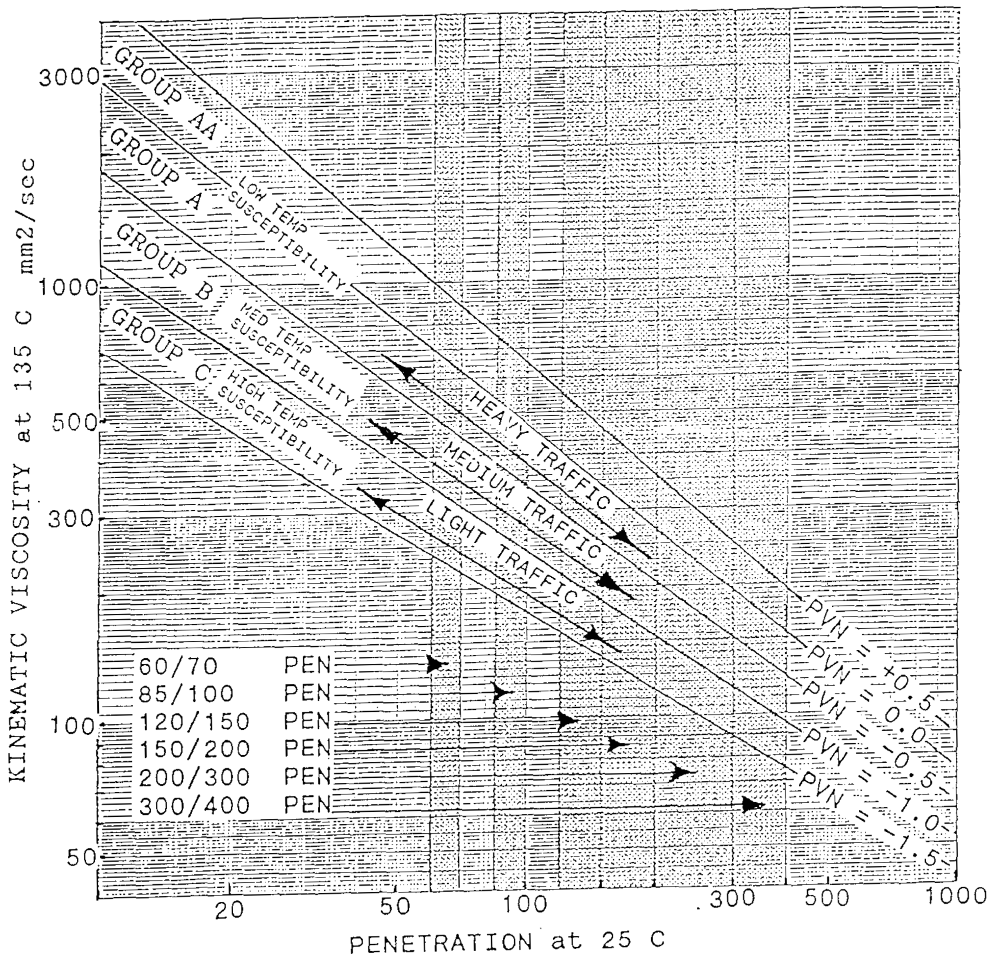


FIG. 29 Illustrating a working specification based on penetrations at 25 C, viscosities at 135 C and temperature susceptibilities of paving asphalts.

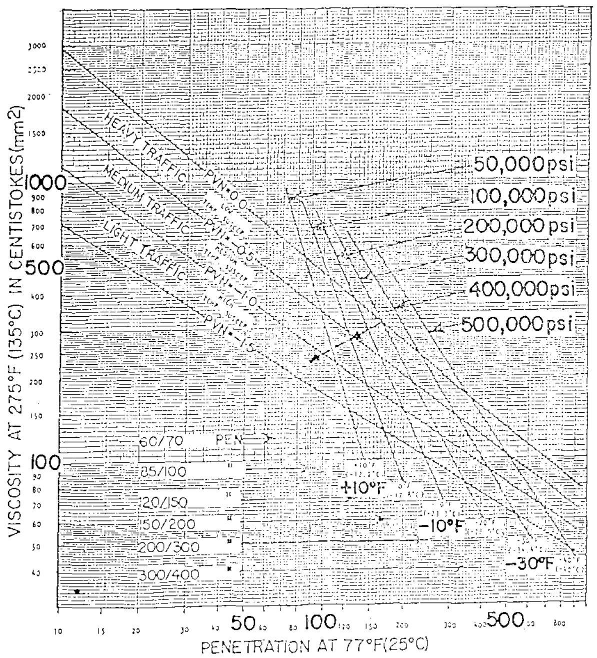


FIG. 30 Chart for selecting paving asphalts with various combinations of temperature susceptibilities and penetrations at 25 C to avoid low temperature transverse pavement cracking at selected minimum winter temperatures.

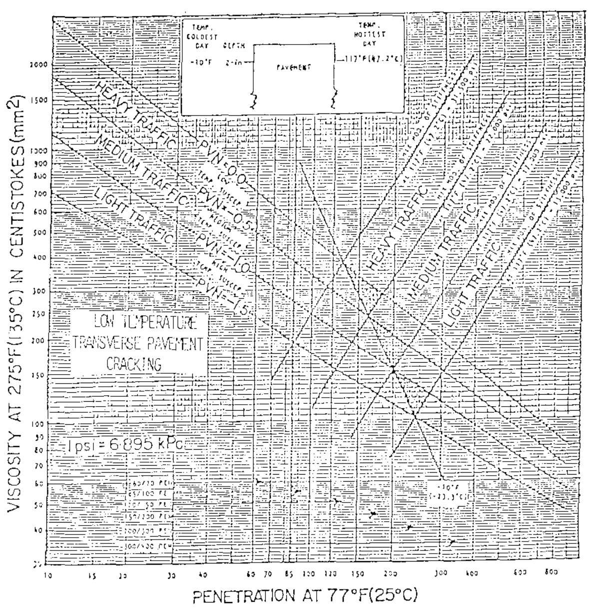


FIG. 31 Illustrating selection of combinations of temperature susceptibility (PVN) and penetration at 25 C for Paving Asphalts for Heavy, Medium and Light traffic in cold climates.

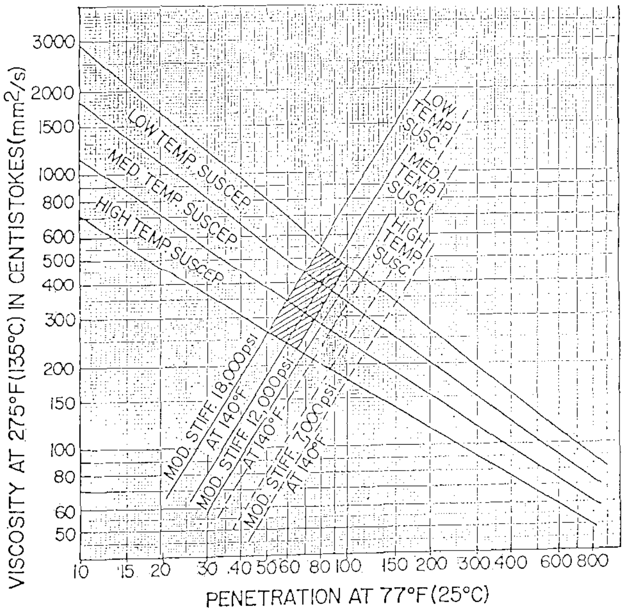


FIG. 32 Illustrating how paving asphalt temperature susceptiblity can be made to work for or against engineers in warm climates.

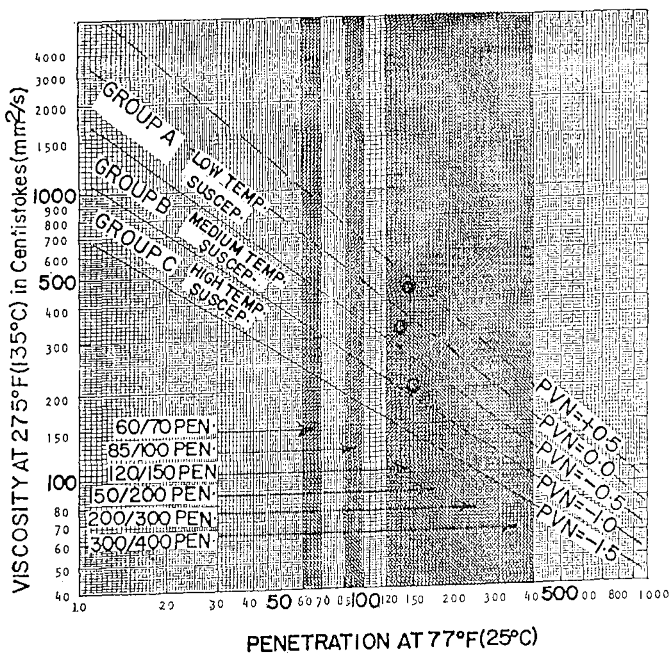


FIG. 33 INFLUENCE OF A POLYMER ON THE TEMPERATURE SUSCEPTIBILITY OF A PAVING ASPHALT

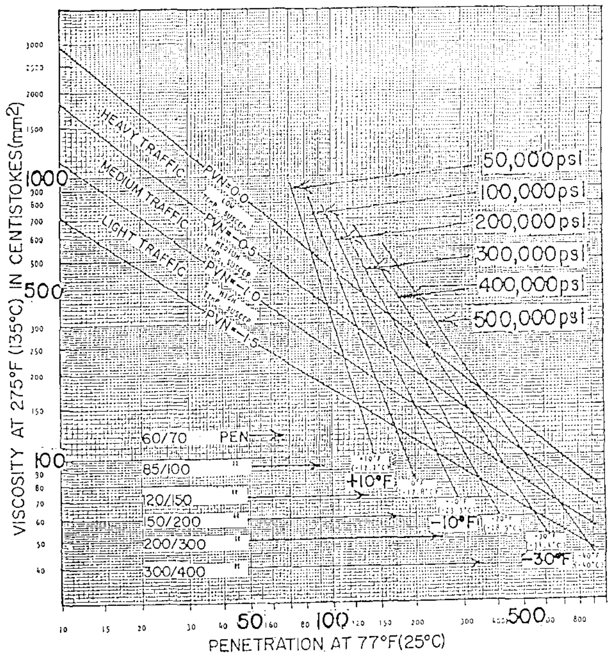


FIG. 34 Illustrating a possible shift to a lower temperature at which low temperature transverse pavement cracking might begin because of the greater elasticity of certain polymer modified asphalts.

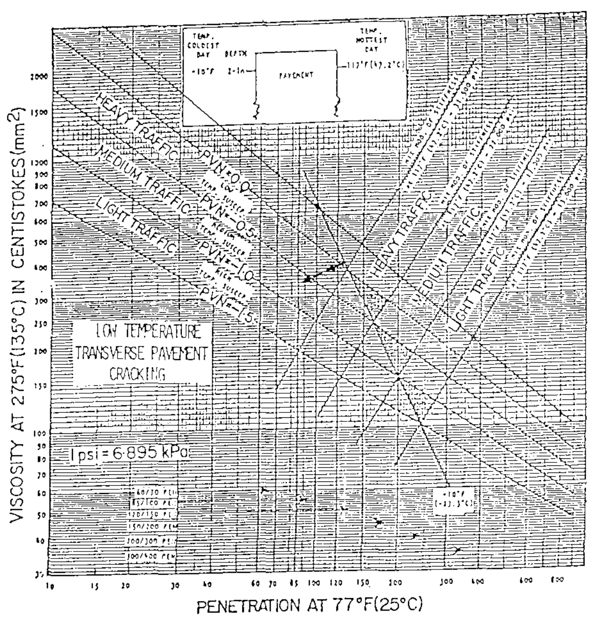


FIG. 34A Illustrating selection of combinations of temperature susceptibility (PVN) and penetration at 25 C for paving asphalts for heavy, medium and light traffic in cold climates where the minimum temperature is -23.3 C.

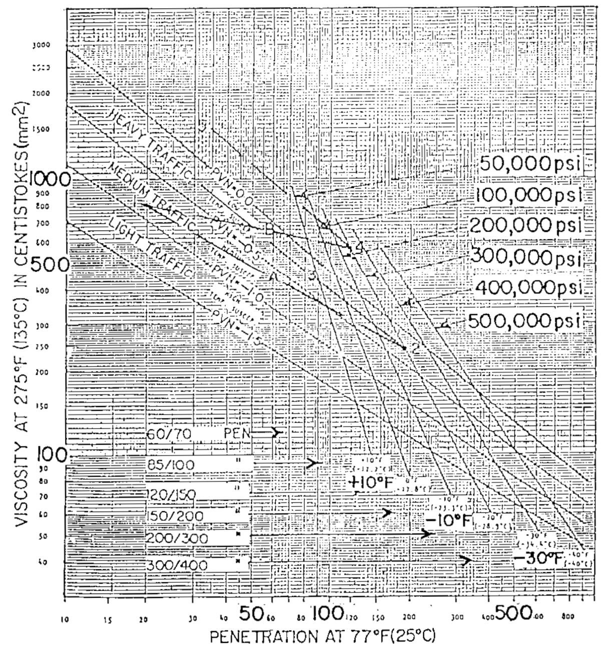


FIG. 35 Illustrating a rational method for pavement recycling in regions subject to freezing.

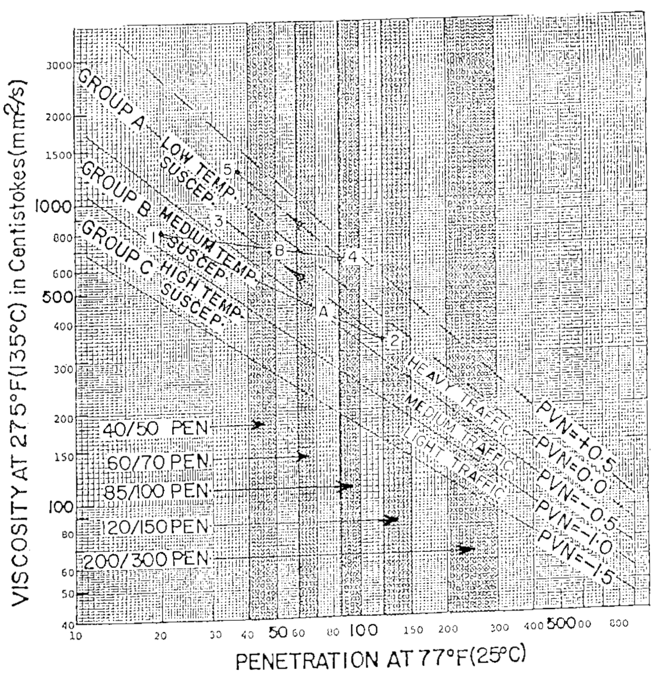


FIG. 36 Illustrating a rational method for pavement recycling in warm climates without freezing.

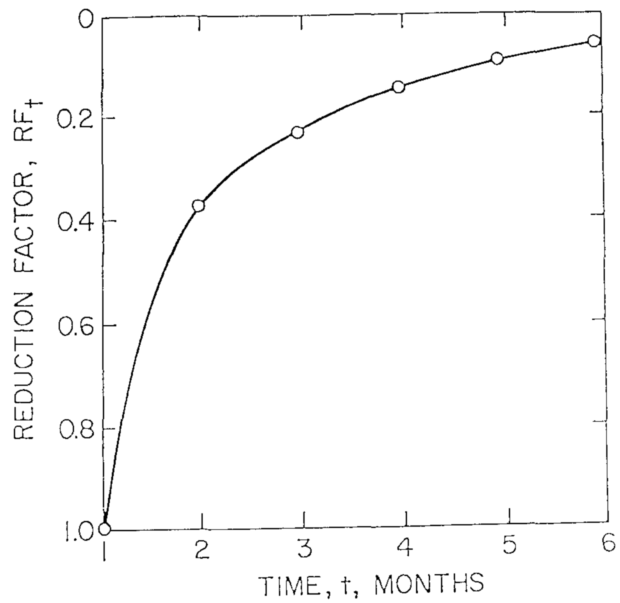


FIG. 37 Demonstrating that a curing period of about six months is required for an asphalt emulsion mix to develop its full strength.

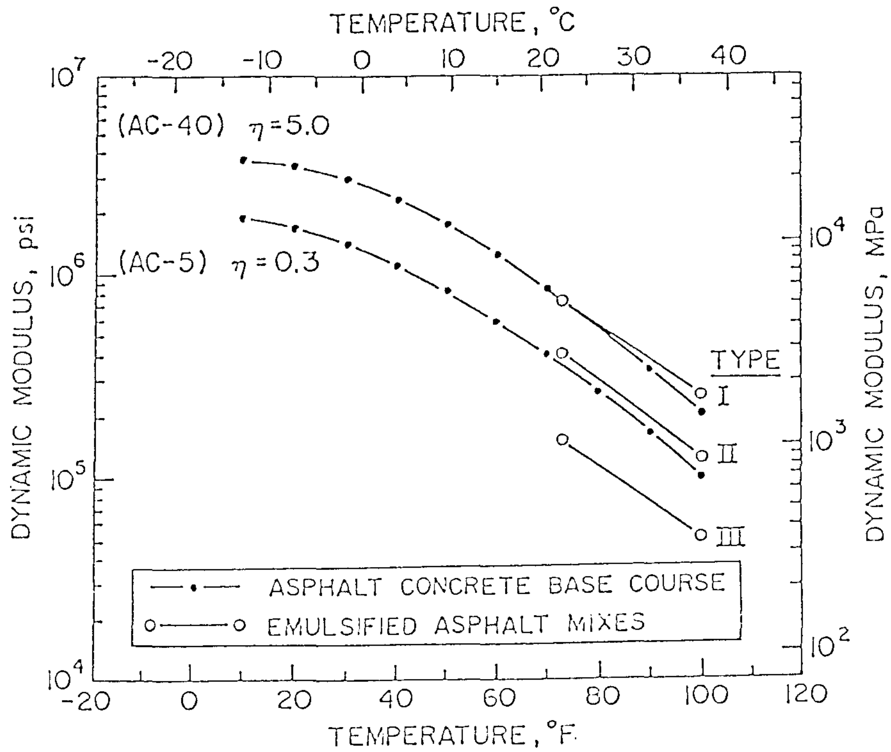


FIG. 38 Demonstrating that depending on its type (I,II or III) an asphalt emulsion mix eventually develops strength equivalent to that of a corresponding hot mix.

APPENDIX A

DETERMINATION OF THE PVN VALUE FOR ANY PAVING ASPHALT MANUFACTURED BY STEAM OR VACUUM DISTILLATION

As indicated by Fig. A, the equation for the least squares line representing a PVN of 0.0 is

$$\log V = 4.25800 - 0.79674 \log P \qquad \text{Equation 1}$$

and for the least squares line representing a PVN or -1.5 is

$$\log V = 3.46289 - 0.61094 \log P \qquad \text{Equation 2}$$

where V is the viscosity in centistokes at 135°C and P is the penetration at 25°C.

The PVN of any asphalt cement for which the penetration at 25°C and viscosity in centistokes at 135°C are known can be calculated from the following equation:

$$PVN = [(\log L - \log X)/(\log L - \log M)]\ (-1.5) \qquad \text{Equation 3}$$

where
X = viscosity in centistokes at 135°C associated with the penetration at 25°C of an asphalt cement
L = viscosity in centistokes at 135°C for a PVN of 0.0 for the penetration at 25°C of the asphalt cement and
M = viscosity in centistokes at 135°C for a PVN of -1.5 for the penetration at 25°C of the asphalt cement.

EXAMPLE

Suppose that the penetration at 25°C of a certain asphalt cement manufactured by steam or vacuum distillation is 150 and its viscosity at 135°C is 194 centistokes. What is its PVN ?

The viscosity L at 135°C for a PVN = 0.0 for an asphalt cement of 150 penetration at 25°C is obtained by substitution into Equation 1

$$\begin{aligned} \log V &= 4.25800 - 0.79674 \log 150 \\ &= 4.25800 - 0.79674\ (2.17609) \\ &= 2.52422 \\ V &= 334.4 \text{ centistokes} = L \end{aligned}$$

The viscosity M at 135 C for a PVN = -1.5 for an asphalt cement of 150 penetration is provided by susbtitution in Equation 2

$$\begin{aligned} \log V &= 3.46289 - 0.61094 \log 150 \\ &= 3.46289 - 0.61094\ (2.17609) \\ &= 2.13343 \\ V &= 136 \text{ centistokes} = M \end{aligned}$$

The PVN can now be obtained by substituting the values L, M and X in Equation 3.

$$\begin{aligned} PVN &= [(2.52422 - \log 194)/(\log 334.4 - \log 136)]\ (-1.5) \\ &= [(2.52422 - 2.28780)/(2.52422 - 2.13343)]\ (-1.5) \\ &= [0.23642/0.39079]\ (-1.5) \\ &= -0.91 \end{aligned}$$

Therefore the PVN for an asphalt cement of 150 penetration at 25° C with a viscosity of 194 centistokes at 135°C is **-0.91.**

An approximate value for the PVN for any paving asphalt can be obtained by interpolation after plotting the point representing corresponding values for penetration at 25°C and viscosity at 135°C in Figure A (which was prepared on the basis of Equations 1, 2 and 3).

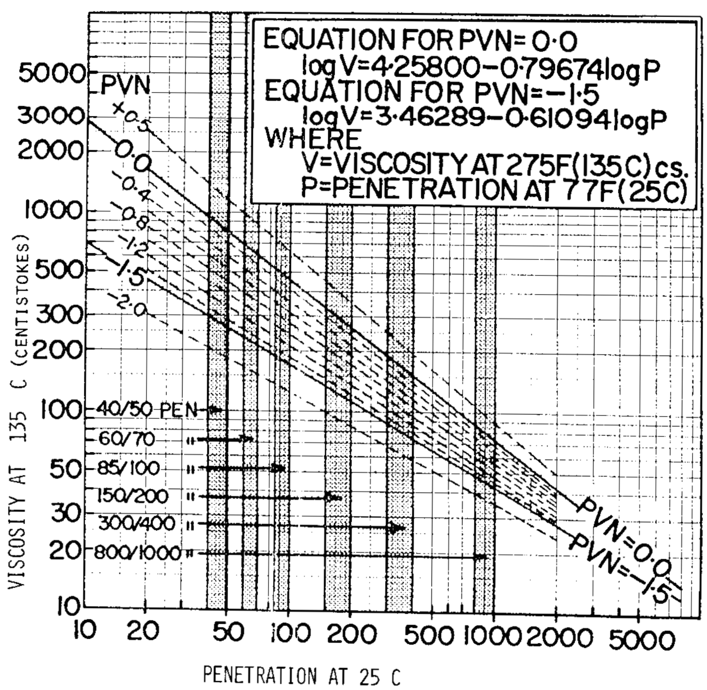


Figure A A chart for the determination of approximate values for Pen-Vis Numbers for asphalt cements

APPENDIX B-1

This specification is for general use for penetration-graded paving asphalts with temperature susceptibility requirements, manufactured by steam or vacuum distillation. It is modelled after ASTM D946 to which temperature susceptibility requirements have been added.

STANDARD SPECIFICATION FOR PENETRATION-GRADED PAVING ASPHALTS WITH TEMPERATURE SUSCEPTIBILITY REQUIREMENTS FOR USE IN PAVEMENT CONSTRUCTION

1. Scope

1.1 This specification covers asphalt cement for use in the construction of pavements.

1.2 This specification applies to the following penetration grades:

60 - 70	150 - 200
80 - 100	200 - 300 and
120 - 150	300 - 400

1.3 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards

D5 Test Method for Penetration of Bituminous Materials
D92 Test Method for Flash and Fire Points by Cleveland Open Cup
D113 Test Method for Ductility of Bituminous Materials
D140 Methods of Sampling Bituminous Materials
D1754 Test Method for Effect of Heat and Air on Asphaltic Materials (Thin-Film Oven Test)
D2042 Test Method for Solubility of Asphalt Materials in Trichloroethylene
D2170 Standard Test Method for Kinematic Viscosity

3. Manufacture

3.1 Asphalt cement shall be prepared by the refining of crude petroleum by steam or vacuum distillation.

4. Properties

4.1 The asphalt cement shall be homogeneous and shall not foam when heated to 347 F (174 C).

4.2 The various grades of asphalt cement shall conform to the requirements prescribed in Table 1.

5. Methods of Sampling and Testing

5.1 The materials shall be sampled and the properties enumerated in this specification shall be determined in accordance with the following ASTM methods:

5.1.1 Sampling - Method D140

5.1.2 Penetration - Method D5

5.1.3 Flash Point - Method D92

5.1.4 Ductility - Method D113

5.1.5 Thin Film Oven Test - Method D1754

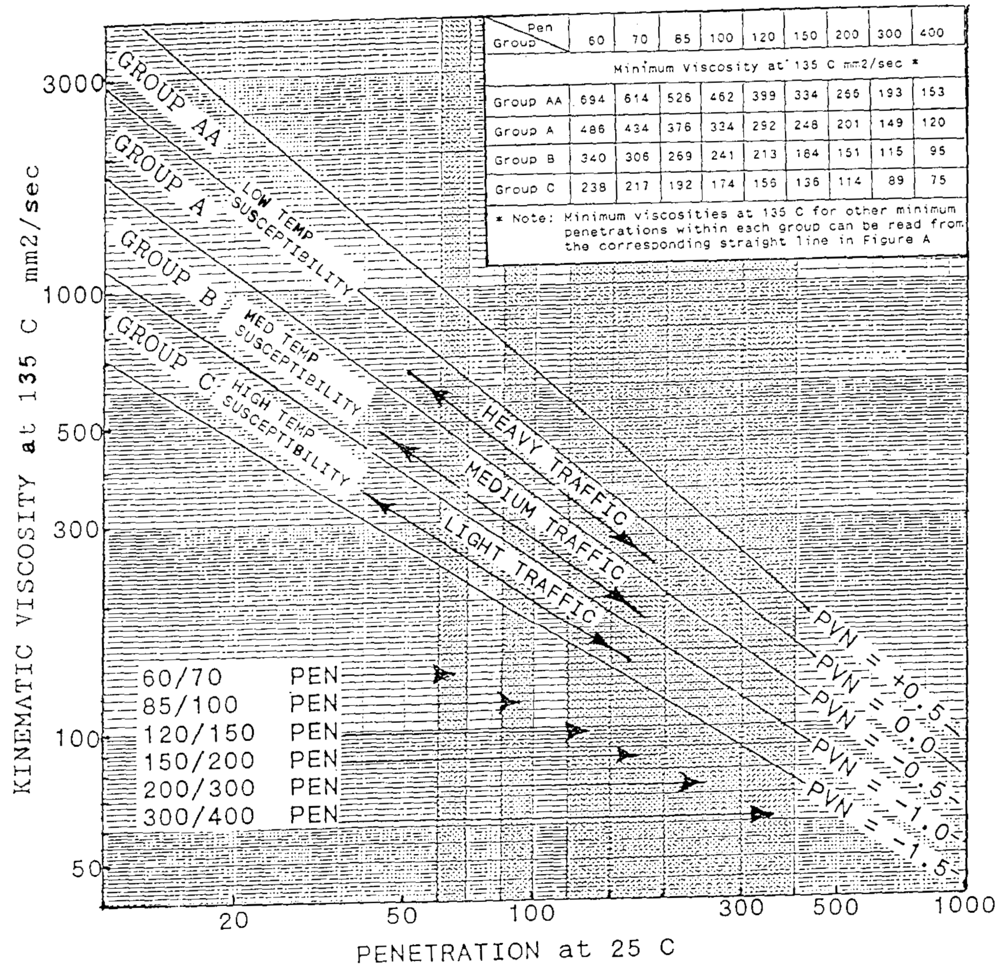
5.1.6 Solubility in Trichloroethylene - Method D2042

5.1.7 Kinematic Viscosity - Method D2170

Table 1. Requirements for Paving Asphalts
for Use in Pavement Construction

Test	PENETRATION GRADE											
	60-70		80-100		120-150		150-200		200-300		300-400	
	min	max	min	max	min	max	min	max	min	max	min	max
Penetration at 25 C (77 F) 100g 5sec	60	70	80	100	120	150	150	200	200	300	300	400
Kinematic Viscosity at 135 C (275 F) mm/s												
Group A	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-
Group B	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-
Group C	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-	see Fig B-1	-
Flash Point (Cleveland Open Cup) F	230	-	230	-	220	-	220	-	175	-	175	-
Ductility at 25 C (77 F) 5 cm/min cm	100	-	100	-	100	-	100	-	100	-	100[A]	-
Solubility in Trichloroethylene, %	99.0	-	99.0	-	99.0	-	99.0	-	99.0	-	99.0	-
Residue from Thin-film Oven Test Retained penetration %	52+	-	47+	-	42+	-	40+	-	37+	-	35+	-
Ductility at 25 C (77 F) 5 cm/min cm after thin-film oven test	50	-	75	-	100	-	100	-	100[A]	-	100[A]	-

[A] If ductility at 25 C (77 F) is less than 100 cm, material will be accepted if ductility at 15.5 C (60 F) is 100 cm at a pull rate of 5 cm/min.



Group \ Pen	60	70	85	100	120	150	200	300	400
	Minimum Viscosity at 135 C mm2/sec *								
Group AA	694	614	526	462	399	334	266	193	153
Group A	486	434	376	324	292	248	201	149	120
Group B	340	306	269	241	213	184	151	115	95
Group C	238	217	192	174	156	136	114	89	75

* Note: Minimum viscosities at 135 C for other minimum penetrations within each group can be read from the corresponding straight line in Figure A

Figure B-1 Illustrating a specification based on penetrations at 25 C, viscosities at 135 C and temperature susceptibilities of paving asphalts

APPENDIX B-2

This working specification is for use with penetration-graded paving asphalts with temperature susceptibility requirements, manufactured by steam or vacuum distillation. It is modelled after ASTM D946 to which temperature susceptibility requirements have been added.

This working specification avoids the need for a manual to indicate its proper application.

WORKING SPECIFICATION FOR PENETRATION-GRADED PAVING ASPHALTS WITH TEMPERATURE SUSCEPTIBILITY REQUIREMENTS FOR USE IN PAVEMENT CONSTRUCTION

1. Scope

1.1 This specification covers asphalt cement for use in the construction of pavements.

1.2 This specification applies to the following penetration grades:

60 - 70	150 - 200
80 - 100	200 - 300 and
120 - 150	300 - 400

1.3 This standard may involve hazardous materials, operations, and equipment. This standard does not purport to address all the safety problems associated with its use. It is the responsibility of whoever uses this standard to consult and establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards

D5 Test Method for Penetration of Bituminous Materials
D92 Test Method for Flash and Fire Points by Cleveland Open Cup
D113 Test Method for Ductility of Bituminous Materials
D140 Methods of Sampling Bituminous Materials
D1754 Test Method for Effect of Heat and Air on Asphaltic Materials (Thin-Film Oven Test)
D2042 Test Method for Solubility of Asphalt Materials in Trichloroethylene
D2170 Standard Test Method for Kinematic Viscosity

3. Manufacture

3.1 Asphalt cement shall be prepared by the refining of crude petroleum by steam or vacuum distillation.

4. Properties

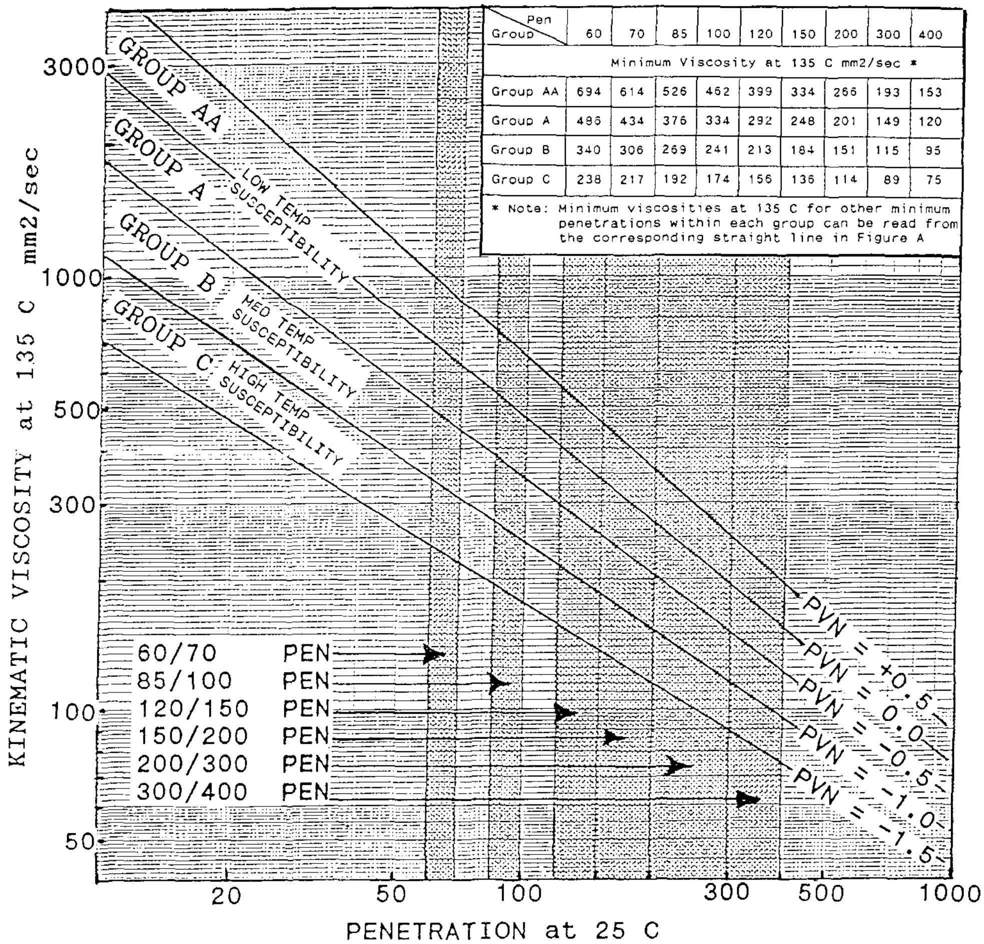
4.1 The asphalt cement shall be homogeneous and shall not foam when heated to 347 F (174 C).

4.2 The various grades of asphalt cement shall conform to the requirements prescribed in Table 1.

5. <u>Methods of Sampling and Testing</u>

5.1 The materials shall be sampled and the properties enumerated in this specification shall be determined in accordance with the following ASTM methods:

5.1.1 Sampling - Method D140
5.1.2 Penetration - Method D5
5.1.3 Flash Point - Method D92
5.1.4 Ductility - Method D113
5.1.5 Thin Film Oven Test - Method D1754
5.1.6 Solubility in Trichloroethylene - Method D2042
5.1.7 Kinematic Viscosity - Method D2170



Group \ Pen	60	70	85	100	120	150	200	300	400
	Minimum Viscosity at 135 C mm2/sec *								
Group AA	694	614	526	462	399	334	266	193	153
Group A	486	434	376	334	292	248	201	149	120
Group B	340	306	269	241	213	184	151	115	95
Group C	238	217	192	174	156	136	114	89	75

* Note: Minimum viscosities at 135 C for other minimum penetrations within each group can be read from the corresponding straight line in Figure A

Figure B-2 Illustrating a working specification based on penetrations at 25 C, viscosities at 135 C and temperature susceptibilities of paving asphalts